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# How Hurricane Attributes Determine the Extent of Environmental Effects: Multiple Hurricanes and Different Coastal Systems

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**ABSTRACT:** The most recent spate of hurricanes to strike the United States and Caribbean (1989 to the present) has occurred when many of the affected areas had long-term water quality and biological data collection efforts ongoing, as well as special follow-up studies. These data have allowed researchers to obtain a much clearer picture of how individual characteristics of hurricanes interact with human land use to lead to various types and degrees of environmental effects. Common deleterious water quality effects associated with hurricanes include excessive nutrient loading, algal blooms, elevated biochemical oxygen demand and subsequent hypoxia and anoxia, fish and invertebrate kills, aquatic animal displacements, large scale releases of chemical pollutants and debris from damaged human structures, exacerbated spread of exotic species and pathogens, and pollution of water with fecal microbial pathogens. These and other effects may or may not occur, or occur to varying degrees, depending upon individual hurricane characteristics including category, point of landfall, wind speed, amount of rainfall, and path after landfall. Landfall in a populous area, a post-landfall trajectory upriver toward a headwater region, passage along a floodplain containing pollution sources (such as wastewater treatment plants, concentrated animal feeding operations, and septic systems), and intensity sufficient to damage power generation will all lead to increased environmental damage. We suggest a number of recommendations for post-hurricane water sampling parameters and techniques, and provide several management-oriented recommendations for better coastal and floodplain land use aimed at lessening the water quality effects of hurricanes.

## Introduction

During the late 1940s through the early 1960s there was considerable hurricane activity affecting the Caribbean and east coast of the United States (Goldenberg 2001). Following that period, there was a lull until a large increase in activity in the mid 1990s which has continued to the present. One factor that separates the present period of hurricane activity from earlier periods is the amount of associated physical, chemical, and biological data available that has been collected largely through long-term monitoring programs. These data allow scientists to assess the ecological effects of individual hurricanes on terrestrial, freshwater, and marine ecosystems.

The data show that in terms of environmental effects no two hurricanes are alike. There have been enough recent hurricanes that we can now associate certain of their characteristics (i.e., category, landfall location, trajectory after landfall, associated rainfall, the human landscape) to the type and severity of ecological damage. To illustrate these relationships we have selected a number of hurricanes that have affected southeastern coastal areas of the United States over a 16-yr period from 1989

to 2005. The list is not meant to be all-inclusive, but rather, includes hurricanes for which both meteorological and ecological data are available. The list is skewed toward Florida and North Carolina (Fig. 1) for two reasons: these states have been affected by the majority of the hurricanes striking the U.S. over this period (Dame et al. 2000), and long-term ecological databases are available in these regions for assessment and comparison of hurricane effects. Although the analyses are based on hurricanes in these areas, most of the principles also apply to hurricanes or other major storms striking mid or north Atlantic states, Central American nations, and the Caribbean. This effort is a brief synthesis of aquatic environmental effects directly resulting from hurricanes and is meant as a guide to researchers and resource managers working in a hurricane-affected area.

Most of the hurricanes discussed within (pre-2004) have some available published information pertaining to water quality. Below we provide some introductory information on the 2004 Florida hurricanes. The Charlotte Harbor watershed, on the southwest Florida coast was hit by Hurricane Charley, a Category 4 on the Saffir-Simpson Hurricane Scale on August 13, 2004 and then by Hurricanes Frances and Jeanne the following month. Hurricane Charley entered Charlotte Har-

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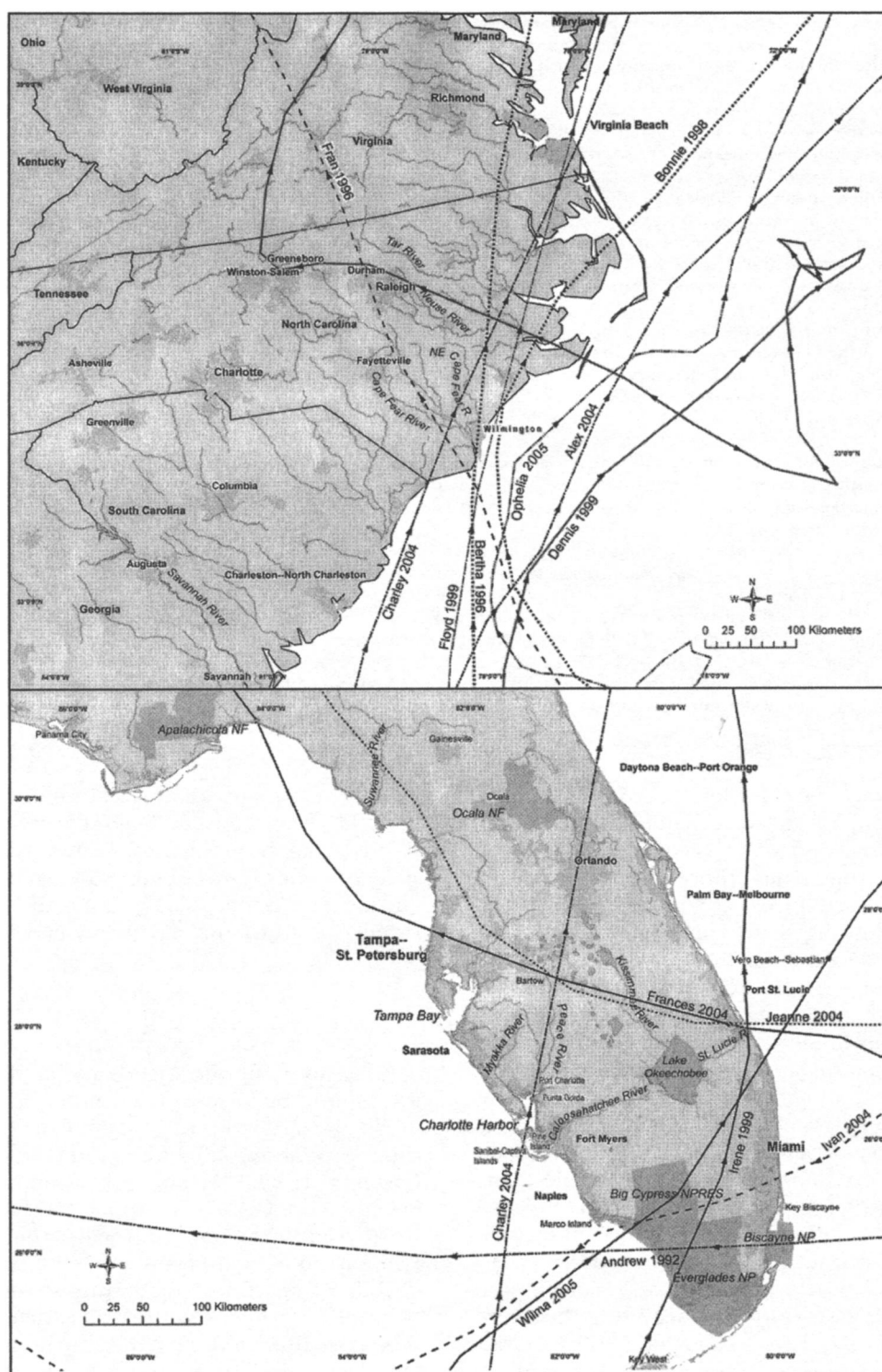


Fig. 1. Upper panel map of trajectories of selected hurricanes that made landfall on or came near the North Carolina coast (trajectories provided by NOAA NHC). Lower panel map of trajectories of selected hurricanes that made landfall along the Florida coast (trajectories provided by NOAA NHC).

TABLE 1. Websites useful in assessing immediate and long-term effects of the hurricanes discussed in this paper.

