Impacts and Recovery from Multiple Hurricanes in a Piedmont–Coastal Plain River System

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Few events in modern society are as frightening and unpredictable as a hurricane. A hurricane's strength, its duration, and the location of its landfall are often uncertain until mere hours before it strikes land. Disruptions from hurricanes—including property loss, infrastructure damage, and human misery—can last weeks or months, and the toll in lives lost can be catastrophic in less developed countries.

However, hurricanes are normal disturbances that natural ecosystems have been affected by and recovered from for millennia. One such ecosystem, the Cape Fear River system in North Carolina, has been struck repeatedly by hurricanes in recent years. The ecosystem-level effects of this recent spate of hurricanes are evident in the severe degradation of water quality, benthic community displacement and mortality, and large-scale fish kills. Since the Atlantic basin is predicted to have above average hurricane activity for the next 10 to 40 years (Goldberg et al. 2000), such environmental degradation is likely to continue.

In recent decades, the lower Cape Fear watershed has undergone extensive transformation, caused mainly by agriculture. Shifts in land use can substantially alter the effects of natural disturbances (Naiman and Turner 2000) and cause extensive alterations to ecosystems distant from those where the land use changes occurred (Dale et al. 2000). Our objectives in this article are to describe the effects of hurricanes on water quality, benthic faunal communities, and fish; discuss how human landscape changes amplify the effects of disturbances; and examine the ways in which this diverse river–estuarine system has responded to and recovered from various characteristics of hurricanes.

HUMAN DEVELOPMENT OF FLOODPLAINS GREATLY COMPOUNDS THE IMPACTS OF HURRICANES ON WATER QUALITY AND AQUATIC LIFE

The lower Cape Fear watershed

The lower Cape Fear River system lies in southeastern North Carolina at approximately 37° north, 77°57' west. Its principal channel is the Cape Fear River, a sixth-order stream (on a scale from first-order small tributaries to twelfth-order large rivers) that arises near Greensboro, North Carolina, in the Piedmont. The lower river is joined by two fifth-order blackwater tributaries, the Black and the Northeast Cape Fear Rivers, which originate in the coastal plain (figure 1). These systems feed the Cape Fear estuary, a system 72 kilometers (km) long that flows unimpeded into the Atlantic Ocean. This region features one major municipality (the city of Wilmington, population 95,000) and several smaller municipalities. Land coverage in the lower watershed is approximately 63% forest, 25% cultivated crop and pastureland, 4% urbanized, and 8% other uses.

A major use of the landscape in the lower watershed is industrial-scale swine and poultry production, especially in the basins of the Black and Northeast Cape Fear Rivers (Cahoon et al. 1999, Mallin et al. 1999a). Statewide, intensive swine production has grown rapidly in recent years, increasing from 2.7 million in 1990 to approximately 10 million by 1998, with some 51% of North Carolina's swine population

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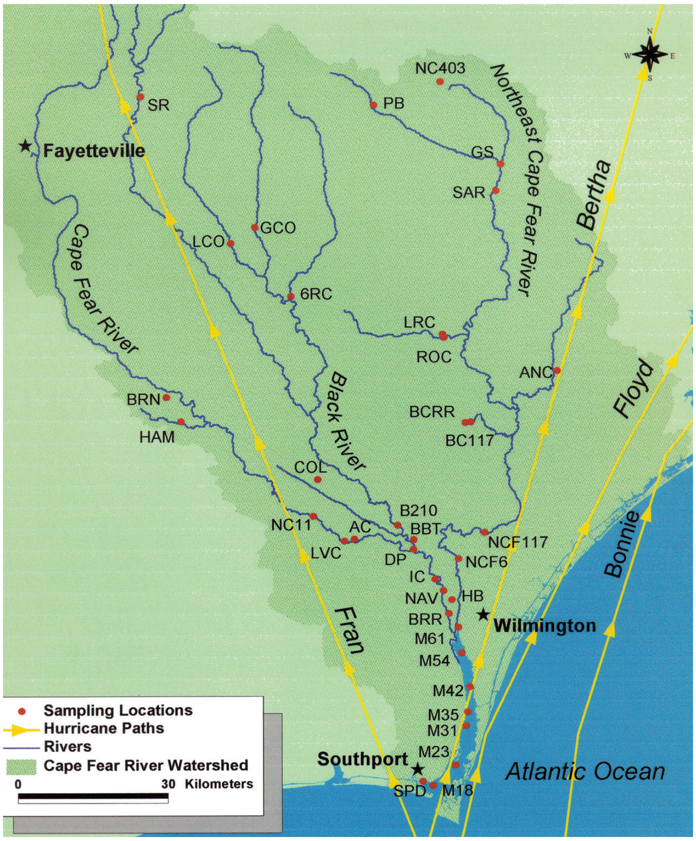

Figure 1. Map of the lower Cape Fear watershed, showing sampling stations.

concentrated in the Cape Fear River basin (Cahoon et al. 1999, Mallin 2000). The concentrated animal feeding operations (CAFOs) feature a system in which hundreds to thousands of swine are raised indoors in close quarters, with their urine and feces flushed by a series of pipes and ditches to outdoor open pools called waste lagoons (Burkholder et al. 1997, Mallin 2000). Although some microbial breakdown occurs in these anaerobic ponds, nutrient-rich liquid from these ponds is sprayed on nearby fields planted with a cover crop such as bermudagrass (figure 2).

The University of North Carolina at Wilmington's Lower Cape Fear River Program operates a network of 35 water-quality sampling stations located throughout the streams, rivers, and estuary in the lower watershed (figure 1). The program, which began in February 1996, includes sampling of the benthic community at several sites. During the course of our study, the lower Cape Fear estuary region was hit by Hurricanes Bertha (12 July) and Fran (5 September) in 1996; by Hurricane Bonnie (26 August) in 1998; and by Hurricanes Dennis (30 August), Floyd (15 September), and Irene (17 October) in 1999. Three of these storms, Fran, Bonnie, and Floyd, had major, long-lasting effects on the area's aquatic resources; the hydrological and ecological effects of these three hurricanes varied considerably, however, a point that we will highlight.

Sampling program

Water quality samples were normally collected monthly, with all 35 sites collected within a 4-day period. Multiparameter field instruments for assessing water quality were used to obtain vertical profiles of water temperature, salinity, conductivity, pH, dissolved oxygen, and turbidity. In the summer, these vertical profiles were obtained more frequently, every 1 or 2 weeks. Water samples were collected and analyzed for total nitrogen (TN), nitrate-N, ammonium-N, total phosphorus (TP), orthophosphate-P, suspended sediments, chlorophyll *a,* fecal coliform bacteria, and, at several stations, biochemical oxygen demand (BOD). After a hurricane, extra samples were collected weekly or biweekly, and extra stations were sampled as well.

