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Ecological Applications, Vol. 9, No. 1. (Feb., 1999), pp. 350-362.

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HURRICANE EFFECTS ON WATER QUALITY AND BENTHOS IN THE CAPE FEAR WATERSHED: NATURAL AND ANTHROPOGENIC IMPACTS

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Abstract. In the summer of 1996, southeastern North Carolina, United States, was struck by two hurricanes, with the second (Hurricane Fran) doing considerably more damage than the first (Hurricane Bertha). The Cape Fear watershed, largest in North Carolina, suffered from severe water quality problems for weeks following Fran, including a massive fish kill in the Northeast Cape Fear River. Post-hurricane flooding caused inputs of riparian swamp water to river channels, and sewage treatment plant and pump station power failures caused diversions of millions of liters of raw and partially treated human waste into rivers. Additionally, several swine waste lagoons were breached, overtopped, or inundated, discharging large quantities of concentrated organic waste into the system, particularly into the Northeast Cape Fear River. Dissolved oxygen (DO) decreased to 2 mg/L in the mainstem Cape Fear River, and fell to zero in the Northeast Cape Fear River for >3 wk. Biochemical oxygen demand in the Northeast Cape Fear River was sixfold greater than in the other tributaries, probably as a result of anthropogenically derived inputs. The Cape Fear Estuary also suffered from hypoxia for several weeks. Following Hurricane Fran, ammonium levels in the Northeast Cape Fear River displayed a distinct increase, and total phosphorus reached its highest concentration in 27 yr. The benthic community, which is dominated by opportunistic species typical of oligohaline to mesohaline estuarine areas, showed a mixed response. There was a significant decline in total benthic abundances immediately after Hurricane Fran at an oligohaline station in the Northeast Cape Fear River, with recovery occurring in ~3 mo. An oligohaline station in the mainstem Cape Fear River, which had relatively rapid DO recovery, did not display significant declines. A mesohaline station 5 km below the confluence of these rivers showed broad and long-lasting benthic declines, but benthic declines were less severe in the lowest reaches of the estuary sampled. The natural hurricane effect of swamp water flooding into river basins led to reduced dissolved oxygen levels and increased light attenuation. However, environmental damage was considerably increased by anthropogenic practices, including the lack of backup generating systems for waste treatment systems and subsequent sewage diversions into rivers, as well as accidents occurring at swine waste lagoons sited on river floodplains.

Key words: benthos; biochemical oxygen demand (BOD); Cape Fear; dissolved oxygen; estuary; hurricane; nutrients; rivers; sewage; swine waste; waste management; water quality.

INTRODUCTION

Hurricanes are acute, catastrophic events that have the capacity to severely alter natural ecosystems. For instance, hurricanes have caused large-scale treefall, trunk snapping, and defoliation in tropical and temperate forests (Tannner et al. 1991, Loope et al. 1994, Valiela et al. 1996). Effects on animal communities have included mortality, displacement, and nest destruction among bird populations (Marsh and Wilkinson 1991, Wiley and Wunderle 1994); mortality among sea turtle nesting populations (Milton et al. 1994); mortality and displacement of nekton and fish (Tabb and Jones 1962, Boesch et al. 1976, Dauer 1984, Knott and Martore 1991), and alterations in oyster populations (Lowery 1992). Demonstrated physical effects on estuarine or coastal waters include alteration of sedimentation patterns (Lowery 1992) and marked temporary changes in salinity (Tabb and Jones 1962, Boesch et al. 1976, Van Dolah and Anderson 1991). Changes in water quality may be slight (Roman et al. 1994, Valiela et al. 1996) or severe (Van Dolah and Anderson 1991, Tilmant et al. 1994). We present evidence demonstrating that water quality degradation by hurricanes can be considerably increased by human practices in hurricane-prone developed regions.

During the summer of 1996, the Cape Fear region of southeastern North Carolina, United States, sustained two hurricanes. On 12 July, Hurricane Bertha made landfall near the city of Wilmington and proceeded north along the coast (Fig. 1). Although some coastal areas suffered damage, there was comparatively little structural damage in the middle and upper Cape Fear watershed. However, heavy rainfall followed the hurricane and persisted for ~2 wk. On 5 September,

Manuscript received 6 August 1997; revised 25 January 1998; accepted 30 April 1998; final version received 21 May 1998.

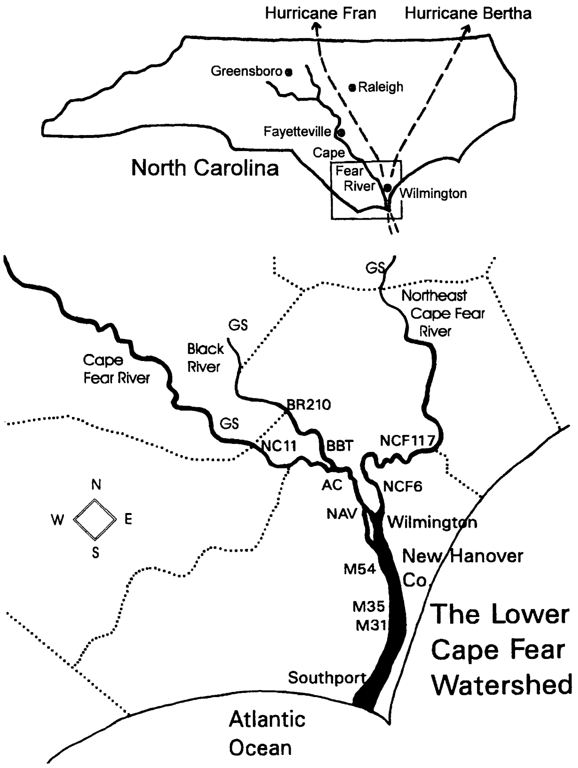

FIG. 1. Map of North Carolina and the lower Cape Fear watershed showing sampling locations, hurricane paths, and locations of USGS river flow gauging stations (GS).

Hurricane Fran made landfall near Wilmington and proceeded up the Cape Fear basin to the Raleigh area in the North Carolina Piedmont (Fig. 1), causing considerable damage to homes, businesses, automobiles, and power lines. Many areas were without power for several days. Heavy rains followed this hurricane as well, especially in the upper region of the Cape Fear watershed.

Hurricane Fran and its aftermath caused devastating environmental impacts to the Cape Fear River and Estuary. Power failures caused numerous municipalities to divert large volumes of raw and partially treated sewage and stormwater runoff into the Cape Fear River (NCDEHNR 1996). Additionally, during the week following the hurricane, at least four hog waste lagoons ruptured, overtopped, or were inundated, releasing millions of liters of raw or partially treated animal waste into the Northeast Cape Fear River (NCF), a major tributary of the Cape Fear Estuary (NCDEHNR 1996). A large fish kill followed, with State environmental personnel reporting thousands of carcasses (including hogchokers, catfishes, carp, bass, sunfish, pickerel, shad, and eels), with deaths attributed to low dissolved oxygen conditions (NCDWQ 1997; North Carolina Division of Water Quality, *unpublished data*).

We have maintained a watershed sampling program since February 1995, as a part of the Cape Fear River Research and Education Program (Mallin et al. 1996). This program allowed us to collect regular water quality data at 16 stations throughout the system before, during, and after the hurricanes. In this report, we describe the physical, chemical, and biological environmental effects caused by both hurricanes, compare the two events, and interpret the role of anthropogenic and natural factors associated with Hurricane Fran in water quality degradation of the lower Cape Fear watershed. We also discuss how altered environmental management practices could have reduced the water quality impacts to the system.