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Lower Cape Fear River Program at the University of North Carolina Wilmington ( <a href="http://www.uncwil.edu/cmsr/aquaticecology/lcfrp/">www.uncwil.edu/cmsr/aquaticecology/lcfrp/</a> ) provides long-term monthly water quality data from 1996 through 2005 from 35 stations located throughout the lower Cape Fear River watershed, as well as interpretive reports. The reports are available in hardcopy as well from the first author of this paper.
Coastal Ocean Research and Monitoring Program (CORMP) ( <a href="http://www.cormp.org/">http://www.cormp.org/</a> ) provides monthly to bimonthly water quality data on Cape Fear River plume and Onslow Bay offshore sites, including graph-making capability. This site also has Power Point presentations representing various CORMP studies on line.
The Center for Applied Aquatic Ecology at North Carolina State University website ( <a href="http://www.ncsu.edu/wq/">http://www.ncsu.edu/wq/</a> ) provides real time data from platforms located in several estuarine and freshwater locations, as well as color graphics and movies of time series of salinity, dissolved oxygen, chlorophyll <i>a</i> , nutrients, and other parameters. Site also has PDFs of many reports and papers on-line.
The North Carolina Department of Natural Resources Division of Water Quality fish kill website ( <a href="http://h2o.enr.state.nc.us/esb/Fishkill/fishkillmain.htm">http://h2o.enr.state.nc.us/esb/Fishkill/fishkillmain.htm</a> ) provides reports on kills from various causes including hurricanes and, where known, the number of deaths and the reasons for the kill.
The Monmod website ( <a href="http://www.marine.unc.edu/neuse/modmon/index.html">http://www.marine.unc.edu/neuse/modmon/index.html</a> ) provides monthly data in colorgraphic form for mid channel stations in the Neuse estuary and transect data from ferry crossings.
U.S. Geologic Survey website for the Peace and Myakka Rivers at <a href="http://waterdata.usgs.gov/fl/nwis/rt">http://waterdata.usgs.gov/fl/nwis/rt</a>
DBHYDRO at South Florida Water Management District: DBHYDRO is the South Florida Water Management District corporate environmental database which stores hydrologic, meteorologic, hydrogeologic, and water quality data. <a href="http://www.sfwmd.gov/org/ema/dbhydro/index.html">http://www.sfwmd.gov/org/ema/dbhydro/index.html</a>
The Florida Fish and Wildlife Research Institute provides a user-friendly mixed qualitative and quantitative fish kill website, sortable by probable cause, month, year, and county at <a href="http://research.myfwc.com/fishkill/">http://research.myfwc.com/fishkill/</a> .
The National Weather Service website ( <a href="http://www.nhc.noaa.gov/pastall.shtml">http://www.nhc.noaa.gov/pastall.shtml</a> ) provides data on hurricane size, trajectory, infrastructure damage, and other information.
The Cape Fear River Run website ( <a href="http://www.uncwil.edu/riverrun/">http://www.uncwil.edu/riverrun/</a> ) utilizes long-term (1996–2005) water quality data, rainfall, hurricane tracks, and land use (i.e., CAFO and WWTP locations) as an interactive teaching tool for middle and high school students.
The Charlotte Harbor Environmental Center website ( <a href="http://www.checflorida.org/WRC/HTML/index.html">http://www.checflorida.org/WRC/HTML/index.html</a> ) provides monthly water quality maps throughout Charlotte Harbor and its watershed including the Peace and Myakka Rivers.
The U.S. Environmental Protection Agency STORET website ( <a href="http://www.epa.gov/storet/">http://www.epa.gov/storet/</a> ) provides State-certified water quality data for numerous areas, arranged by state, station, and date.
The Southeast Environmental Research Center Water Quality Monitoring Network ( <a href="http://serc.fiu.edu/wqmnetwork/">http://serc.fiu.edu/wqmnetwork/</a> ) provides maps, data, and on-line reports for water quality in the Florida Keys and Florida Bay region, funded by South Florida Water Management District.

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bor passing over the barrier islands of Upper Captiva and Cayo Costa, made landfall at the City of Punta Gorda and then traveled northeast, essentially following along the course of a major tributary, the Peace River. After passing through Florida, the following day Charley made a second landfall in South Carolina as a Category 1 hurricane, continuing on through eastern North Carolina.

On September 5, 2004, Hurricane Frances made landfall on the east coast of Florida as a Category 2 and traveled west over the Kissimmee and northern Lake Okeechobee watersheds before passing over the upper Peace River basin and dropping over 25 cm of rain on some areas. On September 26, 2004, Hurricane Jeanne made landfall on the east coast of Florida as a Category 3 and traveled west in essentially the same trajectory over Florida as Hurricane Frances, dropping up to 20 cm of rain along its path. Widespread flooding along the main stem of the Peace River occurred shortly after Hurricane Charley, receded briefly at the end of August and beginning of September, and then continued well into early to mid October 2004. The Caloosahatchee River, which was artificially connected to Lake Okeechobee in the late 1800s and early 1900s, received excessive releases from the lake in September through November for flood pro-

tection of the surrounding communities due to the high levels of rainfall from Frances and Jeanne. Winds from both hurricanes Frances and Jeanne stirred up bottom sediments in Lake Okeechobee, and the freshwater releases from the lake were also laden with nutrients and suspended sediments.

## Methods

### DATA SOURCES

Long-term monitoring data that have provided insight into hurricane effects upon the environment in North Carolina are available from several institutions or programs, including the University of North Carolina (UNC) Wilmington Center for Marine Sciences, the Center for Applied Aquatic Ecology at North Carolina State University, the UNC Chapel Hill Institute for Marine Sciences, and the North Carolina Department of Natural Resources Division of Water Quality (Table 1). Long-term precipitation, river flow, and stage data are available from the U.S. Geologic Survey, and information on specific hurricanes is available from the National Weather Service.

Monthly water quality data collected at gauge stations and other sites for the Peace, Myakka, and Caloosahatchee Rivers, Florida, are available from (STORET, <http://www.epa.gov/storet/>) and for

the Caloosahatchee River from DBYHDRO (<http://www.sfwmd.gov/org/ema/dbhydro/index.html>) along with the originators of the data: the Southwest and South Florida Water Management Districts (Table 1). The Southwest Florida Water Management District began monthly sampling in the Peace River in 1997; to assess the effects of the hurricanes on water quality, a special weekly monitoring program along the Peace and Myakka Rivers began on August 27, 2004 and ended on October 29, 2004, although the collection of lab variables ceased on October 7, 2004. Monthly water quality data for the coastal Charlotte Harbor region are available from the Charlotte Harbor National Estuary Program and STORET. The Florida Fish and Wildlife Research Institute provides a fish kill hotline on their website (Table 1). Quantitative fisheries independent monitoring data for Charlotte Harbor, collected since 1989 and used to compare pre-hurricane and post-hurricane fish assemblages (Philips et al. in press), are also available from the Florida Fish and Wildlife Research Institute.

#### HURRICANE EFFECT QUANTIFICATION

Table 2 rates two types of hurricane effects: ecological and infrastructural. Ecological effects were based on a formula using five categories for river, stream, or estuary data following hurricane arrival in the affected area, with three levels of effect and a numerical value assigned to each (where sufficient data were available): high effect = 3, moderate effect = 2, and low (or no) effect = 1. For dissolved oxygen (DO), high effect has a minimum recorded DO  $<2.0 \text{ mg l}^{-1}$ , moderate effect has a minimum of  $2.0\text{--}4.0 \text{ mg l}^{-1}$ , and low effect has a minimum  $>4.0 \text{ mg l}^{-1}$  (see Diaz and Rosenberg 1995). For five-day biochemical oxygen demand (BOD5), high has a maximum  $>4.0 \text{ mg l}^{-1}$ , moderate has a maximum of  $2\text{--}4 \text{ mg l}^{-1}$ , and low has a maximum  $<2.0 \text{ mg l}^{-1}$  (see Mallin et al. 2006; Tomasko et al. 2006). For fish kills, high is officially reported numbers  $>10,000$ , moderate is officially reported between 1,000 and 10,000, and low is officially reported  $<1,000$ . For nutrient increases, high has a post-hurricane increase  $>2$  times the site average, moderate has an increase between 50% and 100% of the site average, and low has an increase  $<50\%$  of the site average. For fecal coliform bacteria (or *Escherichia coli*), high is  $>10,000 \text{ CFU (colony-forming units) } 100 \text{ ml}^{-1}$ , moderate is  $1,000\text{--}10,000 \text{ CFU } 100 \text{ ml}^{-1}$ , and low is  $<1,000 \text{ CFU } 100 \text{ ml}^{-1}$ . Ratings for the latter three parameters are based on extensive (1994–2005) fecal coliform, nutrient, and fish kill data in the Cape Fear and Neuse, North Carolina, watersheds including dry periods, rainy periods, sewage spills, and animal waste lagoon breaches; see the appro-

