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Dissolved Oxygen Dynamics in Charlotte Harbor and Its Contributing Watershed, in Response to Hurricanes Charley, Frances, and Jeanne—Impacts and Recovery

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ABSTRACT: On August 13, 2004, Hurricane Charley came ashore in the Charlotte Harbor watershed. Surface winds at the time of landfall were estimated at 130 knots. The track of the hurricane roughly followed the floodplain of the Peace River, causing massive defoliation and mortality of native vegetation and planted citrus groves, as well as substantial damage to human habitation and various infrastructure elements. Eight days after landfall, a water quality monitoring effort documented hypoxic (< 2 mg l^{-1}) to nearly anaerobic (< 0.5 mg l^{-1}) dissolved oxygen (DO) values throughout the vast majority of the Peace River's c. 6,000 km^2 watershed. Low DO values appeared to be related to high values of both dissolved organic matter and suspended materials. Hypoxic conditions in Charlotte Harbor itself occurred within 2 wk of landfall. Approximately 3 wk after the landfall of Hurricane Charley, Hurricane Frances struck the east coast of Florida, causing further wind damage and bringing substantial amounts of rain to the Charlotte Harbor watershed. Three weeks later still, Hurricane Jeanne caused similar damage to the same area. In response to the combined effects of these three hurricanes, DO values in the Peace River did not recover to pre-hurricane levels until approximately 2–3 mo later. The spatial and temporal pattern of DO fluctuations appeared to be related to the proximity of sampling locations to the path of the eyewall of the first of the three hurricanes. Within the Harbor itself, the duration of hypoxic conditions was less than that recorded within the Peace River, perhaps reflecting greater dilution of oxygen-poor waters from the watershed with less-affected water from the Gulf of Mexico.

Introduction

On August 13, 2004, the first of three hurricanes to affect the watershed of Charlotte Harbor made landfall at Cayo Costa, Florida (Sallenger et al. 2006). The first of these three, Hurricane Charley, was a category 4 storm on the Saffir-Simpson scale, with surface winds at landfall estimated at 130 knots. Hurricane Charley was the most powerful hurricane to hit the United States since Hurricane Andrew in 1992 (Pasch et al. 2005). Hurricane-force winds were experienced along the storm's entire pathway across peninsular Florida, from Cayo Costa to Ormond Beach (Sallenger et al. 2006). Nine tornadoes were associated with Hurricane Charley's passage through Florida (Pasch et al. 2005). The initial track of Hurricane Charley closely followed the course of the Peace River, the largest source of freshwater inflow to Charlotte Harbor. Within 6 wk, two additional hurricanes, Frances and Jeanne, struck the east coast of Florida, causing further wind damage and bringing substantial amounts of rain and flooding to the Charlotte Harbor watershed.

Several days after the passage of Hurricane Charley, numerous complaints of foul smelling water in the Peace River were received from the public. Concerns about the quality of water in the Peace River were received from officials at numerous public water supply utilities. Surface water withdrawals from the Peace River are one of the primary sources of drinking water for a population of c. 750,000 people in southwest Florida.

In response to the potential health and environmental issues apparent after the passage of Hurricane Charley, additional efforts were undertaken to supplement existing water quality monitoring efforts in the Peace River watershed. These efforts were designed to increase the monthly monitoring frequency to weekly sampling and to add water quality parameters that might prove useful for determining the basis for observed problems with dissolved oxygen (DO) values in the Peace River. Ongoing water quality sampling efforts in Charlotte Harbor were continued to determine the spatial and temporal extent of hypoxic conditions (DO $<$ 2 mg l^{-1}) in the Harbor.

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Materials and Methods

A comprehensive water quality monitoring program for the Peace River watershed has been in place since 1997. This effort replaced a series of informal monitoring programs for the watershed that had been in place since the 1950s. At a series of fixed sites, field parameters (e.g., temperature, DO, pH) are recorded, and water samples are collected for various laboratory-derived parameters (e.g., nutrients, turbidity). Samples are normally collected on a monthly basis.

