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Water Quality Changes in the Guana Tolomato Matanzas National Estuarine Research Reserve, Florida, Associated with Four Tropical Storms

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ABSTRACT

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The objective of this study was to document the effects of extreme wind and rainfall conditions associated with tropical storms on physiochemical variability in a tidal creek, Pellicer Creek, in northeast Florida. High-frequency salinity and meteorological data from the Guana Tolomato Matanzas National Estuarine Research Reserve were examined at a range of temporal scales, from 30-minute to annual intervals. Monthly measures of nutrient and water clarity parameters were compared to salinity variations. It was hypothesized that the four tropical storms impacting the region in 2004 (*i.e.,* Charley, Frances, Ivan, and Jeanne) altered tidal regimes and watershed inputs to Pellicer Creek sufficiently to generate water column conditions that deviated significantly from nonstorm periods. The four tropical systems of 2004 suppressed tidally induced salinity variations. Strong northeasterly winds associated with the storm events initially prompted salinity spikes. However, high rainfall levels during the course of each event ultimately caused strong declines in salinity for extended periods of time. Nitrogen concentrations in Pellicer Creek were significantly elevated after storm events. Because primary production in many of the coastal environments along the east coast of Florida, as well as around the world, is nitrogen limited, increases in nitrogen input represent a potential for enhanced algal production and biomass. Given the major changes in watershed characteristics and global climate patterns expected in future years, the ability to predict the influences of these changes on the estuarine environment will be an essential part of designing, implementing, and justifying management efforts.

ADDITIONAL INDEX WORDS: *Hurricanes, salinity, nutrients, phytoplankton, continuous monitoring.*

INTRODUCTION

Salinity, nutrient concentrations, water clarity, hydrology, organismal abundance, and species diversity are among the key elements that define the overall structure and function of estuaries (BERQUIST *et al.,* 2006; HACKNEY, BURBANCK, and HACKNEY, 1976; IMBERGER *et al.,* 1983; KENNISH, 2004; MCMILLAN, 1974; MONTAGUE and LEY, 2003; ORLANDO *et al.,* 1994). Recent trends in cultural eutrophication and land use within estuarine watersheds have affected the first four parameters and in turn altered the latter two in many ecosystems (CLOERN, 2001; NIXON, 1995). Defining the nature and magnitude of these effects, particularly on broad temporal scales, is difficult without incorporating the influence of variations in meteorological conditions, particularly as it relates to the hydrology of ecosystems (CLOERN *et al.,* 1985; EYRE and PONT, 2003; HAMA and HANDA, 1994; MOORE *et al.,* 2006; SHARLER and BAIRD, 2003). Variability in meteorological conditions occurs over a range of temporal scales and intensities, from daily changes in rainfall and wind to storm events and multidecadal shifts in climate (ENFIELD, MESTAS-NUÑEZ, and TRIMBLE, 2001; GERTEN and ADRIAN, 2000; GOODRICH, 1988; LIVINGSTON *et al.,* 1997; SCAVIA *et al.,* 2002).

Storm events, because of their intensity, can alter the structure and function of ecosystems, despite their relatively short duration (BOESCH, DIAZ, and VIRNSTEIN, 1976; BLOOD *et al.,* 1991; CAHOON, 2006; GREENING, DOERING, and CORBETT, 2006; MALLIN and CORBETT, 2006; TAB and JONES, 1962; TILMANT *et al.,* 1994; VAN DOLAH and ANDERSON, 1991). It is obvious from even cursory empirical observations that storms can have significant and multifaceted effects on estuarine ecosystems, although the magnitude of these alterations is dependent upon the intensity, location, and duration of particular storms. The extreme wind and rainfall conditions associated with storms alter tidal regimes, water circulation patterns, and watershed inputs to estuaries. Documenting these effects can be challenging because most monitoring programs do not deal with the rapid and dramatic changes that occur during storm events, but are limited to sampling under less extreme conditions.

Studies of multiple large storm events involving continuous water quality monitoring, or monitoring more than monthly, are rare. PAERL *et al.* (2001) described the impacts of three

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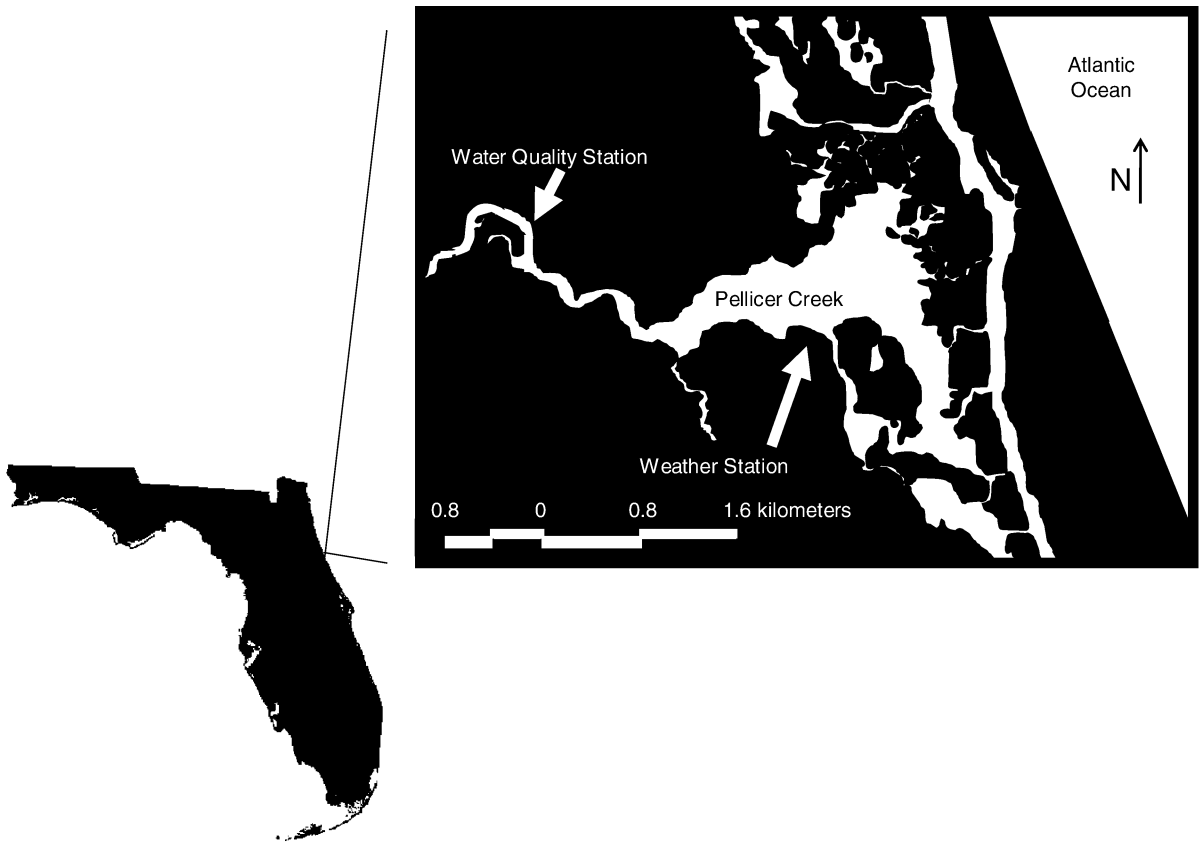