priate websites in Table 1 for data. Final ratings where data were available for all five categories are high (12–15 points), moderate (9–11 points), and low (5–8 points). Example: following Hurricane Bonnie a long-term monitoring station on the lower Northeast Cape Fear River showed minimum DO of zero, BOD5 of  $8.7 \text{ mg l}^{-1}$ , a fish kill exceeding 10,000, fecal coliform bacterial counts of  $23,400 \text{ CFU } 100 \text{ ml}^{-1}$ , total nitrogen (TN) of  $2,230 \text{ } \mu\text{g l}^{-1}$  (1998 average  $1,400 \text{ } \mu\text{g l}^{-1}$ ), and total phosphorus (TP) of  $540 \text{ } \mu\text{g l}^{-1}$  (1998 average of  $211 \text{ } \mu\text{g l}^{-1}$ ) for a point total of 15. In cases where all parameters were not sampled calculations were normalized to those parameters sampled, or benthic macroinvertebrate effects, if available, were used to help assess overall ecological effects. Notes are provided in Table 2 to help explain the ratings for several storms. Infrastructure effect rated by the authors is based on dollars of insured structural damage (low is  $<\$100,000,000$ , medium is  $\$100,000,000\text{--}\$1,000,000,000$ , high is  $>\$1,000,000,000$ ).

#### Results and Discussion

##### TYPES OF ENVIRONMENTAL EFFECTS

Hurricane-induced ecological damage can take many forms, including forest damage and habitat loss in terrestrial ecosystems, radical change to local vegetation, disruptions in soil nutrient cycling, wildlife mortality, and damage to urban wildlife and associated habitats. For the purposes of this overview, we will concentrate on environmental damage to riverine, estuarine, and coastal ocean aquatic ecosystems. The following is a brief overview of environmental effects that can be considered aquatic ecological damage.

##### Nutrient Loading

Nutrient loading to rivers and estuaries has been induced in natural areas by the resuspension of organic sediments and the leaching of downed tree material or exposed saturated soils such as occurred along the west coast of Everglades National Park in Florida following Hurricane Andrew (Tilmant et al. 1994). Considerable nutrient loading, contributed by storm-damaged wastewater treatment plants (WWTP) and a landfill (Tilmant et al. 1994), occurred in Biscayne Bay following that hurricane. In North Carolina, following Hurricanes Fran and Bonnie, and to a lesser extent Floyd, ammonium, TN, and TP concentrations were 2–3 times the annual means at certain river and estuary stations (Mallin et al. 2002). Much of this increased nutrient load entered the system as raw human sewage or animal waste from damaged WWTP and excessive runoff from concentrated animal feeding operations (CAFO), mainly swine and poultry (Mallin et

TABLE 2. Characteristics of various recent hurricanes and the relative effect or damage (high, moderate, low) they caused to the aquatic environment and human infrastructure. Wind speed is sustained at landfall or when hurricane was closest to the coast, and rainfall is the maximum in region where landfall occurred.<sup>1</sup>

Hurricane	Date	Category	Landfall	Storm Surge on Coast (m)	Wind Speed (km h <sup>-1</sup> )	Rain (cm)	Ecological Effect	Infrastructure Damage
Hugo	September 22, 1989	4	Charleston, South Carolina	3.9	220	20	high	high
Note: high BOD5 (at least 5.8 mg l <sup>-1</sup> ) led to near anoxic conditions in the Ashley River and to large fish kills; hypoxia and freshwater input led to extensive downstream nekton displacement.								
Andrew	August 24, 1992	4	Homestead, Florida	5.2	242	18	high	high
Note: In Florida marine waters severe hypoxia occurred along with elevated nutrients and much benthic habitat damage. In Louisiana millions of fish were killed by hypoxia, including many endangered paddlefish.								
Bertha	July 12, 1996	2	Cape Fear, North Carolina	1.6	167	12–20	moderate	moderate
Fran	September 5, 1996	3	Cape Fear, North Carolina	3–4	185	15–30	high	high
Note: high BOD5 (at least 8.2 mg l <sup>-1</sup> ) led to near anoxia and large fish and benthic kills, salinity changes led to benthic species change, and nutrient concentrations greatly increased.								
Bonnie	August 26, 1998	3	Pender County, North Carolina	2	185	20–28	high	moderate
Note: high BOD5 (at least 8.7 mg l <sup>-1</sup> ) led to near anoxia and large fish and benthic kills, salinity changes led to benthic species change, and nutrient concentrations greatly increased.								
Dennis	August 30, 1999	1	Harker's Island, North Carolina	1–1.5	83	18	moderate	low
Floyd	September 15, 1999	2	Cape Fear, North Carolina	3	167	30–45	moderate	high
Note: severe hypoxia (0.8 mg l <sup>-1</sup> ) occurred but built up only slowly, with no fish kills reported. High fecal coliform bacteria counts occurred in urban areas of Wilmington, North Carolina.								
Irene (Florida)	October 15, 1999	1	Key West, Florida	< 1	120	22–37	low	moderate
Irene (North Carolina)	October 17, 1999	2	no landfall		176	13	low	moderate
Isabel	September 18, 2003	2	Outer Banks, North Carolina	2–2.4	167	10–18	moderate	high
Note: wind seiches led to hypoxic swamp water flooding the Chowan River, causing a large fish kill.								
Alex	August 3, 2004	1	Outer Banks, North Carolina	2	157	19	low	low
Charley (Florida)	August 13, 2004	4	Cayo Costa, Florida	1–3	241	13–20	high	high
Note: high BOD5 (at least 8.1 mg l <sup>-1</sup> ) led to severe hypoxia and large, widespread fish kills, and phosphorus concentrations doubled.								
Charley (South Carolina)	August 14, 2004	1	Cape Romaine, South Carolina	2.2	130	10	low	low
Frances	September 5, 2004	2	Hutchinson Island, Florida	1.8–2.4	137	13–38	high	high
Note: severe hypoxia led to large, widespread fish kills.								
Jeanne	September 26, 2004	3	Hutchinson Island, Florida	1.2–1.8	194	25–33	high	high
Note: severe hypoxia reported in the Peace River but reported fish kills were much fewer than following Hurricanes Charley and Frances.								
Ophelia	September 15, 2005	1	Cape Lookout, North Carolina	2–4	121	25–30	moderate	low
Note: a large fish kill occurred in one location, attributed to hypoxia.								

<sup>1</sup> Meteorological data and infrastructure damage information primarily from National Oceanic and Atmospheric Administration hurricane website <http://www.nhc.noaa.gov/pastall.shtml>. Ecological and infrastructure effects are based on quantitative ratings described in the methods. Published sources of ecological data used for Table 2 include Knott and Martore (1991); Tilmant et al. (1994); Davis et al. (1996); Burkholder et al. (1999, 2004); Mallin et al. (1999, 2002); Bales et al. (2000); Paerl et al. (2001); Tomasko et al. (2006); the Lower Cape Fear River Program website ([www.uncwil.edu/cmsr/aquaticecology/lcfrp/](http://www.uncwil.edu/cmsr/aquaticecology/lcfrp/)); the NCDWQ fish kill website (<http://h2o.enr.state.nc.us/esb/Fishkill/fishkillmain.htm>); the Florida Fish and Wildlife Research Institute fish kill website (<http://research.myfwc.com/fishkill/>), the U.S. Environmental Protection Agency STORET website (<http://www.epa.gov/storet/>); and the Southeast Environmental Research Center website (<http://serc.fiu.edu/wqmnetwork/>). It should be noted that some of the hurricanes analyzed within struck Caribbean or Central American nations first, sometimes doing considerable damage, but this analysis is restricted to effects on the U.S. landscape.

al. 1999, 2002; Bales et al. 2000). Extensive nutrient loading occurred in the Neuse River estuary following Hurricane Fran (Burkholder et al. 2004), and in the Neuse estuary and Pamlico Sound following Hurricane Floyd (Paerl et al. 2001; Burkholder et al. 2004, 2006), mainly from damaged or flooded WWTP and CAFO. Along the Peace River, several domestic WWTP lost power or were damaged during Hurricanes Charley, Frances, and Jeanne, causing a reported estimate of over 4,024,000 l of partially treated or untreated wastewater discharge to the river, an underestimate due to meter malfunctions. Several lakes that encompass the headwaters of the upper Peace River are eutrophic to hypereutrophic (FDEP 2003), and much of the nutrient load from the hurricane probably arose from resuspension of these organic sediments and downed leaf and grass material. TP in the Peace River rose from  $0.98 \text{ mg l}^{-1}$  on 5 August before Hurricane Charley to  $2.20 \text{ mg l}^{-1}$  in early November following Hurricanes Charley, Frances, and Jeanne. In the marine biome unusually persistent blooms of the toxic dinoflagellate *Karenia brevis* plagued the west coast of Florida for nearly all of 2005 (Hu et al. 2006). A recent theory suggests that the 2004 hurricanes in south Florida provided the nutrients needed to support those massive blooms through a combination of increased overland runoff and increased submarine groundwater discharge of nutrient-rich water (Hu et al. 2006).