In response to concerns with DO values in the Peace River, regularly visited stations (on a monthly frequency) were sampled out-of-cycle on August 22, 2004, 8 d after the landfall of Hurricane Charley. Sampling frequency for these sites was increased to weekly visits, with the intent of dropping back to monthly sampling when DO values recovered to pre-disturbance levels. The locations of these sites are shown in Fig. 1. Using storm track information supplied in Pasch et al. (2005), the distance between the sample locations and the path of the eyewall of the hurricane was estimated.

Field parameters for Peace River samples were collected with standard water quality probes that were calibrated prior to deployment. At the end of the day, all probes were checked against known standards to ensure data reliability. All probes passed all post-sampling data checks.

For laboratory parameters for Peace River sites (turbidity [NTU], total suspended solids [TSS, mg l^{-1}], color [PCU], and biological oxygen demand [BOD, mg l^{-1}]), samples were brought back to the Tampa laboratory of the Florida Department of Environmental Protection for processing. All laboratory data met all relevant requirements for sample collection, holding times, and analytical techniques specified for the National Environmental Laboratory Accreditation Program.

In the open waters of Charlotte Harbor, a series of stations has been visited on an irregular basis to study various aspects of stratification-induced hypoxia. A model examining the physical and biogeochemical factors contributing to the development of hypoxia in Charlotte Harbor was developed using data from these stations (Camp, Dresser, and McKee, Inc. 1998). Data from these stations were also used to calibrate a historical reconstruction of hypoxia in Charlotte Harbor by Turner et al. (2006). The open waters of Charlotte Harbor itself are sampled via an ongoing water quality monitoring program conducted by the Florida Fish and Wildlife Conservation Commission (FFWCC). On a monthly basis, staff from the FFWCC visit five randomly selected sampling locations within each of several strata within Charlotte Harbor and the lower

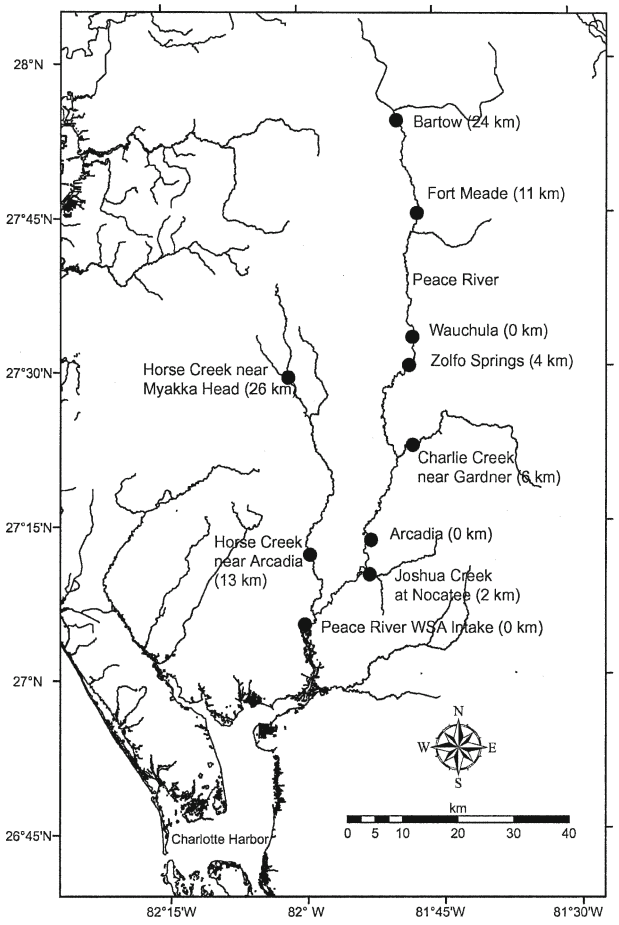

Fig. 1. Location of selected water quality monitoring stations in the Peace River watershed. The headwaters of the Peace River are in central Florida near Lakeland and the river empties into Charlotte Harbor in southwest Florida. Values in parentheses represent distance from the eyewall of Hurricane Charley in kilometers.

reaches of the Peace and Myakka Rivers. For this report, DO data from 0.2 and 2.0 m below the surface were analyzed from the strata Upper Charlotte Harbor.