Figure 1. Location map of Pellicer Creek and Guana Tolomato Matanzas National Estuarine Research Reserve monitoring stations.

sequential hurricanes in 1999 (*i.e.,* Dennis, Floyd, and Irene) on the Pamlico Sound estuary in North Carolina. Data used in the study included continuous (15-minute sampling intervals) and weekly monitoring in the Neuse and Pamlico River estuaries and monthly poststorm sampling in Pamlico Sound. In the Sound, floodwaters created a combination of vertical stratification and high organic matter loads that resulted in hypoxic conditions for approximately 3 weeks. In another example, WALKER (2001) used time-series data from three stations in a southern Louisiana bay system to assess the impacts of two major storms on physical conditions in the water column. He found increases in water level and salinity with onshore winds, as well as decreases in water level and salinity with offshore winds. Large peaks in suspend solids were also associated with the storm events.

The environmental monitoring networks established by the National Estuarine Research Reserve (NERR) program provide an opportunity to examine the effects of storm events on a relevant time scale (KENNISH, 2004). In this study, environmental monitoring data from the Guana Tolomato Matanzas (GTM) NERR in northeast Florida were used to investigate the effects of the 2004 Atlantic hurricane season on water quality in a tidal creek ecosystem, Pellicer Creek (Figure 1).

Four tropical storms affected northeast Florida in the summer of 2004. Hurricane Charley, the first major storm of 2004, struck the southwest coast of Florida in the middle of August as a Category 4 on the Saffir-Simpson hurricane scale (PASCH, BROWN, and BLAKE, 2004), then traveled northeasterly across the state and exited near Daytona Beach as a tropical storm (Figure 2). The next storm, Hurricane Frances, made landfall on Florida's southeast coast as a Category 2 on September 5, 2004, then traveled into the Gulf of Mexico and north through the Big Bend region of Florida, affecting most of north Florida (Figure 2; BEVEN, 2004). The third storm of 2004, Hurricane Ivan, made landfall on the southern coast of Alabama on September 16, 2004, then crossed the southeastern United States before re-entering the Atlantic Ocean and returning south along the Florida coast (Figure 2; STEWART, 2004). Hurricane Jeanne, the final major storm of the 2004 season, made landfall on September 26, 2004, on Florida's east coast, as a Category 3 storm and traveled west-northwest, weakening to a tropical storm as it traveled up the west coast of the state (Figure 2; LAWRENCE and COBB, 2004).

GTMNERR weather and water quality observations from 2004 were compared to 2003, which was not subject to any major land-falling storms in Florida. We hypothesized that the rain and wind associated with storms would significantly alter the typical diel patterns of marine and freshwater exchange within Pellicer Creek, thereby affecting a range of

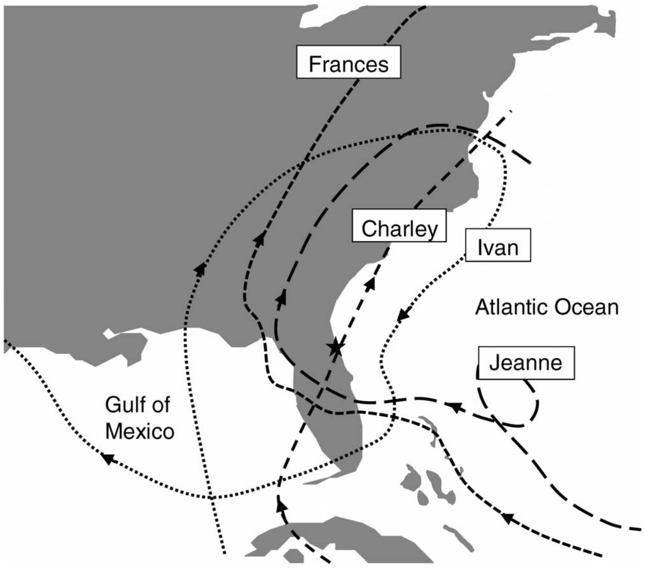

Figure 2. Storm tracks (Charley, France, Ivan, and Jeanne).

important response variables, including salinity, light transparency (*i.e.,* turbidity and dissolved organic matter), nutrient concentrations, and phytoplankton abundances (*i.e.,* chlorophyll *a* concentrations). One of the elements of consideration in the study was the longevity and magnitude of alterations associated with each storm, as well as potential carryover effects from one storm to the next.

METHODS

Site Description

Pellicer Creek is a major tributary of the Matanzas River and is located within the GTMNERR. The GTMNERR lies within the southern temperate climate of northeast Florida (Chen and Gerber, 1990). The area has an average of 140 cm of rainfall annually, with a summer wet season from June to September (Figure 3). Pellicer Creek experiences semidiurnal tides with an average range of 0.6 m (NOAA, 2004). The majority of the creek is surrounded by public conservation lands. Salinity at the sampling site ranges from 0 ppt to 33 ppt.

Data Collection

The GTMNERR manages a meteorological station at the mouth of Pellicer Creek and a water quality monitoring station located approximately 4 km upstream from the weather station (Figure 1). At the weather station, data were recorded with a CR10X-2M data logger at 15-minute intervals. At the water quality station, a YSI 6600 continuous monitoring data sonde collected measurements on salinity and water depth at 30-minute intervals (NOAA, 2004). Weather and water quality data from 2003 and 2004 were downloaded from the Centralized Data Management Office website (http://cdmo.baruch.sc.edu; NOAA, 2004). As 2003 is the first complete year of data for the GTMNERR continuous monitoring program and was not subject to any major storms in Florida, it was used as a reference year. Even though Florida experienced an unusually active storm season in 2004, the annual rainfall total for the Pellicer Creek watershed was only slightly higher than the rainfall total in 2003 (Figure 3; NOAA, 2006). On an annual basis, both years were near the average rainfall total for 1994–2006. Due to data logger malfunctions, the weather station did not record data for a total of 32 days during portions of September, October, and November 2003. Malfunctions at the water quality station resulted in missing salinity and depth data for May 1 to May 12, 2004 and June 27 to July 7, 2004. These missing data may have caused slightly biased averages, but were assumed not to affect general interpretations because they represented only a small portion of the high frequency dataset.