#### *Alterations in Algal Production*

Estuarine algal blooms occurred as a result of nutrient loading in areas of Biscayne Bay following Hurricane Andrew (Tilmant et al. 1994) and Pamlico Sound following Hurricane Floyd (Paerl et al. 2001; Peierls et al. 2003; Burkholder et al. 2004, 2006). In Pamlico Sound chlorophyll *a* levels reached  $23 \mu\text{g l}^{-1}$  after Hurricane Floyd, relative to 2000–2002 means of  $5\text{--}12 \mu\text{g l}^{-1}$  with the peak reflecting a dinoflagellate bloom (Burkholder et al. 2004). As mentioned above, hurricane-induced nutrient inputs possibly led to the sustained *K. brevis* blooms in 2005 along the west Florida coast (Hu et al. 2006). In riverine estuaries severe light attenuation from elevated water color and turbidity will suppress phytoplankton growth, such as in the Cape Fear system following Hurricanes Fran and Floyd (Mallin et al. 2002) and the Neuse River estuary following Hurricanes Fran and Floyd (Burkholder et al. 2004). On a smaller scale, runoff from Hurricane Charley in a normally productive tidal creek (Hewletts Creek, North Carolina; August 2004) led to severe light limitation reflected by an increase in light attenuation from  $2.0 \text{ m}^{-1}$  in July to  $5.6 \text{ m}^{-1}$  in August (Johnson 2005). This hurricane-induced light attenuation led to a decrease in

phytoplankton productivity from  $70 \text{ mg C m}^{-3} \text{ h}^{-1}$  in July to  $<10 \text{ mg C m}^{-3} \text{ h}^{-1}$  in August (Johnson 2005). It is likely that post-hurricane water color increases suppressed phytoplankton productivity in Charlotte Harbor also. Seasonal chlorophyll *a* levels exceeding  $20 \mu\text{g l}^{-1}$  are consistently observed in the tidal reaches of the Peace River during the months of July–September (Morrison et al. 1997; FDEP 2005). Chlorophyll *a* values in the tidal Peace River after Hurricane Frances ranged from 6 to  $12.4 \mu\text{g l}^{-1}$  from 9 September 2004 until weekly sampling ceased for this variable on October 7, 2004. For that same time period, color values in the tidal Peace River ranged from a maximum of 350 platinum cobalt units (PCU) on September 9 to a low of 250 PCU from September 26 until weekly sampling of this variable ended on October 7, 2004.

#### *Hypoxia*

A common effect of hurricanes is severe DO depletion (hypoxia or anoxia). Anthropogenic sources of BOD caused decreases in DO in the Wando and Ashley Rivers upstream of Charleston Harbor, South Carolina, following Hurricane Hugo in part due to failure of sewer and septic systems (Van Dolah and Anderson 1991); in Biscayne Bay from damaged and flooded WWTP and a landfill along the Black Creek Canal following Hurricane Andrew (Tilmant et al. 1994); in the Cape Fear River basin from CAFO and WWTP that were either flooded or without power after Hurricanes Fran, Bonnie, and Floyd (Mallin et al. 1999, 2002); and in the Neuse River estuary following Hurricane Fran from WWTP and CAFO as well (Burkholder et al. 1999, 2004). As an example long-term BOD<sub>5</sub> average values for the lower Northeast Cape Fear River are approximately  $1.0 \text{ mg l}^{-1}$  (Mallin et al. 2006); after Hurricane Bonnie anthropogenically influenced areas of this river showed BOD<sub>5</sub> as high as  $8.7 \text{ mg l}^{-1}$  (Mallin et al. 1999).

In the Charlotte Harbor watershed, high BOD loads in the Peace River (maximum recorded BOD<sub>5</sub> of  $8.06 \text{ mg l}^{-1}$ ) resulted in an unprecedented decline in DO levels all along the main stem of the Peace River and upper Charlotte Harbor for several weeks following the passage of Hurricane Charley (Tomasko et al. 2006). While previous research has demonstrated that the bottom waters of upper Charlotte Harbor annually experience seasonal hypoxia events as inflows from the Peace and Myakka Rivers reach over  $53$  to  $158 \text{ m}^3 \text{ s}^{-1}$  during the summer wet season and the water column in the harbor stratifies (Fraser 1997; Camp Dresser and McKee 1998), the 2004 hypoxic event following Hurricane Charley affected the surface waters of the harbor also (Tomasko et al. 2006). Several weeks after Hurricane Charley, DO levels seemed to be

recovering throughout the Peace River and Charlotte Harbor with levels rising above  $2 \text{ mg l}^{-1}$  in some instances. These levels receded to low levels again in some areas after the landfall of Hurricane Frances and continued through Hurricane Jeanne, not recovering to pre-Charley levels for 3 mo after the storms began (Tomasko et al. 2006).

An important result of severe hypoxia and anoxia are fish kills, sometimes of massive proportions. We note here that anthropogenic sources are not the only sources of hypoxia. BOD loads can enter rivers and estuaries from the leaching of dissolved organic materials from downed and submersed vegetation and organic soils, such as occurred in Everglades National Park (Tilmant et al. 1994), and by the flooding of blackwater swamps, such as in the Cape Fear River tributaries (Mallin et al. 2002). Hurricane-induced flooding or wind or barometric seiches can draw large quantities of hypoxic swamp water into river channels or estuaries, causing fish kills. This has occurred in Florida Bay following Hurricane Donna (Tabb and Jones 1962) and after Hurricanes Isabel and Ophelia in North Carolina (<http://h2o.enr.state.nc.us/esb/Fishkill/fishkillmain.htm>).

#### Fish Kills

Fish kills are environmental effects of hurricanes that are very visible to the public. Fishermen and other citizens reported large fish kills in south Florida following Hurricane Andrew (Tilmant et al. 1994) and in the Charleston Harbor region following Hurricane Hugo (Van Dolah and Anderson 1991). While large fish kills were not seen by regulators or researchers in south Florida after Andrew, following Andrew's arrival in Louisiana massive fish kills on the scale of millions were reported by agency personnel, including the loss of 29,000 endangered paddlefish (*Polyodon spathula*) (Lovelace and McPherson 1995). After Hurricane Hugo, state biologists in South Carolina reported the elimination or displacement of nekton from the Ashley River and marsh creeks due to hypoxia or osmotic stress from salinity alterations (Knott and Martore 1991). State biologists and academic researchers documented massive fish kills (10,000+) in the Cape Fear River system following Hurricanes Fran and Bonnie (Mallin et al. 1999, 2002) and in the Neuse River estuary (1,000,000+) following Hurricane Fran (Burkholder et al. 1999, 2004), due mainly to anoxia or severe hypoxia. Following Hurricane Charley, there is documentation of extensive fish kills in many areas in the state; large fish kills also occurred in Florida following Hurricane Frances, and to a lesser extent Hurricane Jeanne (<http://research.myfwc.com/fishkill/>). Following Charley, kills were numerous particularly in the upper Charlotte Harbor and Peace River

