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Effects of Hurricanes, Land Use, and Water Management on Nutrient and Microbial Pollution: St. Lucie Estuary, Southeast Florida

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ABSTRACT

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Multiple hurricanes impacted southeast Florida during 2004 and 2005, producing record rainfall and large-scale stormwater runoff into the urbanized St. Lucie Estuary (SLE). To assess effects on water quality, field samples were taken in June and November 2005 and March 2006 along the SLE's three main segments: the South Fork, connected *via* the C-44 canal to Lake Okeechobee; the North Fork, which receives residential and agricultural runoff from the C-23 and C-24 canals; and the Middle Estuary, which flows into the Indian River Lagoon and Atlantic Ocean. Salinities were <1‰ throughout the normally brackish estuary during the 2005 samplings, but returned to near-normal levels by March 2006 in all but the South Fork. Low salinities in 2005 correlated with low dissolved oxygen, high turbidity, elevated nitrogen and phosphorus concentrations, and high fecal and total coliform counts. Highest turbidity (84.4 NTU), nitrate (37.9 μM), and total dissolved nitrogen (130.8 μM) concentrations occurred in the South Fork, whereas the highest ammonium (15.4 μM), soluble reactive phosphorus (10.5 μM), and total dissolved phosphorus (13.8 μM) concentrations occurred in the North Fork. High fecal and total coliform counts occurred in tidal creeks adjacent to dense residential areas that rely on septic tanks for on-site sewage disposal. The data suggest that increased stormwater retention, minimization of freshwater releases from Lake Okeechobee, and enhanced treatment of both stormwater and sewage are needed to mitigate future stormwater-driven water quality perturbations in the SLE.

ADDITIONAL INDEX WORDS: *Rainfall, stormwater, salinity, nitrogen, phosphorus, coliform, bacteria.*

INTRODUCTION

The St. Lucie Estuary (SLE) comprises one of the largest estuaries on the east coast of Florida and is a primary tributary to the southern Indian River Lagoon (IRL). Located along the Martin County/St. Lucie County line near the City of Stuart in southeast Florida, the SLE is classified as Class III waters suitable for recreation, propagation, and maintenance of a healthy, well-balanced population of fish and wildlife (62–302.530 Florida Administrative Code [F.A.C.]). The upper SLE includes the lower-salinity North and South forks of the St. Lucie River, which converge to form the higher-salinity Middle Estuary (Figure 1). The Middle Estuary flows east to the IRL and St. Lucie Inlet, which was dug in 1892 to facilitate tidal exchange between the SLE and Atlantic Ocean.

The SLE has experienced increasing human impacts because of population growth, land-use changes, and alteration of watershed drainage patterns (FDEP Staff, 2009; SFWMD, FDEP, and FDACS Staff, 2009). Historically, the SLE had a relatively small natural watershed. However, the network of locks and water control structures constructed during the past century to allow drainage for expanding urban growth and agriculture has artificially enlarged that boundary. Hydrological alterations began in 1924, when the South Fork of the SLE was physically connected to Lake Okeechobee *via* the C-44 canal (St. Lucie canal; Blake, 1980). Additional modifications, extending to the headwaters of the North Fork, were made during the early and mid 1900s to increase the receiving capacity of this system (Herren *et al.,* 2011). The increased receiving capacity was needed to accommodate freshwater inputs from the C-23 and C-24 canals connected to the North Fork in the 1950s and the previously connected C-44 Canal, which together have expanded the natural watershed to include most of Martin and St. Lucie counties (Figure 1). Although the C-44 Canal normally conveys runoff from the C-44 basin to the SLE (Figure 1), periodic freshwater releases (2500–10,000 cfs) have been made from Lake Okeechobee to control lake water levels (Doering, 1996).

Freshwater releases from Lake Okeechobee through the C-44 have caused extreme fluctuations in salinity and pollution in the SLE, severely affecting seagrass and oyster reef commu-

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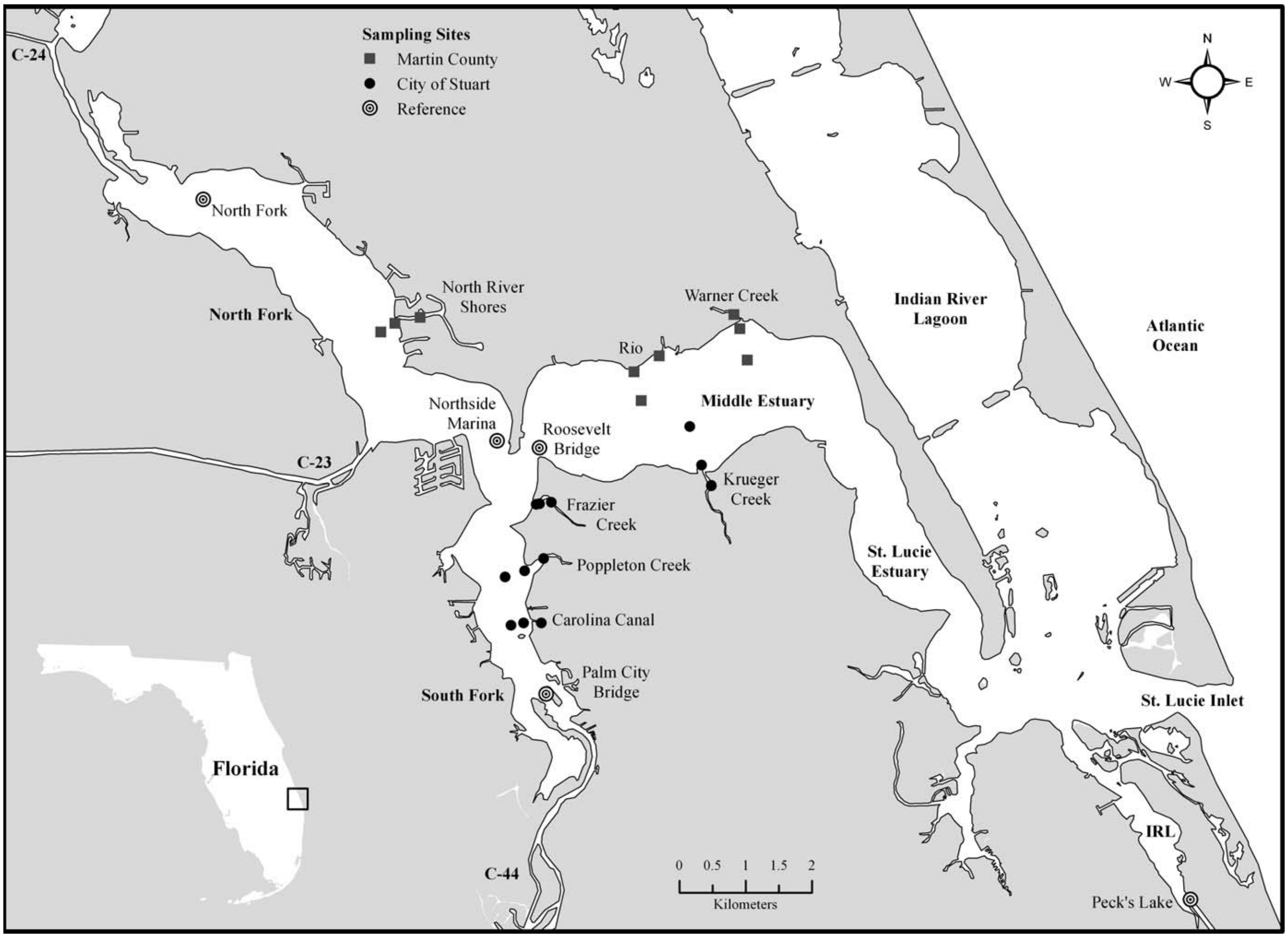

Figure 1. Sampling locations within the St. Lucie Estuary and Indian River Lagoon, Florida.

nities through hyposmotic stress, sedimentation, light reduction, nutrient enrichment, and harmful algal blooms (Haunert and Startzman, 1985; Phlips *et al.*, 2012). Historical accounts indicate that the flora and fauna of the SLE were once rich and diverse and that good water quality supported submerged aquatic vegetation and oyster reefs (Chamberlain and Hayward, 1996). This historical condition is thought to have resulted from the combination of relatively clean freshwater inputs (Chamberlain and Haywood, 1996) and close proximity to the highly diverse and productive IRL (Gilmore, 1977; Virnstein and Campbell, 1987). During the past several decades, however, the SLE has become a phytoplankton-based system that no longer supports permanent or extensive oyster and seagrass communities (Chamberlain and Hayward, 1996; Phlips, Badylak, and Grosskopf, 2002).

Pollution in the SLE now includes elevated concentrations of fecal coliform bacteria, which could be related to the increased use of septic tanks in the surrounding urban watersheds in the City of Stuart and Martin County (Belanger, Price, and Heck, 2007). Studies in the Florida Keys documented how on-site sewage disposal systems (septic tanks and shallow injection wells) enrich shallow groundwaters with dissolved nutrients, coliform bacteria and viruses that are transported into nearshore surface waters *via* submarine groundwater discharge (SGD; Griffin *et al.,* 1999; Lapointe, O'Connell, and Garrett, 1990; Paul *et al.,* 1995a,b). Studies in Jupiter (Lapointe and Krupa, 1995a) and Tequesta (Lapointe and Krupa, 1995b), which are located at the southern end of the IRL, showed that dissolved nutrients and two bacterial indicators of sewage pollution—fecal coliform and total coliform—were also transported *via* SGD into downstream tributaries of the Loxahatchee River and the IRL. These studies also reported high concentrations of sedimentary coprostanol in the receiving waters, confirming direct inputs of septic tank effluent from human wastewater sources.

Elevated concentrations of fecal coliforms typically follow periods of heavy rainfall in urbanized areas along the land–sea interface (Mallin *et al.,* 2000; Weiskel, Howes, and Heufelder, 1996). Once riverine surface waters become contaminated by fecal organisms, their survival and growth is dependent on environmental factors, such as salinity, nutrients, organic matter, and irradiance. Cook and Hamilton (1971) found that

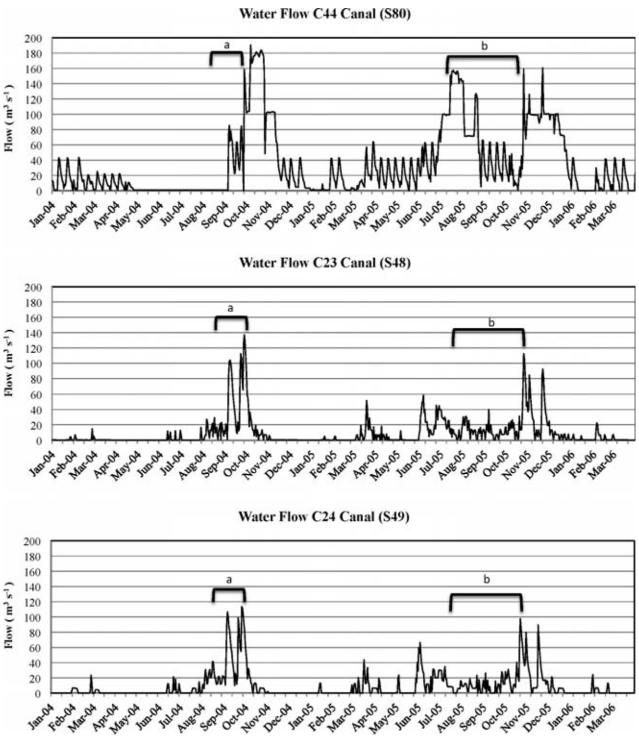

Figure 2. Flow into the St. Lucie Estuary through the C-44, C-23, and C-24 canals. (a) Hurricanes Charlie, Frances, and Jeanne passed through south central Florida in 2004. (b) Hurricanes Dennis, Katrina, Rita, and Wilma crossed over Florida in 2005.

fecal coliform bacteria multiplied rapidly in estuarine waters characterized by low salinity, low sunlight, and enrichment with nutrients and organic matter. These conditions have been documented in estuarine systems following hurricane events (Paerl *et al.,* 1998; Valiela *et al.,* 1996; Van Dolah and Anderson, 1991).