Benthic infauna were sampled at four sites in the Cape Fear River system: station NCF6, a low-salinity site in the Northeast Cape Fear River; station NAV, a low-salinity site in the Cape Fear River; station M54, an upper- to midsalinity site below the city of Wilmington; and station M31, a lower estuary, midsalinity site that experiences saltwater intrusions from the adjacent Snow's Cut (figure 1). Benthic samples were taken quarterly from winter 1996 through spring 2000 (as in Mallin et al. 1999a). Hurricanes Fran, Bonnie, and Floyd occurred before regular fall sampling, so monthly samples of sediments were taken (using a Ponar grab sampler) for 3 months after each hurricane to monitor recovery of the benthic community in 1996, 1998, and 1999. Five grab samples were taken at each station on each sampling date. Species richness was measured as number of taxa (species or genus for most taxa; higher taxa for oligochaetes, nemertea, and platyhelminthes). We used the Shannon-Weiner Index to measure diversity (Brower et al. 1998).

Different storms, different impacts

Storm impacts were variable across the Cape Fear watershed. Hurricane Bertha arrived at Wilmington, then proceeded due north up the coast (figure 1). Whereas Bertha caused considerable infrastructure damage in the Wilmington area and had some localized effects on water quality, the hurricane had little inland impact in the Cape Fear River basin. In contrast, after making landfall at Wilmington, Fran followed the Cape Fear River northwest and had severe impacts on cities far upstream, such as Raleigh and Greensboro in the Piedmont. The impact of Hurricane Fran on all three main tributaries was exceptional (figure 3). In fact, this hurricane caused record peak 1-day flow levels in the Cape Fear River (Bales et al. 2000). Heavy infrastructure damage and power outages occurred basinwide. Hurricane Bonnie made landfall just north of Wilmington and moved north through the Northeast Cape Fear River watershed toward the New and Neuse Rivers (figure 1), causing most structural damage, flooding (figure 3), and water-quality impacts in the Black River and Northeast Cape Fear River basins.

Dennis stayed 90 km offshore of Cape Fear and did not cause major damage to infrastructure in this region; its primary impacts were in the Neuse River area. The principal im-

Figure 2. Industrial-scale swine farm (CAFO, or concentrated animal feeding operations) in the Cape Fear watershed, showing hog houses, waste lagoon, spray field, and runoff path from waste draining into a nearby eutrophic pond.

pacts of Dennis in the Cape Fear basin were attributable to heavy rainfall and saturation of the ground. Hurricane Floyd was a vast storm in area. It landed at Wilmington and moved northwest along the upper coastal plain, east of Raleigh but upstream of the New, Neuse, and Pamlico estuaries (figure 1). Heavy rains from Floyd led to the maximum recorded daily water levels at gauging stations on the Black and Northeast Cape Fear Rivers (Bales et al. 2000) and to levels approaching those generated by Hurricane Fran in the Cape Fear River (figure 3). Hurricane Irene remained 65 km offshore of Cape Fear and did not make landfall, but delivered even more rainfall to the already saturated coastal area (Bales et al. 2000).

Flooding, water color, and phytoplankton

The geographic impact of the storms is reflected well by the light attenuation coefficient *k,* a measure accounting for parameters that absorb or reflect solar irradiance in the water column. In the Cape Fear watershed, principal factors attenuating light are turbidity from the Piedmont in the Cape Fear River and elevated water color from dissolved organic materials leached from swamp vegetation in the Black River and Northeast Cape Fear River basins (figure 4). Figure 5 compares post-hurricane *k* values with long-term average *k* values at a series of stations ranging from the uppermost mainstem station, station NC11, downstream to station IC (which includes influence from the Black River), to station NAV in the upper estuary (figure 1). The Northeast Cape Fear River is represented by station NCF6. Stations M61, M35, and M18 are located in the estuary proper. The elevated *k* values at station NC11 after Hurricanes Fran and Floyd show how the two storms caused extensive Piedmont runoff, while Hurricane Bonnie missed the Piedmont and affected only the coastal plain. The overall impact of basinwide runoff caused by Hurricanes Fran and Floyd far exceeded that caused by Hurricane Bonnie (figure 5).

The combined impacts of the three storms greatly increased light attenuation in summer and fall 1999. Median *k* for the river and estuary before Dennis was 2.68 per meter (m), while after Dennis, Floyd, and Irene, it was 4.35, 4.46, and 4.34 per m, respectively. The darkly colored water in the river plume following Hurricane Floyd was traced by oceanographers on a ship far to the southwest, along the South Carolina coast (Cahoon et al. 2001).

In the lower estuary and coastal ocean, the principal implication of such elevated light attenuation values was decreased phytoplankton production. Our monthly chlorophyll *a* data show large post-hurricane decreases compared with nonhurricane years (table 1). Inputs of swamp water rich in dissolved organic materials led to more intense offshore

Table 1. Chlorophyll a *concentrations (micrograms per liter) before and after major hurricanes at channel marker 23 in the lower Cape Fear estuary, compared with September data in years with no hurricanes.*

Year	Prehurricane	Post-hurricane
1996 (Fran)	10.3 (August)	0.9 (September)
1998 (Bonnie)	5.5 (August)	1.8 (September)
1999 (Floyd)	1.7 (September)	0.2 (October)
1995 (no hurricane)	15.4 (August)	11.3 (September)
1997 (no hurricane)	9.8 (August)	6.5 (September)

water color; they also probably led to increased offshore respiration rates in the plankton. An example of this factor came from a report from a researcher in South Carolina who regularly takes classes offshore to conduct phytoplankton productivity experiments using the light–dark bottle incubation method (Eric T. Koepfler, Coastal Carolina University, Conway, SC, personal communication, 1999). He reported that 3 weeks after the landfall of Hurricane Floyd, South Carolina's coastal waters were unusually darkly stained, salinities were 3 to 5 parts per thousand lower than normal, and planktonic respiration rates were 10 to 50 times greater than the previous year's levels.

Storms and nutrient loading to downstream waters

Heavy flooding can lead to elevated nutrient concentrations in downstream estuarine waters (Rabalais et al. 1998). Our data indicate that some hurricanes caused increased nutrient inputs to the Cape Fear estuary.