United States Geological Survey (USGS) discharge measurements for 2003–2004 taken at a station just upstream (<500 m) from the Pellicer Creek water quality station were downloaded from http://waterdata.usgs.gov. The months of August, September, and December of 2003 and January, April, October, November, and December of 2004 were incomplete and therefore not used in data analysis.

In addition to continuous *in situ* monitoring data, water was collected on a monthly basis using grab sampling methods at the Pellicer Creek site in accordance with NERR guidelines (Kennish, 2004; NOAA, 2004). One integrated sample from the entire column of water and two samples from 1 m above the bottom were collected with a Polyvinyl Chloride (PVC) pole (Venrick, 1978). In addition, an ISCO automatic sampler was deployed monthly to collect water samples from 1 m above the bottom every 2.5 hours for one complete tidal

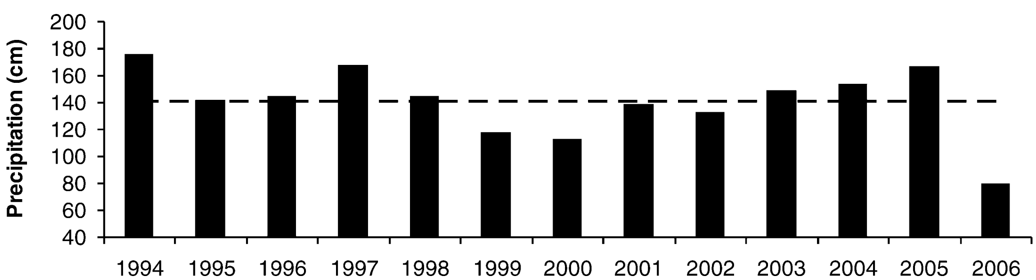

Figure 3. Annual rainfall totals, Hastings, Florida (NOAA, 2006).

cycle (25 hours). Samples from both collection methods were brought back to the lab on ice and processed in a similar manner for the determination of nutrient concentrations, including total nitrogen (TN), total dissolved nitrogen (TDN), total phosphorus (TP), total dissolved phosphorus (TDP), nitrate + nitrite ($NO_3 + NO_2$), ammonium (NH_4), and soluble reactive phosphorus (SRP), as well as water clarity parameters such as chlorophyll *a,* colored dissolved organic matter (CDOM), and turbidity.

Water Chemistry

Whole water samples were used to determine concentrations of TN, TP, chlorophyll *a,* and turbidity. To determine TN and TP, samples were digested and measured colorometrically on a Bran-Luebbe autoanalyzer (TN) and a dual-beam scanning spectrophotometer (TP) (APHA, 1998). Analysis methods for TDN and TDP were the same as those for TN and TP, respectively, but samples were filtered first through PALL A/E glass-fiber filters (1-μm pore size) (APHA, 1998). Chlorophyll *a* was processed using the SARTORY and GROBBELAAR (1984) ethanol extraction method. Chlorophyll *a* concentrations (uncorrected) were determined spectrophotometrically according to Standard Methods (APHA, 1998). Turbidity was measured in Nephelometric Turbidity Units using a LaMotte Model 2020 Turbidimeter.

For soluble nutrient and CDOM analyses, whole water was filtered through glass-fiber filters (1-μm pore size). Concentrations of NH_4 and $NO_3 + NO_2$ were determined colorometrically on a Bran-Luebbe autoanalyzer (APHA, 1998; STRICKLAND and PARSONS, 1972). Concentrations of SRP were measured on a dual-beam scanning spectrophotometer at 882 nm following standard methods (APHA, 1998). Values of CDOM were measured against a platinum-cobalt standard using a dual-beam scanning spectrophotometer (APHA, 1998).

Data Analysis

Descriptive statistics of the 2003–2004 time series were used to explore inter- and intraannual variability in salinity, rainfall, wind speed, wind direction, nutrient concentrations, and water clarity. SANGER *et al.* (2002) and WENNER *et al.* (2004) measured storm effects by looking at the time it takes for a water quality parameter to return to prestorm conditions. They defined "prestorm" as 2 weeks before the storm and "poststorm" as 4 weeks after. A similar approach was taken in this study. Descriptive statistics were calculated for salinity values before and after storms and for summer seasons of both years. Summer was defined as the period between June and September of 2003 and 2004. The SAS statistical software version 8 (SAS INSTITUTE, INC., 1999) was used to calculate all test statistics ($\alpha = 0.05$).

Nonparametric tests were used after determining that most parameters were not normally distributed according to the Kolmogorov-Smirnov test for goodness-of-fit. The Wilcoxon sign-rank test was used to explore interannual variation by testing for differences between median values during the summer of 2003 and summer of 2004. The Spearman's Rank Correlation was used to examine the relationship between the rate of freshwater flow and salinity. Discharge and salinity were strongly negatively correlated ($\rho = -0.95$, $p < 0.0001$). Because the discharge dataset was sparse, correlations were calculated between salinity, rainfall, and all other parameters to determine the associations between water column conditions and the interchange of marine and freshwater masses. Simple regressions were performed to evaluate the dependency of environmental parameters on salinity. Multiple regressions were not useful because of signs of multicollinearity.

Graphs of 30-minute salinity and water depth data for each diel ISCO sampling event were used to determine the times at which high and low tides occurred. Water samples and *in situ* observations from those times were used in correlation and regression calculations. The rainfall data used in the correlation analysis, obtained from the GTMNERR weather station, consisted of daily totals averaged for the intervals between monthly ISCO sampling events. September, October, and November 2003 rainfall averages were not used in correlation calculations because of data logger malfunctions during those months.