During the summer of 2004, multiple hurricanes (Charley, Frances, Jeanne) impacted south-central Florida, with two of these—the "Twin Hurricanes" (Frances, September 5th; Jeanne, September 26th)—making landfall near the City of Stuart and the SLE. The postlandfall trajectory of all three hurricanes overlapped in the Kissimmee River basin, causing record rainfall and drainage into Lake Okeechobee. The following 2005 hurricane season was the most active on record, with four hurricanes (Dennis, Katrina, Rita, and Wilma) making landfall in Florida between July and late October. Because of high water levels in Lake Okeechobee following hurricanes Frances and Jeanne, major freshwater releases occurred in fall of 2004, pulsed releases in winter/spring 2005, and major releases again during the active hurricane season in summer and fall of 2005 (Figure 2). In spring 2005, levels of fecal coliform bacteria in the SLE exceeded state standards, leading to considerable concern by the public as well as local governments and regulatory agencies as to the source(s) and cause(s) of this fecal contamination (62–302.530 F.A.C.).

To better understand the consequences of human alteration of land uses on hurricane-related runoff and nutrient and microbial fecal pollution in the SLE following the 2004 and 2005 hurricane seasons, we conducted a monitoring study at 25 stations in the SLE between June 2005 and March 2006 (Figure 1). The approach involved sampling along inshore to offshore transects in seven urbanized locations as well as four reference sites in the SLE and one reference site in the IRL. The first two samplings (June 2005, November 2005) were conducted during periods of large freshwater releases from the C-44 following the 2004 and 2005 hurricanes and the final sampling (March 2006) was conducted during a period of relatively lower discharges (Figure 2).

METHODS

Selection of Study Sites

To assess the contribution of local septic tanks to fecal coliform and nutrient contamination of the SLE, three sampling locations were established in Martin County and four in the City of Stuart. All seven locations (six of the locations were tidal creeks) were surrounded by dense residential and/or urban land uses that relied on septic tanks for on-site sewage disposal. At each location, samples were collected at three sites (A, B, C) aligned along an inshore (A) to offshore (C) gradient that generally extended from the upper reaches of the tidal creeks to the open waters of the SLE. In Martin County the three locations included Warner Creek, Rio, and North River Shores. In Stuart, the four locations included Carolina Canal, Poppleton Creek, Frazier Creek, and Krueger Creek (Figure 1). In addition to the seven transect sampling locations, five reference sites were sampled, which included the North Fork, Northside Marina, the Roosevelt Bridge, and the South Fork (Palm City Bridge) sites in the SLE and the Peck's Lake site in the IRL (Figure 1).

Coliform and Nutrient Sampling

All 25 sites were sampled three times during the period of study. The sampling dates were June 13, 2005, November 8, 2005, and March 8, 2006. Environmental field data collected during the samplings included salinity, temperature, dissolved oxygen, and turbidity. Temperature and dissolved oxygen were measured in the field with Oakton meters, which were calibrated before and after sampling. Turbidity and salinity were measured in the laboratory using a HACH Model 2100 A Turbidimeter (data reported as nephelometric turbidity units [NTU]) and a Denver Instrument salinity/conductivity meter (data reported *per* thousand [‰]). All sampling was carried out by HBOI Environmental Laboratory (HBEL, Inc., Sanford, Florida) personnel, and the sample containers, preservation protocols, and maximum holding time before analysis were initiated *per* analytical and quality control (QC) requirements.

Duplicate water samples ($n = 2$) were collected during ebbing tides for analysis of fecal coliform, total coliform, enterococci, dissolved inorganic nitrogen (DIN = ammonium plus nitrate plus nitrite), total dissolved nitrogen (TDN), soluble reactive phosphorus (SRP), and total dissolved phosphorus (TDP). For microbial analysis, standard methods were used for enumeration of fecal and total coliforms (Eaton, Clesceri, and Green-

Table 1. *Field measurements for the St. Lucie Estuary (SLE) and the Indian River Lagoon (IRL) reference site separated by the three (June 2005, November 2005, and March 2006) sample collection dates. Estuary section means are provided individually for each sampling date and comprehensively for the combination of all three sampling dates. Seasonal means for each sampling date include data from all three sections of the SLE. The overall mean for the SLE is also provided for each field parameter and includes data from the three estuary sections and the three collection dates. Asterisks (*) represent reference sites; Martin County sites are italicized, and City of Stuart sites are in normal font.*

		June 13, 2005					
Estuary Section	Site	Salinity (‰)	Temperature (°C)	DO (mg/l)	Turbidity (NTU)	pH	Depth (ft)
South Fork	Palm City Bridge*	0.21	30.8	6.5	37.9	7.5	6.6
	Carolina Canal-A	0.26	31.1	4.4	64.1	7.3	3.0
	Carolina Canal-B	0.22	30.3	5.5	30.3	7.4	3.6
	Carolina Canal-C	0.21	29.8	6.0	44.8	7.4	3.0
	Poppleton Creek-A	0.29	30.7	3.4	407.0	7.4	2.0
	Poppleton Creek-B	0.23	30.7	5.3	87.6	7.5	3.5
	Poppleton Creek-C	0.21	30.8	5.9	42.3	7.5	4.7
	Frazier Creek-A	0.23	32.8	3.7	39.9	7.9	3.4
	Frazier Creek-B	0.23	29.8	5.5	47.1	7.6	8.0
	Frazier Creek-C	0.22	30.0	5.9	42.8	7.5	10.0
	Section Mean (SD)	0.23 ± 0.03	30.7 ± 0.9	5.2 ± 1.0	84.4 ± 114.5	7.5 ± 0.2	4.8 ± 2.6
North Fork	North Fork*	0.24	29.6	4.4	8.6	7.3	6.8
	N River Shores-A	*0.49*	*30.8*	*7.3*	*11.6*	*7.2*	*5.2*
	N River Shores-B	*0.28*	*29.5*	*5.2*	*12.3*	*7.4*	*5.8*
	N River Shores-C	*0.27*	*29.4*	*5.6*	*12.8*	*7.5*	*7.6*
	North Side Marina*	0.28	30.0	4.62	19.7	7.44	10.0
	Section Mean (±SD)	0.31 ± 0.10	29.8 ± 0.6	5.4 ± 1.1	13.0 ± 4.1	7.4 ± 0.1	7.1 ± 1.9
Middle Estuary	Roosevelt Bridge*	0.22	28.5	5.6	43.7	7.5	7.3
	Rio-A	*0.46*	*27.9*	*6.5*	*34.4*	*7.6*	*2.8*
	Rio-B	*0.34*	*28.1*	*6.3*	*23.5*	*7.5*	*2.7*
	Rio- C	*0.27*	*27.9*	*6.2*	*22.0*	*7.5*	*4.4*
	Krueger Creek-A	0.49	28.0	9.8	31.1	7.3	3.4
	Krueger Creek-B	0.35	29.9	6.1	36.7	7.7	5.4
	Krueger Creek-C	0.26	29.0	5.8	42.9	7.7	6.0
	Warner Creek-A	*0.14*	*27.1*	*5.1*	*5.4*	*6.1*	*2.4*
	Warner Creek-B	*0.57*	*27.1*	*7.1*	*23.0*	*7.4*	*3.9*
	Warner Creek-C	*0.34*	*27.8*	*6.5*	*27.0*	*7.5*	*7.8*
	Section Mean (± SD)	0.34 ± 0.13	28.1 ± 0.8	6.5 ± 1.3	29.0 ± 11.4	7.4 ± 0.5	4.6 ± 1.9
	Seasonal Mean (±SD)	0.29 ± 0.11	29.5 ± 1.4	5.7 ± 1.3	47.9 ± 77.0	7.4 ± 0.3	5.1 ± 2.3
IRL Reference	Peck's Lake*	27.00	31.3	11.1	10.1	8.0	10.0
Comprehensive Section Means (±SD)	South Fork	1.00 ± 1.49	25.4 ± 4.2	6.2 ± 1.9	56.7 ± 69.6	7.6 ± 0.3	3.7 ± 2.6
	North Fork	3.43 ± 4.68	25.6 ± 3.5	6.6 ± 1.9	9.8 ± 4.1	7.5 ± 0.4	5.4 ± 2.8
	Middle Estuary	5.72 ± 7.85	25.2 ± 2.8	7.0 ± 1.6	20.3 ± 13.2	7.5 ± 0.5	3.5 ± 2.2
Overall SLE Means (±SD)		3.37 ± 5.80	25.3 ± 3.5	6.6 ± 1.8	32.7 ± 48.7	7.6 ± 0.4	4.0 ± 2.6

berg, 1998). A well-mixed known-volume of sample was pipetted into a series of tubes with dilutions of lauryl tryptose broth (LTB) and incubated at 35 ± 0.5°C for 48 hours. The positive (coliform present) tubes were inoculated into brilliant green bile (BGB) broth and incubated at 35 ± 0.5°C for an additional 48 hours. The positive (fecal coliform present) LTB tubes were inoculated into EC tubes and incubated at 44.5 ± 0.2°C for an additional 24 hours. Using Table 9221 IV in *Standard Methods for the Examination of Water and Wastewater,* 20th edition (Eaton, Clesceri, and Greenberg, 1998), the most probable number (mpn) was determined from the different counts of positive and negative tubes. The results for fecal coliform and total coliform are presented as mpn/100 ml. For enterococci, a well-mixed sample of known volume was filtered through a sterile sieve using sterile apparatus. The filter was placed onto a sterile petri dish containing mEI agar and incubated in an inverted position for 24 ± 2 hours at 41°C. The blue halo colonies were counted as colony-forming units (cfu) and expressed as cfu/100 ml.