SITE DESCRIPTION

The Cape Fear watershed encompasses ~23 310 km^2, with numerous small tributaries leading into the main stem Cape Fear River, the Black River, and the Northeast Cape Fear River (Fig. 1). The main stem Cape Fear is a sixth-order stream originating well into the Piedmont near Greensboro, North Carolina, United States, whereas the Black and Northeast Cape Fear Rivers are fifth-order blackwater streams draining the Coastal Plain. The Black River watershed makes up 17% and the Northeast Cape Fear watershed makes up 18% of the total Cape Fear drainage basin (EA Engineering 1991). We maintain 16 sampling stations along the estuary and lower rivers, and include data herein from several key fresh and brackish stations noted on Fig. 1. NC11 is on the main stem Cape Fear River and represents inputs to the lower watershed. AC is located ~15 km downstream of NC11 and ~5 km downstream of a pulp and paper mill discharge. B210 represents inputs from the Black River to the lower watershed, whereas BBT is affected by both the Black and main stem Cape Fear Rivers. NCF117 represents inputs from the upper Northeast Cape Fear watershed to the lower watershed. All of these stations are freshwater. Upper estuarine stations included NCF6, an oligohaline site located in the lower Northeast Cape Fear River ~10 km upstream of Wilmington, and NAV, another oligohaline station located 10 km downstream of where the Black River enters the main stem Cape Fear River. M35 is located at Channel Marker 35 in the mesohaline estuary.

The benthic community was sampled at four oligohaline to mesohaline stations, including NAV, NCF6, and Channel Marker 31 (M31), located ~3.4 km downstream of M35. An additional station, Channel Marker 54 (M54), was sampled because of its location at the approximate turbidity maximum zone (Mallin et al. 1997*a*), an important transitional region for benthic community composition. At each station, samples were taken in ~2.5 m water depth.

METHODS

Rainfall data were obtained from the North Carolina Climate Office at North Carolina State University, and river flow data were obtained from the U.S. Geological

Survey, Raleigh, North Carolina. Salinity and dissolved oxygen (DO) values were collected weekly or once every two weeks at 14 stations by obtaining vertical profiles, using a Solomat 803PS Multiparameter Water Quality Probe displayed on a Solomat 803 datalogger (Solomat Neotronics, Norwalk, Connecticut, USA). Light attenuation coefficients, *k*, were obtained monthly at 0.5-m intervals by collecting vertical PAR data with a LICOR-1000 datalogger (LI-COR, Lincoln, Nebraska, USA) coupled to a spherical sensor and applying the data to standard formulas (Raymont 1980). Five-day biochemical oxygen demand (BOD5) data were obtained following Standard Methods (APHA 1995). BOD5 data were collected monthly from stations NC11, AC, B210, BBT, and NCF117 (Fig. 1). Nutrients were analyzed from surface water samples collected monthly at all stations. Orthophosphate was analyzed from filtered samples using a Technicon AutoAnalyzer (Clindus Technologies, Paramus, New Jersey, USA). Ammonium, nitrate + nitrite, total phosphorus (TP), and total Kjeldahl nitrogen (TKN) were analyzed using Standard Methods (APHA 1995). Organic phosphorus was computed as the difference between total phosphorus and orthophosphate, and total nitrogen (TN) was computed as the sum of TKN plus nitrate.

Benthic samples were taken on six occasions at the M31 and M54 stations: 11 December 1995, 28 March, 19 August, 1 October, 31 October, and 17 December 1996. At NAV, samples were taken 11 December 1995, 28 March, 19 August, 31 October, and 17 December 1996. At NCF6, samples were taken 11 December 1995, 28 March, 31 October, and 11 December 1996. Sampling in the upper stations immediately after Hurricane Fran was attempted, but valid samples were not obtained because of the high amount of debris in those areas at that time. All samples were taken with a Petite Ponar grab (Wildco, Saginaw, Michigan, USA), 15 × 15 cm opening, 15 cm depth. Five grab samples were taken at each station on each sampling date (grabs were kept only if the grab was full, in order to standardize the volume sampled). Samples were sieved through a 0.5-mm mesh screen, preserved in 10% formalin, and subsequently transferred to 70% ethanol for later identifications. Differences in infaunal abundances were compared among sampling dates for common taxa (contributing $\geq$ 3% of the individuals at a site) and for higher taxonomic groups, using ANOVA on log-transformed abundances. Because of differences in faunal composition at the four sites (reflecting salinity and other riverine gradients), comparisons between dates were conducted separately for each site.

RESULTS

Rainfall and river flow.—The Cape Fear River Basin experienced broad rainfall extremes in the summer of 1996. Wilmington rainfall was 31.8 cm for July, 9.9 cm higher than the 1985–1994 average. Hurricane Bertha, which made landfall along the southeast coast of North Carolina on 12 July, accounted for much of the July rainfall in the Wilmington area. Rainfall from Bertha also accounted for a minor peak in flow for the two coastal plain tributaries, the Northeast Cape Fear and the Black Rivers (Fig. 2). However, Bertha produced little or no rainfall for the middle and upper regions of the Cape Fear River Basin, and there was no Bertha-induced peak in flow for the main stem Cape Fear River (Fig. 2).

During the four days before Hurricane Fran made landfall on 5 September near Southport (Fig. 1), the entire Cape Fear River Basin received rainfall ranging from 1 to 14 cm from a continental weather system (Bales and Childress 1996). As Fran passed through North Carolina on 5–6 September, the Cape Fear River Basin experienced precipitation amounts ranging from 5 to 20 cm. Following the hurricane from 9 to 12 September, continental storm systems deposited 7–20 cm of additional rain throughout the region (Bales and Childress 1996). Total rainfall amounts for the month of September typically average 10–15 cm in the Cape Fear Basin. For September 1996, Greensboro (26.7 cm), Fayetteville (26.9 cm), and Wilmington (30.7 cm) substantially exceeded those averages (North Carolina Climatologist Office records), inducing record or near-record flows in all three tributaries (Fig. 2).

Water flow at a gauging station at Lock and Dam Number 1 on the Cape Fear River (Fig. 1) peaked at 1262 m^3/s on 13 September. For the month, the mean flow rate was 588 m^3/s, compared with 14-yr average September discharges of $\sim$105 m^3/s. The previously recorded monthly maximum for those years was 570 m^3/s, which occurred during February 1989. On the Northeast Cape Fear River at a gauging station $\sim$100 km upstream of Wilmington (Fig. 1), peak flow was 268 m^3/s measured on 8 September, and September 1996 mean discharge was 110 m^3/s. The average flow for September for the years 1940–1996 was $\sim$14.2 m^3/s (U.S. Geological Survey records). A gauging station $\sim$65 km upstream of Wilmington (Fig. 1) reported a peak flow of 393 m^3/s for the Black River on 10 September, its highest daily peak since 495 m^3/s was recorded in 1984 (Bales and Childress 1996). For the month of September 1996, the Black River discharge averaged 136 m^3/s. Typical September flows average $\sim$15.5 m^3/s (1952 to present), comparable to discharges measured on the Northeast Cape Fear River (U.S. Geological Survey records).

Dissolved oxygen.—Just prior to Hurricane Bertha, dissolved oxygen levels in the lower river and estuary averaged $\sim$4–7 mg/L (Fig. 3). After the passage of Bertha, dissolved oxygen levels dropped substantially at stations NAV (oligohaline site on the mainstem Cape Fear River), NCF6 (oligohaline site on the Northeast Cape Fear River), and M35 (mesohaline site in the Cape Fear Estuary). The hypoxic conditions at these three sites resulted from the heavy rains and subsequent