RESULTS

Basic Physiochemical Conditions

The bimodal rainfall pattern described for the study area by JORDAN (1984) and CHEN and GERBER (1990) was reflected in the elevated precipitation in summer and late winter/early spring of both 2003 and 2004 (Figure 4). In 2003, the latter half of July and the first half of August experienced frequent days of moderate rainfall, with a corresponding drop in daily salinity averages at the end of July. By August 2, mean daily salinity was below 1 ppt. Salinity values did not rise above 1 ppt until August 25, after which salinity increased until a rainfall event occurred on October 7 and salinity values temporarily declined. Wind speed during this period was minimal. By contrast, the tropical storms of 2004 caused several instances of elevated mean daily wind speed, and corresponding spikes were observed in salinity and water depth (Figure 4). Several days of rain from July 15–20, 2004, resulted in a daily mean salinity below 1 ppt on July 19. Afterward, salinity values increased to approximately 15 ppt until the passage of the first tropical storm. The USGS monthly discharge data for 2003–2004 indicated that September 2004 experienced the highest mean discharge of all months for which data were available (Figure 5). Salinity, precipitation, water depth, and wind speed were all more variable during the summer of 2004 than during the summer of 2003 (Figure 4).

Median chlorophyll *a* concentrations were similar for both years of the study (Table 1). Median TN and TDN concentrations were higher in 2004 than 2003. Much of the TN was in soluble form (TDN) in both years. Median $NO_3 + NO_2$ and NH_4 represented roughly 10% of TDN. The NH_4 levels were about four times as high as $NO_3 + NO_2$ concentrations in both years. Median TP, TDP, and SRP concentrations were lower in 2004 than 2003, and more than 70% of TP was in the soluble form (TDP). Roughly 50% of mean TDP was present as SRP.

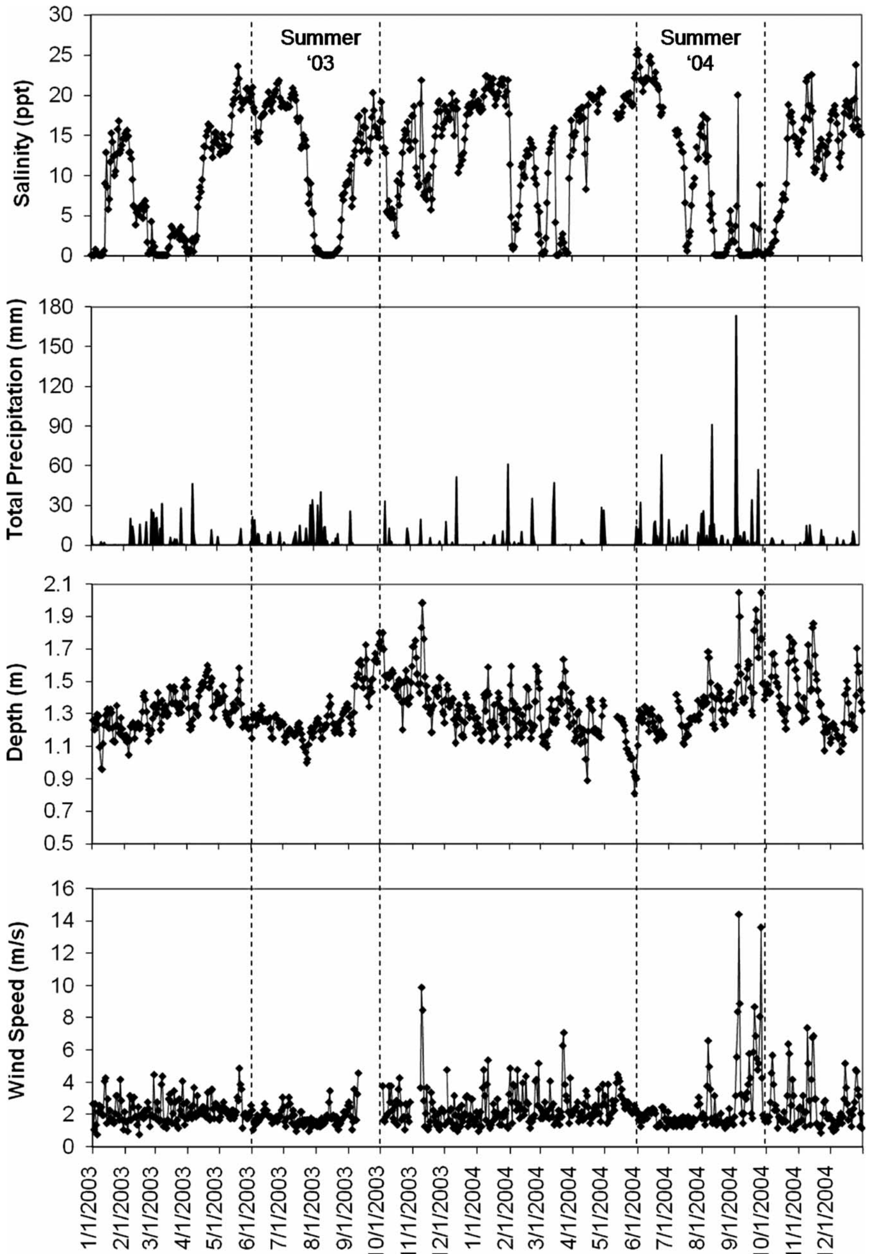

Figure 4. Daily averages for entire time series (2003–2004). (A) Salinity; (B) total precipitation; (C) water depth; (D) wind speed.

Salinity and Meteorological Conditions during Storm Events

The salinity and weather time series available for Pellicer Creek made it possible to examine immediate storm effects. During the passage of Hurricane Charley, the Pellicer Creek weather station recorded a maximum wind speed of 17.9 m/s and a total of 129.6 mm of rainfall (Table 2). The weather station was experiencing southeasterly winds before the passage of Charley, but shifted to the north-northeast and increased in strength during the storm. North-northeasterly winds blew up-creek, coinciding with a temporary increase in salinity. During the 2 weeks before Charley, mean daily salinity was 12.2 ppt. After the storm passed, heavy rainfall in the Pellicer Creek catchment caused salinities in the creek to drop to less than 1 ppt (Figure 6). Salinity stayed below 1 ppt for 11 days, after which it began to rise, showing more typical tidal oscillations. Salinity remained below the 2-week prestorm average for a total of 20 days until the next storm event on September 5.

During Hurricane Frances, maximum wind speed at Pellicer Creek was 18.8 m/s and the storm dropped 204.5 mm of rain at the Pellicer Creek weather station (Table 2). Average

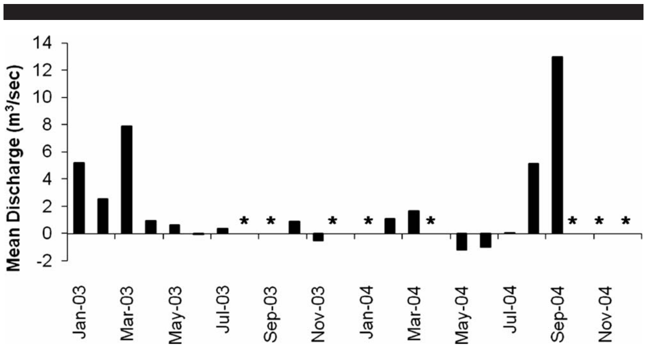

Figure 5. The USGS mean monthly discharge in Pellicer Creek (*data not collected).