For nutrients, surface water samples were collected into clean, high-density polyethylene (HDPE), 250-ml bottles using a pole dipper. The water samples were held on ice in a cooler and subsequently filtered through a 0.7 μm GF/F filter and frozen until analysis. Within 28 days of collection, the samples were analyzed for ammonium (NH_4^+) and nitrate plus nitrite ($NO_3^- + NO_2^-$; hereafter, referred to as *nitrate*), and SRP (PO_4^{3-}) at the HBEL, Inc. These analyses also allowed for the subsequent calculation of dissolved inorganic nitrogen (DIN = ammonium + nitrate) and total dissolved nitrogen (TDN = DIN + DON). All samples were analyzed on a Bran and Luebbe TRAACS 2000 analytical console (nitrate plus nitrite) or an Alpkem nutrient autoanalyzer (TDN, TDP, ammonium, nitrite, SRP). Detection limits were 0.08 μM for ammonium, 0.05 μM for nitrate plus nitrite, 0.003 μM for nitrite, and 0.001 μM for TDP and SRP. The methods for collection, handling, and processing of the water samples for low-level nutrient analysis followed a strict quality assurance/ QC protocol developed by HBEL, Inc., to prevent problems

Table 1. *Extended.*

November 8, 2005						March 8, 2006					
Salinity (‰)	Temperature (°C)	DO (mg/l)	Turbidity (NTU)	pH	Depth (ft)	Salinity (‰)	Temperature (°C)	DO (mg/l)	Turbidity (NTU)	pH	Depth (ft)
0.18	25.0	7.0	67.3	7.4	6.6	0.40	22.0	8.2	59.2	8.1	2.0
0.20	24.0	4.6	49.1	7.0	3.0	1.40	21.0	7.8	21.8	7.9	0.9
0.18	24.0	7.0	72.3	7.5	3.6	1.10	21.0	8.2	52.0	8.1	1.1
0.18	25.0	7.2	74.2	7.5	3.0	1.40	22.0	8.2	57.6	8.0	0.9
0.24	24.0	2.1	26.2	7.0	2.0	1.60	21.0	8.2	26.7	8.1	0.6
0.18	25.0	6.7	71.0	7.6	3.5	1.90	21.0	8.5	27.6	8.1	1.1
0.18	24.0	7.1	84.0	7.5	4.7	3.80	21.0	8.3	29.7	8.0	1.4
0.20	25.0	2.4	14.2	7.1	3.4	4.20	20.0	7.8	12.7	8.0	1.0
0.20	25.0	2.4	23.6	7.1	8.0	4.60	20.0	8.2	14.4	8.0	2.4
0.18	24.0	6.5	60.5	7.6	10.0	5.40	20.0	8.2	13.7	8.1	3.0
0.19 ± 0.02	24.5 ± 0.5	5.3 ± 2.2	54.2 ± 24.6	7.3 ± 0.2	4.8 ± 2.6	2.58 ± 1.74	20.9 ± 0.7	8.2 ± 0.2	31.5 ± 18.2	8.0 ± 0.1	1.5 ± 0.8
0.17	25.0	5.3	12.3	7.1	6.8	9.00	21.0	8.8	7.4	7.9	2.1
0.30	*26.0*	*5.0*	*9.3*	*7.0*	*5.2*	*9.30*	*23.0*	*9.7*	*6.0*	*7.8*	*1.6*
0.17	*25.0*	*5.8*	*10.1*	*7.0*	*5.8*	*9.70*	*22.0*	*9.1*	*5.2*	*8.0*	*1.8*
0.16	*25.0*	*5.7*	*10.6*	*7.8*	*7.6*	*10.00*	*22.0*	*8.7*	*4.6*	*8.0*	*2.3*
0.15	25.0	5.5	12.1	7.1	10.0	11.00	21.0	8.7	4.2	8.0	3.0
0.19 ± 0.06	25.2 ± 0.4	5.5 ± 0.3	10.9 ± 1.3	7.2 ± 0.3	7.1 ± 1.9	9.80 ± 0.77	21.8 ± 0.8	9.0 ± 0.4	5.5 ± 1.3	7.9 ± 0.1	2.2 ± 0.6
0.15	24.0	5.9	27.9	7.0	7.3	12.00	21.0	8.6	4.2	8.0	2.2
0.25	*26.0*	*6.0*	*25.7*	*7.3*	*2.8*	*19.00*	*24.0*	*9.3*	*9.0*	*8.1*	*0.9*
0.25	*27.0*	*6.2*	*26.2*	*7.3*	*2.7*	*19.00*	*23.0*	*9.6*	*8.9*	*8.2*	*0.8*
0.42	*26.0*	*6.0*	*27.5*	*7.4*	*4.4*	*17.00*	*22.0*	*9.2*	*4.8*	*8.1*	*1.3*
0.52	25.0	4.0	16.1	7.2	3.4	13.00	21.0	8.1	5.6	7.6	1.0
0.24	25.0	5.9	27.1	7.4	5.4	14.00	20.0	8.5	5.2	8.0	1.6
0.17	24.0	6.6	46.1	7.3	6.0	15.00	21.0	8.5	3.8	8.0	1.8
0.11	*27.0*	*5.0*	*11.2*	*6.4*	*2.4*	*16.00*	*24.0*	*9.6*	*8.2*	*8.0*	*0.7*
0.87	*25.0*	*5.6*	*28.3*	*7.1*	*3.9*	*20.00*	*22.0*	*8.3*	*6.7*	*8.1*	*1.2*
1.10	*26.0*	*5.9*	*21.5*	*7.3*	*7.8*	*19.00*	*22.0*	*9.6*	*4.0*	*8.2*	*2.4*
0.41 ± 0.33	25.5 ± 1.1	5.8 ± 0.7	25.8 ± 9.1	7.2 ± 0.3	4.6 ± 1.9	16.40 ± 2.84	22.0 ± 1.3	8.9 ± 0.6	6.0 ± 2.0	8.0 ± 0.2	1.4 ± 0.6
0.28 ± 0.23	25.0 ± 0.9	5.5 ± 1.4	34.2 ± 23.9	7.2 ± 0.3	5.2 ± 2.3	9.55 ± 6.64	21.5 ± 1.1	8.6 ± 0.6	16.1 ± 17.0	8.0 ± 0.1	1.6 ± 0.7
12.00	26.0	6.5	17.4	7.6	10.0	29.00	21.0	8.3	3.7	7.9	3.0

associated with sample contamination and excessive holding times and to provide accurate and reliable data (Gunsalus, 1997).

Statistical Analyses

Data were analyzed using SPSS 11.0 and SPSS 19.0 for the Macintosh. The Shapiro-Wilk test (W statistic) was used to test for normality, and Levene's test of equality of error variances was used for homoscedasticity. Normally distributed data sets for the variables from the different sites, dates, and segments of the SLE were compared using the General Linear Model (GLM, Type III sum of squares). Data not normally distributed were compared using either the Kruskal-Wallis H test (three or more groups), or the Mann-Whitney U test (two groups). *Post hoc* multiple comparisons were made using Tukey's Honestly Significant Difference test. Linear regression and ANOVA were used to test for significance of fecal and total coliform data *vs.* salinity. For all analyses, differences were considered significant at $p \leq 0.05$.

RESULTS

Salinity

Although salinity was highly variable among the stations throughout the study, unusually low salinities occurred during the June and November 2005 samplings. Salinity at all stations in the SLE proper (Peck's Lake excluded) was significantly ($p < 0.001$, $n = 25$) higher in March 2006 than they were in June and November 2005 (Table 1; Figures 3 and 4). When SLE segments were compared, the South Fork stations ($n = 30$) had lower average salinity when compared with the North Fork ($n = 15$) and Middle Estuary stations ($n = 30$; Table 1). Average salinity at Peck's Lake in the IRL was significantly ($p < 0.001$; $n = 25$) higher (22.67 ± 9.29‰) than at SLE sites overall (3.37 ± 5.80‰) and remained higher than other sites when June 2005, November 2005, and March 2006 were analyzed separately (Table 1).

In June 2005, South Fork salinity was abnormally low and significantly ($p = 0.028$; $n = 10$) lower than the salinity was in

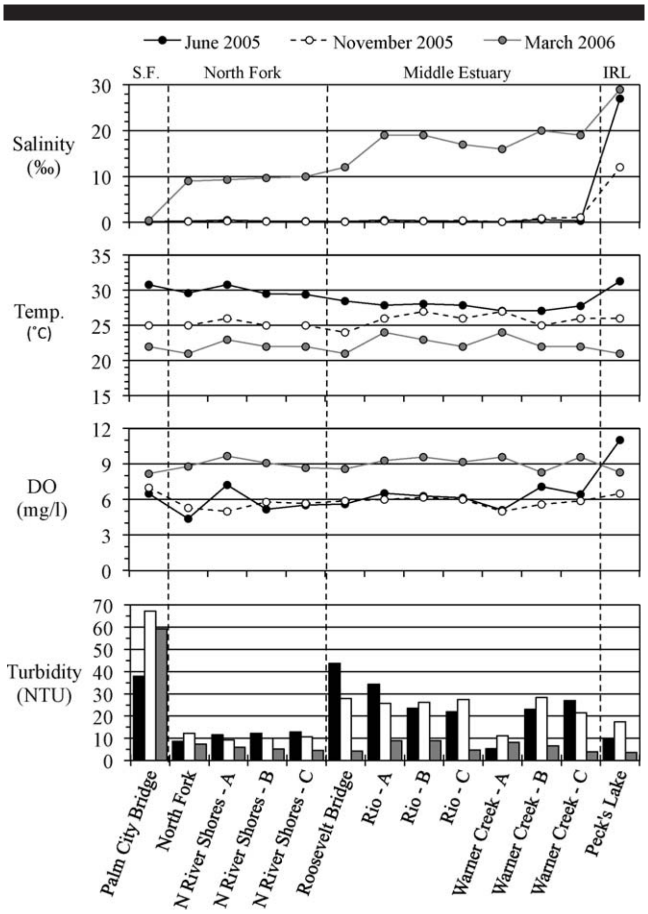

Figure 3. Salinity (‰), temperature (°C), dissolved oxygen (DO; mg/l), and turbidity (nephelometric turbidity units, NTU) at the Martin County sites.

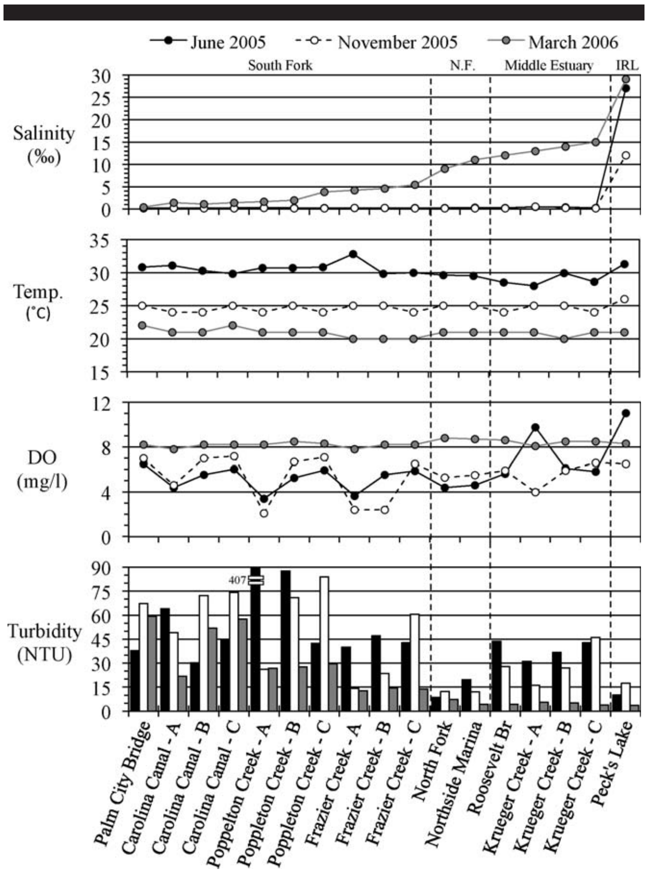

Figure 4. Salinity (‰), temperature (°C), dissolved oxygen (DO; mg/l), and turbidity (nephelometric turbidity units, NTU) at the City of Stuart sites.

the North Fork and Middle Estuary (Table 1). In November 2005, salinities were again low but were more similar among the North Fork, South Fork, and Middle Estuary (Table 1). During the March 2006 dry season sampling, salinities were higher, and again, were significantly ($p < 0.001$; $n = 10$) lower in the South Fork than they were in the North Fork and Middle Estuary (Table 1).