Results

The temporal patterns of DO values in the Peace River watershed varied spatially. In the upper portion of the watershed, DO values at Bartow in the upper portion of the watershed are regularly hypoxic (DO < 2 mg l^{-1}; Fig. 2), and the data do not support a hurricane-related DO crash at this site. At Fort Meade, DO values appear to have been affected by Hurricane Charley, and DO values took approximately 3 mo to recover to pre-hurricane levels. In the middle portion of the Peace River, DO values appeared to have dropped to hypoxic levels in response to the passage of Hurricane Charley,

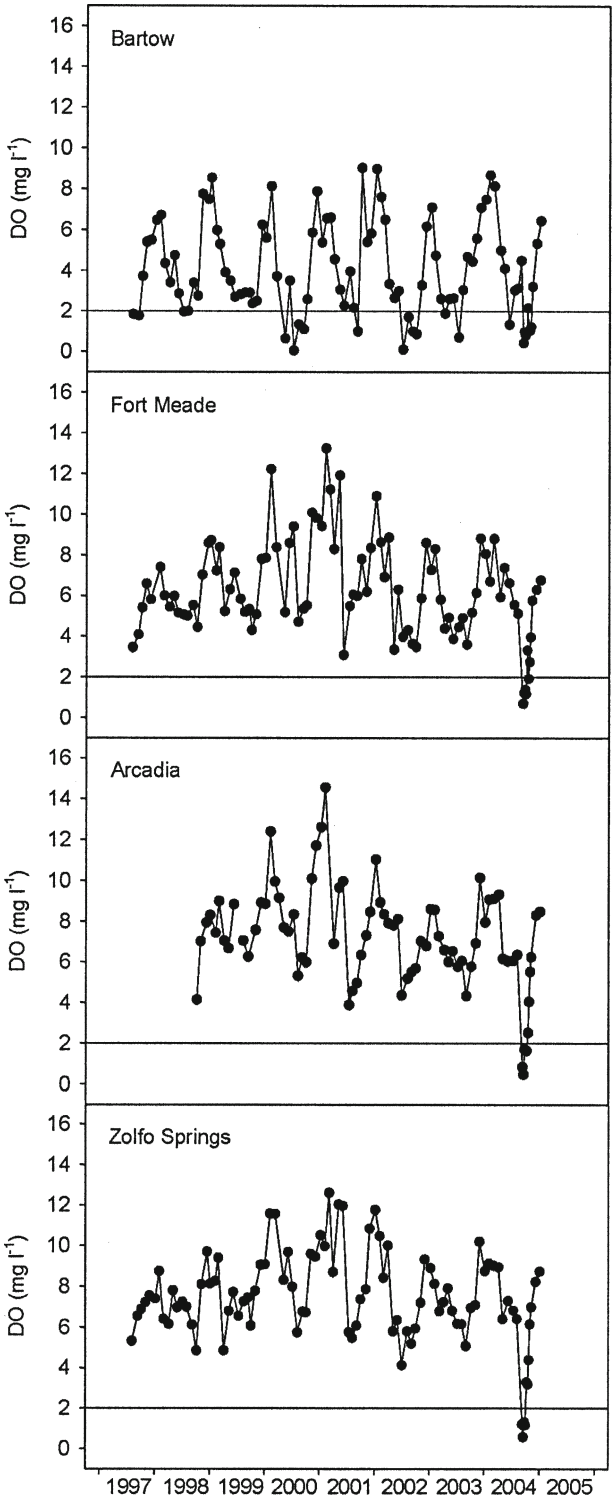

Fig. 2. Dissolved oxygen time series for selected long-term water quality monitoring stations in the Peace River watershed. Data were collected monthly except immediately following the passage of Hurricane Charley when samples were collected on a weekly basis. The dark line indicates 2 mg l^{-1}.

and recovery to pre-disturbance levels took approximately 3 mo.