Table 2. *Total rainfall and maximum wind speed experienced at Pellicer Creek during the passage of the 2004 tropical systems.*

Storm	Dates of Meteorological Impact	Total Rainfall (mm)	Maximum Wind Speed (m/s)
Charley	August 11–15	129.6	17.9
Frances	September 3–6	204.5	18.8
Ivan	September 20	34.2	10.3
Jeanne	September 25–26	61.2	18.3

salinity 2 weeks before the storm was 1.8 ppt due to freshwater inputs caused by Charley. On September 5, salinity peaked at 29.8 ppt during a wind-induced saltwater surge up the creek and then quickly dropped to zero after passage of the storm (Figure 6). Water remained fresh and exhibited little salinity variability until September 20, when salinities were elevated due to northeast winds associated with Tropical Storm Ivan (Figure 6). Salinities fell after the initial spike and remained under 1 ppt until September 25.

Salinity in Pellicer Creek increased to 8.9 ppt on September 26 during Hurricane Jeanne, then dropped on September 27 and remained below 1 ppt for 10 days (Figure 6). After Jeanne, salinity remained below the pre-Charley average of 12.2 ppt for more than 3 weeks (September 28–October 21). The passage of each storm resulted in spikes in water depth due to a combination of wind-induced movement of marine water upstream and subsequent peaks in freshwater outflow from the creek watershed due to high rainfall inputs to the Pellicer Creek catchment.

Temporal Trends in Water Column Characteristics

The influence of multiple storms in 2004 on salinity in Pellicer Creek was evident in a comparison of summer median values in 2003 (Table 3). Median salinity during the summer of 2003 was significantly higher than during the summer of 2004. Rainfall and wind speed medians were not different between years, but both showed larger ranges (higher maxima) during the summer of 2004 than during the summer of 2003.

Salinity was inversely related to rainfall amounts, reflecting the influence of discharge from the catchment (Figure 7; Table 4). Water clarity parameters (*i.e.,* CDOM and turbidity) showed bimodal distributions, coinciding with the typical late winter and summer rainfall peaks described for this region by Jordan (1984) and Chen and Gerber (1990) (Figure 7). The fact that CDOM levels were closely tied to watershed discharge was reflected in the strong inverse correlation between salinity and CDOM and the strong positive relationship between rainfall and CDOM (Table 4). Simple regression analysis showed that salinity accounted for 56% of the variability in CDOM (Table 5). Turbidity showed weak positive relationships (nonsignificant) with both salinity and rainfall, as might be expected from the complex suite of factors that contribute to turbidity, including wind-induced sediment resuspension (Figure 7, Table 4).

Chlorophyll *a* also showed a bimodal distribution, peaking in the early summer and late fall of both years, before the peaks in rainfall (Figure 7). August and September of 2004 exhibited lower chlorophyll *a* concentrations and suppressed diel variability compared with the same months in 2003 (Figure 7). Phytoplankton levels (in terms of chlorophyll *a* concentration) entering Pellicer Creek from the estuary were typically higher than those entering the creek from the catchment. This pattern was illustrated by the positive correlation between chlorophyll *a* and salinity (Table 4). Regression analysis indicated that salinity was responsible for 47% of the variability in chlorophyll *a* concentrations (Table 5). This pattern was further illustrated by the observation that chlorophyll *a* concentrations were lower during the poststorm high flow period of September 14–15, 2004, than during the period of September 23–24, 2003, which was not preceded by tropical storms (Figure 8).

Nitrogen concentrations generally followed rainfall levels (Figure 7). Low salinities corresponded with high TN values,

Table 1. *Median and [range] of chlorophyll and nutrient values obtained from monthly grab and diel sampling in Pellicer Creek during 2003 and 2004 as well as* p *values obtained from Wilcoxon signed rank tests between years (H_0: 2003 = 2004,* N *= 166).*

Parameter	2003	2004	*p* Value
Chlorophyll *a* (μg/L)	5.3 [0–24.4]	4.8 [0.3–32.0]	0.4444
TN (mg/L)	0.5913 [0.1270–1.4124]	0.6786 [0.1798–1.8550]	0.0014*
TDN (mg/L)	0.5340 [0.1567–1.3090]	0.5629 [0.0099–1.4068]	0.0090*
NO_{2+3} (mg/L)	0.0122 [0–0.2027]	0.0096 [0–0.1035]	0.0002*
NH_4 (mg/L)	0.049 [0–0.173]	0.047 [0–0.473]	0.1125
TP (mg/L)	0.085 [0.034–0.169]	0.071 [0.042–0.172]	0.0056*
TDP (mg/L)	0.064 [0.026–0.145]	0.054 [0.022–0.138]	0.0039*
SRP (mg/L)	0.037 [0.007–0.091]	0.027 [0.007–0.069]	<0.0001*

* Significant values at the 95% confidence level.

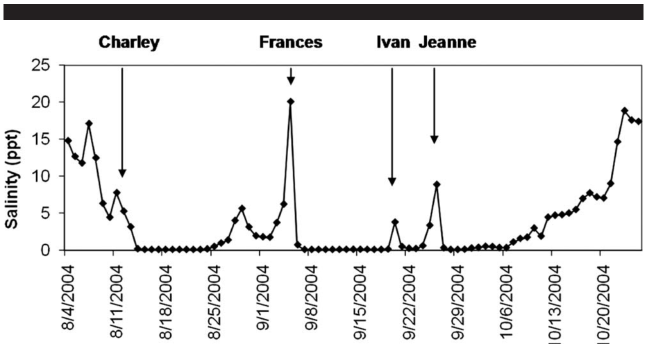

Figure 6. Mean daily salinity at the Pellicer Creek water quality station 2 weeks before Hurricane Charley and 4 weeks after Hurricane Jeanne.

indicating that freshwater flow from the creek watershed is enriched with nitrogen. This observation is further supported by the fact that TN, TDN, and $NO_3 + NO_2$ were all negatively correlated with salinity (Table 4). Also, TN and TDN were significantly positively correlated with rainfall. Regression equations indicated that salinity was responsible for 50% of the variability in TN and TDN (Table 5). The difference in nitrogen concentrations between flow regimes is illustrated by comparing the diel sampling period of September 23–24, 2003, and the poststorm period of September 14–15, 2004 (Figure 8). The TN concentrations in the creek in the latter period were twofold higher than in the former period.