In contrast to June and November 2005, the March 2006 sampling showed increasing salinity along upstream-to-downstream gradients in the SLE (Figures 3 and 4). For example, salinities at the Martin County sites in March 2006 increased from 0.4‰ upstream at Palm City Bridge to 12.0‰ downstream at Roosevelt Bridge; in the North Fork, salinity increased from 9.0‰ upstream at the reference site to 10.0‰ downstream at North River Shores-C; and in the Middle Estuary, salinity increased from 12.0‰ at the Roosevelt Bridge to 19.0‰ downstream at Warner Creek-C (Figure 3). For Stuart, the March 2006 data similarly showed increasing salinity from 0.4‰ upstream at Palm City Bridge in the South Fork to 5.4‰ downstream at Frazier Creek-C; in the North Fork, salinity increased from 9.0‰ upstream at the reference site to 11.0‰ downstream at Northside Marina; and in the Middle Estuary, salinity increased from 12.0‰ at the Roosevelt Bridge to 15.0‰ downstream at Krueger Creek-C (Figure 4). The lowest recorded salinities consistently occurred at the Palm City Bridge, indicating that the South Fork was the major freshwater source to the SLE during all samplings.

Temperature

Water temperatures in the SLE were significantly ($p < 0.001$; $n = 25$) warmer in June 2005 than they were in November 2005 and March 2006, averaging 25.3 ± 3.5°C overall (Table 1, Figures 3 and 4). Similarly, Peck's Lake temperatures were warmest in June 2005, were moderate in November 2005, and were the coolest in March 2006 (Table 1). When SLE segments were compared, no significant differences were found overall in November 2005 or in March 2006. In June 2005, however, the Middle Estuary was significantly ($p < 0.001$; $n = 10$) cooler than the North Fork and South Fork (Table 1).

Dissolved Oxygen (DO)

Overall, DO in the SLE was significantly ($p < 0.001$; $n = 25$) higher in March 2006 than it was in June and November 2005 (Table 1; Figures 3 and 4). At the Peck's Lake reference site, DO was twofold higher than it was in the SLE in June 2005, but it was similar to the SLE in November 2005 and March 2006 (Table 1). Within the SLE, DO concentrations were not significantly different between June and November 2005. However, November 2005 DO at the Palm City Bridge station was significantly ($p = 0.018$; $n = 12$) higher than the averages were at the North Fork station and the Roosevelt Bridge station (Table 1). With the exception of two sites in June 2005 (Poppleton Creek-A and Frazier Creek-A) and three sites in November 2005 (Poppleton Creek-A and Frazier Creek-A and B), DO concentrations at all sites during all midday samplings were ≥4.0 mg/l (Table 1).

Turbidity

Turbidity in the SLE was marginally ($p = 0.086$; $n = 25$) lower in March 2006 than it was in June and November 2005 (Table 1; Figures 3 and 4). Turbidity at Peck's Lake was consistently lower than it was in the SLE during all three samplings (Table 1). Comparing segments of the SLE, the South Fork had significantly ($p < 0.001$; $n = 36$) higher and more variable turbidity, overall, than did the North Fork and Middle Estuary (Table 1). This pattern generally held for the individual samplings as well. In June 2005, turbidity in the South Fork was higher than it was in the Middle Estuary, which, in turn, was higher than it was in the North Fork (Table 1). In November 2005, following hurricane Wilma, the South Fork was significantly ($p < 0.001$; $n = 10$) more turbid than the Middle Estuary and North Fork were (Table 1). In March 2006, turbidity in the South Fork was lower, but still significantly ($p < 0.001$; $n = 10$) higher than were the Middle Estuary and North Fork averages (Table 1).

Fecal Coliforms

Overall, fecal coliforms were significantly ($p = 0.003$; $n = 50$) more abundant in the SLE in June 2005 than they were in November 2005 or March 2006 (Table 2; Figures 5 and 6) and were correlated significantly with salinity over the period of study ($p = 0.004$; $n = 78$). At the IRL reference site, Peck's Lake, fecal coliform counts were generally lower than they were in the SLE (Table 2). Fecal coliform counts were statistically similar among the three segments of the SLE (Table 2).

In June 2005, no significant difference was seen in fecal coliform counts in the North Fork, South Fork, and Middle Estuary (Table 2). However, site effects in Martin County were significant ($p < 0.001$; $n = 26$), with North River Shores-A (1250 ± 495 mpn/100 ml) highest among sites and exceeding the FDEP 800 mpn/100 ml maximum for a single sample for Class III surface waters (Figure 5; 62–302.530 F.A.C.). In the City of Stuart, three sampling sites—Poppleton Creek-A, Poppleton Creek-B and Frazier Creek-B—also exceeded the FDEP 800 mpn/100 ml maximum for a single sample (Figure 6; 62–302.530 F.A.C.). The lowest fecal coliforms were measured at Peck's Lake (8 ± 8 mpn/100 ml).

In November 2005, the South Fork stations had counts significantly ($p = 0.028$; $n = 26$) higher than the North Fork and Middle Estuary stations (Table 2). At all sites in Martin County, with the exception of the Palm City Bridge (205 ± 49 mpn/100 ml) and Rio-A (150 ± 28 mpn/100 ml), counts were <100 mpn/100 ml (Figure 5). In the City of Stuart, the effects of location were significant ($p = 0.002$; $n = 34$) with high counts (Figure 6) at Poppleton Creek-B (500 ± 0.0 mpn/100 ml; November maximum) and Poppleton Creek-A (400 ± 141 mpn/100 ml). The lowest counts occurred at Northside Marina (26 ± 12 mpn/100 ml; November minimum) and the Roosevelt Bridge (30 ± 0.0 mpn/100 ml). The North Fork sites were marginally ($p = 0.058$; $n = 34$) lower than the South Fork and Middle Estuary sites (Table 2). Overall, no sites had ≥800 mpn/100 ml counts in the November 2005 sampling.

In March 2006, counts in the South Fork were again significantly ($p = 0.014$; $n = 26$) higher than they were in the North Fork and Middle Estuary sites (Table 2). In Martin County, effects of location were significant ($p < 0.001$; n = 26), with Palm City Bridge (80 ± 0 mpn/100 ml) and Warner Creek-A (65 ± 21 mpn/100 ml) higher than the other sites, which were all below 50 mpn/100 ml (Figure 5). In the City of Stuart, effects of location were also significant ($p = 0.001$; $n = 34$) with high counts >200 mpn/100 ml at Poppleton Creek-A (220 ± 113 mpn/100 ml; March maximum). Low counts (<5 mpn/100 ml) occurred at two North Fork sites (North Fork and Northside Marina) and at Krueger Creek-B and C (Figure 6). The lowest counts of the entire study were observed at Peck's Lake in this sampling (Table 2). Overall, no sites had ≥800 mpn/100 ml counts in the March 2006 sampling.

Total Coliforms

Overall, total coliform counts were significantly ($p < 0.001$; n = 78) lower in March 2006 than they were in June and November 2005 (Table 2) and correlated significantly with salinity ($p < 0.001$, $n = 78$) over the period of study. The Peck's Lake reference site, with an overall average of 72 ± 95 mpn/100 ml, had consistently lower total coliform counts than the SLE (overall average of 1301 ± 1284 mpn/100 ml; Table 2). Among SLE segments, the South Fork and Middle Estuary counts averaged more than twofold higher than did the North Fork counts (Table 2).

In June 2005, there were no significant effects among segments of the SLE: North Fork sites had the lowest average counts, and the South Fork and Middle Estuary had the highest (Table 2). When sites were compared in Martin County, Warner Creek-A (8000 ± 1414 mpn/100 ml) was significantly ($p < 0.001$; $n = 26$) higher than other sites (Figure 5). In Stuart, site maxima occurred at Poppleton Creek-A and B (4000 ± 1414 mpn/100 ml and 3200 ± 2545 mpn/100 ml, respectively); the minimum occurred at the North Fork station (240 ± 0.0 mpn/100 ml; Figure 6).

In November 2005, the total coliform count in the South Fork was higher than that it was in the North Fork and Middle Estuary (Table 2). Among sites in Martin County, Rio-B (3700 ± 1838 mpn/100 ml) had the highest counts, significantly higher than most other stations. The Palm City and Roosevelt bridges, Rio A-C, and Warner Creek-B all had counts >1000 mpn/100 ml (Figure 5). In the City of Stuart, the November maximum occurred at Frazier Creek-A (3350 ± 2333 mpn/100 ml), and the minimum occurred at Northside Marina (500 ± 0.0 mpn/100 ml; Figure 6).

In March 2006, the South Fork, North Fork, and Middle Estuary had similar counts (Table 2). In Martin County, the

Table 2. *Mean (±SD) concentrations of fecal coliforms, total coliforms, and enterococci by segment of the St. Lucie Estuary (SLE) and sampling date. Comprehensive segment means (±SD) represent the combination of all three sampling dates. Seasonal means (±SD) for each sampling date includes data from all three segments of the SLE. The overall mean (±SD) for the SLE includes data from the three segments over the three collection dates for each biological parameter.*

Sampling Date	Estuary Section	Fecal Coliforms (mpn/100 ml)	Total Coliforms (mpn/100 ml)	Enterococci (cfu/100 ml)
June 13, 2005	South Fork	421 ± 370	2347 ± 1008	–
	North Fork	422 ± 500	1134 ± 704	–
	Middle Estuary	234 ± 195	2405 ± 2017	–
	Seasonal Mean	346 ± 341	2128 ± 1499	–
	IRL Reference	8 ± 8	8 ± 8	–
November 8, 2005	South Fork	244 ± 145	2095 ± 789	236 ± 110
	North Fork	32 ± 6	486 ± 276	14 ± 7
	Middle Estuary	106 ± 77	1339 ± 913	120 ± 97
	Seasonal Mean	147 ± 132	1471 ± 965	145 ± 124
	IRL Reference	76 ± 76	185 ± 78	17 ± 4
March 8, 2006	South Fork	88 ± 53	382 ± 272	182 ± 220
	North Fork	9 ± 14	279 ± 228	128 ± 266
	Middle Estuary	16 ± 24	243 ± 500	72 ± 193
	Seasonal Mean	43 ± 52	306 ± 367	127 ± 215
	IRL Reference	0	23 ± 0	3 ± 3
Comprehensive	South Fork	251 ± 263	1608 ± 1149	209 ± 171
	North Fork	154 ± 332	633 ± 566	71 ± 188
	Middle Estuary	119 ± 149	1329 ± 1551	96 ± 151
	Overall SLE Mean	179 ± 245	1301 ± 1284	136 ± 174

North Fork and North River Shores-A sites had the highest counts (515 ± 544 and 490 ± 580 mpn/100 ml, respectively; other sites had counts ≤300 mpn/100 ml (Figure 5). In the City of Stuart, Krueger Creek-A had the highest count (1640 ± 1923 mpn/100 ml) and was the only site with counts >1000 mpn/100 ml. Krueger Creek-B (23 ± 0.0 mpn/100 ml) had the lowest counts (Figure 6).