Hurricane Bertha did not go inland into the Cape Fear watershed, and thus caused no increases in river or estuary nutrient levels. Hurricane Fran caused greatly increased concentrations of TN to enter the system, particularly in the blackwater tributaries (table 2). Hurricane Bonnie caused elevated TN in the upper Northeast Cape Fear River at station SAR (figure 1), a CAFO-rich area; however, river TN concentrations following Hurricanes Floyd (table 2) and Irene were no greater than average and were considerably lower than average in the estuarine stations. Because of the extensive and prolonged flooding of lowland areas in the Cape Fear basin, it is likely that a considerable amount of denitrification occurred on the floodplain, helping to explain the comparatively low TN concentrations. Ammonium-N concentrations were unremarkable at most stations following all six hurricanes. The exceptions were stations along the Northeast Cape Fear River (SAR, NCF117, NCF6—see figure 1), where ammonium-N concentrations were particularly elevated on occasion (table 2). Nitrate-N concentrations, however, were unusually low following the hurricanes (table 2). It is likely that the hypoxic-to-anoxic conditions caused inorganic N to be in the reduced ammonium form rather than in the oxidized nitrate form.

Total phosphorus concentrations were considerably increased after Fran, Bonnie, and Floyd, especially so in the Northeast Cape Fear River (table 2). The peak concentration of 540 micrograms per liter (µg per L) occurred at station SAR after Hurricane Bonnie, with 380 µg per L occurring at station NCF117 after Hurricane Fran. Riverine orthophosphate-P concentrations were increased by two- or threefold after ma-

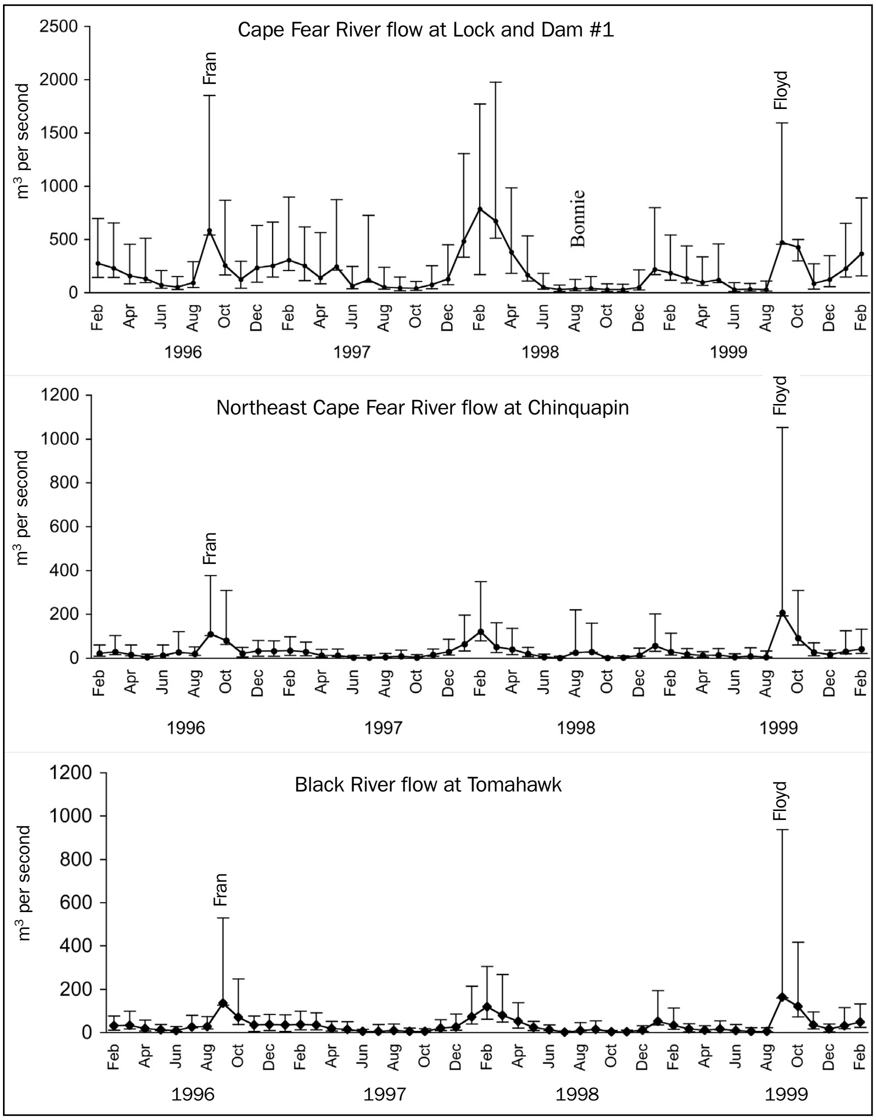

Figure 3. Mean, maximum, and minimum monthly river flow in the three main Cape Fear tributaries, February 1996 through February 2000 (data courtesy of US Geological Survey, Raleigh, NC).

Table 2. Maximum post-hurricane nutrient concentrations (micrograms per liter) at selected Cape Fear River and estuary stations, compared with long-term (May 1995–May 2000) averages.

Station	Average	Fran	Bonnie	Floyd
Total nitrogen				
SAR	1389	1960	2230	1050
NCF117	1193	2360	870	1250
NCF6	1122	2100	870	1250
B210	1018	1750	810	860
NAV	1295	970	860	480
M54	1153	1670	860	540
Ammonium-N				
SAR	108	50	210	100
NCF117	56	140	67	240
NCF6	64	60	165	230
B210	45	80	10	80
NAV	79	40	40	80
M54	93	50	20	160
Nitrate-N				
SAR	484	60	10	30
NCF117	262	60	40	10
NCF6	299	25	10	10
B210	220	50	30	10
NAV	454	80	5	60
M54	361	70	60	30
Total phosphorus				
SAR	211	250	540	170
NCF117	100	380	170	190
NCF6	106	360	200	190
B210	79	200	100	190
NAV	152	150	150	130
M54	138	230	110	170
Orthophosphate-P				
SAR	93	96	215	100
NCF117	41	88	133	100
NCF6	39	81	41	80
B210	26	84	50	50
NAV	54	56	41	40
M54	44	66	69	40

jor hurricane events, but estuarine concentrations were not notably affected (table 2).

Researchers from the US Geological Survey estimated that the total load of N carried by the Cape Fear River after Hurricane Fran was similar to that carried after Hurricane Floyd (Bales et al. 2000). Although nutrient concentrations were lower following Floyd, the prolonged high volume of water equalized the load. Bales and colleagues (2000) also found that total N and P yields (amount delivered per area of drainage basin) were highest in the Northeast Cape Fear River, compared with all of the rivers sampled in North Carolina after Floyd. We note that the Northeast Cape Fear River basin contains among the highest concentrations in the country of CAFOs per watershed (Mallin 2000).