A similar contrast between high and presumably low watershed outflow periods was not observed for phosphorus. The TDP was inversely correlated with salinity and positively correlated with rainfall, whereas TP showed no significant relationships (Table 4). This pattern was exemplified by the similarity in TP concentrations observed during the diel sampling event of September 23–24, 2003, and the high flow period of September 14–15, 2004 (Figure 8). The proportion of particulate phosphorus in TP concentrations peaked in June and July of both years (Figure 9). In contrast, TP was 100% dissolved phosphorus during the diel sampling events of August and September 2004 (Figure 9). The disparity in the relationships of TP and TDP to salinity suggests that particulate phosphorus concentrations were controlled by factors other than freshwater discharge (*i.e.,* wind-induced sediment resuspension).

DISCUSSION

The results of this study provide a glimpse into the time scale and magnitude of water quality changes in a tidal creek ecosystem after multiple storm events. One of the most direct and obvious effects of storms is the alteration of salinity regimes as it relates to wind-induced tidal surge and rainfall-induced freshwater runoff from the watershed. It is difficult to model the relationship between salinity and rainfall with simple regression analyses. To correctly define the dependence of salinity on rainfall and describe tropical storm effects, it is necessary to employ a transfer function model with Autoregressive Moving Average (ARMA) errors, time lags, and multiple explanatory variables (*e.g.,* wind speed, wind direction, and tidal effects; Niu, Edmiston, and Bailey, 1998). However, for the applications in this study, it was not necessary to model rainfall effects on salinity, as salinity was a reasonable measure of the proportion of marine and freshwater inputs to the creek at a particular location and time. Model relationships developed from the limited discharge data available for the Pellicer Creek confirm the existence of a strong correlation between discharge and salinity. Based on the latter observation, salinity values were used throughout the study to explore the relative influence of fresh and salt water on water column characteristics in the creek.

Salinity was influenced by storm events in several significant ways. Strong onshore and upstream winds during storms drove high salinity marine water well up into the tidal creek, beyond the normal range associated with tidal exchange, although the effect was relatively short-lived. Conversely, the high rainfall totals associated with the tropical storms resulted in significantly increased discharges of freshwater from the watershed, which drove down salinities for extended periods of time, overwhelming the normal diel tidal fluctuations. These findings are comparable to those of Sanger *et al.* (2002) and Wenner *et al.* (2004) who concluded that surges associated with storms that approached the east coast from the Atlantic generally cause short-term increases in salinity, while rainfall inputs result in longer-term salinity decreases. The observations in this study also support those of Steward *et al.* (2006) who studied the effects of the 2004 Atlantic hurricane season on seagrass communities of Florida's east coast. They measured water quality conditions in the Indian River Lagoon approximately weekly during and after the 2004 hurricane season and observed salinity and water clarity decreases after the storms.

Table 3. *Median and range (based on daily averages) describing the distribution of salinity, daily rainfall totals, and wind speed for the 2003–2004 wet seasons and* p *values obtained from Wilcoxon signed rank tests between summer seasons (H_o: summer 2003 = summer 2004).*

Parameter	Season	*N*	Median	*p* Value	Range
Salinity (ppt)	summer 03	110	14.8		[0.1–21.9]
	summer 04	110	6.3	0.0095*	[0.1–25.7]
Rainfall (mm)	summer 03	101	0.0		[0–39.9]
	summer 04	121	0.3	0.3636	[0–173.2]
Wind speed (m/s)	summer 03	101	1.8		[1.0–4.6]
	summer 04	121	1.8	0.6986	[1.2–14.4]

* Significant values at the 95% confidence level.