Enterococci

June 2005 data revealed high coliform levels throughout the estuary, thus *Enterococcus* spp. (enterococci) measurements

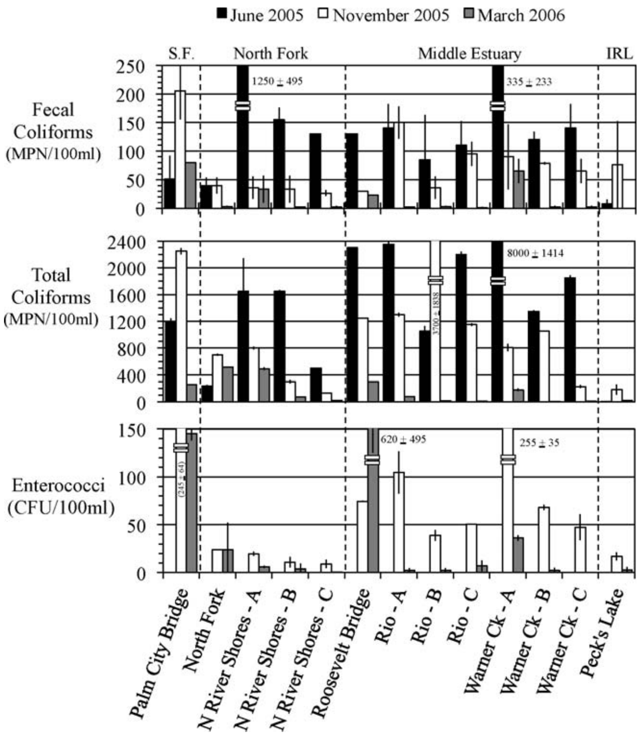

Figure 5. Fecal coliform (mpn/100 ml), total coliform (mpn/100 ml), and enterococci (cfu/100 ml) counts (±SD) at the Martin County sites.

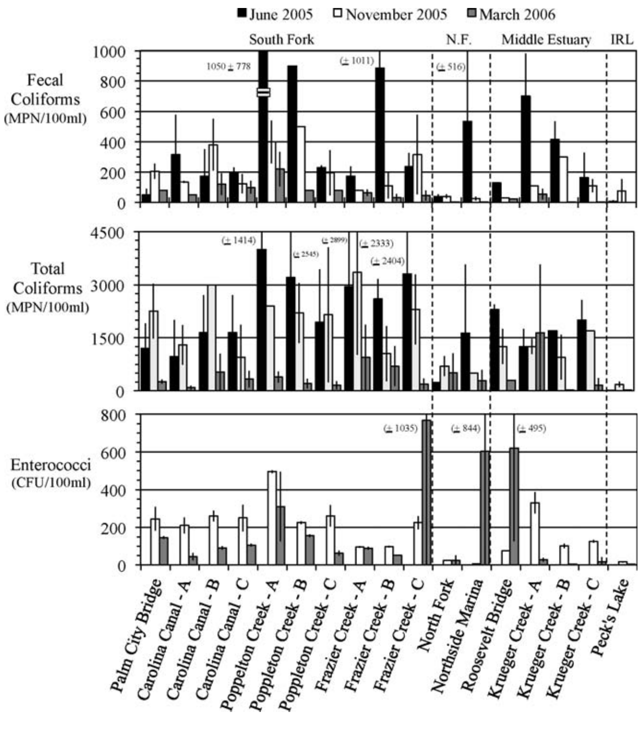

Figure 6. Fecal coliform (mpn/100 ml), total coliform (mpn/100 ml), and enterococci (cfu/100 ml) counts (± SD) at the City of Stuart sites.

were added to the sampling protocol in November 2005 and March 2006. Overall, enterococci counts in the SLE were statistically similar in November 2005 and March 2006 (Table 2). However, counts at the IRL reference site at Peck's Lake were significantly lower than they were in the SLE in both November 2005 and March 2006 (Table 2). Segments of the SLE were similar overall, with the South Fork stations twofold higher than the North Fork and Middle Estuary stations were (Table 2; Figures 5 and 6).

In November 2005, enterococci numbers were significantly higher in the South Fork stations compared with the North Fork and Middle Estuary stations (Table 2). In Martin County, Warner Creek-A (255 ± 35 cfu/100 ml) and Palm City Bridge (245 ± 64 cfu/100 ml) had significantly ($p < 0.001$; $n = 26$) higher counts than did other sites (Figure 5). Warner Creek-A, Palm City Bridge, and Rio-A were all >100 cfu/100 ml. In Stuart, enterococci counts were significantly ($p \leq 0.001$; $n = 34$) higher at Poppleton Creek-A (495 ± 7 cfu/100 ml) and Krueger Creek-A (330 ± 57 cfu/100 ml) than at other sites (Figure 6). Frazier Creek-C and all sites in Poppleton Creek and Carolina Canal had counts >200 cfu/100 ml, and all Krueger Creek sites had counts >100 cfu/100 ml. The lowest counts were measured at Northside Marina (7 ± 4 cfu/100 ml; Figure 6). Ten of the 25 sampling stations (40%) exceeded the U.S. Environmental Protection Agency (EPA) limit for a single sample (158 cfu/100 ml) in November (Figures 5 and 6; 40 CFR 131.41 [EPA Staff, 2004]).

In March 2006, enterococci counts were again higher in the South Fork than they were in the North Fork and Middle Estuary (Table 2); however, because of the high variability among sites and replicates, the differences were not significant. In Martin County, the Roosevelt Bridge (620 ± 495 cfu/100 ml), downstream of the Shepard's Park anchorage, had significantly ($p = 0.027$; $n = 26$) higher counts than all other sites, except the Palm City Bridge (145 ± 7 cfu/100 ml; Figure 5). In Stuart, the highest counts were at Frazier Creek-C (768 ± 1035 cfu/100 ml) in the Shepherd's Park moorings (Figure 6). Similarly high counts were found downstream of the Shepherd's Park anchorage at the Roosevelt Bridge (620 ± 495 cfu/100 ml) and at Northside Marina (603 ± 844 cfu/100 ml). Poppleton Creek had a strong high-to-low, inshore-to-offshore enterococci gradient, from 310 ± 184 (A) to 155 ± 7 (B) to 62 ± 14 cfu/100 ml (C; Figure 6). Four of the 25 stations (16%) exceeded the EPA limit for a single sample in March (158 cfu/100 ml; Figures 5 and 6; 40 CFR 131.41 [EPA Staff, 2004]).

Dissolved Nitrogen

All forms of nitrogen measured, including ammonium, nitrate, DIN, and TDN, were significantly ($p < 0.001$; $n = 156$) higher in the SLE in June and November 2005 than they were in March 2006 (Table 3; Figures 7 and 8). Ammonium averages were statistically similar in June and November 2005, but dropped in March 2006 (Table 3). Nitrate concentrations were several-fold higher than ammonium was (Table 3). Like ammonium averages, DIN and TDN concentrations were statistically similar in June and November 2005, but decreased by March 2006 (Table 3).

When segments of the SLE were compared, spatial variations were observed for ammonium, nitrate, DIN, and TDN. Ammonium concentrations were significantly ($p = 0.010$; $n = 72$) higher in the North Fork than they were in the South Fork and Middle Estuary (Table 3). Nitrate in the South Fork was twofold higher than it was in the Middle Estuary and fivefold higher than it was in the North Fork; DIN was higher in the South Fork than it was in the Middle Estuary or the North Fork (Table 3). The TDN was also highest in the South Fork, lower in the Middle Estuary, and lowest in the North Fork (Table 3). For nitrate, DIN, and TDN, the highest average concentrations (Figures 7 and 8) consistently occurred at the Palm City Bridge, just down gradient of the C-44 canal (Figure 1). In March 2006, canals in both Martin County and the City of Stuart had high-to-low, inshore-to-offshore gradients in ammonium, DIN, nitrate, and TDN, indicating there were local sources of nitrogen during low flows from the C-44 (Figures 7 and 8).

Dissolved Phosphorus

Both forms of phosphorus measured—SRP and TDP—were significantly ($p < 0.001$; $n = 156$) higher in the SLE in June and November 2005 than they were in March 2006 (Table 3; Figures 9 and 10). The SRP concentrations were similarly high in June and November 2005, but decreased by March 2006 (Table 3). In comparison, TDP concentrations gradually decreased between the June 2005 and March 2006 (Table 3).

In June and November 2005, comparisons among SLE segments showed the highest SRP and TDP concentrations in the North Fork (Table 3). Nevertheless, SRP concentrations in the North Fork were only marginally ($p = 0.065$; $n = 156$) higher than were those in the South Fork and were statistically similar to those in the Middle Estuary (Table 3; Figures 9 and 10). The TDP was also statistically similar among the three SLE segments (Table 3; Figures 9 and 10). Local, increasing, inshore-to-offshore phosphorus gradients for SRP and TDP at North River Shores and Warner Creek in Martin County (Figure 9) also suggest that phosphorus inputs to the SLE at these locations were insignificant compared with inputs from the North Fork in June and November 2005.

In March 2006, however, the pattern changed. The TDP was significantly ($p \leq 0.002$; $n = 50$) higher in the South Fork than it was in the North Fork and Middle Estuary (Table 3). The SRP concentrations were significantly ($p < 0.001$; $n = 50$) higher in both the South and North forks than they were in the Middle Estuary (Table 3). Evidence for local inputs of phosphorus occurred at Warner Creek, where small, but significant, high-to-low, inshore-to-offshore concentration gradients were observed for TDP and SRP (Figure 9). Both TDP and SRP were significantly higher at Palm City Bridge than at other sites, which were all in the range 1.9–3.5 μM TDP and 1.4–2.3 μM SRP.