Sparks and colleagues (1990) noted that inorganic nutrients originating from upper river drainage basins accumulate in sediments during floods and are recycled within floodplains. This evidently occurred during Hurricane Floyd, but not noticeably so during Hurricanes Fran and Bonnie. From stream stations that drain subwatersheds rich in CAFOs (stations SAR, GS, 6RC, LCO, GCO—see figure 1), our February 2000 samples yielded the highest nitrate concentrations we had seen in 5 years of sample collection at those sites (1200 to 1500 µg N per L). River flow levels had decreased from October 1999 to generally low levels in November and December 1999 and early January 2000 (figure 3). Rainfall-driven flows increased dramatically in late January and remained high in early February 2000 (figure 3), when we took samples. We suspect that the massive flooding from Floyd deposited nutrient-rich animal waste on upper floodplain areas during September and early October 1999, where it remained until January and February 2000 rains carried it back into the lotic system.

Hurricane impacts on river dissolved oxygen

Biochemical oxygen demand is often used as a measure of the organic inputs to a water body. Respiration by the resident bacteria that process this organic material can use up large quantities of dissolved oxygen when the BOD load is excessive. Dissolved oxygen (DO) in the lower Cape Fear watershed is normally at or just below the North Carolina State water quality standard of 5 mg per L during summer (Mallin et al 1999b, Mallin 2000). Thus, any further additions of BOD can drive the DO concentrations downward to levels stressful to aquatic fauna. The hurricanes have repeatedly done so in the Cape Fear River system. A general pattern has emerged, with hurricane-to-hurricane variability controlling the severity of DO reduction (figure 6). DO at station NC11, the uppermost station of the Piedmont-derived Cape Fear River, has been affected the least by hurricanes. The coastal plain–derived Black River enters the Cape Fear River above station IC (figure 2), lowering DO levels there. DO at Station IC is also

Figure 4. Aerial view of the turbid Cape Fear River joining the blackwater Black River on the North Carolina coastal plain.

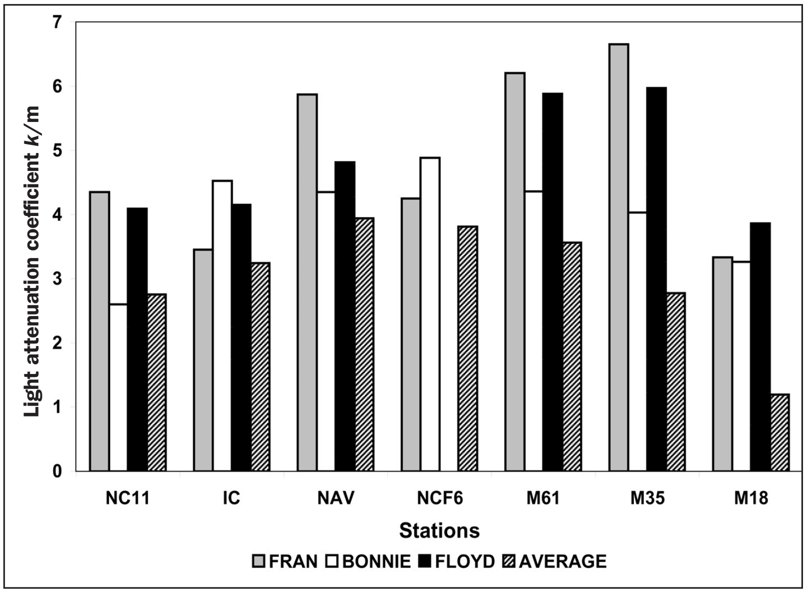

Figure 5. Light attenuation coefficient* k *at selected Cape Fear River and estuary stations after three major hurricanes, compared with long-term averages.

normally depressed by BOD loading from a large pulp and paper mill downstream of station NC11 (figure 6). The Northeast Cape Fear River has been the most affected system (figure 6), with impacts ranging from severe hypoxia to prolonged anoxia. The water at stations NCF6 and NCF117 is fresh to slightly brackish, but its downstream movement is slowed by incoming tides. Thus, natural hydrology may play a role in retaining waters with low DO for extended periods. Impacts on DO at the estuarine stations (M61 and stations downstream) have been quite severe in the upper-to-middle estuary, with notable recovery close to the ocean's influence (figure 6). Hurricane Floyd affected estuarine DO less than did Hurricanes Fran and Bonnie. Hurricanes Bertha and Dennis caused some reductions in DO, but Hurricane Irene, which occurred during late fall when cooler waters were present, caused no stressful DO levels.

We used *in situ* continuous monitors to compare DO levels in the hardest-hit tributary, the Northeast Cape Fear River, after Hurricanes Bonnie and Floyd (figure 7). Prehurricane DO levels in 1998 were measured at 5.9 mg per L, 3 weeks before Hurricane Bonnie's landfall. Six days before Hurricane's Floyd's landfall, DO levels were 3.2 mg per L, reflecting the influence of Hurricane Dennis in August 1999 (figure 7). Our posthurricane samples indicated that conditions were near anoxic within 6 days after Hurricane Bonnie's landfall and remained that way for approximately 3 weeks (figure 7). In contrast, 6 days after Hurricane Floyd's landfall, DO levels were 2.1 mg per L, and DO concentrations did not decrease to near-anoxia until about 17 days after landfall. Recovery to levels exceeding 2.0 mg per L occurred for both hurricanes by 30 days after landfall; recovery to 4.0 mg per L was achieved more rapidly after Hurricane Floyd than after Bonnie (figure 7). Thus, DO concentrations decreased much more rapidly after Hurricane Bonnie than after Hurricane Floyd and recovered more slowly, with the organisms exposed to near-anoxic conditions for a longer period. In terms of reduced DO, the extensive flooding associated with Hurricane Floyd had less impact on fish habitat than did the effects of Fran or Bonnie.

Hog waste, human sewage, and other sources of biochemical oxygen demand

What drives the severe post-hurricane anoxia and hypoxia episodes? One cause that can be considered natural is swamp water flooding into streams and rivers. In blackwater systems, low DO in swamp water is considered a result of extended contact with the organic-rich swamp floor and the heterotrophic microbial activity occurring there (Meyer 1992). Hurricane-induced rainfall and flooding flush hypoxic water out of the riparian swamp forest and into the lotic systems that drain these areas. Storm water runoff from swamps is somewhat elevated in BOD, but less so than storm water that drains areas of heavy anthropogenic influence (Mallin 2000).