In the main tributaries to the Peace River, DO values appear to have taken approximately 3 mo to recover to pre-hurricane levels in both Charlie Creek and Joshua Creek (Fig. 3). In Horse Creek, DO values did not drop to hypoxic levels at Myakka Head, but such a drop was seen at Arcadia. The amount of time required for DO values to recover to pre-hurricane levels for Horse Creek at Arcadia was the shortest of all locations where hypoxic conditions occurred.

Values for turbidity for Peace River stations collected in the days after Hurricane Charley were above the median value for Florida streams (4.5 NTU), but were less than the threshold value for the top 10% of Florida streams (21.0 NTU; Table 1). Turbidity values at all sites were higher on August 22, 2004 than the top 10% threshold for values collected at sites with historical water quality data. For TSS, values for Peace River stations ranged from slightly higher to slightly lower than the median value for Florida streams (6.5 mg l^{-1}), but consistently higher than median values at each site. All stations had TSS values well below the value for the top 10% of Florida streams (26.5 mg l^{-1}).

For values of color, all sites had values in excess of 200 platinum-cobalt units (PCU; Table 1), indicating a substantial amount of dissolved organic matter was present throughout sampled locations.

Values of BOD (mg l^{-1}) in the water column varied with location (Table 1). The only site sampled for this parameter that did not go hypoxic, Horse Creek at Myakka Head, was the only site that did not have a BOD level higher than the threshold value for the top 10% of Florida streams (3.57 versus 5.10 mg l^{-1}). At the other five locations, all of which went hypoxic after the passage of Hurricane Charley, BOD values were higher than the threshold value for the highest 10% of values for Florida streams (5.10 mg l^{-1}). As BOD is not normally collected at these sites, there are not long-term water quality data sets available for comparative purposes.

Data from the FFWCC monitoring program show that DO values in both surface and bottom waters within Upper Charlotte Harbor recovered to pre-hurricane levels within 1 mo after the passage of Hurricane Charley (Fig. 4). Surface layer DO levels remained above 5.0 mg l^{-1} 10 d after the passage of Hurricane Charley (data from August 23, 2004) but fell to below 2.0 mg l^{-1} within the next 5 d. The data suggest a second, less intense drop in DO values occurred near the end of September, which would reflect either a delayed response to effects of Hurricane Frances or a rather rapid response to effects from Hurricane Jeanne. Although sample