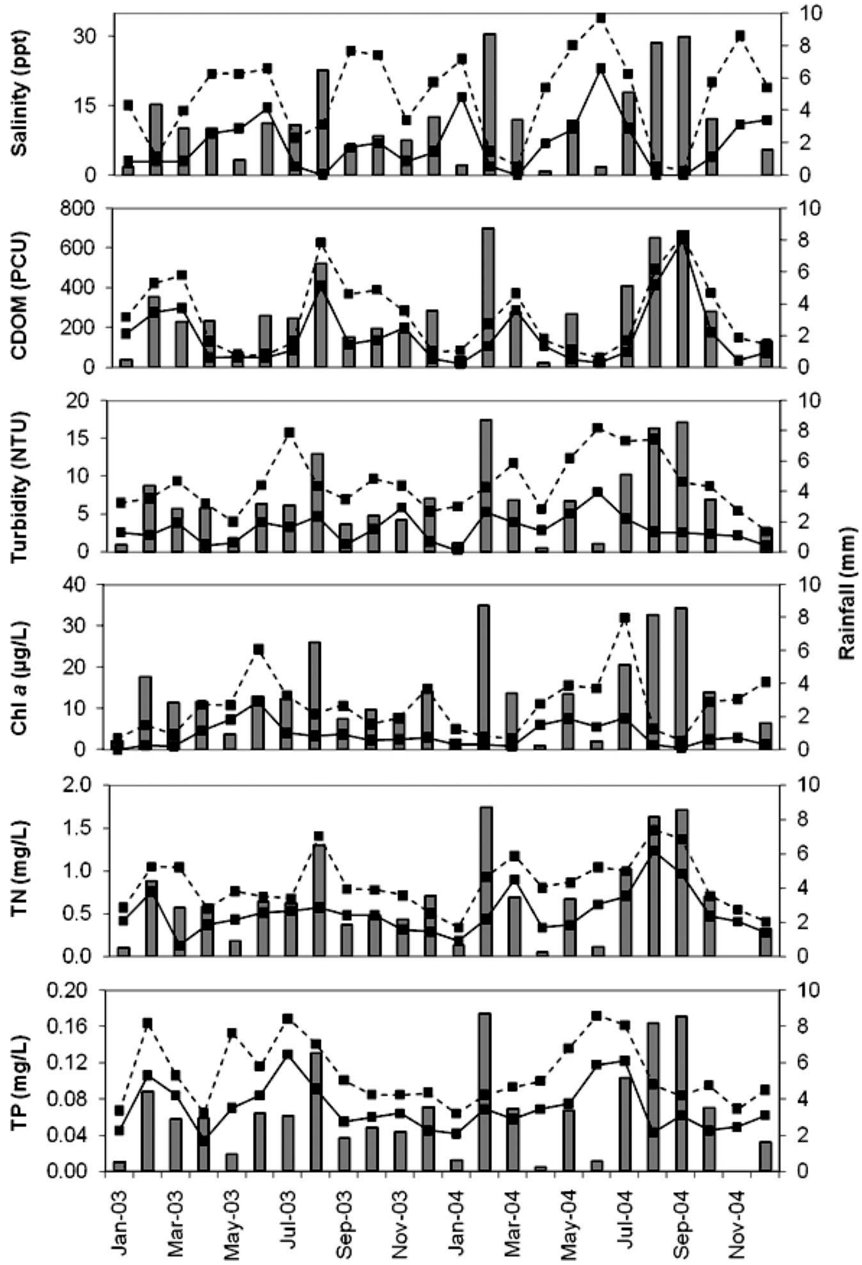

Figure 7. The 2003–2004 mean monthly rainfall (represented by gray bars) collected from the Pellicer Creek weather station, plotted relative to maximum (dashed top line) and minimum (solid bottom line) monthly nutrient concentrations, phytoplankton biomass, and water clarity parameters determined from diel sampling. (A) Salinity → (F) TP.

The relative magnitude of the storm effects on Pellicer Creek are exemplified by comparing salinity regimes in the summer periods of 2003 and 2004. Median salinities for 2004 were nearly threefold lower than 2003, although both years had extended periods of low salinity. In 2003, the period was restricted to August, the month when rainfall totals peaked. In 2004, multiple extended periods of low salinity were observed from July through early October, in large part due to the multiple storm events in the late summer.

The timing of the tropical storm season has important ecological implications (Mallin and Corbett, 2006; Michener *et al.,* 1997). Typically, the ground is not saturated in early fall and soils are dry enough to absorb initial rain events and recharge wetlands. However, excessive rainfall associated with storms can change the magnitude of river discharge, thereby altering the normal seasonal variability in salinity and nutrient concentrations.

In conjunction with alterations in salinity regimes, storm

Table 4. *Spearman correlation coefficients between rainfall, salinity, and all other parameters.*

	Salinity		Rainfall	
	ρ (rho)	*p* Value	ρ (rho)	*p* Value
Rainfall	−0.63	<0.0001*		
SRP	−0.17	0.2591	0.20	0.1987
TDP	−0.30	0.0359*	0.40	0.0092*
TP	0.03	0.8525	0.20	0.2042
$NO_3 + NO_2$	−0.33	0.0228*	0.27	0.0935
NH_4	−0.15	0.3091	0.30	0.0570
TDN	−0.68	<0.0001*	0.60	<.0001*
TN	−0.66	<0.0001*	0.71	<.0001*
Chl *a*	0.60	<0.0001*	−0.26	0.0913
Turb	0.28	0.0562	0.25	0.1059
CDOM	−0.81	<0.0001*	0.65	<.0001*

* Significant values at the 95% confidence level.

Table 5. *Simple regression coefficients of salinity* vs. *all other parameters at one high and one low tide per month (*N = *48).*

Regression Equation	r^2	*p* Value
log (TDN) = −0.41 − 0.18log (salinity)	0.50	<0.0001*
log (TN) = −0.28 − 0.17log (salinity)	0.50	<0.0001*
log (Chl *a*) = 0.91 + 0.31log (salinity)	0.47	<0.0001*
log (CDOM) = 5.49 − 0.35log (salinity)	0.56	<0.0001*

* Significant values at the 95% confidence level.

events affected other water column characteristics in Pellicer Creek related to the substantial rainfall inputs to the watershed. Storm-induced flooding of watersheds can alter nutrient inputs to estuaries (Paerl *et al.,* 2006) and impact the potential for hypoxia (Tomasko, Anastasiou, and Kovach, 2006). As seen from the current data, nitrogen concentrations in Pellicer Creek outflows were significantly elevated after major rainfall events. This effect is illustrated by the more than twofold higher TN concentration at the Pellicer Creek site on comparable dates in 2003 and poststorm 2004. The multiple storm impact is also reflected in the higher median concentrations of both TN and TDN in 2004 compared to 2003. The strong negative correlation between salinity and TN further demonstrates the role of the creek watershed in nitrogen load to the estuary. Conversely, the lack of significant relationships between TP or SRP and rainfall or salinity suggests a lesser role for the creek as a source of phosphorus to the estuary.

Because primary production in many coastal environments along the east coast of Florida (Phlips *et al.,* 2002), as well as around the world (Cloern, 2001), are nitrogen limited, increases in nitrogen input represent a potential for enhanced algal production and biomass (Mallin and Corbett, 2006; Paerl *et al.,* 2006). Recent research in the Suwannee River estuary has shown that increases in nutrient load during flood periods can be correlated to increases in the standing crop of phytoplankton in the nearshore environment (Bledsoe *et al.,* 2004; Bledsoe and Phlips, 2000). Even episodic nutrient pulses associated with storm events may have important consequences for estuarine ecology, such as the stimulation of harmful algal blooms. For example, it has been hypothesized that a major bloom of the toxic dinoflagellate *Pyrodinium bahamense* in the Indian River Lagoon of Florida may have been in part stimulated by the pulse in nutrient load resulting from the high rainfall El Niño event of 2001/2002 (Phlips *et al.,* 2004a, 2004b, 2006). Increases in nutrient concentrations and organic matter can also have consequences for higher trophic levels. In Chesapeake Bay, annual differences in biomass and the abundance of macroinvertebrates were attributed to differences in rainfall patterns and consequent differences in nutrient inputs between years (Bilkovic *et al.,* 2006).