The principal anthropogenic sources contributing to anoxia and hypoxia in the Cape Fear watershed are human sewage and swine waste (Mallin et al. 1999a, Mallin 2000). These are highly labile sources of BOD; unlike swamp water, they also contain high numbers of potentially pathogenic enteric microbes. Hog waste is also an extremely concentrated source of nutri-

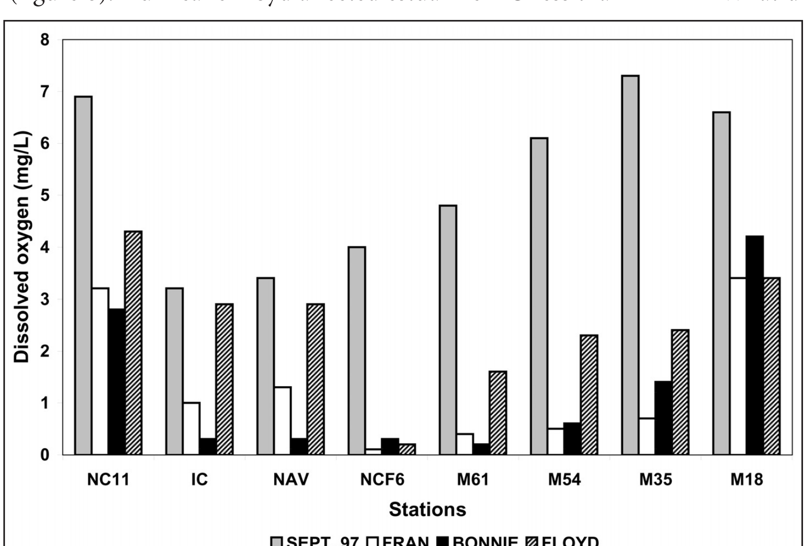

Figure 6. Surface dissolved oxygen concentrations at selected Cape Fear River and estuary stations following three major hurricanes, compared with September 1997, a nondisturbance year.

Table 3. Comparison of post-hurricane biochemical oxygen demand (mg per L) with long-term (1996–1999) averages at stations in the Cape Fear, Black, and Northeast Cape Fear Rivers.

	BOD5			
Station	**Average**	**Post-Fran**	**Post-Bonnie**	**Post-Floyd**
Cape Fear River				
NC11	1.0	1.6	1.7	1.7
AC	1.5	1.6	6.0	1.1
Black River				
B210	0.9	1.5	2.8	0.6
BBT	1.3	1.2	6.0	1.0
Northeast Cape Fear River				
SAR	NA	NA	8.7	1.2
NCF41	NA	NA	8.4	NA
NCF53	NA	NA	3.6	NA
NCF117	1.1	8.2	4.2	2.4
NCF6	NA	NA	3.6	1.7

NA, no data available.

ents, and there are lesser but still elevated amounts in human sewage (Burkholder et al. 1997, Cahoon et al. 1999, Mallin 2000).

Problems with human sewage treatment facilities are twofold. Hurricanes often cause widespread loss of electrical power. If sewage treatment plants and pump stations have no independent backup generating systems, they are often forced to reroute untreated or partially treated sewage into receiving waters (Mallin et al. 1999a). In the Cape Fear watershed, approximately 287 million liters of sewage were so rerouted after Hurricane Fran; approximately 43.7 million liters were rerouted after Hurricane Bonnie, mostly in the Northeast Cape Fear watershed. Strength of the rerouted sewage can vary considerably. For instance, the town of Burgaw rerouted 3.8 million liters of untreated waste (BOD undetermined) into a tributary of the Northeast Cape Fear River; and the city of Wilmington had to reroute approximately 38 million liters of partially treated sewage (BOD = 36 mg per L) into the lower Northeast Cape Fear River. A second major problem stems from siting facilities on river floodplains, where they are vulnerable to inundation by floodwaters. This was a particular problem after Hurricane Floyd, when some 24 municipal treatment plants were flooded; the damage was compounded by flooding in many municipal collection systems as well. The amount of sewage contacting the environment could not be estimated. The impact of sewage that is rerouted or otherwise released depends upon the degree of treatment, the physical characteristics of the receiving waters, and the amount of flow and subsequent dilution. Flooded septic systems may also contribute to river BOD. This problem, largely unquantifiable, is caused primarily by siting such systems on river floodplains.

The siting of CAFOs on river floodplains also poses major environmental problems. Large quantities of concentrated waste can enter nearby water bodies through lagoon breaches and floodwater inundation. After Hurricane Fran, there were four such major incidents in the Northeast Cape Fear River and one incident in the Black River basin (Mallin et al. 1999a). Only one major incident was reported after Hurricane Bonnie (a lagoon inundation) in the Northeast Cape Fear River basin. However, after Hurricane Floyd, there were 13 reported lagoon floodings or lagoon breaches in this watershed, mostly in the Northeast Cape Fear River basin. According to a study that compared the geographic coordinates of coastal plain CAFOs with satellite images of the area a week after Hurricane Floyd, the number of flooded CAFOs may have been much higher (Wing et al. 2002). An analysis that we conducted after Hurricane Fran indicated that the contributions of swine waste to anoxia and hypoxia well exceeded that of human wastewater, most likely because swine waste is much more concentrated than human sewage (Mallin et al. 1999a).

A highly polluting but legal practice performed after major weather incidents by swine farm operators is spraying liquid waste on rain-saturated fields. This occurred after Hurricanes Fran and Bonnie to prevent rain-swollen waste lagoons from overtopping. One week after Hurricane Bonnie, in the upper Northeast Cape Fear River near the town of Sarecta (station SAR; figure 1) our field sampling crews reported heavy spraying on saturated fields that were subsequently deluged by rains from Tropical Storm Earl. We collected BOD samples all along the river, finding the highest BOD levels (8 to 9 mg per L) just downstream of the reported spraying and lower BOD farther downstream, where sewage had been

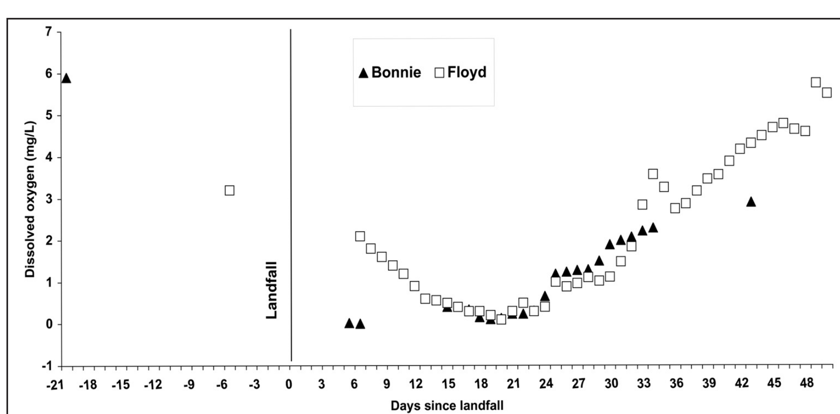

Figure 7. Surface dissolved oxygen concentrations before and after Hurricanes Bonnie and Floyd at a fixed location on the Northeast Cape Fear River (station NCF117).

rerouted (table 3). The high nutrient concentrations at station SAR after Hurricane Bonnie (table 2) also very likely reflect the effects of swine waste spraying.