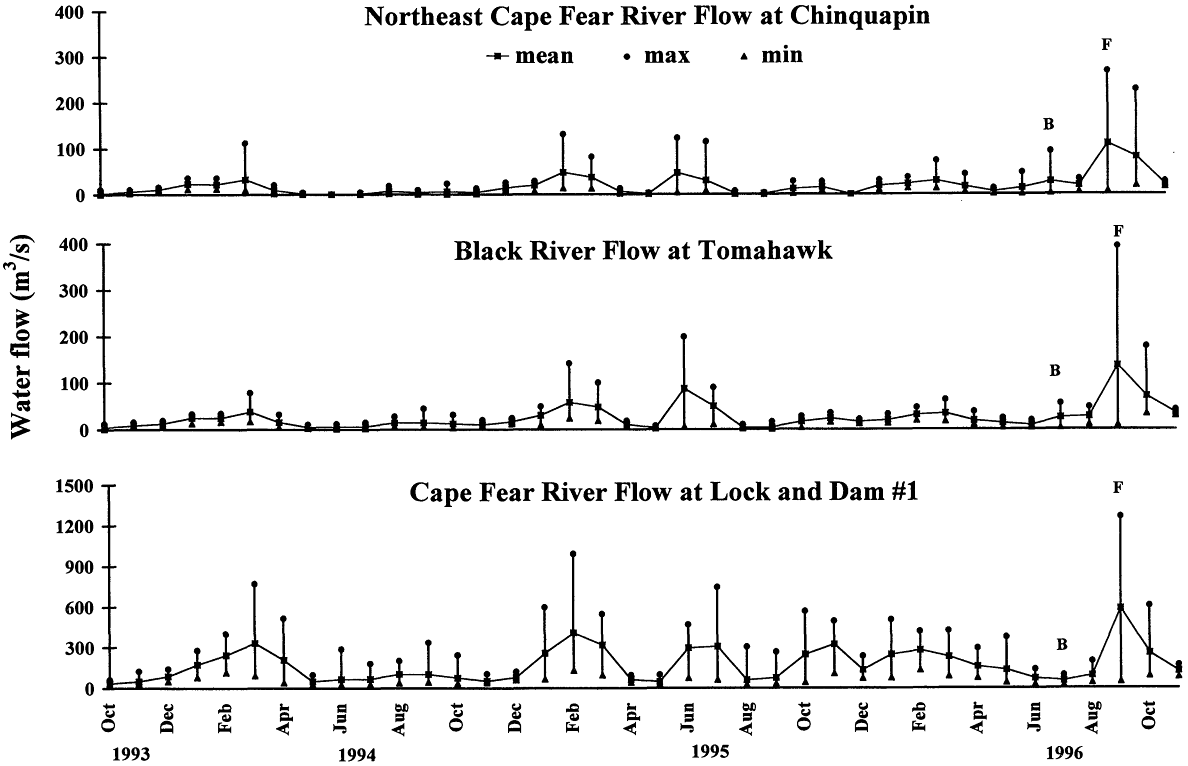

FIG. 2. River flow data (October 1993–November 1996) for the three main tributaries in the lower Cape Fear watershed. Note the difference in scale on the y-axis for the mainstem Cape Fear River. B, Hurricane Bertha; F, Hurricane Fran.

flooding of swamp waters with low dissolved oxygen into the Cape Fear and Northeast Cape Fear Rivers. However, dissolved oxygen levels at NC11, an upstream riverine site, remained relatively constant after Bertha. As mentioned previously, heavy precipitation from this storm primarily affected the coast and did not significantly affect the Cape Fear River Basin upstream of NC11. Dissolved oxygen concentrations gradually returned to pre-Bertha levels at the estuarine stations by late August (Fig. 3).

After Fran and the subsequent period of heavy rainfall, dissolved oxygen levels at all sites in the Cape Fear River Basin fell to 0–2 mg/L. At the main stem site NC11, dissolved oxygen concentrations showed the most rapid recovery, increasing to 5.6 mg/L by the last week of September. However, anoxic conditions (0–0.2 mg/L) in the Northeast Cape Fear River at NCF6 and hypoxic conditions at NAV and M35 (<3 mg/L) persisted until early October (Fig. 3). Surface and bottom DO concentrations at the benthic sampling location

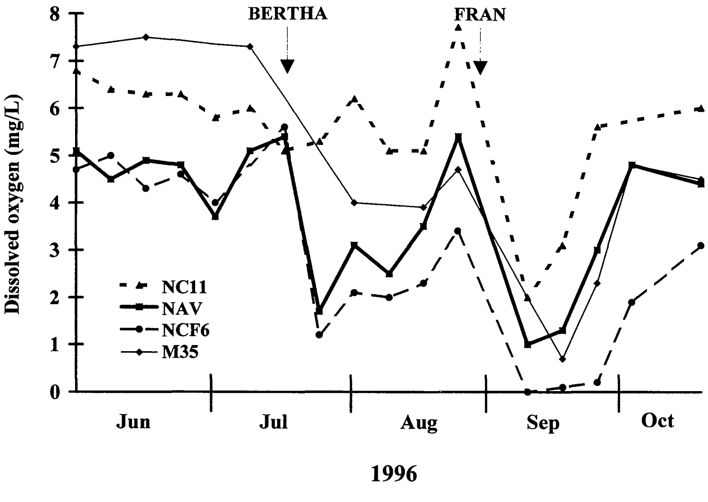

FIG. 3. Surface dissolved oxygen data for selected stations in the lower Cape Fear watershed, June–October 1996, with arrival of both hurricanes noted.

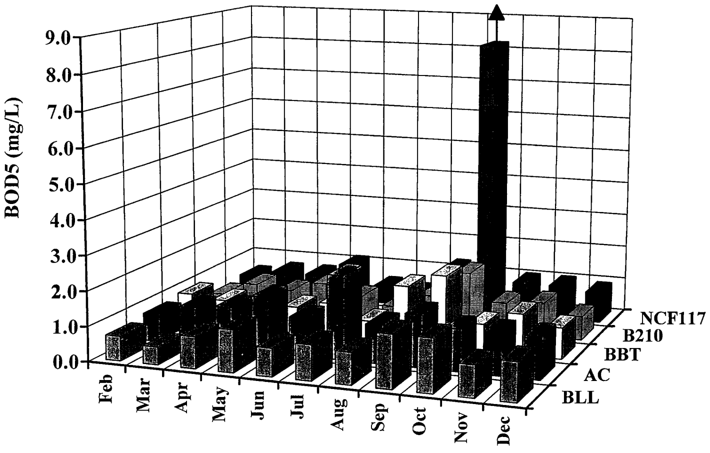

FIG. 4. BOD5 at selected stations in the lower Cape Fear watershed, February–December 1996. During September, in the Northeast Cape Fear river sample, all dissolved oxygen was used during the test; thus, the actual BOD5 was likely greater.

M54 were low: 0.5 and 0.4 mg/L on 16 September, 1.1 and 0.8 mg/L on 24 September, and 4.0 and 3.8 mg/L on 14 October, respectively.

The Black River, with a swampy watershed and average river flows similar to those of the Northeast Cape Fear, experienced hypoxic conditions following Hurricane Fran. Approximately two weeks after the 5 September storm, dissolved oxygen was 2.0 mg/L at B210 and 0.4 mg/L at BBT. During the same period along the Northeast Cape Fear River, DO at NCF117 was 0.4 mg/L and DO at NCF6 was 0.1 mg/L. By the second week in October, ~6 wk after Fran, DO levels in the Black River had recovered to 5.4 mg/L at B210 and 4.1 mg/L at BBT, whereas DO in the Northeast Cape Fear River lagged behind, with 4.5 mg/L at NCF117 and 3.1 mg/L at NCF6.

BOD5.—Biochemical oxygen demand analysis was performed monthly at five sites: NC11, AC, BBT, B210, and NCF117 (Fig. 1). With two exceptions, 5-d BOD was low (<2.2 mg/L) at all five sites during each month in 1996 (Fig. 4). Station AC showed a BOD5 of 2.4 mg/L in July prior to Hurricane Bertha. There was no unusual BOD5 measured at any station during August 1996, ~4 wk after Hurricane Bertha. In September 1996, the BOD5 concentration at NCF117 was measured at >8.2 mg/L (the sample exhausted >8.2 mg/L dissolved oxygen prior to end of 5 d). This sample was collected 12 d after Hurricane Fran during a period when the Northeast Cape Fear River experienced near-anoxic conditions. The Black River and main stem Cape Fear River data exhibited no similar maxima in BOD5 after the hurricane (Fig. 4). The contrast between B210 and NCF117 (two similar blackwater environments) should be noted and will be examined in the *Discussion.*

Light attenuation.—The average light attenuation coefficient (k) of 15 lower Cape Fear sites, representing the riverine and estuarine CFR, NCF, and Black Rivers, was 3.51/m during 1996 (Fig. 5). July (pre-Bertha, k = 3.67/m) and August (post-Bertha, k = 3.72/m) data were nearly equivalent, suggesting little long-term effect on water color and suspended particles from Hurricane Bertha. The data do depict a substantial peak in light attenuation (k = 5.27/m) for the entire Cape Fear River during September following Hurricane Fran (Fig. 5). The average light attenuation at all Cape Fear River sites was still high in October, averaging 3.96/m.