Nitrogen : Phosphorus Ratios

The TDN : TDP ratios in the SLE were lowest in June 2005 and increased in November 2005 and March 2006 (Table 3; Figures 9 and 10). Similarly, DIN : SRP ratios were lowest in June 2005 and increased in November 2005 and March 2006

Table 3. *Mean (±SD) dissolved nutrient concentrations by section of the St. Lucie Estuary (SLE) and sampling date. Comprehensive section means (±SD) represent the combination of all three sampling dates. Seasonal means (±SD) for each sampling date includes data from the three estuary sections. The overall mean (±SD) for the SLE includes data from the three estuary sections over the three collection dates for each parameter.*

Sampling Date	Estuary Section	Ammonium (μM)	Nitrate (μM)	DIN (μM)	DON (μM)	TDN (μM)	SRP (μM)	DOP (μM)	TDP (μM)	TDN : TDP Ratio	DIN : SRP Ratio
June 13, 2005	South Fork	6.7 ± 4.8	27.1 ± 6.1	33.8 ± 4.1	97.0 ± 38.8	130.8 ± 38.8	4.8 ± 0.5	6.2 ± 4.8	11.0 ± 4.9	7.6 ± 2.4	11.8 ± 1.6
	North Fork	15.4 ± 5.5	7.6 ± 1.1	23.0 ± 4.9	77.4 ± 9.8	100.4 ± 10.6	10.5 ± 2.4	3.3 ± 0.6	13.8 ± 2.8	6.5 ± 2.6	3.1 ± 2.0
	Middle Estuary	6.5 ± 3.9	20.5 ± 10.0	26.9 ± 7.1	81.7 ± 24.5	108.6 ± 24.9	7.4 ± 3.2	4.0 ± 1.1	11.4 ± 3.8	11.4 ± 14.5	6.7 ± 4.7
	Seasonal Mean	8.4 ± 5.7	20.5 ± 10.2	28.9 ± 6.9	87.0 ± 29.6	115.8 ± 31.3	7.0 ± 3.1	4.7 ± 3.3	11.7 ± 4.1	8.9 ± 9.3	8.0 ± 4.6
	IRL Reference	0	0.9 ± 0.1	0.9 ± 0.1	118.2 ± 4.9	119.1 ± 5.0	1.0 ± 0.1	1.3 ± 0.1	2.2 ± 0	53.4 ± 2.2	0.9 ± 0.1
November 8, 2005	South Fork	6.8 ± 3.5	37.9 ± 15.6	44.7 ± 12.9	78.1 ± 12.8	122.8 ± 25.0	4.2 ± 0.6	3.8 ± 0.9	7.9 ± 1.1	11.1 ± 3.7	15.0 ± 1.3
	North Fork	12.4 ± 2.3	8.8 ± 0.7	21.1 ± 2.1	71.0 ± 4.8	92.1 ± 4.7	10.5 ± 1.5	1.6 ± 0.4	12.1 ± 1.2	6.5 ± 2.8	3.3 ± 2.7
	Middle Estuary	8.3 ± 2.5	25.2 ± 13.0	33.5 ± 13.4	82.2 ± 21.9	115.7 ± 22.0	7.1 ± 2.9	2.2 ± 1.1	9.3 ± 3.4	16.2 ± 18.7	8.4 ± 7.1
	Seasonal Mean	8.5 ± 3.5	27.0 ± 16.6	35.5 ± 14.5	78.3 ± 16.2	113.8 ± 23.5	6.6 ± 3.1	2.7 ± 1.3	9.3 ± 2.7	12.2 ± 12.3	10.0 ± 6.4
	IRL Reference	13.9 ± 3.5	12.5 ± 0.5	26.4 ± 4.0	55.7 ± 1.1	82.1 ± 5.0	5.5 ± 0	0.8 ± 0.2	6.3 ± 0.2	13 ± 0.3	4.8 ± 0.7
March 8, 2006	South Fork	3.5 ± 0.6	28.6 ± 3.7	32.1 ± 3.5	58.6 ± 9.2	90.7 ± 11.7	2.8 ± 0.1	2.3 ± 1.2	5.1 ± 1.2	11.8 ± 2.0	18.0 ± 2.7
	North Fork	1.6 ± 0.4	1.3 ± 2.3	3.0 ± 2.5	45.4 ± 1.4	48.4 ± 2.7	2.1 ± 0.4	1.2 ± 0.2	3.3 ± 0.3	12.2 ± 5.0	4.3 ± 7.5
	Middle Estuary	2.1 ± 0.8	6.4 ± 2.5	8.4 ± 3.1	42.3 ± 6.0	50.7 ± 6.4	1.7 ± 0.3	0.7 ± 0.2	2.4 ± 0.3	16.8 ± 6.9	9.4 ± 8.6
	Seasonal Mean	2.6 ± 1.0	14.2 ± 12.4	16.8 ± 13.3	49.4 ± 10.2	66.2 ± 22.0	2.2 ± 0.57	1.4 ± 1.0	3.7 ± 1.5	13.9 ± 5.4	11.8 ± 8.4
	IRL Reference	1.7 ± 0.4	0	1.7 ± 0.4	57.2 ± 10.2	58.9 ± 10.6	0.9 ± 0	0.1 ± 0.1	1.0 ± 0.1	57.7 ± 6.5	2.0 ± 0.6
Comprehensive	South Fork	5.7 ± 3.6	31.2 ± 10.7	36.9 ± 9.6	86.1 ± 35.3	114.8 ± 31.9	3.9 ± 1.0	4.1 ± 3.2	8.0 ± 3.8	10.2 ± 3.3	14.9 ± 3.2
	North Fork	9.8 ± 6.9	5.9 ± 3.7	15.7 ± 9.9	64.6 ± 15.5	80.3 ± 24.5	7.7 ± 4.4	2.0 ± 1.0	9.7 ± 5.0	8.4 ± 4.4	3.6 ± 4.4
	Middle Estuary	5.6 ± 3.7	17.3 ± 12.3	22.9 ± 13.8	68.7 ± 26.6	91.7 ± 35.1	5.4 ± 3.6	2.3 ± 1.6	7.7 ± 4.8	14.8 ± 13.9	8.2 ± 6.8
	Overall SLE Mean	6.4 ± 4.7	20.6 ± 14.2	27.1 ± 14.2	71.6 ± 25.8	98.6 ± 34.4	5.3 ± 3.3	3.0 ± 2.5	8.2 ± 4.5	11.7 ± 9.5	9.9 ± 6.7

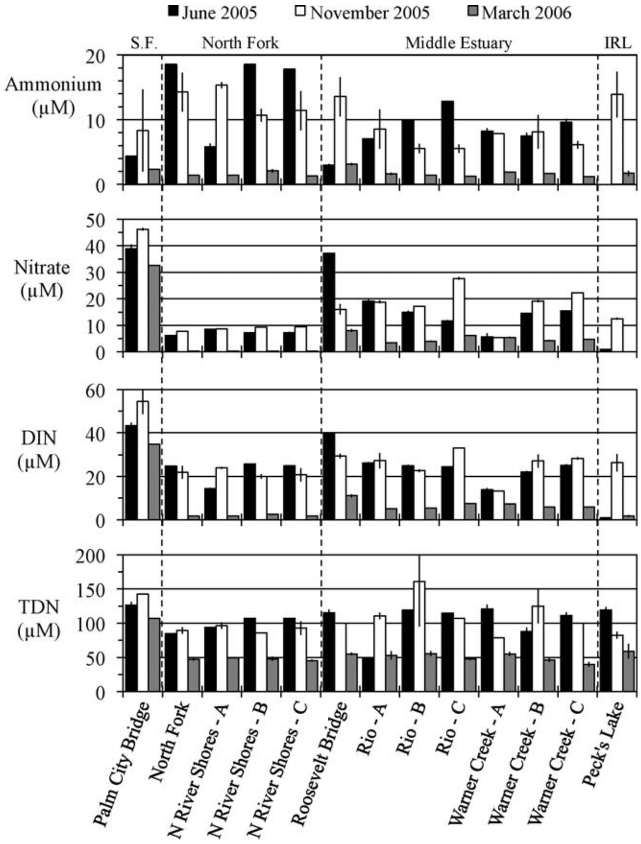

Figure 7. Ammonium, nitrate, dissolved inorganic nitrogen (DIN), and total dissolved nitrogen (TDN) concentrations (±SD) at the Martin County sites.

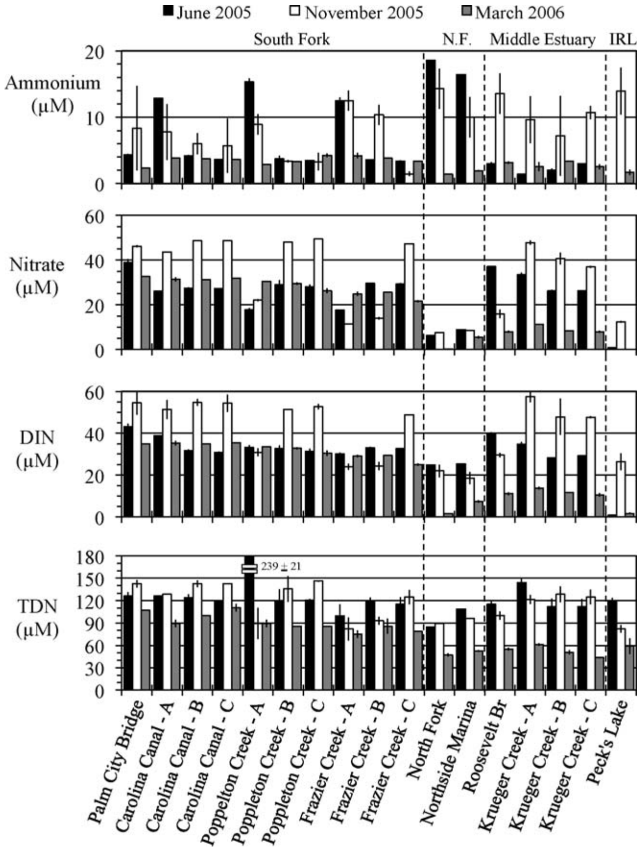

Figure 8. Ammonium, nitrate, dissolved inorganic nitrogen (DIN), and total dissolved nitrogen (TDN) concentrations (±SD) at the City of Stuart sites.

(Table 3). The IRL reference site at Peck's Lake had an overall average TDN : TDP ratio of 41.4 ± 22.3 and a DIN : SRP ratio of 7.7 ± 3.7.

Comparison among SLE segments revealed significant ($p < 0.001$; $n = 102$) differences in both TDN : TDP and DIN : SRP ratios (Table 3; Figures 9 and 10). The TDN : TDP ratios were higher in the Middle Estuary than they were in the South Fork and North Fork (Table 3). In contrast, DIN : SRP ratios were higher in the South Fork than they were in the Middle Estuary and North Fork (Table 3).

DISCUSSION

This study demonstrated the linkages between high rainfall associated with multiple hurricanes over a 2-year period, large-scale stormwater discharges from Lake Okeechobee *via* the C-44 canal, and downstream effects on nutrient and microbial fecal pollution in the SLE. Because of the physical connection to Lake Okeechobee, two watersheds now influence the health of the SLE—the Lake Okeechobee watershed, which includes the Everglades Agricultural Area (EAA), the Kissimmee River and the Kissimmee River watershed, and the adjacent St. Lucie River watershed. Both watersheds have been greatly altered by human activities, including intensive management of water levels in support of human land-use changes. Today, these two watersheds comprise wetlands that have been extensively drained for agriculture. Between 2004 and 2006, 52% and 58% of the land use in the Lake Okeechobee and St. Lucie River watersheds, respectively, were dedicated to agricultural practices (Zhang *et al.,* 2007; SWET, 2008). Cattle and citrus production were the predominant agricultural activities with 29% and 31% pasture and rangeland use and 7% and 23% citrus production in the Lake Okeechobee and St. Lucie River watersheds, respectively. Although sugarcane, which is primarily grown in the EAA, comprises only 12% of the Lake Okeechobee watershed (Zhang *et al.,* 2007), nitrogen loading from this land use and ultimately the EAA subbasins, has been significant because of the back-pumping of multiple canals that drain this area during the wet season (Kratzer and Brezonik, 1984; McCormick, James, and Zhang, 2010; SFWMD Staff, 1983a,b; Zhang *et al.,* 2007). The cumulative area of improved (780,677 acres; 315,929 ha) and unimproved (339,663 acres; 137,457 ha) pastures and rangelands (39,351 acres; 15,924 ha) in both watersheds, potentially make these agricultural landscapes significant nutrient and microbial contributors to the SLE. The government-sponsored Payment for Environmental Services program and eight pilot projects, seven in the