The benthic fauna: Impacts and recovery

Benthic infauna, the animals living on or in river sediments, are an important trophic link between production (microalgae, detritus) and higher animals (fish, crabs, shrimp, birds). Changes in this group may reflect long-term environmental changes, including changes in the ecosystem brought about by disturbances such as hurricanes. Benthos are relatively sedentary after settlement, often constrained to an area of only a few meters throughout their life, and they can be relatively long-lived, with lifespans of several months to a year for some species. This site-specificity and longevity makes this group particularly susceptible to environmental fluctuations in the estuary: They do not escape extreme conditions, as many fish do, yet they are sufficiently long-lived to be exposed to variations in environmental conditions over time. Factors that may be particularly important influences on survival and growth of benthos include DO levels (Boesch et al. 1976, Dauer 1984, Aschan and Skullerud 1990, Mallin et al. 1999a), inputs of nutrients (Beukema 1991, Posey et al. 1995, 1999), changes in productivity on the scale of weeks or more (Posey et al. 1999), increased sedimentation, changes in sediment characteristics (Wilson 1991), and increased turbidity (Rhoads and Young 1970). As indicated above, there were significant changes in many of these physical parameters associated with the multiple hurricane events in the Cape Fear system. One might expect concordant changes in the benthic community as well.

As in most estuarine systems, density, diversity, and number of species (species richness) show some fluctuations over time in the Cape Fear estuary (figure 8) reflecting interannual variations in recruitment patterns and seasonal variations in physical conditions and predators (Boesch et al. 1976, Dauer 1984). In the Cape Fear estuary, the most noticeable variations have been in seasonal peaks in benthos density and diversity (density normally peaks after the late winter recruitment period, and diversity is greatest in spring or summer for most years; figure 8). After Hurricane Fran, there was a trend toward lower species richness and diversity, but there was no long term, estuarine-wide trend for either species richness or diversity over time with successive hurricanes. However, when sites are examined separately, there was a steady decline in species richness at the lowest estuarine site, station M31, over the 4-year period (figure 9). This site—the only one where a consistent decline was observed—is, unlike the other three sites, dominated primarily by mesohaline polychaetes such as *Mediomastus, Streblospio, Nereis,* and *Laeonereis,* with many rarer polychaetes present on some sampling dates. Many of these polychaetes (especially some of the rarer taxa) cannot maintain populations with prolonged freshwater exposure. We believe the decline in species richness over time at station M31 reflects loss of some of the more marine-oriented taxa with repeated freshwater events, combined with possible stress from hypoxia. Although recovery may eventually take place if disturbances are removed, the repeated occurrence of hurricanes in this region has been sufficiently frequent to prevent reestablishment of these populations. If land development (including addition of more CAFOs) increases in the Cape Fear River drainage basin, the magnitude of rain events needed to affect lower estuarine populations may also be expected to decline, leading to greater frequency of disturbance and possibly to more persistent effects on the community.

Total faunal abundance varied strongly over time and exhibited different magnitudes of response with different hurricane events. Declines in total density normally occur within this system during late summer and fall. Declines beyond these seasonal fluctuations occurred after Hurricanes Fran and Bertha and Bonnie, but were not strongly evident after Hurricane Floyd (figure 8). However, declines were not extreme, given background variability, and recovery of abundance to prehurricane levels occurred within weeks to months (figure 8). Quick recovery may have obscured more dramatic, acute declines at some sites, as post-hurricane sampling at some sites took place several weeks after the passage of Hurricanes Fran and Bonnie. In general, abundance was least affected at station NAV; the sharpest declines were at stations NCF6 and M54, perhaps because of the the severe decreases in DO decreases at those stations (figure 6). The individual dominant taxa showed some variability

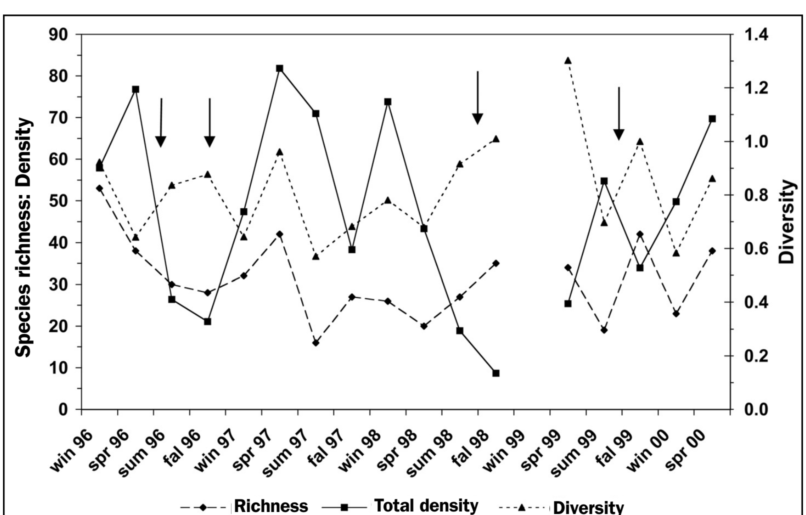

Figure 8. Patterns of benthic diversity (H′), species richness (number of taxa), and total faunal abundance (number per 225 cm²) at four sites sampled in the Cape Fear estuary. Arrows indicate timing of Hurricanes Bertha and Fran in 1996, Hurricane Bonnie in 1998, and Hurricane Floyd in 1999.

in responses to hurricanes, with insects and amphipods exhibiting some increases after hurricanes in the upper sites relative to the nonhurricane year and to summer patterns. Both groups are able to exhibit quick population responses to disturbance events because of their direct development (amphipods) or dispersal by winged adults (insects; Mallin et al. 1999a), both of which may allow initiation of recovery before the spring larval recruitment period of polychaetes or many estuarine clams. The most obvious effect at lower sites was the loss of selected taxa after hurricanes, especially the polychaete *Streblospio* and juvenile clams. Only one site, the upper estuarine site in the mainstem Cape Fear River (station NAV), showed consistency over time in dominance patterns, with oligochaetes being the most common taxa during all seasons.