Attenuation values at NC11 (main stem CFR upriver site) averaged ~3.03/m for 1996, and there was no apparent effect on light attenuation from Bertha at this site (Fig. 5). After Hurricane Fran (September), however, the high, sediment-laden river flow increased k to 4.35/m. Light attenuation remained high during October 1996 (k = 3.81/m). At BBT, the 1996 mean k value was 3.44/m (Fig. 5). July and August data were nearly equivalent and no direct effects from Bertha were observed (Fig. 5). The strongest light attenuation occurred at this station during September (k = 6.20/m) and October (k = 4.37/m), following Hurricane Fran. This section of the Black River experienced significant flooding from darkly stained swamp water, in addition to turbidity loading from the Cape Fear River. The Northeast Cape Fear River did not experience a notable light attenuation increase following either Bertha or Fran (Fig. 5). This site is heavily influenced by swamp waters throughout the year, so that the substantial flooding of streamside swamps did not alter k values following the storm.

During 1996, the mean light attenuation k value at the estuarine station M35 averaged 3.15/m (Fig. 5). There was a substantial peak in light attenuation (k = 6.65/m) at M35 following Hurricane Fran, resulting from high turbidities and increased dissolved organic matter influxes from the blackwater tributaries. Light attenuation also remained higher than average during October (k = 4.28/m). Unfortunately, no July data were available for M35 and comparisons with Hurricane Bertha are not possible.

Nutrients.—Our data revealed no discernible effects from Hurricane Bertha on nutrient levels in the Cape Fear River system in August (Fig. 6). However, those samples were not collected until nearly 3 wk after the

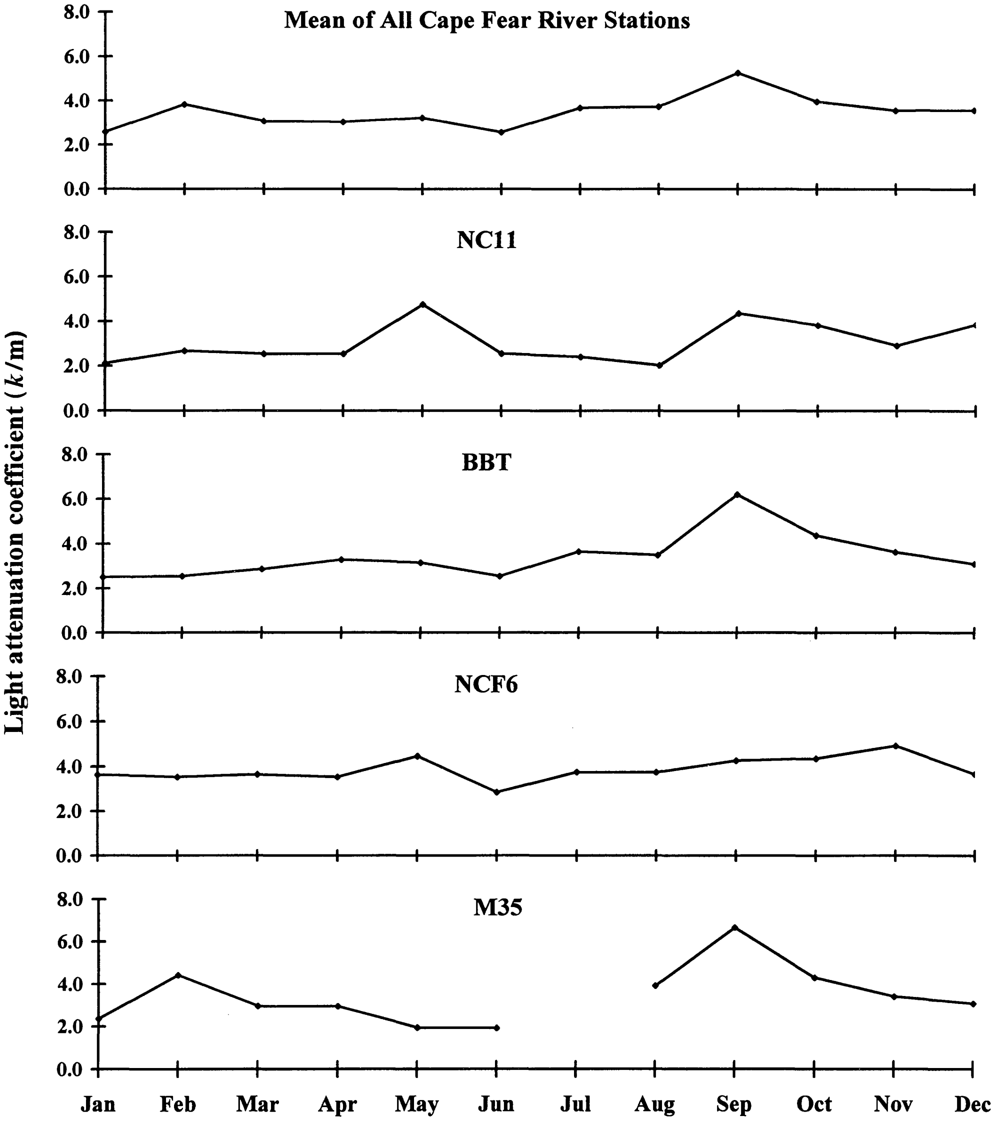

FIG. 5. Light attenuation coefficient *k* at selected stations in the lower Cape Fear watershed, January 1996–January 1997. August data were collected 18 d after Hurricane Bertha; September data were collected 12 d after Hurricane Fran.

storm had passed, and July samples were collected prior to Bertha's arrival. If Bertha-driven nutrient loading to the system occurred, it was localized and ephemeral, because effects of that storm were mainly limited to the coastal region, and river flows upstream were not increased by Bertha (Fig. 2).

There were no stations in the main stem Cape Fear River or Estuary that exhibited significant increases in total nitrogen (TN) concentrations following Hurricane Fran, relative to 1996 mean values. However, stations located in the Black River (B210), and especially in the Northeast Cape Fear River, (NCF6 and NCF117), showed distinct TN peaks in September (Fig. 6). At B210, the TN concentration in September was 1750 μg/L (1996 mean = 1326 μg/L). NCF6 had a September TN concentration of 2100 μg/L (1996 mean = 1415 μg/L), and NCF117 had a September concentration of 2360 μg/L (1996 mean = 1487 μg/L).

Nitrate + nitrite levels were extremely low throughout the Cape Fear system following Hurricane Fran (Fig. 6). Because dissolved oxygen levels approached or reached anoxic conditions at virtually all stations, most of the inorganic nitrogen existed in its reduced form as ammonium. However, the main stem Cape Fear River and Estuary exhibited relatively low concentrations of ammonium as well. In contrast, stations along the Northeast Cape Fear and Black Rivers exhibited uncharacteristically high ammonium levels (Fig. 6). The Black River site B210 had a 1996 peak during September of 80 μg/L, and NCF117 had a 1996 peak during September of 140 μg/L. Mean 1996 ammonium levels at these two blackwater stations were 28 μg/L