(<http://research.myfwc.com/fishkill/>). In the two latter areas the primary fish affected were *Micropterus salmoides*, *Lepomis macrochirus*, *Paralichthys albigutta*, *Lutjanus griseus*, *Arius felis*, *Epinephelus itajara*, and *Centropomus undecimalis* (Stevens et al. 2006). Stevens et al. (2006) documented a dramatic drop in the normal summer fish abundance in the tidal Peace River and a shift to resilient freshwater, estuarine, and nonindigenous species, some of which are capable of respiring at the water's surface. Fish abundances and assemblages in the nearby tidal Myakka River, located 8 km from the Peace River, were similar to normal summer catches, and by September 10 (28 d post-storm), fish assemblages in the tidal Peace River resembled normal summer assemblages. Champeau (unpublished data) also reported that the abundance of sport fish, such as *M. salmoides*, decreased in the Peace River, but appeared unaffected in the nearby Myakka River. *M. salmoides* were not collected in sampling efforts until 6 mo post-storm, and those collected were adults, indicating that some found areas of refuge within floodplains and tributaries less affected by the hurricanes. Stevens et al. (2006) noted a large increase in the number and size of *Farfantepenaeus duorarum* following Hurricane Charley and that shrimp landings reported to the state's fisheries-dependent monitoring program doubled compared to those in previous years. In a similar situation, the commercial catch of shrimp increased significantly in Pamlico Sound following Hurricane Floyd (Burkholder et al. 2004).

#### Benthic Fauna

Benthic dwelling organisms, especially sessile animals are at particular risk due to poor water quality caused by hurricanes. Mortality among benthic organisms due to hypoxia and benthic community transformations caused by salinity changes have been documented in the Cape Fear River estuary following Hurricanes Bertha, Fran, and Bonnie (Mallin et al. 1999, 2002). Longer-term effects have been seen as well; after a series of hurricanes (Bertha, Fran, Bonnie, and Floyd) a significant decrease in benthic species richness occurred from 1996 to 1999 in the Cape Fear Estuary (Mallin et al. 2002). In the Ashley River and nearby tidal creeks following Hurricane Hugo, high mortality due to extreme hypoxia occurred among decapod crustaceans, including blue crab (*Callinectes sapidus*), penaeid shrimp and palaemonid shrimp (Knott and Martore 1991). In addition to hypoxia induced mortality, the freshet associated with Hurricane Hugo led to downstream displacement of decapod crustaceans (and fish) as they sought saltier water (Knott and Martore 1991).



### *Chemical Pollution*

Hurricane effects to human structures can cause the release of various types of chemical pollutants and widespread debris. This was demonstrated in Biscayne Bay following Hurricane Andrew, when large amounts of petroleum oil and motorboat fuel were seen in the vicinity of marinas. This pollution was attributed to leakage from sunken motorboats and from a collapsed boat storage facility (Tilmant et al. 1994). During Hurricane Floyd an industrial waste storage lagoon filled with chromium waste was breached, releasing its material into the Cape Fear River. Wood, aluminum siding, portable toilets, insulation materials, pool cages, trash cans, sunken boats, and other debris from anthropogenic sources were found along the shoreline throughout Charlotte Harbor and its tributaries subsequent to Hurricane Charley. Unlike natural forest debris, leachate from anthropogenic waste may cause substances toxic to aquatic fauna (e.g., metals, fungicides, petrochemicals) to enter the water or sediments.

### *Nonnative Species*

Hurricanes can increase the spread of exotic species and pathogens. In Florida citrus canker disease caused by the bacterial pathogen, *Xanthomonas axonopodis* pv. *citri*, is spread by wind-driven rain, contaminated equipment and personnel, movement of infected plant material, and other methods. This disease is of grave concern to the state's \$8.5 billion citrus industry as all citrus trees within 580 m of a tree infected with the disease must be destroyed and the area quarantined for a minimum of 2 yr (DOACS 2005). The range of this disease affecting the Florida citrus industry expanded as much as fourfold as a result of the 2004 and 2005 hurricane seasons (Irey et al. 2005) to the 3,533 km under quarantine as of October 2005 (DOACS 2005).

### *Microbial Pathogens*

An environmental effect of immediate concern to human health is the loading of microbial pathogens as fecal bacteria, protozoans, and viruses into receiving waters during and following hurricanes. Total coliform bacteria counts were elevated in the Black Creek Canal feeding Biscayne Bay following Hurricane Andrew (Tilmant et al. 1994). Fecal coliform bacteria counts were as high as 23,400 CFU 100 ml<sup>-1</sup> following Hurricane Bonnie in the Cape Fear and Northeast Cape Fear Rivers (Mallin et al. 2002), and as high as 2,000 CFU 100 ml<sup>-1</sup> in the Neuse River estuary following Hurricane Fran (Burkholder et al. 2004) from WWTP bypasses and CAFO-related incidents. Urban lakes and streams in Wilmington, North Carolina, were affected by

unusually high fecal coliform counts of 12,250 CFU 100 ml<sup>-1</sup> following Hurricanes Floyd and Irene, contributed by sanitary sewer overflows and excessive urban runoff (Mallin et al. 2002). In the Charlotte Harbor region, fecal and total coliform bacteria levels in the Peace River on 27 August 2004, the date of first sampling after Hurricane Charley, ranged from 40 to 95 CFU 100 ml<sup>-1</sup> and 90 to 620 CFU 100 ml<sup>-1</sup>, respectively. Enterococci levels ranged from 110 to 830 CFU 100 ml<sup>-1</sup> along the Peace River. After WWTP malfunctions along the Peace River due to Hurricanes Frances and Jeanne, much higher measurements were collected by WWTP staff, whereby fecal coliform bacteria were too numerous to count. As a reference, both North Carolina and Florida use a fecal coliform bacteria standard of 200 CFU 100 ml<sup>-1</sup> as a recreational freshwater standard. Excessive growths of mold following flood damage also can severely exacerbate human respiratory ailments.

### *Other Environmental Issues*

Other aquatic environmental problems that potentially may occur include loss of submersed aquatic vegetation, damage to coral reefs, mortality among threatened or endangered species, long-term damage to sport or commercial fisheries, damage to bird and sea turtle nesting sites, and other habitat loss. Marine debris like derelict crab and lobster traps may continue to deplete these resources as well as harm other marine organisms, such as sea turtles. In Charlotte Harbor, Hurricane Charley created a small pass through Upper Captiva Island, and in several isolated areas, downed trees dragged by high winds dredged seagrass beds. The authors of this paper do not consider coastal erosion to be ecological damage, or a negative environmental effect. Beach erosion, dune movement, the opening and closing of inlets, and creation of overwash fans are phenomena that are part of the natural shoreline evolution, especially for barrier islands (Young et al. 1999). We will briefly discuss shoreline effects later, as they are a common measure of a hurricane's overall effect.

## HURRICANE ATTRIBUTES AFFECTING ENVIRONMENTAL EFFECTS

### *Landfall Location*

The location of hurricane landfall is of paramount importance to the local citizenry as typically winds are strongest before the hurricane loses strength as it travels over land (Robinson 2005). If the storm surge arrives on the normal high tide, severe damage to coastal human infrastructure can occur. From a water quality standpoint, areas that are heavily populated also contain more human-