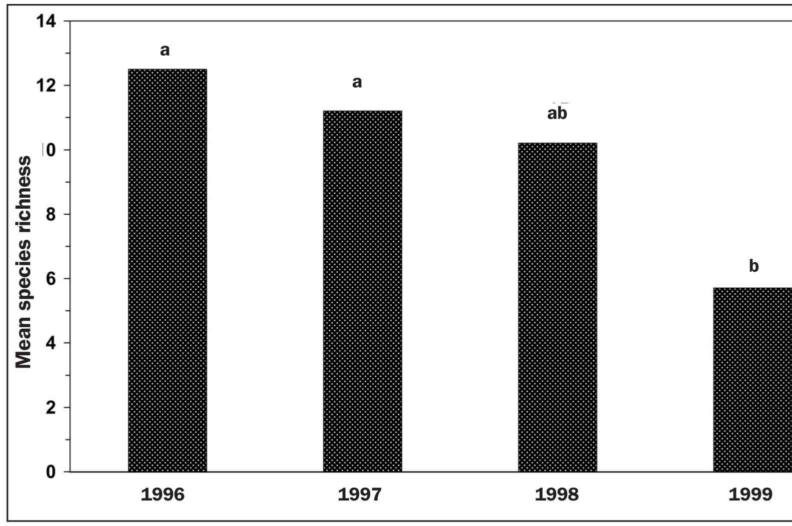

Figure 9. Annual patterns of benthic species richness at the lower estuarine site M31. Bars indicate mean annual number of species sampled, based on equal numbers of samples for each year. Analysis of variance indicates a marginally significant difference in species richness among years ($p < 0.06$) and bars labeled with the same letter (a or b) do not differ significantly (Duncan's Multiple Range Test, $p < 0.05$).

To summarize, responses by the benthic community to multiple hurricanes in the Cape Fear River system included long-term declines in species richness at the most saline site (station M31) and short-term decreases in abundance and changes in species composition at most sites. However, the benthic community appeared remarkably resilient to repeated hurricane events—few major long-term changes were apparent, probably because of the opportunistic lifestyle of the dominant species found in this estuary (Dauer 1984, Mallin et al. 1999a, Posey et al. 1999). The polychaetes *Maranzellaria* and *Mediomastus,* the dominant insect larvae, and oligochaetes are opportunistic taxa that exhibit rapid recovery in population numbers and can quickly colonize an area after a disturbance (Boesch et al. 1976, Aschan and Skullerud 1990, Whitehurst and Lindsay 1990, Posey et al. 1999). The dominance of these taxa in the Cape Fear estuary is typical of many river-dominated estuarine systems, but may also reflect the area's long history of disturbance from channelization, dredging, and upstream development and agricultural runoff. The benthic community in the Cape Fear estuary may reflect those taxa that have already undergone selection for periodic, strong disturbance events. However, the reduction of taxa in the estuary may reflect cumulative impacts from repeated hurricane disturbances.

Fish kills: The visible evidence of pollution

The most visible effects of storm-induced anoxia and hypoxia on aquatic biota are the carcasses of dead fish. Fish kills have been reported anecdotally or recorded by professionals after various storms in the past (Tabb and Jones 1962, Knott and Martore 1991). Hurricane Bertha did not cause any major fish kills. Following Hurricane Fran, there were reports of fish kills throughout the Cape Fear system, as there were in other large coastal rivers such as the Neuse (Burkholder et al. 1999). The Northeast Cape Fear River hosted a particularly large kill numbering in the thousands. This kill was centered at station NCF117, where we recorded prolonged and severe hypoxia (Mallin et al. 1999a). In the aftermath of Hurricane Bonnie, another massive fish kill, conservatively estimated at 10,000 fish, occurred at the NCF117 location. A wide variety of species were affected (Mallin 2000), including largemouth bass *(Micropterus salmoides),* catfish *(Ictalurus* spp.), chain pickerel *(Esox niger),* various sunfish *(Lepomis* spp.), and the low-DO tolerant hogchoker *(Trinectes maculates),* as well as invertebrates, including blue crabs *(Callinectes sapidus),* shrimp *(Peneaus* spp.), and crayfish *(Procambarus* spp). Smaller kills occurred elsewhere, including one in the upper Northeast Cape Fear River (station SAR; see figure 1), where high BOD was recorded after swine lagoon waste was sprayed on rain-saturated fields (table 3; Mallin 2000).

North Carolina Division of Water Quality records indicated that no large fish kills attributed to Hurricanes Dennis, Floyd, and Irene occurred statewide (NCDENR 1999). In contrast to Bonnie and Fran, Floyd produced only a small kill at station NCF117, which occurred 21 days after landfall of the hurricane, when DO concentrations in that area were the lowest (figure 7). At the peak of the kill, we counted only 18 carcasses at the site where thousands had died after Bonnie. Interestingly, the post-Floyd carcasses all appeared to be adults rather than juveniles and small fish, which were abundant on the shores after Fran and Bonnie.

Recent theory (Junk et al. 1989) suggests that regular flooding is good for riverine fish production, in part because it allows fish access to the rich food sources of the floodplain. The inundated floodplain serves as an excellent nursery ground for young fish, providing vegetative cover and substrate (Bayley 1995). The limited fish kill after Floyd consisted only of large individuals that are likely to have been confined

Table 4. Comparison of long-term (May 1995–May 2000) geometric mean fecal coliform bacterial counts (colony-forming units per 100 milliliters) at selected lower Cape Fear watershed stations.

Station	Geometric mean	Post-Fran	Post-Bonnie	Post-Floyd
NC11	20	44	131	26
AC	22	29	3,783	27
NAV	53	11	4,453	10
M54	31	228	199	11
SAR	48	38	2,588	23
NCF117	29	34	1,355	16
NCF6	41	112	2,075	7
GS	68	20	23,400	19
ROC	91	21	10,530	16
BC117	189	51	16,900	420
COL	31	9	9	9

Note: Samples were collected 11 to 14 days after Hurricane Fran, 5 to 8 days after Hurricane Bonnie, and 19 to 22 days after Hurricane Floyd.

to the channel. We suspect that, after Floyd, the smaller fish utilized the floodplain, where they had greater protection from large piscine predators that remained confined to river channels, and they also had a refuge from BOD-inducing wastes that flowed down the channels. This situation, coupled with dilution of the BOD-inducing pollutants by massive flooding upstream, kept fish kills after Hurricane Floyd to a minimum.

Thus, rain and runoff differences among the hurricanes produced varying effects on the fishery. Runoff from Fran and Bonnie concentrated hog waste, human sewage, and other pollutants in the river channels, which led to inescapable DO sags and massive fish kills. In contrast, the floodplain flooding produced by Floyd provided refuges for small and juvenile fishes, limiting mortality in this community.

The Black River and Northeast Cape Fear River systems have been restocked with hatchery-raised freshwater species after each hurricane, which helps the recovery process of this community. Estuarine species whose populations are affected by hurricane activity must depend on immigration from marine waters to repopulate affected areas. If benthic food supplies diminish because of repeated anoxia episodes, repopulation may take longer.