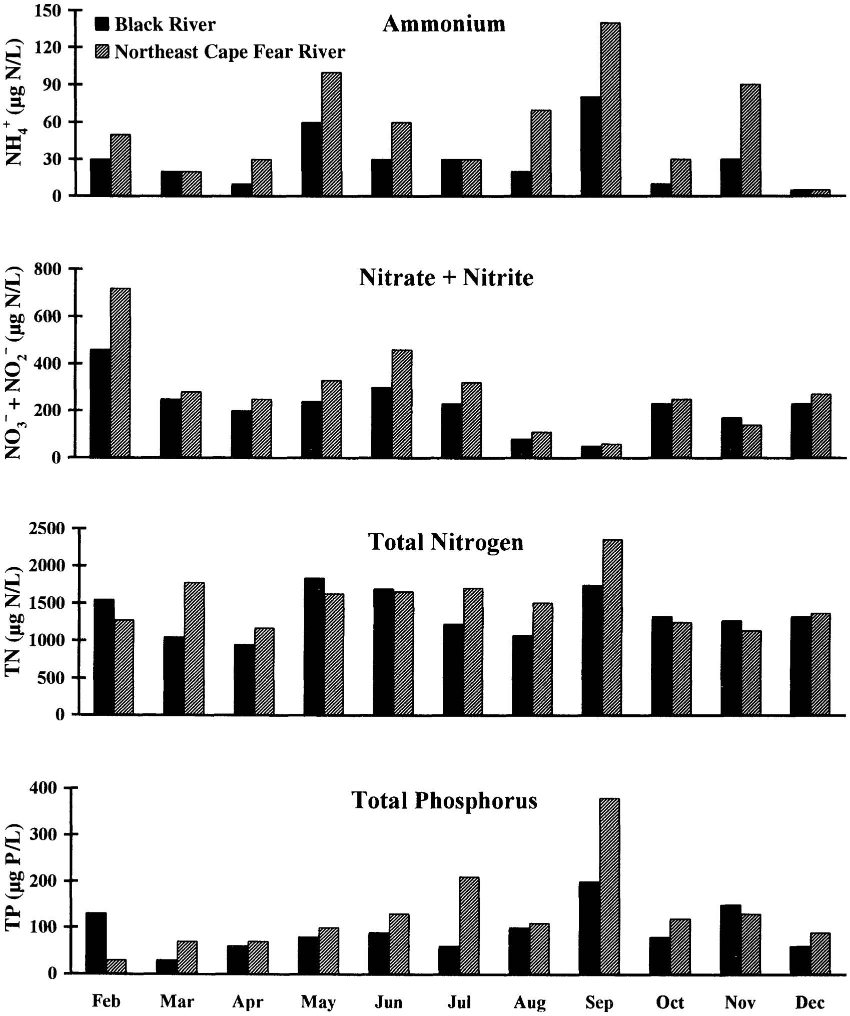

FIG. 6. Nutrient concentrations in the Black and Northeast Cape Fear rivers, January–December 1996.

at B210 and 54 µg/L at NCF117. Overall, the data indicated that organic species and ammonium dominated nitrogen composition at these blackwater sites following Hurricane Fran.

As with nitrogen, the main stem Cape Fear River and Estuary exhibited no distinct September increase in phosphorus following Hurricane Fran. However, both NCF117 and B210 displayed significant peaks in organic phosphorus and total phosphorus (Fig. 6) in September. At NCF117, organic P concentrations measured 292 µg/L following Hurricane Fran, compared with the 1996 mean of 79 µg/L, whereas TP measured 380 µg/L, compared with the 1996 mean of 124 µg/L. At B210, there was a peak in organic phosphorus measured at 116 µg/L, twice the 1996 average of 58 µg/L, and TP measured 200 µg/L, compared with the 1996 mean of 88 µg/L.

Benthos.—Over the year of sampling, benthic species composition and abundance were characterized by temporal and spatial variability (Table 1), as is common in oligohaline estuarine areas (Holland 1985, Nichols 1985, Hines et al. 1987, Holland et al. 1987, Posey et al. 1993). However, in addition to this common variability, fauna at several sites showed post-hurricane declines that were qualitatively correlated with dissolved oxygen loss and flow events. Hurricane Fran led to near-anoxic conditions at the NCF6 site and hypoxic conditions at the NAV and lower estuarine sites (Fig. 3). At NCF6 in the Northeast Cape Fear River, there was a significant decline in total faunal abundance after Hurricane Fran, relative to all other sampling periods (Table 1). This decline primarily reflected the absence of amphipods and low numbers of insect larvae at this site following the hurricane. DO recovery to pre-hurricane conditions at this site was observed by mid-October. Return of total faunal abundances and abundances of major taxa to pre-hurricane levels occurred by mid-December. The NAV station exhibited hypoxic conditions after Fran, but recovered to DO concentrations of ~4.0 mg/L in ~2 wk (Fig. 3). The NAV station

TABLE 1. Abundances of numerically common infauna and higher taxonomic groups at each site and sampling period. Numbers indicate mean (±1 SE) per sample. The *F* value is from ANOVA comparing abundances among sampling periods; means having the same superscript do not differ significantly (SNK test, $P > 0.05$).