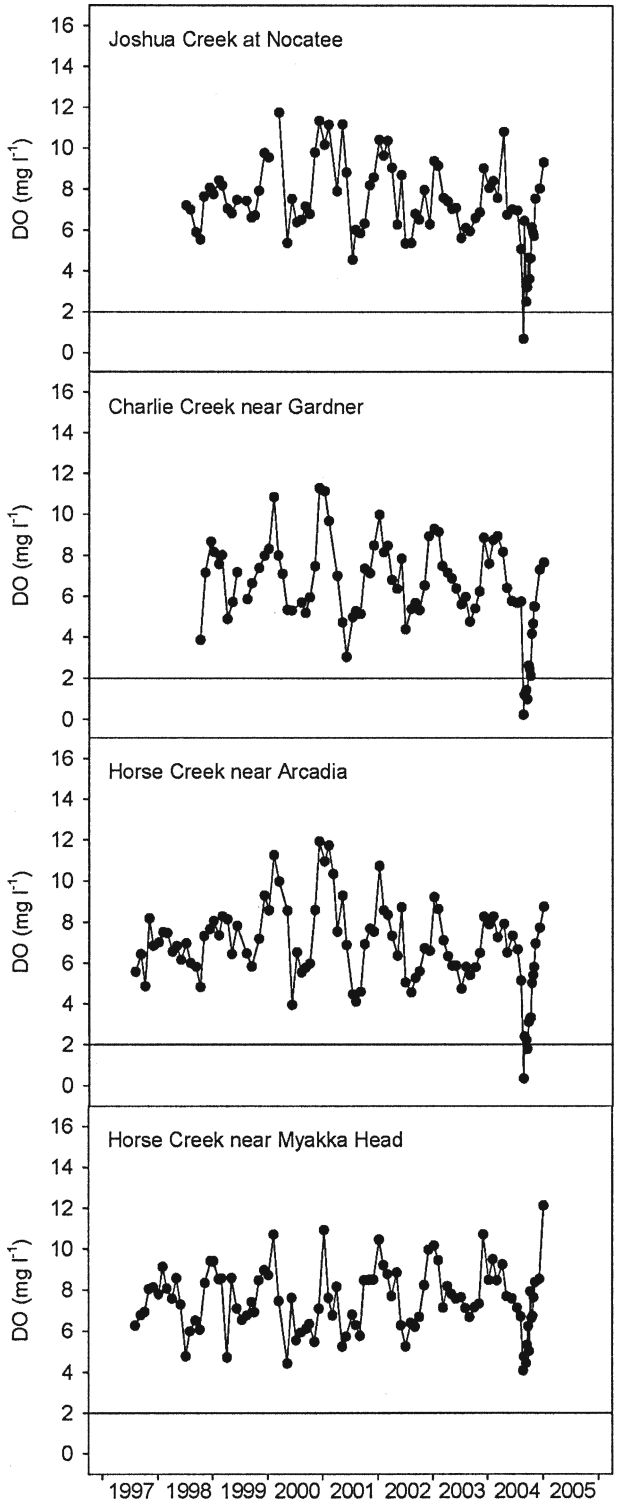

Fig. 3. Dissolved oxygen time series for selected long-term water quality monitoring stations on three major tributaries to the Peace River. Data were collected monthly except immediately following the passage of Hurricane Charley when samples were collected on a weekly basis. The dark line indicates 2 mg l^{-1}.

sizes differed, no difference was found for DO values when comparing data from 0.2 versus 2.0 m depths (Mann-Whitney W test; $p = 0.70$).

Discussion

Hypoxic conditions are regularly experienced in Charlotte Harbor (Camp, Dresser, and McKee Inc. 1998; Turner et al. 2006), especially during the July to September rainy season of southwest Florida. Factors involved in the development of hypoxia are high rates of freshwater inflow, resultant stratification of the water column, and water temperatures in excess of c. 30°C (Turner et al. 2006). Recurrent wet season hypoxia within Charlotte Harbor is not thought to be a completely natural phenomenon, as evidence suggests that organic loads to the bottom sediments within the Harbor have increased substantially over the past century (Turner et al. 2006).

In the Peace River itself, hypoxic conditions are normally restricted to the upper regions of the watershed, particularly for the Peace River at Bartow (Fig. 2). Recurrent hypoxic conditions at Bartow are most probably related to the detrimental influence of water discharged from Lake Hancock, which lies just upstream from the Bartow site, and which may well be the most polluted large lake in the state of Florida (FDEP 1996). At locations other than Bartow, hypoxic conditions were previously unrecorded for stations in the mainstem of the river itself (Fig. 2) and also within the river's main tributaries (Fig. 3), prior to Hurricane Charley.