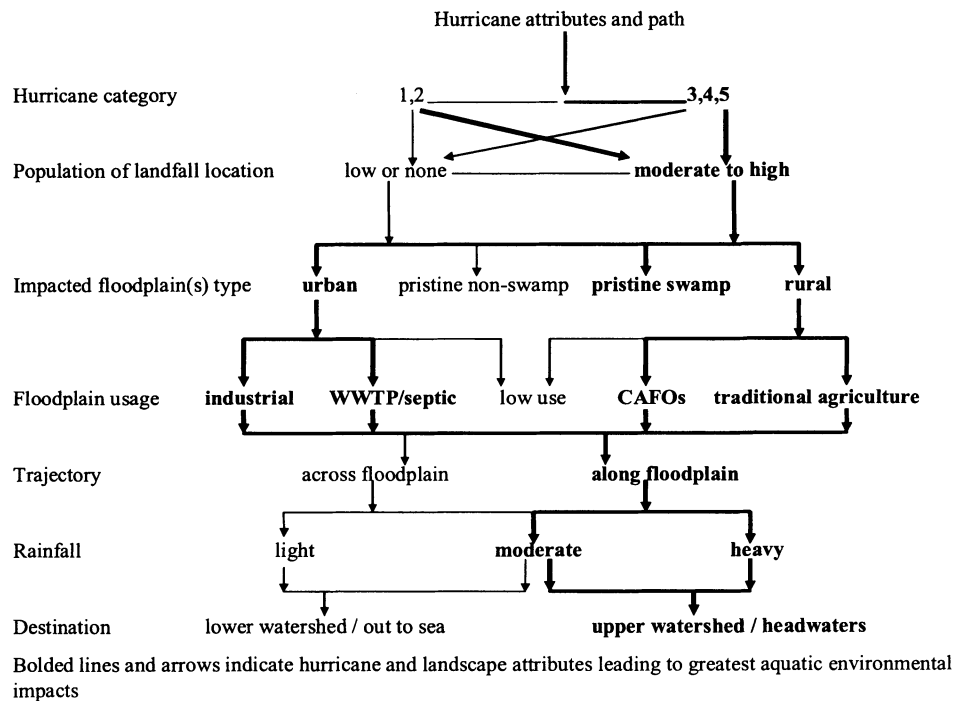


Fig. 2. Conceptual diagram of how hurricane and landscape attributes combine to inflict the most severe effects to the aquatic environment.

generated pollutants, either stored for future use, currently in use, or as waste products (Fig. 2). As mentioned, in the heavily populated Biscayne Bay area Hurricane Andrew caused the release to the environment of numerous pollutants from a landfill, WWTP, and sunken or stored boats (Tilmant et al. 1994). On the far end of the spectrum Hurricane Alex primarily affected North Carolina's Outer Banks (Fig. 1), and while it caused flooding and shoreline erosion on Ocracoke Island, there was little or no environmental damage such as fish kills, hypoxia, and releases of fecal bacteria (Table 2).

The coast of Charlotte Harbor is surrounded largely by an extensive conservation lands buffer system of over 21,600 hectares of mangrove, salt marsh, freshwater wetland, and upland habitats (Corbett et al. 2005), which provided invaluable protection against further deleterious effects to the environment and municipalities near Hurricane Charley's landfall. Had the storm made landfall on a more urbanized system than Charlotte Harbor, such as Sarasota or Tampa Bay to the north (Fig. 1), the cost of insured damages alone for Florida would have been much greater than the \$6.8 billion estimate.

#### *Trajectory Following Landfall*

While landfall location plays an important role in the amount of environmental damage a hurricane

may cause, the ultimate extent of such damage can be greatly magnified by the trajectory or path of the hurricane following landfall. Trajectories following a tributary or taking a hurricane inland toward upper watersheds will cause much higher pollutant loading (nutrients, BOD, chemical contaminants, fecal bacteria) than trajectories that pass largely over forests or even back out to sea. Hurricane Hugo came ashore in the Charleston, South Carolina area, causing great infrastructure damage, then proceeded inland (upriver) and caused severe hypoxia and salinity changes in the upper Ashley and Wando Rivers, and subsequent defaunation of nekton in affected areas (Knott and Martore 1991; Van Dolah and Anderson 1991). Hurricane Bertha came ashore in Wilmington, causing considerable localized damage, but then proceeded due north out of the basin (Fig. 1), with low to moderate ecological effect to the Cape Fear watershed (Mallin et al. 2002). Later that year (Table 2) Hurricane Fran also came ashore at Wilmington but headed inland upstream along the Cape Fear River, doing massive damage even in upper watershed cities such as Raleigh and Greensboro (Fig. 1). The loading of pollutants, particularly BOD from human sewage and septic facilities and animal waste from CAFO, was severely damaging to both the Cape Fear River ecosystem (Mallin et al. 1999) and the Neuse River ecosystem (Burkholder et al. 1999, 2004). In an

example of a trajectory away from urbanized or agricultural landscape, Hurricane Andrew (following landfall in the urbanized Biscayne Bay region) proceeded to pass through Everglades National Park (Fig. 1), but its passage had no notable short-term effect on freshwater nutrient levels in the Park (Roman et al. 1994). Good sport fishing was reported in the Park following the storm (Tilmant et al. 1994). Hurricanes Frances and Jeanne made landfall on the Florida east coast and followed similar trajectories over the Florida panhandle, passing over the north Lake Okeechobee and Kissimmee and Peace Rivers' watersheds (Fig. 1). These hurricanes stirred up bottom sediments of the lake and dropped over 20 cm of rainfall along their course, causing flooding in the Peace River and catastrophic freshwater releases from the lake into the Caloosahatchee and St. Lucie Rivers on the east coast for several weeks. Hurricane Wilma in 2005 made landfall off Marco Island, Florida, and passed over southern Florida, while dropping large amounts of rainfall into the Kissimmee River watershed. Once again, the Caloosahatchee and St. Lucie Rivers received tremendous releases as a result of elevated water levels in Lake Okeechobee. As mentioned, coastal nutrient loading from sustained freshwater release (surface and groundwater) likely helped support extensive *K. brevis* blooms in 2005 (Hu et al. 2006).

#### *Intensity, Wind Speed, and Hurricane Category*

Hurricane category is defined by central pressure, storm surge, and wind speed - the most relevant attribute to this discussion: category 1 = 120–152 km h<sup>-1</sup> (75–95 mi h<sup>-1</sup>), category 2 = 153–176 km h<sup>-1</sup> (96–110 mi h<sup>-1</sup>), category 3 = 177–208 km h<sup>-1</sup> (111–130 mi h<sup>-1</sup>), category 4 = 209–248 km h<sup>-1</sup> (131–155 mi h<sup>-1</sup>), and category 5 = >249 km h<sup>-1</sup> (> 155 mi h<sup>-1</sup>). Damage from hurricanes increases exponentially with wind speed (NOAA AOML 2005); the higher the wind speed is on arrival, the more damage is likely to power grids. Hurricanes of category 5, 4, or 3 will lead to power failures, and hurricanes of category 2 and 1 may do so, depending on the hurricane path and speed. Loss of power can cause sewage pump stations to fail and raw sewage to spill into the nearby environment, and loss of power can cause WWTP to malfunction or cease operations as well. Operators are forced to bypass raw or partially treated sewage into receiving waters; in the Cape Fear River watershed approximately 287 m l of sewage were rerouted following Hurricane Fran (Mallin et al. 1999), 44 m l were rerouted following Hurricane Bonnie (Mallin et al. 2002), and over 4 m l of partially treated and untreated waters spilled into the Peace River basin subsequent to

Hurricanes Charley, Frances, and Jeanne. WWTP with backup generating systems can avoid discharging this pollution, unless the backup systems fail as well.

#### *Size of Hurricane*

The size of a hurricane is measured by the radius of either 15 m s<sup>-1</sup> winds or the outer closed isobar (National Hurricane Center) and can make a tremendous difference on the areal extent of environmental effects. The radius of maximum sustained winds in Hurricane Charley was only 16–24 km wide (NWS 2004), while by comparison hurricane force winds during Hurricane Katrina extended 200 km from the eye of that storm (NCDC 2005). On Florida's west coast, Hurricane Charley followed a course over the northern tip of Pine Island and central Charlotte Harbor before making landfall again at Punta Gorda on the east wall of the Harbor and moving up the Peace River (Fig. 1). The cities of Punta Gorda and southern Port Charlotte were devastated with widespread structural damage, and mangroves and other vegetation directly within the hurricane's path suffered extensive mortality. Cities north of Port Charlotte experienced relatively minor structural damage, and mangroves and other flora along the Harbor's upper west wall and southeastern Charlotte Harbor suffered relatively little to no mortality. In contrast to Charley, Hurricane Floyd was a vast storm that dropped large amounts of rain throughout the Coastal Plain, leading to widespread flooding throughout eastern North Carolina (Bales et al. 2000; Wing et al. 2002).

#### *Time of Landfall*

Hurricanes arrive in the southeastern U.S. and Caribbean between June and December (Robinson 2005). Air and water temperatures and the amount of solar radiation can effect hurricane aquatic ecological damage in at least two ways. In mid summer evapotranspiration of water from the ground and vegetation is much greater than during cooler months; e.g., in North Carolina the evapotranspiration rate in July is twice that of October (Robinson 2005). Flooding may be lessened in early season storms because more water is likely to be lost to the atmosphere than in cooler months. Water temperature directly affects the ability of the water to hold DO, with warmer water less able to retain DO than cooler water. Because of this, hurricane induced hypoxia may be stronger from summer storms than from late fall storms when the water is cooler. In the Cape Fear area there are on average 17 d in July when the air temperature exceeds 32°C, whereas in September that number drops to five and in October it is less than one (Robinson 2005).