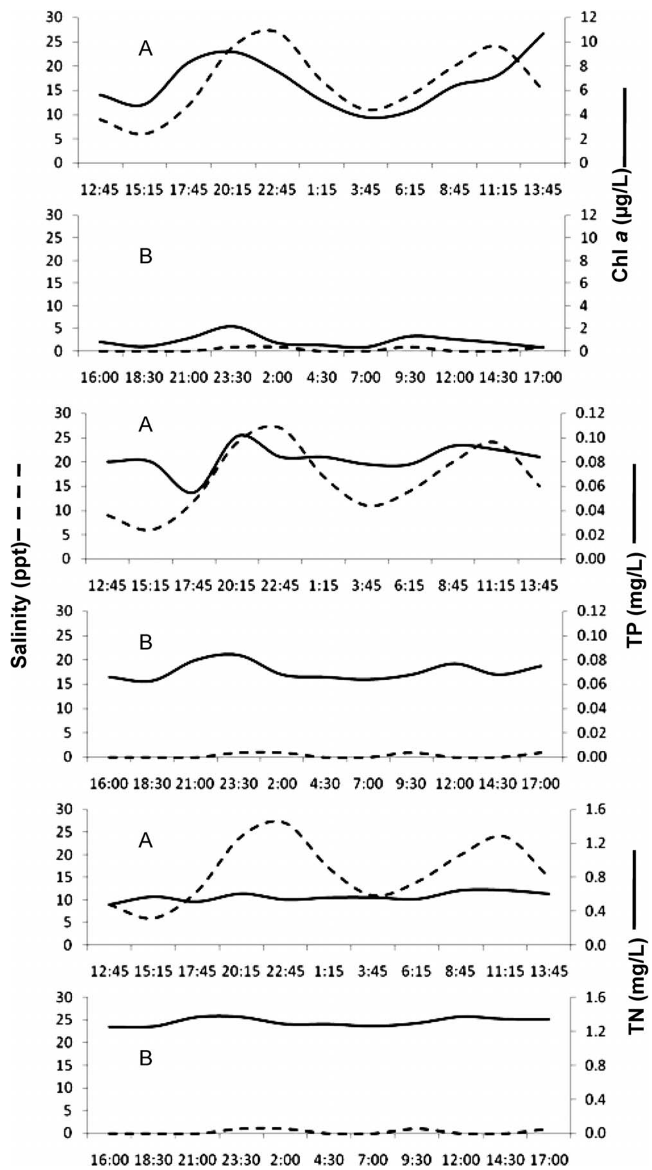

Figure 8. Diel patterns in salinity, chlorophyll, and nutrient concentrations observed during the period of September 23–24 of 2003 (A) and the poststorm high flow period of September 14–15, 2004 (B).

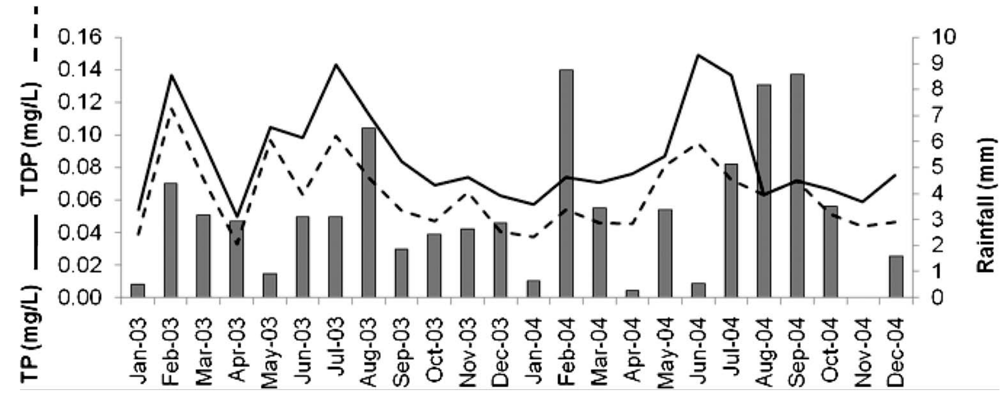

Figure 9. Mean monthly particulate phosphorus (TP-TDP) concentrations.

The limited spatial extent of this study prevents any conclusions about how far nutrients are dispersed from the Pellicer Creek catchment into the adjacent estuary or the ultimate fate of the bioavailable forms of nutrients. The relative importance of dilution and transport out of the system in this highly flushed estuary may also contribute to the impact of nutrient loads on the response of primary production (PHLIPS *et al.,* 2004b). However, at the Pellicer Creek water quality station, patterns in chlorophyll *a* concentrations, and the associations between chlorophyll *a* and salinity, indicate that phytoplankton biomass entering Pellicer Creek from the estuary on the flood tide is greater than the biomass coming out from the creek watershed. This observation is analogous to that observed in other similar ecosystems, such as the Suwannee River estuary, where phytoplankton biomass in the river is depressed by low light availability and short water residence time, and biomass peaks just outside the river mouth where the high nutrients from the river mix with clear oceanic water (BLEDSOE *et al.,* 2004; BLEDSOE and PHLIPS, 2000).

The pronounced deviations in salinity regimes caused by storm events can result in changes in the structure and function of tidal creeks and estuaries (FRAZER *et al.,* 2006; PAERL *et al.,* 2001, 2006; SWITZER *et al.,* 2006). For example, in the estuarine environment associated with Pellicer Creek, commercial blood ark (*Anadara ovalis*), ponderous ark (*Noetia ponderosa*), and hard clam (*Mercenaria mercenaria*) populations were devastated by the multiple freshwater pulses associated with the 2004 storms and did not begin to recover in the region until 2006 (NUÑEZ, personal communication). Situations of freshwater pulses affecting benthic community structure were also documented at Cape Fear, North Carolina, where six hurricanes in 4 years resulted in shifts of benthic infauna from marine to freshwater community structure (MALLIN *et al.,* 1999).

Estuarine communities are not only affected by changes in the relative magnitude of freshwater inputs, but also by the rate of change. In a Florida Bay study, MONTAGUE and LEY (1993) found that stations with large salinity fluctuations had relatively low biomass and unstable species composition. RIDLER, DENT, and ARRINGTON (2006) observed negative posthurricane impacts on seagrass communities in Southeast Florida during the 2004 storm season. By contrast, recent observations of seagrass communities in the Indian River Lagoon before and after the 2004 storm season show considerable resilience to the events (STEWARD *et al.,* 2006). Similarly, research on the response of fish communities to the 2004 storms showed an initial short-term impact but rapid recovery (PAPERNO *et al.,* 2006; STEVENS, BLEWETT, and CASEY, 2006). The results of the present study indicate that the tropical storms of 2004 greatly accelerated the rates and magnitudes of change in salinity within Pellicer Creek, but the effects on the benthic plant or fish communities remain undocumented.

CONCLUSIONS

The meteorological and water quality monitoring networks established by the NERR program provide opportunities to examine ecological processes that are stochastic in nature and subject to considerable short-term variability, such as storm events. The results of this study at the GTMNERR reveal that multiple storm events can have significant impacts on a range of key water quality parameters that play major roles in defining ecosystem structure and function. Recent advances in the development of hydrodynamic models of estuarine circulation, such as those recently described for the GTMNERR (SHENG *et al.,* this issue), will ultimately provide an opportunity to predict how future storm patterns will affect the spatial and temporal distribution of water quality parameters. The NERR monitoring networks will provide essential data for calibration and validation of these models. Given the major changes in watershed characteristics and global climate patterns expected in future years, the ability to predict the impacts of these changes will be an essential part of designing, implementing, and justifying management efforts.

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