The combination of widespread hypoxic conditions in both the Harbor itself, and also throughout the majority of the watershed of the Peace River, appears to have been a phenomenon not reported previously. Widespread effects of low DO values associated with the passage of hurricanes have been previously documented for Florida Bay after Hurricane Donna (Tabb and Jones 1962), Chesapeake Bay after Hurricane Agnes (Boesch et al. 1976), Charleston Harbor after Hurricane Hugo (Van Dolah and Anderson 1991), Waquiot Bay, Massachusetts, after Hurricane Bob (Valiela et al. 1996), Biscayne Bay after Hurricane Andrew (Tilmant et al. 1994), and the lower Cape Fear River, North Carolina, after Hurricane Fran (Mallin et al. 1999, 2002).

Water quality data collected after the passage of Hurricane Charley indicate that factors responsible for the widespread DO crash in the Peace River watershed were probably associated with elevated levels of both dissolved and suspended materials. Even though levels of turbidity and TSS were elevated at most sites, compared with long-term data sets, these values were not above the threshold

TABLE 1. Water quality parameters for various locations. Values represent samples gathered 22 August 2004. Median refers to median value for sites based on period of record for water quality monitoring. Top 10% and Top 25% refer to threshold values for highest 10% and 25% of values at each site. – not available. WSA = Water Supply Authority. Florida Median and top 10% values for Florida streams from FDEP (1996).

	Turbidity (NTU)	TSS (mg l^{-1})	Color (PCU)	BOD (mg l^{-1})
Peace River at Wauchula	9.5	6.0	210	7.22
Median	—	—	—	—
Top 25%	—	—	—	—
Top 10%	—	—	—	—
Peace River at Arcadia	9.8	8.0	210	8.06
Median	3.4	5.0	120	—
Top 25%	6.4	9.1	200	—
Top 10%	8.4	13.0	223	—
Peace River at WSA	16.5	9.0	210	7.70
Median	—	—	—	—
Top 25%	—	—	—	—
Top 10%	—	—	—	—
Joshua Creek at Nocatee	12.9	5.0	225	6.50
Median	2.5	2.6	82	—
Top 25%	3.9	5.7	121	—
Top 10%	5.2	10.5	185	—
Horse Creek at Myakka Head	6.6	8.0	210	3.57
Median	2.0	2.0	150	—
Top 25%	3.3	6.0	321	—
Top 10%	4.7	7.2	500	—
Horse Creek at Arcadia	10.1	6.0	225	7.64
Median	2.4	1.8	148	—
Top 25%	3.0	4.0	256	—
Top 10%	4.5	6.5	367	—
Florida median value	4.5	6.5	—	1.50
Florida highest 10%	21.0	26.5	—	5.10

of the highest 10% of values for Florida streams (Table 1).

Values of color, an indicator of the amount of dissolved organic matter in the water column, were higher than 200 PCU, values typically seen in blackwater streams with elevated levels of tannins and other organic compounds (FDEP 1996). Values of BOD were higher than the median value for Florida streams for all sites sampled after Hurricane Charley (Table 1). All sites that had post-Charley hypoxic conditions also had BOD values higher than the threshold value for the worst 10% of Florida streams.

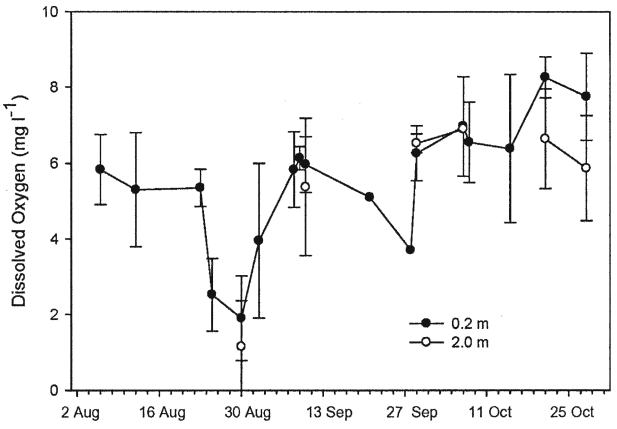

Fig. 4. Dissolved oxygen time series for samples taken at 0.2 and 2.0 m depth within the strata Upper Charlotte Harbor. Data represent means and standard deviations of 5 randomly located stations. The dark line indicates 2 mg l^{-1}.