The microbial threat to human health

The combination of power outages, flooding, hog waste, and human sewage leads to an increased risk of human illness through contact with potentially pathogenic microbes. Human and animal wastes are rich in bacteria, viruses, and pathogens that have the potential to cause disease (Crane et al. 1983, Hill and Sobsey 1998). We were unable to collect samples for the indicator microbes (fecal coliform bacteria) until 2 to 3 weeks after Hurricanes Bertha and Fran. Concentrations (table 4) were unremarkable, suggesting that these bacteria largely settled to the sediments or were deactivated within that 2- to 3-week period, or that dilution from high flows occurred. After Hurricane Bonnie, however, we conducted extensive fecal coliform sampling within 1 week of landfall. The results indicated high concentrations in many locations, well in excess of the North Carolina water standard for human contact of 200 colony-forming units (CFU) per 100 milliliters (ml) water (table 4). Concentrations were particularly high in the Cape Fear River downstream of station NC11, at stations in the Northeast Cape Fear River, and at certain stations near sewage bypasses, such as downstream of the Burgaw Wastewater Treatment Plant at station BC117 (table 4; figure 1). Fecal coliform counts were very low at Colly Creek (station COL) a near-pristine blackwater swamp station; they were high at stations that drained areas with large numbers of CAFOs, such as Goshen Swamp (station GS), Rockfish Creek (station ROC), and station SAR (table 4). In general, fecal coliform levels were high in areas where human waste was rerouted or swine waste entered the system through breaches, inundations, or spray field runoff.

We were able to sample within 10 days after Hurricane Dennis. There were no power outage problems or CAFO discharges, and fecal coliform levels were unremarkable. Our sampling after Hurricanes Floyd and Irene also found only background levels of enteric pathogen indicators in the lower Cape Fear system (table 4); we were unable to sample for nearly 3 weeks after landfall of these two storms, again showing the likelihood of bacterial settling, deactivation, or dilution within that time frame. Sampling conducted by the North Carolina Division of Water Quality within 5 days of Floyd's landfall found fecal coliform counts exceeding 2500 CFU per 100 ml in upper Northeast Cape Fear River areas (Wrenn 1999). As noted, several swine waste lagoon inundations and overflows occurred in the Northeast Cape Fear River watershed; however, the floodwaters appeared to have spread out over the floodplain and deposited waste material there. Fecal coliforms and other pollutants were largely diluted in the floodwaters reaching the estuary. Elevated microbial pathogen abundances caused by floodwaters in the upstream areas had a deleterious effect on human health. In a survey conducted 1 month after Floyd, hospital-reported microbial-induced illnesses, including diarrhea and asthma, in flooded areas were significantly higher than in the same period in 1998 (CDC 2000). Besides spreading pathogenic microbes, floodwaters promote the growth of mold and mildew, which exacerbate symptoms of asthma (CDC 2000). Public health workers reported outbreaks of gastrointestinal and respiratory disease in residents of shelters for displaced flood victims (CDC 2000).

Post-Floyd water contamination was a different story in the Wilmington metropolitan region. Flooding led to sanitary sewer overflows (David Mayes, Wilmington Stormwater Services Department, NC, personal communication, 2000); moreover, extensive runoff probably carried bacteria-containing materials such as pet waste into urban streams. As part of another research program, we regularly sampled urban streams throughout the city for the 24-month period before

Hurricane Floyd. Our samples (collected 1 week after landfall) showed that fecal coliform counts in city watersheds reached maximum 2-year concentrations after Hurricane Floyd, with elevated counts a month later following rains from Irene (table 5).

Table 5. Comparison of geometric mean fecal coliform counts (colony-forming units per 100 milliliters) from October 1997 through July 1999 in Wilmington urban watersheds.

Watershed	Geometric mean	Post-Floyd	Post-Irene
Greenfield Lake	210	10,914	3138
Burnt Mill Creek	315	12,250	3643
Barnards Creek	132	2440	466
Smith Creek	129	1080	450

What can we expect from hurricanes?

Predicting the effects of a hurricane on an ecosystem with any degree of accuracy is tricky, especially when based on only one or even two previous events. Long-term data sets are essential for the detection and analysis of disturbance and recovery in lotic systems (Sparks et al. 1990). Our long-term data have provided us with a number of insights about the responses this anthropogenically influenced system have to hurricanes. A hurricane's direction after landfall controls not only the magnitude of river flow but also the input of light-attenuating materials (suspended sediments or organic color, or both) to the coastal ocean. If a hurricane does not directly affect developed areas, its effect on the aquatic environment will most likely be limited to somewhat greater nutrient and organic color loading and reduced river DO from swamp water inputs.

Human land use magnifies the impacts of major disturbances, such as hurricanes, on an ecosystem (Van Dolah and Anderson 1991, Tilmant et al. 1994, Mallin et al. 1999a, Goldberg et al. 2000, Naiman and Turner 2000). If a hurricane's path takes it into an area of extensive human infrastructure, a predictable effect of hurricanes is loss of electrical power, which leads to rerouting of partially treated or untreated human sewage into streams from pump stations and treatment plants. Location of CAFOs, including waste lagoons and spray fields, on river floodplains has proved to lead to excessive nutrient, BOD, and pathogen loading to watercourses draining these areas. Even in circumstances in which breaches in waste lagoons do not occur, lagoons become inundated by floodwaters and operators spray hog waste onto rain-saturated fields located on floodplains. In the Northeast Cape Fear River basin, sewage rerouting and inputs of swine waste led to high nutrient, fecal coliform, and BOD loading and severe hypoxia. Sharp decreases in benthic organism abundances and the preponderance of hurricane-induced fish kills in this tributary are the result.

The fish community appeared to be unharmed by the flooding after Hurricanes Dennis, Floyd, and Irene. Floods are a natural disturbance to which fish communities are adapted, and such disturbances may in fact be necessary for healthy community development (Junk et al. 1989, Sparks et al. 1990, Naiman and Turner 2000). However, hurricanes that cause structural damage but not extensive flooding (such as Hurricanes Fran and Bonnie) caused large fish kills, which clearly demonstrates the ecologically damaging effects a natural disturbance coupled with large-scale human alterations of a watershed.

Recommendations

Hurricanes that cause infrastructure damage lead to microbiologically unsafe conditions in water bodies for a period of days or weeks. This appears to be the case for both large river systems and smaller drainages associated with urban areas. Peak abundances of fecal pathogen indicators are most likely to be detected in samples collected within a week of hurricane landfall. We recommend that, after hurricanes, civic health authorities immediately post signs at water access points to alert citizens that contact with the water can lead to microbe-related health problems. Warning citizens away from potentially contaminated waters for at least 3 weeks after hurricanes may be a reasonable approach to mitigate the threat to human health.

The loss of electrical power associated with hurricanes demonstrates that mandatory independent backup generating systems, at least for waste treatment plants, would help alleviate loading of nutrients, BOD, and microbial pathogens into the environment. Finally, these hurricanes demonstrate the risks that human habitation of floodplains entails, with consequent destruction of property and release of pollutants from flooded septic systems. The construction of CAFOs and their spray fields on floodplains creates the potential for large-scale damage to aquatic systems.

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