Taxa	*F*†	Dec 1995	Mar 1996	Aug 1996	1 Oct 1996	31 Oct 1996	Dec 1996
NCF6							
Amphipoda sp.	1.8$^{\text{NS}}$	0.2 (0.2)	2.0 (1.4)	0.0 (0.0)	···	0.0 (0.0)	0.0 (0.0)
Cyanthura sp.	25.23***	0.0^{a} (0.0)	0.8^{b} (0.4)	4.0^{c} (1.0)	···	0.0^{a} (0.0)	0.0^{a} (0.0)
Gammarus palustris	4.43*	5.4^{a} (3.0)	0.0^{b} (0.0)	0.0^{b} (0.0)	···	0.0^{b} (0.0)	0.0^{b} (0.0)
Gamarus tigrinus	2.03$^{\text{NS}}$	1.8 (1.4)	0.0 (0.0)	0.0 (0.0)	···	0.0 (0.0)	0.0 (0.0)
Chironomidae spp.	2.05$^{\text{NS}}$	8.2 (5.6)	0.0 (0.0)	0.0 (0.0)	···	0.0 (0.0)	1.8 (1.8)
Procladius sp.	3.13*	0.0^{a} (0.0)	1.4^{ab} (0.9)	1.7^{b} (0.7)	···	0.0^{a} (0.0)	0.4^{ab} (0.2)
Oligochaeta	2.89$^{\text{NS}}$	1.2 (0.5)	0.2 (0.2)	1.7 (0.7)	···	1.4 (0.9)	5.2 (1.7)
Marenzelleria virdis	11.85***	0.0^{a} (0.0)	8.0^{b} (4.0)	0.0^{a} (0.0)	···	0.0^{a} (0.0)	0.0^{a} (0.0)
Total amphipods	3.54*	7.4^{a} (3.3)	3.4^{ab} (1.6)	4.0^{a} (1.0)	···	0.0^{b} (0.0)	1.2^{ab} (0.6)
Total isopods		0.0 (0.0)	0.0 (0.0)	0.0 (0.0)		0.0 (0.0)	0.0 (0.0)
Total insects	1.60$^{\text{NS}}$	8.4 (5.8)	3.2 (1.0)	1.7 (0.7)	···	0.2 (0.2)	4.4 (1.9)
Total bivalves	0.88$^{\text{NS}}$	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	···	0.0 (0.0)	0.2 (0.2)
Total polychaetes	4.81**	0.8^{a} (0.4)	8.4^{b} (4.2)	0.3^{a} (0.3)	···	0.6^{a} (0.4)	0.4^{a} (0.2)
Total infauna	4.11*	19.2^{a} (8.8)	17.0^{a} (4.6)	7.7^{a} (1.2)	···	2.2^{b} (0.9)	12.2^{a} (3.9)
NAV							
Polypedilum sp.	6.20**	0.0^{a} (0.0)	7.4^{b} (3.7)	···	···	1.0^{ab} (1.0)	7.0^{bc} (0.9)
Procladius sp.	8.87**	0.0^{a} (0.0)	8.4^{b} (2.5)	···	···	7.0^{b} (3.5)	11.4^{b} (1.0)
Oligochaeta	2.48$^{\text{NS}}$	23.0 (4.1)	56.8 (18.1)	···	···	39.0 (10.1)	114.6 (31.8)
Marenzelleria virdis	10.73***	0.0^{a} (0.0)	28.6^{b} (10.6)	···	···	0.0^{a} (0.0)	0.0^{a} (0.0)
Total amphipods	2.05$^{\text{NS}}$	0.4 (0.2)	2.2 (1.4)	···	···	0.0 (0.0)	4.0 (1.9)
Total isopods	0.84$^{\text{NS}}$	0.2 (0.2)	0.0 (0.0)	···	···	0.0 (0.0)	0.0 (0.0)
Total insects	4.82*	7.4^{a} (2.9)	18.6^{b} (4.8)	···	···	14.7^{b} (1.5)	20.2^{b} (1.2)
Total bivalves	0.84$^{\text{NS}}$	0.4 (0.2)	4.0 (3.3)	···	···	2.0 (0.6)	4.6 (3.0)
Total polychaetes	7.29**	4.4^{a} (3.7)	30.0^{b} (10.0)	···	···	0.0^{a} (0.0)	3.2^{a} (3.0)
Total infauna	4.53*	36.8^{a} (9.6)	112.6^{ab} (29.0)	···	···	55.7^{ab} (11.7)	160.6^{b} (40.3)
M54							
Gammarus palustris	1.83$^{\text{NS}}$	4.8 (4.1)	0.8 (0.8)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Monoculodes sp.	18.53***	0.5^{a} (0.3)	7.0^{b} (1.7)	0.8^{a} (0.8)	0.0^{a} (0.0)	0.0^{a} (0.0)	0.3^{a} (0.3)
Edotea sp.	2.03$^{\text{NS}}$	0.8 (0.5)	2.8 (1.7)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Oligochaeta	3.87*	1.5^{a} (0.6)	0.8^{a} (0.4)	6.25^{b} (1.7)	0.6^{a} (0.4)	1.2^{a} (0.6)	1.5^{a} (0.6)
Marenzelleria virdis	46.07***	0.0^{a} (0.0)	43.6^{b} (17.4)	2.0^{c} (0.7)	0.0^{a} (0.0)	0.0^{a} (0.0)	0.3^{a} (0.3)
Mediomastus sp.	41.01***	10.75^{a} (1.9)	0.0^{b} (0.0)	2.0^{c} (0.7)	0.2^{b} (0.2)	0.0^{b} (0.0)	0.0^{b} (0.0)
Total amphipods	11.95***	5.3^{a} (3.9)	9.0^{b} (2.0)	0.8^{c} (0.8)	0.0^{c} (0.0)	0.2^{c} (0.2)	0.3^{c} (0.3)
Total isopods	10.16***	1.8^{a} (0.3)	5.4^{ab} (1.6)	1.25^{ac} (0.5)	0.0^{c} (0.0)	0.0^{c} (0.0)	0.0^{c} (0.0)
Total insects	18.82***	0.0^{a} (0.0)	0.0^{a} (0.0)	0.0^{a} (0.0)	0.2^{a} (0.2)	2.2^{b} (0.4)	0.3^{a} (0.3)
Total bivalves	0.86$^{\text{NS}}$	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.2 (0.2)	0.0 (0.0)
Total polychaetes	23.68***	13.0^{a} (1.6)	43.8^{b} (17.4)	5.5^{c} (1.6)	0.8^{d} (0.5)	0.6^{d} (0.4)	0.3^{d} (0.3)
Total infauna	21.06***	22.0^{a} (3.5)	59.6^{b} (18.0)	13.8^{a} (3.7)	4.6^{c} (1.2)	4.4^{c} (0.7)	2.5^{c} (0.6)
M31							
Marenzelleria virdis	53.99***	3.20^{ab} (1.6)	127.4^{c} (36.6)	2.5^{a} (11.5)	0.2^{ab} (0.2)	0.0^{b} (0.0)	0.2^{ab} (0.2)
Mediomastus sp.	12.91***	2.2^{a} (1.4)	5.0^{a} (0.8)	1.5^{a} (1.5)	6.0^{a} (2.6)	36.6^{b} (9.3)	184.4^{b} (33.6)
Total amphipods	7.21***	1.8^{a} (0.4)	1.8^{a} (0.8)	1.5^{a} (0.5)	0.0^{b} (0.0)	0.0^{b} (0.0)	0.2^{b} (0.2)
Total isopods		0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Total insects	0.90$^{\text{NS}}$	0.4 (0.4)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Total bivalves	6.26***	0.0^{a} (0.0)	4.6^{b} (1.9)	1.0^{a} (1.0)	0.3^{a} (0.3)	0.4^{a} (0.2)	0.4^{a} (0.2)
Total polychaetes	21.69***	10.2^{a} (2.3)	137.8^{b} (37.6)	12.5^{a} (9.5)	15.0^{a} (3.2)	43.2^{c} (11.0)	193.6^{b} (33.6)
Total infauna	21.66***	12.8^{a} (2.4)	144.2^{b} (39.4)	16.5^{a} (9.5)	18.7^{a} (3.4)	43.6^{c} (11.0)	194.4^{b} (33.8)

Note: Ellipses indicate that no data were collected.

* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$; NS, no significant difference among seasons.

† Degrees of freedom by site, are: NCF6 (4, 19); NAV (3, 15); M54 (5, 22); M31 (5, 23).

was not characterized by significant declines in infaunal abundances after Fran (Table 1). However, the high variability in faunal counts at this site made statistical determination of patterns difficult. NAV had no amphipods or polychaetes in the first samples collected after Fran (in contrast to other sampling periods), and had 50% lower total infaunal abundances at that time than in sampling periods either before or following the hurricane effects. Four taxa at NCF6 (*Cyathura* sp., *Gammarus palustris, Procladius* sp., and *Marenzelleria virdis*) and three taxa at NAV (*Procladius* sp., *Polypedilum* sp., and *Marenzelleria*) exhibited significant temporal variability independent of hurricane effects.

M54 represented a mid-estuary site that was located near the turbidity maximum zone. In addition to prolonged DO decreases, this site also experienced lowered salinity after Hurricane Fran, probably related to high river flow conditions. Bottom water salinity was zero for >1 mo after the storm, climbing to 12 g/kg by November. Freshets periodically occur at this location (Mallin et al. 1996); however, the post-Fran freshet was longer than normal. Several benthic groups, including isopods, polychaetes, and total infauna, exhibited lower abundances in the sampling periods after Hurricane Fran. Recovery of these taxa was slower than at the other sites, with total infaunal abundances in December 1996 not significantly different from the 1 October 1996 samples, but significantly lower than those observed in the previous December (Table 1). Total amphipod abundances at M54 also exhibited an overall decline after Hurricane Bertha (August samples). However, the lack of data from the previous year makes it difficult to assess Bertha's effects. *Monoculodes* sp., oligochaeta, *Marenzelleria virdis,* and *Mediomastus* sp. exhibited significant temporal variability in numbers at M54. M31 was the farthest downstream site; it exhibited a short-term DO decline and a minor drop in salinity (12 g/kg bottom salinity immediately after Fran and 20 g/kg by November). Fauna in this region showed a mixed response. The polychaete *Mediomastus* had higher abundances after Hurricane Fran than in pre-storm samples. At M31, only amphipods displayed a statistically significant decline in numbers after Hurricane Fran.

DISCUSSION

Increased light attenuation through loading of darkly stained swamp water to rivers can be considered a natural environmental effect of a hurricane's aftermath. For instance, in one area of Everglades National Park, it was reported that water color was darker than normal following Hurricane Andrew (Roman et al. 1994). One likely biotic effect of increased water color and particulate matter from Hurricane Fran on the lower Cape Fear Estuary and nearshore ocean would be a decrease in phytoplankton and benthic algal primary production (Alpine and Cloern 1988, Mallin and Paerl 1992). Light attenuation has been cited as a periodic limiting factor to phytoplankton productivity in the Cape Fear Estuary, mainly during winter months (Mallin et al. 1997*a*). There are no productivity rates available during these months, but phytoplankton chlorophyll *a* biomass in the lower estuary during September and October 1996 was 3.2 and 3.4 μg/L, respectively, compared with 13.6 and 12.8 μg/L in those same months during 1995 (Mallin et al. 1996). September light attenuation coefficients were the highest system-wide since data collection began in July 1994. The heavy flooding and increased light attenuation following the hurricanes probably also caused coastal ocean light limitation during the fall of 1996.