In 2004 in the upper Cape Fear Estuary, July water temperatures were approximately 30°C versus October temperatures of approximately 23°C ([www.uncwil.edu/cmsr/aquaticceology/lcfrp/](http://www.uncwil.edu/cmsr/aquaticceology/lcfrp/)). DO under saturating conditions in October would be approximately 8.5 mg l<sup>-1</sup>, versus 7.5 mg l<sup>-1</sup> in July; during July any additions of BOD would more rapidly depress DO to hypoxic conditions. Tides and water levels at the time of landfall can increase storm surge and erosion rates if a hurricane makes landfall at high tide. Hurricane Charley made landfall on a falling tide, 2 h after high tide at Punta Gorda, where storm surge reached a maximum of 2 m (USACE 2006). Storm surge was higher in the southeastern portion of the storm's path, whereby storm surge reached 3 m and was reported to have overtopped Fort Myers Beach in some places.

#### *Rainfall: A Double-edged Sword*

Very heavy rainfall in an urban area can lead to severe surface water contamination by fecal microbes from several sources (Fig. 2). Storm water runoff is a well-known source of microbial contamination and hurricane-induced runoff will magnify this effect. Some communities use combined sanitary and storm drain systems that become flooded during heavy rainfall, causing overflows of sanitary sewer line contents (NRC 1993). Sanitary sewer lines themselves may flood or back up due to excessive rains or failures at pump stations, exposing surface water bodies to microbial pollution, as in urban streams of the Wilmington area following Hurricanes Floyd and Irene (Mallin et al. 2002). In addition to these urban sources of pollution, flooded septic systems in saturated soils along river floodplains will add nutrients, BOD, and fecal bacteria to surface waters (Knott and Martore 1991; Mallin et al. 1999). In rural areas upstream of Wilmington, high rainfall from Hurricanes Fran, Bonnie, and Floyd caused flooding to CAFO that added the same types of pollutants to nearby and downstream surface waters (Mallin 2000). When hurricane-induced rainfall is added to already-saturated soils, then very damaging floodwaters can be expected. An example of this is the extensive flooding following Hurricane Floyd, which followed heavy rains from Hurricane Dennis (Bales et al. 2000).

Flooding increases the dispersal of certain exotic species to different areas within a given watershed. Hurricane-induced flooding in the Cape Fear River basin allowed *Ctenopharyngodon idella* to escape from ponds where they had been stocked to control excess vegetation and enter the main river ([www.uncwil.edu/cmsr/aquaticceology/lcfrp/](http://www.uncwil.edu/cmsr/aquaticceology/lcfrp/)); fortunately, *C. idella* had been sterilized before introduction to the ponds and have not formed

a reproducing population in the river. Stevens et al. (2006) documented a dramatic drop in the normal summer juvenile fish species abundance in the tidal Peace River in southwestern Florida during late August and September 2004 subsequent to Hurricanes Charley, Frances, and Jeanne and a shift to freshwater and exotic species.

On the other hand, extreme flooding is a natural, although rare, occurrence and may cause little damage to aquatic organisms. Prolonged, high rainfall floods river floodplains, allowing fish that are normally confined to river channels access to the floodplain where they can find shelter among terrestrial vegetation and an abundance of food sources. Flooding occurs annually along tropical floodplains such as the Amazon River (Junk et al. 1989), where the ecosystem is adapted to this pulse disturbance. In developed nations such as the U.S., most rivers are now regulated and no longer annually flood; yet fisheries still normally do not suffer ill effects when flooding does occur (Bayley 1995). Despite the massive flooding in North Carolina, following Hurricane Floyd there were no large fish kills recorded in the Cape Fear, Neuse, or other river basins (NCDENR 1999; Mallin et al. 2002; Burkholder et al. 2004), in contrast to massive fish kills verified following Hurricanes Fran and Bonnie (Burkholder et al. 1999; Mallin et al. 2002). In Pamlico Sound, there were no negative effects of Hurricane Floyd on shrimp or bivalve mollusk landings, although *C. sapidus* landings declined through a combination of storm effects and overfishing (Burkholder et al. 2004). In southwest Florida, monitoring of the Peace River did not detect *M. salmoides* until 6 mo after the passage of Hurricane Charley, and those that were collected were adults, indicating that the river's floodplains and smaller tributaries were a source of refuge (Champeau unpublished data).

Dilution caused by flooding can lessen pollutant effects. Hurricane Floyd caused massive flooding throughout the coastal plain of North Carolina (Bales et al. 2000; Paerl et al. 2001; Mallin et al. 2002; Burkholder et al. 2004). Pesticide concentrations following Hurricane Floyd in the North Carolina Neuse and Tar Rivers were lower than concentrations previously measured under normal flow conditions, indicating dilution by the floodwaters (Bales et al. 2000). Compared with Hurricane Fran, DO concentrations were higher and nutrient concentrations much lower in the Cape Fear (Mallin et al. 2002) and Neuse (Burkholder et al. 2004) estuaries following Hurricane Floyd. Besides dilution, retention of nutrient-rich floodwaters on a floodplain for extended periods may enhance loss of nitrogen through denitrification, plant uptake, microbial uptake, or soil adsorption. Hurricane

Floyd caused a massive, darkly stained freshwater plume to enter the coastal ocean at Cape Fear and flow south into South Carolina marine waters. Dilution by the vast amounts of freshwater, along with floodplain retention, had reduced pollutant levels to the extent that nutrients and fecal bacteria in the plume remained at background concentrations, and DO concentrations in the plume remained above  $3.0 \text{ mg l}^{-1}$  on all occasions sampled (Cahoon et al. 2001).

#### *Speed of Passage*

A fast moving hurricane may bring violent destruction to infrastructure and subsequent release of pollutants to the environment, but some other attributes may not be as severe. Hurricane Andrew was powerful and destructive, yet it moved so fast ( $50 \text{ km h}^{-1}$ ; Pimm et al. 1994) that little shoreline erosion occurred to area beaches, mangrove swamps, and the shallow seafloor (Tilmant et al. 1994). Hurricane Dennis spent 4 d offshore of the Outer Banks of North Carolina, pounding the coast through several high tides, causing heavy coastal erosion and shoreline retreat (Young et al. 1999).

#### *Human Development of River Floodplains*

Human use of river floodplains is a major factor in determining hurricane-induced pollution to a river or estuary. This is obvious in an extreme situation such as Hurricane Katrina in 2005 where large urban areas that were constructed below sea level suffered massive destruction. In North Carolina some 24 municipal WWTP were flooded following Hurricane Floyd (Mallin et al. 2002). More common situations involve floodplains used for agriculture (including CAFO) and suburban and rural communities. North Carolina's massive swine production industry includes many CAFO located on floodplains. CAFO include long, low, barn like structures housing hundreds to thousands of animals in close confinement, open outdoor ponds where the massive amounts of animal waste are pumped (called animal waste lagoons), and fields where the liquid waste lagoon supernatant is sprayed periodically (Mallin 2000). In extreme flood situations hog houses themselves may be flooded with consequent mass mortality, as occurred following Hurricane Floyd on the North Carolina's Coastal Plain (Mallin et al. 2002; Wing et al. 2002). In an analysis comparing the Global Positioning System (GPS) coordinates of North Carolina Coastal Plain CAFO locations on a map with satellite images of the area a week after Hurricane Floyd, Wing et al. (2002) estimated that as many as 237 swine CAFO had coordinates within the satellite-based flooded area. More commonly,

CAFO pollute nearby waterways during and after hurricanes such as Fran and Bonnie through lagoon breaches, overtopping, and operators spraying waste onto waterlogged spray fields to avoid overtopping (Mallin et al. 1999, 2002; Mallin 2000).