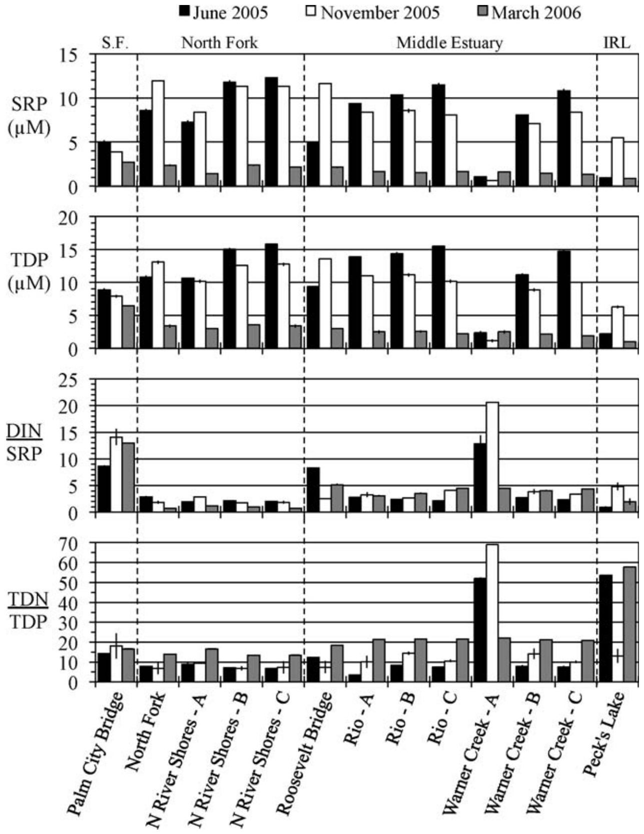

Figure 9. Soluble reactive phosphorus (SRP) and total dissolved phosphorus (TDP) concentrations, and DIN : SRP and TDN : TDP molar ratios (±SD) at the Martin County sites.

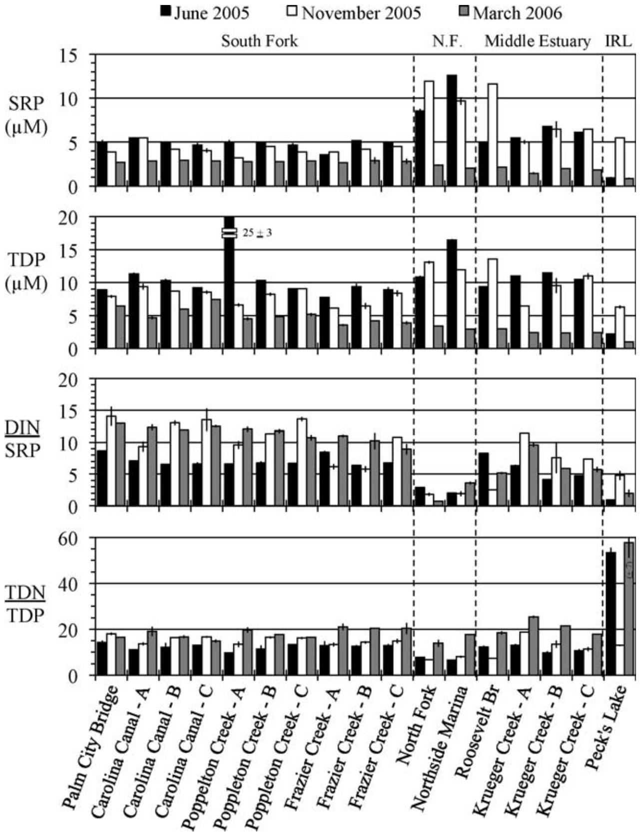

Figure 10. Soluble reactive phosphorus (SRP) and total dissolved phosphorus (TDP) concentrations, and DIN : SRP and TDN : TDP molar ratios (±SD) at the City of Stuart sites.

Lake Okeechobee watershed and one in the St. Lucie River watershed, were recently implemented to encourage agricultural landowners to provide on-site water management services in the form of retention or nutrient (TN and TP) load reduction (Balci *et al.,* 2012). With 1,159,691 acres (469,310 ha) of suitable cattle ranch lands incorporated into approximately 1144 farms accommodating >287,000 cattle in these two watersheds in 2007, landowners could play an important role in improving the quality of the water reaching the SLE (USDA Staff, 2009; SWET, 2008; Zhang *et al.,* 2007). Urban growth and high-density residential development along the coastal areas have increased dramatically in recent decades, much of which has relied on septic tanks for on-site sewage disposal. These types of poorly planned land uses and wastewater disposal are well known to be the primary causes of both nutrient (Howarth *et al*., 2000) and microbial fecal pollution (Mallin, 2006) in rivers, bays, and coastal waters of the United States.

The overriding importance of the posthurricane discharges *via* the C-44 in the water-quality degradation of the SLE was evident in our study. Data from June and November 2005, when excessive C-44 discharges occurred, showed significantly lower salinity and DO and higher turbidity, nitrate, TDN, SRP, TDP, and total coliforms compared with March 2006, when relatively low flows occurred (Figure 2; USACE and SFWMD Staff, 2004). The identification of the C-44 discharges as the primary source of water-quality degradation was indicated from spatial comparisons among segments of the SLE that consistently showed the South Fork, which directly received the C-44 discharges, had lower salinity, higher concentrations of turbidity, nitrate, DIN, and TDN than did the North Fork and Middle Estuary. The only exceptions to these spatial nutrient trends are higher ammonium, SRP, and TDP concentrations in the North Fork, compared with the South Fork, in June and November 2005. This phenomenon could be linked to the high density of golf courses directly adjacent to the North Fork, the C-23 canal, and the drainage of lands supporting citrus and row crops by the C-23 and C-24 canals (Graves, Wan, and Fike, 2004). These data support previous conclusions of water-quality impairment of the source water in the C-44 Canal (FDEP Staff, 2003). A stream-condition index (SCI) was used to evaluate the impairment status of the C-44 Canal under the Impaired Waters Rule (IWR) in 2003 (FDEP Staff, 2003). The two SCI evaluations performed in 2003 within the C-44 canal failed, according to the IWR guidelines, suggesting that the canal be evaluated for inclusion on the impaired-waters list. It was reasonably demonstrated that the biological impairment was associated with nutrient enrichment (nitrogen and phosphorus).

Accordingly, the large freshwater discharges from the C-44 in June and November 2005 (Figure 2) resulted in nutrient over-enrichment of the SLE. The average TDN concentrations for the Middle Estuary in June and November were 108.6 and 115.7 μM, respectively, values more than twofold higher than the proposed 51.4 μM TN target for this estuary (62–304.705 F.A.C; Parmer *et al.,* 2008). These TDN values were considerably higher than the TDN values measured in October 2004, following the 2004 hurricanes, along the Caloosahatchee River at the Franklin Lock (70.9 μM), which also receives Lake Okeechobee discharges conveyed to the west coast of Florida (Lapointe and Bedford, 2007). Similarly, the average TDP concentrations for the Middle Estuary in June and November were 11.4 and 9.3 μM, respectively, values more than threefold higher than the proposed 2.61 μM TP target for this estuary (62–304.705 F.A.C; Parmer *et al.,* 2008). These TDP concentrations for the SLE are also proportionally higher than the corresponding TDP concentrations measured in the Caloosahatchee River at the Franklin Lock in October 2004, which averaged ~2.0 μM (Lapointe and Bedford, 2007). The corresponding stoichiometry of the TDN : TDP ratio in the C-44 discharges was relatively low in June 2005, averaging ~11, considerably lower than the value of 35 at the Franklin Lock in October 2004 (Lapointe and Bedford, 2007). Even though the TDN and TDP concentrations were several-fold lower throughout the SLE in March 2006 than they were in June and November 2005, all sites still remained above the proposed targets for TDN and TDP, with the exception of TDP at the Peck's Lake reference site.

The exceptionally high concentrations of TDN and TDP, combined with a low N : P ratio, provided environmental conditions conducive to cyanobacterial bloom development in the SLE. Shortly after the June 2005 sampling, extensive surface blooms of the toxic cyanobacterium *Microcystis aeruginosa* occurred in the SLE in response to influxes of freshwater and nutrient loads from Lake Okeechobee *via* the C-44 canal (Phlips *et al.,* 2012). These blooms resulted in microcystin concentrations ranging from 163–1188 μg/l (Phlips *et al.,* 2012); concentrations high enough to affect human health (Carmichael, 2001; Carmichael *et al*., 2001). Lake Okeechobee, a eutrophic lake, experiences frequent cyanobacterial blooms (Havens *et al.,* 1996) and was the source not only of the excessive nutrient inputs during our study but also the cyanobacterial biomass that culminated in these harmful algal blooms (HABs) in the SLE (Phlips *et al.,* 2012). Blooms of the nonnitrogen-fixing *Microcystis aeruginosa* could have been triggered not only by the high nutrient concentrations, but also by the favorable stoichiometric shifts to the low TDN : TDP ratios (~9) that occurred in June 2005 (Fujimoto *et al.,* 1997; Smith, 1983).

In addition to the severe effects of the C-44 discharges on water quality in June and November 2005, localized nutrient pollution from septic tanks was apparent in our study in March 2006, when relatively low flows from the C-44 occurred. In Martin County, significant inshore-to-offshore concentration gradients were observed for ammonium at Rio and for TDN at Warner Creek. In the City of Stuart, significant gradients were observed for ammonium at Carolina Canal, nitrate at Poppleton Creek, and DIN and nitrate at Frazier and Krueger creeks. Possible local sources of phosphorus in Martin County included Warner Creek, North River Shores, and Rio, but only Warner Creek showed a significant TDP gradient during the March sampling. Significantly higher TDP and SRP concentrations in the North Fork during June and November 2005 indicate that it can be a significant source of phosphorus to the SLE. Similar evidence of localized nutrient pollution from septic tanks has been reported for the SLE (Belanger, Price, and Heck, 2007), the Florida Keys (Lapointe, O'Connell, and Garrett, 1990), and the Loxahatchee River estuary (Lapointe and Krupa, 1995a,b).

The greater number of violations of coliform standards in the lower salinity June and November 2005 samplings compared with the higher salinity March 2006 samplings underscores the role of the C-44 freshwater discharges in exacerbating septic tank–derived, microbial fecal pollution in the SLE. This phenomenon was due, in part, to coliform bacteria's inability to survive in moderate to highly saline seawater (Hanes and Fragala, 1967). Between August 2006 and June 2007, Ortega *et al.* (2009) studied bacterial indicators at three of the established study sites (Palm City Bridge, Poppleton Creek C, and Roosevelt Bridge) and concluded that microbial contamination was correlated with salinity. Once riverine surface waters become contaminated by fecal indicator organisms, their growth and survival is dependent on environmental factors, including salinity, nutrients, solar radiation, and organic matter (Hanes and Fragala, 1967; Ortega *et al.,* 2009; Sinton, Davies-Colley, and Bell, 1994). Schaefer *et al*. (2011) found that *Escherichia coli* and other fecal bacteria either act as primary pathogens or cause opportunistic infections in the bottlenose dolphin (*Tursiops truncatus*) in the IRL, where the risk of infection increased during periods of high rainfall in areas with a high number of septic tanks.