Problems of low dissolved oxygen have been associated with a number of hurricanes. In 1960, Hurricane Donna churned up large amounts of mud and organic matter in north Florida Bay and the lower Everglades, resulting in oxygen depletion of the water and a large kill of fish and invertebrates (Tabb and Jones 1962). In 1972, Hurricane Agnes caused a massive freshet to enter the Chesapeake Bay, resulting in strong salinity stratification with low dissolved oxygen levels beneath the pycnocline (Boesch et al. 1976). Hurricane Hugo in 1989 led to hypoxic and anoxic conditions in the major tributaries feeding Charleston Harbor, with reports of fish kills (Knott and Martore 1991, Van Dolah and Anderson 1991). The DO decline was attributed to decomposition of debris and leaf litter and the failure of septic and sewer systems, which overflowed into the system (Van Dolah and Anderson 1991). There were short-term (3-d) hypoxic conditions in Waquiot Bay associated with Hurricane Bob in 1991, attributed, in part, to reduced solar irradiance and photosynthesis (Valiela et al. 1996). In 1992, the nearshore waters of Biscayne Bay suffered declines in DO to near zero, attributed to high turbidity and loss of primary productivity (Tilmant et al. 1994). We will demonstrate that the severe dissolved oxygen problems following Hurricane Fran resulted from a combination of natural, agricultural, and urban sources.

The Black and Northeast Cape Fear Rivers make excellent comparative systems because they drain similar-sized watersheds, are both blackwater systems, and have similar land use patterns. Along the lower rivers are extensive riparian swamp forests, and among the tributary streams are numerous large-scale swine and poultry farming facilities. These types of animal production facilities are variously known as intensive livestock operations (ILOs) or concentrated animal operations (CAOs), and feature a system in which thousands of swine or fowl are raised in long, shed-like structures, with their urine and feces rinsed into nearby open lagoons. The waste material undergoes sludge settling and receives some anaerobic breakdown in the lagoons; when lagoon levels rise enough, the liquid effluent is normally sprayed onto nearby fields with a grass covering, usually Bermuda grass (Westerman et al. 1985).

Both the Black and Northeast Cape Fear watersheds suffered from heavy post-hurricane rainfall, judging from their relatively similar river flow rates following Hurricane Fran (Fig. 2), and both rivers suffered from decreased DO following the hurricanes. Swamp water is naturally low in dissolved oxygen, and inputs into blackwater rivers from flooding will lower river DO concentrations (Meyer 1992). However, swamp-derived organic materials in blackwater rivers are largely composed of refractory carbon compounds, with a low BOD5 (Meyer 1990, 1992). Following Hurricane Fran, BOD5 was six times higher and dissolved oxygen concentrations were 80% lower in the Northeast Cape Fear River at NCF117 than in the Black River at B210. The major difference in impacts was probably anthropogenic, caused, in part, by at least four swine waste lagoons breaching, overtopping, or being inundated on the Northeast Cape Fear floodplain, and allowing large quantities of raw and partially treated swine urine and feces to enter the river. One lagoon was reported to have overtopped and discharged into the Black River watershed (NCDEHNR 1996). Authors of another study reported that swine waste lagoon liquid from five tested waste lagoons had an average COD of 1839 mg/L, with a range of 970–2255 mg/L (Westerman et al. 1990). Lagoon sludge was reported to have an average COD of 67 430 mg/L (J. Barker, NCSU, *unpublished data*); thus, these concentrated and highly labile effluents are likely to exert a major oxygen demand on already oxygen-poor waters. A previous incident demonstrated this effect: in July 1995, a poultry waste lagoon in the upper Northeast Cape Fear watershed ruptured, releasing 32.6×10^6 L of waste into tributary creeks, which subsequently entered the river (Mallin et al. 1997*b*). This created a dissolved oxygen sag that reached its minimum of 1.0 mg/L at a NCF117, 90 km downstream, 17 d after the rupture. Until the aftermath of Hurricane Fran, this DO reading was the lowest on record (during 27 yr) at this station.

In addition to outright waste release incidents, lagoon operators sprayed unknown amounts of liquid wastes on already saturated fields to prevent other lagoons from overtopping in the rains following Hurricane Fran (NCDEHNR 1996, WMS 1996). A third anthropogenic source that may have contributed to BOD loading was an unknown number of septic systems flooded by heavy rainfall along the floodplain. Finally, at least five of the aforementioned publicly owned treatment facilities malfunctioned along the Northeast Cape Fear River, releasing to the watershed $\sim 3.7 \times 10^6$ L of human waste in various stages of treatment. Treatment plant and pump station failures diverted $\sim 17.8 \times 10^6$ L of human sewage into the Black River watershed. The majority of the human sewage diversions ($\sim 265 \times 10^6$ L) occurred along the main stem Cape Fear River basin (NCDEHNR 1996). Human sewage has an average BOD of ~200 mg/L (Clark et al. 1977); however, the liquid diverted following Hurricane Fran ranged from concentrated sewage to waste heavily diluted by storm water runoff, so quantification of the BOD load would be very speculative. Nevertheless, the main stem received a sizable BOD load from human sewage, but its greater flow (Fig. 2) allowed DO levels to increase to acceptable levels more quickly than those of the Northeast Cape Fear (Fig. 3) or the Black River. Additionally, blackwater rivers are already more oxygen-stressed than Piedmont rivers in summer (Meyer 1990, 1992, Mallin et al. 1996), further lengthening recovery time from BOD pollution incidents.

Ammonium and phosphorus are nutrients that, in elevated concentrations, are characteristic of human and animal wastewater (Clark et al. 1977, Donham et al. 1985, Westerman et al. 1990, Burkholder et al. 1997). With available background monitoring data, it is possible to utilize pulses of these nutrients as evidence of anthropogenic inputs to a water body. Thus, in 1995 we attributed a water column "spike" in ammonium in the lower Northeast Cape Fear River to an upstream poultry waste lagoon rupture 10 d earlier (Mallin et al. 1997*b*). Following Hurricane Fran, both ammonium and phosphorus reached notable peaks (Fig. 6); a check of North Carolina Department of Environment, Health, and Natural Resources records indicated that total phosphorus concentrations in the Northeast Cape Fear River at NCF117 following Hurricane Fran were the highest recorded in 27 yr of available data. These nutrient concentrations were >50% higher than those in the Black River and the main stem Cape Fear River, and we conclude that anthropogenic loading, primarily concentrated animal waste, was largely responsible for these burdens. Elevated nutrients were also noted following Hurricane Andrew: canals and nearshore waters of Biscayne Bay displayed significant increases, particularly near the South Dade Landfill, and northeast Florida Bay showed elevated phosphorus, possibly as a result of sediment disturbance and leaching from downed vegetation (Tilmant et al. 1994). A non-anthropogenic, ephemeral pulse of ammonium occurred in Waquiot Bay following Hurricane Bob, and was attributed to water column mixing of decaying benthic macroalgae (Valeila et al. 1996).

Because of their trophic position and relatively sedentary life-style, benthos have been used to assess the magnitude and longevity of disturbance effects in estuarine and riverine systems (e.g., Boesch et al. 1976, Dauer 1984, Whitehurst and Lindsey 1990, Knott and Martore 1991). A major storm event such as Hurricane Fran may impact benthos through a variety of mechanisms, including increased sedimentation, introduction of contaminants, changes in DO, short-term changes in salinity, and disturbance from increased flow. Both salinity and DO affected abundances and diversity of benthos after the passage of Hurricane Hugo over Charleston, South Carolina (Knott and Martore 1991), and Tropical Storm Agnes over the Chesapeake Bay (Boesch et al. 1976). In both of these storms, salinity affected distributions and abundances of certain species, but low DO was thought to have had the strongest overall effect on benthic community composition.