Of course, traditional agricultural fields will undergo increased runoff and cause elevated inputs of organic nutrients and carbon, suspended sediments, and pesticides to nearby waterways (Fig. 2). Humans build houses on river floodplains, and in rural areas these often include septic systems. In the Ashley River floodplain septic systems flooded after Hurricane Hugo (Knott and Martore 1991) as they did along the Northeast Cape Fear River following Hurricanes Fran and Bonnie (Mallin et al. 1999, 2002). In the floodplain of the Northeast Cape Fear River several local WWTP were affected by power losses or flooding, causing rerouting (bypassing) of raw or partially treated human sewage into river tributaries, greatly increasing nutrients and BOD.

During hurricanes, human structures on floodplains also become sources of debris. Large debris such as wood, aluminum, insulation, and roofing tiles from damaged structures and sunken vessels affect the environment by degrading habitat or adding chemical pollutants to the receiving water bodies of hurricane-affected areas. Some of this debris becomes imbedded within shoreline habitat and is difficult to remove without causing further harm to the shoreline vegetation or becomes buried within the bottom sediments and difficult to locate. Efforts to eliminate natural debris, such as downed trees, along rivers to ease flooding and aid navigation after a hurricane have the potential to destroy snag-and-root habitats important for fish and macroinvertebrates. There were incidents of all the above within the Charlotte Harbor watershed after Hurricanes Charley, Frances, and Jeanne in 2004.

### RECOMMENDATIONS

#### *Land Use Recommendations*

After the record-setting hurricane seasons of 2004 and 2005 and with an increase in Atlantic hurricane activity predicted to last the next 10–40 yr (NOAA 2005), land-use decision makers need to refocus their efforts towards coastal hazard mitigation. Obviously controlling the magnitude, path, or rainfall of a hurricane is beyond our control, but humans can limit some of the environmental effects of a given hurricane with some precautionary measures. Natural shoreline buffer systems should be preserved and setbacks for coastal development increased. Since power outages are an important key to properly functioning WWTP, it should be imperative that WWTP, both large and small, be equipped with backup power generation systems

not dependent upon the grid. These backup systems should be functional for at least several days. The consequences of power failures to WWTP and subsequent rerouting of raw sewage were clearly demonstrated following Hurricanes Hugo, Fran, Bonnie, and Charley.

Hurricanes demonstrate the environmental risks involved in building along coasts and river floodplains (Fig. 2). Human structures are damaged and destroyed causing widespread release of pollutants and during very severe weather even regulated rivers inundate floodplains. As mentioned within, septic systems become flooded and add pollution to the rivers and estuaries. WWTP situated on floodplains run the risk of flood damage in addition to power outages. All WWTP spills from either power outages or overflows should be reported to state and local agencies and publicized to local citizens for health safety concerns; these data should be freely made available to researchers assessing environmental effects from WWTP failures as well. And clearly, situating CAFO on floodplains provides reservoirs of pollutants including pathogenic fecal microbes, nutrients, and BOD that can reach waterways through lagoon breaches, overtopping, or outright flooding, as occurred in North Carolina following Hurricanes Fran, Bonnie, and Floyd. Construction of impervious surfaces (housing, roads, drives, parking lots, industrial-scale hog and poultry houses) on floodplains reduces available green space for pollution absorption and facilitates increased runoff of pollutants into water bodies. What should be encouraged on floodplains (and uplands) are the protection of natural wetlands and the construction of installed wetlands. Wetlands serve many purposes that are relevant to hurricane induced problems, such as mitigating storm water runoff, aiding in flood control, absorbing nutrients and other pollutants that otherwise directly enter the rivers and estuaries, and buffering of storm surges (the massive upriver storm surge from Hurricane Katrina near New Orleans has often been cited as being facilitated by wetland losses in the Mississippi delta (St. Pé personal communication)). Preservation of creek and river sinuosity and natural shorelines should be encouraged. Again using Hurricane Katrina as an example, marsh channelization and construction of canals, as well as the construction of river levees upstream, accelerated the storm surge and flooding effects of the storm.

#### DATA COLLECTION FOLLOWING HURRICANES

What should scientists be prepared to look for immediately following a hurricane? From a human health standpoint widespread sampling of fecal bacteria (fecal coliform bacteria, *E. coli*, or Enterococci) should be initiated. Results take 24 h but the

data will provide public health officials with locations of water areas that should be avoided by the public or where shellfishing should be closed. Scientists and the regulatory community can use these data to assess sources of pollution, such as failing WWTP, sewer mains, pump stations, or CAFO. Because of localized power outage problems a mobile laboratory equipped to sample such pathogen indicators would be a useful acquisition by state governments. Since hypoxia and anoxia are hurricane symptoms with multitrophic level consequences, sampling of DO and BOD should be prioritized. While the former parameter will key researchers and regulators to areas where fish and invertebrate kills may be expected, the latter will help pinpoint source areas of the BOD load. Nutrients, and especially chlorophyll *a*, are useful long-term measures to assess ecosystem effects such as algal blooms or severely restricted algal production. If the hurricane's landfall or path brings damage to toxic chemical storage facilities (such as petrochemicals, pesticides, industrial chemicals) then sampling for these parameters (while expensive!) is an option as these can be both public health and ecosystem health issues.

#### LONG-TERM DATA USAGE

Collection of long-term data can be extremely valuable to researchers and regulators in terms of ecological analyses of major storm effects or other events such as droughts or pollutant spills. These data provide seasonal backgrounds against which hurricane and post-hurricane data can be compared. In the Cape Fear River system long term dissolved oxygen records show normal summer decreases in non-hurricane years but very pronounced drops during hurricane years and years in which major pollution incidents occurred (Mallin 2000). Other pollution-oriented data such as phosphorus or BOD<sub>5</sub> can be overlaid as well on such graphs. The collection of key data before, during, and after storm events can be enhanced to a finer scale (hours or less) by using real-time remote monitoring systems (RTRM). These solar powered platforms normally gather physical-chemical data including water temperature, pH, salinity, turbidity, and DO, as well as meteorological data (Glasgow et al. 2004). Real time meteorology data provide advance warning of storm properties on a very localized scale, while the water quality instruments indicate trends and present conditions hazardous to wildlife (such as rapidly decreasing DO or changing salinity) in addition to providing a continuous record for given parameters. Examples of such RTRM data for the hurricane-prone Neuse River Estuary can be found at: <http://www.ncsu.edu/wq/>.

Long-term data are not only useful to researchers, but are available to regulators as well. Regulators need these data since they are often officially responsible for explaining ecological effects of hurricanes to the public; such data have potential legal ramifications in terms of assessing pollution sources. On a more positive note, long-term data in relation to major storm passage can be used to provide excellent teaching tools. The Cape Fear River Run website (<http://www.uncwil.edu/riverrun/>) uses long-term water quality data, rainfall, hurricane tracks, and land use (i.e., CAFO and WWTP locations) as an interactive teaching tool for middle and high school students.

Our analyses were based on hurricanes in the southeastern U.S., but the results are applicable to major storms elsewhere. In the mid and north Atlantic States, major effects to water quality have been documented from Tropical Storm Agnes in Chesapeake Bay (Boesch et al. 1976) and Hurricane Bob in the Cape Cod area (Valiela et al. 1996). States such as Virginia and Maryland are periodically affected by hurricanes, and significant areas in these states have floodplains containing massive poultry CAFO, hurricane-vulnerable sources of numerous pollutants. Environmental effects are also major consequences of the hurricanes that strike Central American and Caribbean nations, and the typhoons that affect nations bordering the Pacific Ocean. Hurricanes are powerful forces that can be very destructive, yet they are natural occurrences that ecosystems are adapted to. Present research and monitoring techniques allow us to understand how hurricane characteristics interact with the natural and human environment. The human landscape is a major factor in controlling the amount of environmental damage a given storm causes. Ecologically sound development practices in hurricane prone areas are imperative for the protection of our natural resources from storm-enhanced pollution problems. Federal, state, and local government boards that are often commissioned in the wake of a severe storm typically contain politicians, emergency management personnel, health officials, and perhaps sanitary engineers, but rarely do they include scientists. Scientists able to explain the ecological effects of hurricane and landscape attributes (i.e., Fig. 2) need to be consulted so boards, managers, and politicians may better understand such interactions when recommending future coastal and floodplain zoning and development issues.

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