The widespread distribution of hypoxic conditions in the Peace River watershed was most likely associated with high levels of both suspended and dissolved organic matter, and the very high BOD values at those same locations. A similar situation was documented by Mallin et al. (1999) for the lower Cape Fear River after the passage of Hurricane Fran.

Within the Peace River watershed, sites located less than 20 km from the path of the eyewall of Hurricane Charley were the only locations to experience hurricane-associated crashes in DO values (see Figs. 2 and 3). While these sites were also the only locations where widespread defoliation and mortality of trees was clearly evident (Tomasko personal observation), the sources of BOD cannot be entirely attributed to defoliation and other

nonanthropogenic effects. Although the degree of urbanization of the Peace River watershed has been quantified at less than 10%, there are approximately 23 domestic and 39 industrial point source discharges within the watershed (Coastal Environmental, Inc. 1995). Lipp et al. (2001) found that contamination of waters within both the Peace River and Charlotte Harbor with indicators of human fecal influence was widespread, particularly during periods of elevated freshwater inflow.

Despite the probable influence of wastewater and industrial point source discharges in the Peace River watershed, subbasins without such discharges (e.g., Joshua Creek, Charlie Creek, Horse Creek) also displayed hypoxic conditions in the weeks after Hurricane Charley (see Fig. 3). The DO conditions that regularly occur within the Peace River at Bartow subbasin (which contains 4 domestic and 9 industrial point source discharges) were not recorded at more pristine sites within the watershed until after the passage of Hurricane Charley.

In Charleston Harbor, the widespread decline in DO values after Hurricane Hugo was partly attributed to decomposition of leaf litter associated with wind damage to affected portions of the watershed (Van Dolah and Anderson 1991). Hypoxic conditions in the Peace River watershed and Charlotte Harbor could be related to elevated turbidity, as appeared to be the case after the passage of Hurricane Andrew over Biscayne Bay (Tilmant et al. 1994). In the open waters of Charlotte Harbor, the hurricane-related DO crash occurred under the condition of salinity stratification (data not shown), as was also noted for the Chesapeake Bay's DO crash after the passage of Hurricane Agnes (Boesch et al. 1976).

In the lower Cape Fear River, DO values appeared to have recovered to pre-Hurricane Fran levels within 1 mo (Mallin et al. 1999). During the 6 wk after the landfall of Hurricane Charley, the Peace River watershed was also affected by landfalls of Hurricanes Frances and Jeanne (see Sallenger et al. 2006). Perhaps associated with these multiple effects, DO values in the Peace River watershed (for those locations where hypoxic conditions occurred in response to Hurricane Charley) took between 2 and 3 mo to recover to pre-disturbance levels (Figs. 2 and 3).

The combined effects of Hurricanes Charley, Frances, and Jeanne appear to be related to the previously unrecorded widespread hypoxic conditions found in both Charlotte Harbor and throughout the majority of the Peace River watershed. Portions of the Peace River watershed within 20 km of the path of the eyewall of Hurricane Charley experienced subsequent hypoxic conditions, while areas more than 20 km from the path of the eyewall did not. Hypoxic conditions seemed to be associated with both dissolved and suspended materials. The high BOD values at hypoxic locations were most likely associated with a combination of both natural and anthropogenic influences within the Peace River's watershed, with the relative proportion of anthropogenic versus natural effects probably varying from subbasin to subbasin. Elevated inflows of river water into Charlotte Harbor created salinity stratification associated with subsequent widespread hypoxia in the Harbor, which was probably also related to the high BOD values of that inflow water. At affected sites in the watershed, DO values took approximately 2–3 mo to recover to pre-hurricane levels. Within the Harbor itself, it appeared that recovery of DO values took only ca. 1 mo, perhaps reflecting greater rates of flushing associated with a closer proximity to the Gulf of Mexico.

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