Benthos at several sites exhibited significant declines in abundance after the passage of Hurricane Fran, relative to previous time periods, especially in the Northeast Cape Fear site NCF6 and the mid-estuary site M54. Observations of grabs taken after the hurricane did not indicate dramatic changes in sediment composition or provide evidence of significant deposition. Both NCF6 and M54 had higher concentrations of N and P associated with storm runoff. Although chronic nutrient loading may affect benthic communities (Beukema 1991), there is less evidence to suspect significant effects from short-term increases. The upper estuarine sites, NAV and NCF6, regularly experience freshwater conditions, and significant declines in freshwater-tolerant taxa, such as oligochaetes and insect larvae, suggest that salinity decrease was not the primary factor driving faunal changes in the upper estuary. However, prolonged bottom freshwater conditions at M54 in the mid-estuary may have contributed to the severe and long-lasting reductions in benthic fauna in this area.

Low DO was probably the most important environmental change associated with the passage of Hurricane Fran, causing general declines among a variety of benthos. NCF6 had prolonged near-anoxic conditions and M54 had substandard surface and bottom DO concentrations for an extensive period. Low DO associated with organic enrichment has been well demonstrated to reduce abundances of several infaunal groups (Dauer 1984, Aschan and Skullerud 1990, Tsutsumi 1990, Weston 1990). Storm-associated low DO has been suggested to cause declines in abundance of several of the taxa observed in our samples, including certain amphipods (e.g., *Cyathura, Corophium, Leptocheirus,* and *Gammarus*; Boesch et al. 1976, Whitehurst and Lindsey 1990), isopods, and certain polychaetes (e.g., *Streblospio, Nereis,* and *Marenzelleria*; Boesch et al. 1976, Dauer 1984). Taxa more tolerant of low DO, such as the capitellid polychaete *Mediomastus* (Aschan and Skullerud 1990), exhibited more variable responses and actually increased in abundance at the lowest estuarine station, M31. At M31, significant decreases were only detected for amphipods. Decreased storm effects may reflect the burrowing lifestyle of many of the polychaete species dominant at this station, which allows them to withstand short periods of hypoxia and the influence of tidally introduced oceanic waters. Significant hurricane effects were not demonstrated at the oligohaline Cape Fear River site NAV, reflecting high background variability in this region and, possibly, the relatively rapid recovery of bottom-water DO to 5.0 mg/L by 4 October.

There was recovery of benthic fauna within 2–4 mo at some locations, providing further evidence to support the idea that the rapid reproduction and opportunistic nature of many estuarine benthos will lead to high resiliency in benthic community composition and abundances (Dauer 1984, Posey and Hines 1991, Posey et al. 1996). However, recovery did not occur at equal rates among all sites. NCF6 and M31 differed in their recovery rates, possibly reflecting differences in the dominant taxa present. NCF6 was dominated by amphipods and insect larvae, whose brooding reproductive strategies or adult dispersal can allow rapid increases in population numbers after a disturbance. Among the taxa most affected at M54 were polychaetes that must rely upon spring recruitment for recovery. Although the mechanisms causing benthic declines at the sites may have been similar, life history characteristics may have played a role in the variable recovery rates.

ENVIRONMENTAL POLICY AND HURRICANE EFFECTS

Human activities, particularly those concerned with waste treatment, significantly magnified the deleterious effects of Hurricane Fran on water quality. Power outages caused diversions of $>265 \times 10^6$ L of inadequately treated human sewage into the Cape Fear River system; statewide, $\sim 800 \times 10^6$ L were diverted (NCDEHNR 1996). Much of this diverted material could have been properly treated, had backup generating systems been mandated for publicly owned waste treatment facilities. In some situations, local industries offered the use of generators to treatment facilities, but these facilities were inadequately wired to utilize the generators (H. Strickler, General Electric Corporation, *personal communication*). Siting of animal waste lagoons was also a major environmental hazard. Our analysis demonstrates that several lagoon incidents contributed to serious water quality damage in the Northeast Cape Fear basin; statewide, there were ≥ 22 lagoon incidents attributed to Fran (NCDEHNR 1996). Apparently this is the first report of animal waste lagoons as a significant source of pollution during and following a hurricane. This is probably because the large increase in CAOs in hurricane-prone areas is a recent phenomenon, with the North Carolina swine population increasing to 9.8×10^6 animals in 1997 (NCDA 1997). Swine or poultry CAOs are abundant or increasing in other hurricane-prone states such as Delaware, Maryland, South Carolina, and Virginia, as well as midwestern states such as Iowa and Missouri, which are subject to flooding and tornadoes. Lagoon breaches and other incidents have happened previously for a variety of reasons (Burkholder et al. 1997, Mallin et al. 1997*b*). However, much of the post-Hurricane Fran animal waste loading was a direct result of siting waste lagoons on river floodplains, either through lagoon accidents or spraying of lagoon liquid on rain-saturated floodplains. Finally, many private residences built on river floodplains suffered flooding and problems with septic systems. The hurricane dangers associated with floodplains have been recognized for years (Miller 1980). It is evident that systems handling large quantities of animal waste materials can be especially problematic when sited in environmentally risky areas.

There have been significant human sewage pollution problems associated with hurricanes in other highly developed areas such as Biscayne Bay (Tilmant et al. 1994) and Charleston Harbor (Van Dolah and Anderson 1991), as well as in the Cape Fear watershed. Although they are subject to power outages from mainline failures, treatment plant backup generators can be retrofitted. Legislation was introduced in the North Carolina General Assembly in February 1997 to require on-site generators for wastewater treatment plants that are permitted to discharge waste. Legislation to prohibit construction of new animal waste lagoons and to prohibit expansion of existing facilities in locations subject to flooding by a 100-yr flood was also introduced in the North Carolina General Assembly in February 1997. The requirement for on-site alternate generators was not acted upon in 1997. However, legislation was passed prohibiting construction of new waste lagoons and hog houses on the 100-yr floodplain. This prohibition did not include liquid spray fields, however. Lagoons already present on floodplains will remain potential hazards until retired from use and pumped down. The siting of residences in flood-prone areas is also likely to remain problematic, depending on land use planning efforts (or lack thereof). Although Hurricane Fran, in particular, led to large-scale environmental damage, the experiences garnered from this event have led to serious policy discussions and some improved environmental policy changes.

Data garnered from Hurricanes Bertha and Fran, along with reports from other hurricanes, show that the degree of impact to the aquatic environment depends on other factors besides the severity of the hurricane. Foremost is the amount and type of floodplain development, with the presence of sewer systems, landfills, and CAOs greatly exacerbating the amount of water quality degradation (Knott and Martore 1991, Van Dolah and Anderson 1991, Tilmant et al. 1994), whereas little water quality damage occurs when there is minimal anthropogenic input (Roman et al. 1994, Valiela et al. 1996). Geography is also important. Hurricanes impacting poorly flushed bays or inland river floodplains will increase the magnitude and duration of impacts (Tabb and Jones 1962, Boesch et al. 1976, Van Dolah and Anderson 1991). Impacts to well-flushed bays will be either slight (Valiela et al. 1996) or intense, but relatively short-lived (Tilmant et al. 1994). Although hurricanes will always be factors of coastal life, it is clear that environmentally sound floodplain management can minimize their impacts on coastal water quality.

ACKNOWLEDGMENTS

Funding was provided by the Cape Fear River Program, the North Carolina Division of Marine Fisheries (Contract Number M6047), the University of North Carolina Water Resources Research Institute (Projects 70136 and 70156), and the Z. Smith Reynolds Foundation. We thank B. Baldridge and other volunteers from Cape Fear RiverWatch, and D. Parsons for helping with field data collection. For information, we thank L. Ausley, J. Bushardt, S. Petter, and R. Shiver of the North Carolina Division of Water Quality, and J. Barker of North Carolina State University for unpublished data. River flow data were provided by J. Bales and D. Walters of the U.S. Geological Survey, Raleigh, North Carolina, and rainfall data was provided by T. Keever of the State Climatologist Office, North Carolina State University, Raleigh, North Carolina, USA.

This is Contribution No. 200 of the Center for Marine Science Research, the University of North Carolina at Wilmington.

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