Similar fecal pollution problems have been reported for other rivers and estuaries following storm events and hurricanes. In the Charlotte Harbor estuary in southwest Florida, microbial fecal pollution increased following heavy rainfall in late fall and winter of 1997–98, suggesting that the increased rainfall and streamflow associated with El Niño conditions were important causative factors (Lipp *et al.,* 2001). In the anoxic 70-km Neuse River segment between Kinston and New Bern, North Carolina, concentrations of nutrients and fecal coliforms increased following hurricane Fran in 1996, when fecal coliforms ranged from 20 to >2000 cfu/100 ml (Burkholder *et al.,* 2004). This pattern reflects the increased survival and growth of fecal coliforms with decreasing salinity and increasing nutrients and organic matter (Cook and Hamilton, 1971). Organic phosphorus has been identified as a primary nutrient limiting bacterial growth and biochemical oxygen demand in blackwater streams in the southeastern United States (Mallin *et al.,* 2004). Accordingly, phosphorus availability may have been a factor in our study because the overall decrease in fecal and total coliforms in the March 2006 sampling correlated with not only with increased salinity but also with significantly lower concentrations of both SRP and TDP. For example, TDP concentrations were approximately threefold higher in June (11.7 μM) and November 2005 (9.3 μM) than they were in March 2006 (3.7 μM).

Localized, surface-water fecal contamination from septic tanks was apparent for sites in both Martin County and the

City of Stuart during the study, especially in the June and November 2005 samplings. This bacterial transport was likely facilitated by the moderate to excessively drained soils adjacent to Rio, the North River Shores, and Carolina canals and the Warner, Krueger, Frazier, and Poppleton creeks, which are primarily composed of Jonathan, Paola, and St. Lucie sands (McCollum and Cruz, 1981; USDA, 2012). Permeability through these soils is rapid, and the water table in most areas is >183 cm deep (McCollum and Cruz, 1981). In June 2005, fecal coliforms exceeded the single sample limit (>800 mpn/100 ml) established by FDEP for Class III waters at four of these seven creek sites, but no exceedances were recorded in November 2005 or March 2006 (62–302.530 F.A.C.). Although total coliform criteria were removed from federal rules and F.A.C. for Class III recreational waters, total coliform concentrations were high at six of the seven creek sites in June 2005 and four of the seven creek sites in November, based on historical Florida Department of Environmental Regulation maximum standards for a single sample (>2400 mpn/100 ml; 17–3.121 F.A.C.). No sites exceeded that historical criterion in March 2006. Enterococci counts exceeded the EPA limit for a single sample (158 cfu/100 ml) at 13 sites in November and only seven in March 2006 (40 CFR 131.41). All of the fecal and enterococci violations and high total coliform counts were in, or adjacent to, densely populated residential creeks or canal systems that relied on septic tanks for on-site sewage disposal. The only exception to this pattern was the Palm City Bridge in the South Fork, where the enterococci standard was violated in both November 2005 and March 2006. Enterococci are slightly more tolerant of saltwater than are coliforms (Hanes and Fragala, 1967), which may partially explain the higher concentrations seen in the South Fork during the last two sampling events. Inconsistently higher concentrations seen in the mainstems of the SLE, such as the Palm City Bridge site, as opposed to those inside the canals could be a consequence of small sewage system failures associated with high freshwater inputs and other hurricane-related conditions (Lipp *et al.,* 2001; Tomasko, Anastasiou, and Kovach, 2006). However, although minor spills occurred in the watershed just before each of the three sampling events, records indicate that they did not affect the water samples collected during the study (FDEM, 2012).

In recent decades, low salinity and poor water quality associated with managed freshwater releases into the SLE has negatively affected the biological resources in this system. A salinity envelope of 9.9–56 m^3 s^{-1} (350–2000 cfs) was identified in the IRL-S Project Implementation Report as a favorable range of inflow and related salinity for juvenile marine fish, oysters, and submerged aquatic vegetation (SAV; USACE and SFWMD Staff, 2004). Figure 2 shows that this range was clearly exceeded at the C-44, C-23, and C-24 in 2004 and 2005. Fish populations in the SLE show a high incidence of abnormal lesions, including fin erosion, spots or patches of inflamed or blood-congested skin, and ulcers (Graves, Thompson, and Fike, 2002). Such lesions have been associated with a low-salinity–tolerant pathogenic fungus, *Aphanomyces invadans,* which was correlated with low salinities and high nutrients in the Middle and Upper SLE (Graves, Thompson, and Fike, 2002; Sosa *et al.,* 2007). After direct hits by Hurricanes Frances and Jeanne in September 2004, a temporary decline in the number of saltwater species and a simultaneous increase in the number of freshwater and oligohaline species were documented in the SLE, the nearby St. Sebastian River, and the IRL (Paperno *et al.,* 2006; Switzer *et al.,* 2006). The eastern oyster (*Crassostrea virginica*) and SAV were both historically abundant in the SLE as "keystone species," forming hard-bottom reefs and seagrass beds that provided habitat for a wide variety of estuarine organisms. Although oyster reefs and seagrass beds were abundant in the 1940s and 1950s, the SLE no longer supports healthy, stable populations of these valued ecosystem components (Chamberlain and Hayward, 1996; Graves, Thompson, and Fike, 2002; Ibis Environmental, Inc. Staff, 2007; Robbins, 2011; URS Greiner Woodward Clyde, 1999). Extended periods with salinity levels <12‰ can be fatal to oysters or inhibit their feeding, reproduction, and growth (Funderburk *et al.,* 1991; Heilmayer *et al.,* 2008). Releases from the C-44 can decrease salinity to <5‰ within 24 hours and can extend for weeks to months (Figure 2).

In addition to hyposmotic stress, low-salinity conditions recorded during the June and November 2005 samplings in the SLE were associated with high turbidity (and heavy sedimentation) from suspended solids, which also limits the distribution of SAV (Funderburk *et al.,* 1991; Gallegos and Kenworthy, 1994; Steward and Green, 2007). Turbid C-44 discharges reduce water transparency in the SLE because of increased colored, dissolved organic matter and phytoplankton biomass (from nutrient enrichment), all of which can decrease productivity and the growth of seagrasses (Duarte, 1991; Dunton, 1994). The latest SLE seagrass mapping effort, conducted in 2007, through the SFWMD, showed low densities of *Halodule wrightii* and *Halophila johnsonii* in the Middle Estuary near the Rio site and no SAV in the North and South forks (Ibis Environmental, Inc. Staff, 2007). Between 2007 and 2011, the study area experienced a 5-year prolonged drought. In 2011, toward the end of the drought, SFWMD staff documented a sparse bed of *Ruppia maritima* near the North Fork reference site, thus showing the resiliency of the SLE when not subjected to unnaturally high freshwater inputs (Figure 1; Robbins, 2011). The first goal of the IRL Surface Water Improvement and Management (SWIM) Plan, which includes the SLE, is to "attain and maintain water and sediment of quality sufficient to support a healthy, macrophyte-based, estuarine lagoon ecosystem" (SFWMD and SJRWMD Staff, 1994, p. 2; Steward *et al.,* 2003). Clearly, the excessive freshwater discharges from the C-44 during this 2005–06 study are not consistent with the IRL SWIM plan.

Massive freshwater releases into the SLE eventually flow into the IRL and subsequently out St. Lucie Inlet and, to a lesser extent (~8%), Ft. Pierce Inlet, thus bathing the nearshore coral and sabellariid worm rock reefs (N. Smith, unpublished data; Lapointe, 2006). Prolonged exposure to turbid, nutrient-rich, low-salinity water negatively affects coral health, making them more susceptible to bleaching and potentially to death (Goreau, 1964; Jokiel *et al.,* 1993; Kerswell and Jones, 2003; Yentsch *et al.,* 2002). The shallow (<10 m) nearshore reefs immediately south of St. Lucie Inlet in St. Lucie Inlet Preserve State Park (SLIPSP) are exceptional in that they support the northernmost extent of scleractinian corals in southeast Florida (Beal *et al.,* 2012; Jaap and Hallock, 1990). Monitoring of SLIPSP reefs in June, July, and August 2004 indicated that corals were not bleached before the passing of Hurricanes Frances and Jeanne in September 2004 (L.W. Herren, personal observation). Reef monitoring conducted between February 2005 and March 2006, indicated generally poor water quality (high sedimentation and elevated nitrogen isotope values [~ 6‰] in reef macroalgae), the transport of woody debris onto the reef tract and coral bleaching in SLIPSP (L.W. Herren, personal observation; Lapointe, 2006). Coral species most affected by bleaching during the period of this study were *Montastrea cavernosa* and *Oculina diffusa,* but bleaching of *Diploria clivosa, Isophyllia sinuosa, Siderastrea siderea,* and the zooanthid *Palythoa caribaeorum* were also observed (L.W. Herren, personal observation; Lapointe, 2006).

CONCLUSIONS

Multiple hurricanes affected South Florida in 2004 and 2005, resulting in record rainfall and excessive freshwater releases into the SLE from the C-44 canal and, to a lesser extent, from the C-23 and C-24 canals. The data show that the effects on the SLE were severe, illustrating how human alteration of watersheds can magnify the effects of hurricanes on estuarine ecosystems (Mallin *et al.,* 2002). The discharges caused dramatic reductions in salinity to near-freshwater levels (<1‰) within the SLE (normally >12‰) in June and November 2005, which correlated with reduced dissolved oxygen, higher turbidity, higher concentrations of dissolved nitrogen and phosphorus, and higher fecal coliform and total coliform counts. The highest turbidity and concentrations of nitrate and TDN were consistently in the South Fork, which was directly affected by discharges from Lake Okeechobee *via* the C-44 canal. In contrast, ammonium, SRP, and TDP concentrations in June and November 2005 (the high-flow period) were highest in the North Fork, which is bordered by multiple golf courses and receives residential and agricultural (i.e., citrus and row crop) runoff through the C-23 and C-24 canals. Citrus, row crops, and golf courses are all documented to be significant contributors of ammonium and phosphorus to the SLE through stormwater runoff (Graves, Wan, and Fike, 2004). In March 2006, the South Fork also had the highest ammonium, SRP, and TDP concentrations. High fecal and total coliform counts in violation of FDEP and EPA standards were observed in tidal creeks of the SLE adjacent to dense residential and urban land uses that relied on septic tanks for on-site sewage disposal. Dense surface blooms of the toxic cyanobacterium *Microcystis aeruginosa* followed the reduced salinity and high nutrient concentrations in June 2005, a phenomenon possibly related to the low TDN : TDP ratios (~9) at this time (Fujimoto *et al.,* 1997). These excessive freshwater releases and their associated water quality effects have caused fish lesions, loss of SAV and oyster beds, diminished recreational uses and ecological services in the SLE, and coral stress in downstream coastal waters (Graves, Thompson, and Fike, 2002; Lapointe, 2006). Considering that hurricane activity is predicted to be above average in the coming decades (Goldberg *et al.,* 2000), such degradation could continue. Public outcry about the effects of these excessive freshwater discharges has been considerable (Harris, 2005; Heuvelmans, 1974; Swartz, 2005), and water managers have established both salinity (USACE and SFWMD Staff, 2004) and nutrient targets (62–304.705 F.A.C; Parmer *et al.,* 2008; USACE and SFWMD Staff, 2004) for the SLE. Improved capacity for storage, minimization of freshwater releases from Lake Okeechobee, and treatment of stormwater runoff and sewage in the watersheds of the SLE, extending to Lake Okeechobee and the Kissimmee River basin, must be implemented if these problems are to be moderated in the future.

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