# Assessing the Effects of Nutrient Management in an Estuary Experiencing Climatic Change: The Neuse River Estuary, North Carolina

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ABSTRACT / Eutrophication is a serious water quality problem in estuaries receiving increasing anthropogenic nutrient loads. Managers undertaking nutrient-reduction strategies aimed at controlling estuarine eutrophication are faced with the challenge that upstream freshwater segments often are phosphorus (P)-limited, whereas more saline downstream segments are nitrogen (N)-limited. Management also must consider climatic (hydrologic) variability, which affects nutrient delivery and processing. The interactive effects of selective nutrient input reductions and climatic perturbations were examined in the Neuse River Estuary (NRE), North Carolina, a shallow estuary with more than a 30-year history of accelerated nutrient loading and water quality decline. The NRE also has experienced a recent increase in Atlantic hurricanes and record flooding, which has affected hydrology and nutrient loadings. The authors examined the water quality consequences of selective nutrient (P but not N) reductions in the 1980s, followed by N reductions in the 1990s and an increase in hurricane frequency since the mid-1990s. Selective P reductions decreased upstream phytoplankton blooms, but increased downstream phytoplankton biomass. Storms modified these trends. In particular, upstream annual N and P concentrations have decreased during the elevated hurricane period. Increased flushing and scouring from storms and flooding appear to have enhanced nutrient retention capabilities of the NRE watershed. From a management perspective, one cannot rely on largely unpredictable changes in storm frequency and intensity to negate anthropogenic nutrient enrichment and eutrophication. To control eutrophication along the hydrologically variable freshwater–marine continuum, N and P reductions should be applied adaptively to reflect point-source–dominated drought and non–point-source–dominated flood conditions.

The Neuse River Estuary (NRE) typifies many U.S. estuarine ecosystems that have experienced nutrient enrichment since a rapid post-World War II increase in urban, agricultural, and industrial development in their watersheds (Boesch and others 2001; National Research Council 2000; Nixon 1995). The most obvious and problematic result of nutrient enrichment in this system is accelerated primary production, or eutrophication, evidenced by increases in nuisance algal blooms, hypoxia and anoxia, finfish and shellfish kills, altered nutrient cycling and overall declines in habitat, natural resource values, and the ecologic condition of the estuary (Christian and others 1991; Copeland and Gray 1991; Lenihan and Peterson 1998; Paerl and others 1990, 1995, 1998).

Research conducted over the past several decades in the NRE has identified increases in phosphorus (P) and nitrogen (N) loading as key culprits responsible for eutrophication, with P being problematic in the upstream freshwater riverine segment and N being the key driver in the more saline downstream waters (Boyer and others 1994; Christian and others 1991; Paerl 1987; Paerl and others 1995; Rudek and others 1991). Inputs of N and P to the NRE have, over the past three decades, been dominated by nonpoint sources (>70%) (Dodd and others 1993; Lebo and others 2000; North Carolina Department of Environment and Natural Resources 2002; Stow and others 2001). Changes in watershed

activities since the 1960s suggest that point-source N and P inputs to the NRE have increased by 45%, whereas non–point-source inputs of these nutrients have increased by 135% (Stow and others 2001). These trends have created a compelling case for nutrient reductions to stem advancing eutrophication (Copeland and Gray 1991; North Carolina State Senate 1996).

Beginning in the mid-1980s, steps were taken to reduce P inputs in the upstream freshwater section of the river by enhancing P removal in wastewater discharge. These practices included the implementation of secondary and tertiary effluent treatments and the establishment of effluent concentration limits for P. In addition, a statewide phosphate detergent ban was enacted in January 1988 (North Carolina Department of Environment and Natural Resources 1998). These steps significantly reduced P loads to the river and estuary (Copeland and Gray 1991; Lebo and others 2000; Stanley 1992; Stow and others 2001). These point-source P control measures may have shifted the source of P inputs from primarily point to non–point sources. However, inputs of P from point sources continue to be an issue because only a few wastewater treatment plants have adopted tertiary treatment for the removal of P (Litke 1999). Since simultaneous N input reductions were lacking during this time, excessive N loading continued to be problematic, largely because N inputs controlled algal growth and bloom formation in the downstream estuarine region (Boyer and others 1994; Paerl and others 1995, 2004; Rudek and others 1991).

Phytoplankton account for more than 80% of the organic matter production in the NRE (Paerl and others 1998). Therefore, phytoplankton production is essential for controlling eutrophication. In 1996, the North Carolina State Senate convened a panel of scientists and managers for the purpose of recommending an N-reduction strategy to reduce phytoplankton production (chlorophyll *a*) effectively as a means of improving water quality (North Carolina State Senate 1996). This panel recommended a 30% reduction in N loading, based on mean 1991–1995 loads. This recommendation has since been mandated by the North Carolina State House (15A NCAC 2B .0232-.0240).

In addition to anthropogenic nutrient enrichment, the NRE has experienced a pronounced and sustained increase in tropical storm and hurricane activity, starting in the mid-1990s. Since then, 8 hurricanes and 10 tropical storms have affected the NRE watershed, causing extensive flooding, sedimentation, and other large-scale hydrologic and biogeochemical perturbations to this estuary and the downstream Pamlico Sound (Bales 2003; Paerl and others 2001; Peierls and others 2003; Burkholder and others 2004).

We examined the long-term nutrient and hydrologic record for the upstream portion of the NRE, with an emphasis on inorganic and total concentrations as well as the loading rates of the two limiting nutrients, N and P. We analyzed historical trends and patterns of nutrient concentration, nutrient loading, and phytoplankton biomass levels to determine whether the effects of the nutrient management efforts could be detected and discerned from the impacts of the recent hurricanes that have affected the region. Chlorophyll *a* (Chl*a*) was used as an indicator of phytoplankton community biomass response to nutrient inputs over time and space. Our analysis used hydrologic and water quality data collected over the preceding 25 years (since 1979) by the State of North Carolina (Department of Environment and Natural Resources, Division of Water Quality), university researchers (University of North Carolina at Chapel Hill, East Carolina University), federal agencies (United States Geological Survey), and industry (Weyerhaeuser Co.). Our overall objective was to detect and evaluate the effects of nutrient management efforts on nutrient concentrations and loading in an estuarine ecosystem experiencing climatic change through a predicted increase in Atlantic hurricane activity (Goldenberg and others 2001).

## Methods and Materials

### Research Site

The NRE drains 16,000 km$^2$ or approximately 25% of North Carolina's central coastal plain and piedmont region (Figure 1). This shallow estuary is a key tributary of the Albemarle–Pamlico Estuarine Sound (APES), the largest coastal lagoonal ecosystem in the United States and a key fisheries nursery for the mid-Atlantic coastal region (Copeland and Gray 1991). The APES's lagoonal nature is a critical feature promoting its fertility. The combination of its large size and long water residence time (~1 year) ensures effective utilization and retention of nutrients entering the system (Geise and others 1979; Pietrafesa and others 1996). This characteristic is also thought to be a key reason why the APES exhibits a high degree of sensitivity to enhanced nutrient loading, as nutrients entering the system remain there and are recycled numerous times to support primary and secondary production (Christian and others 1991, 2004). The NRE also is heavily influenced by the lagoonal properties of the APES, as tidal exchange is greatly dampened and water residence time is relatively long, ranging from 30 to more than 90 days (Luettich and others 2000). On the basis of annual primary production rates (Paerl and others
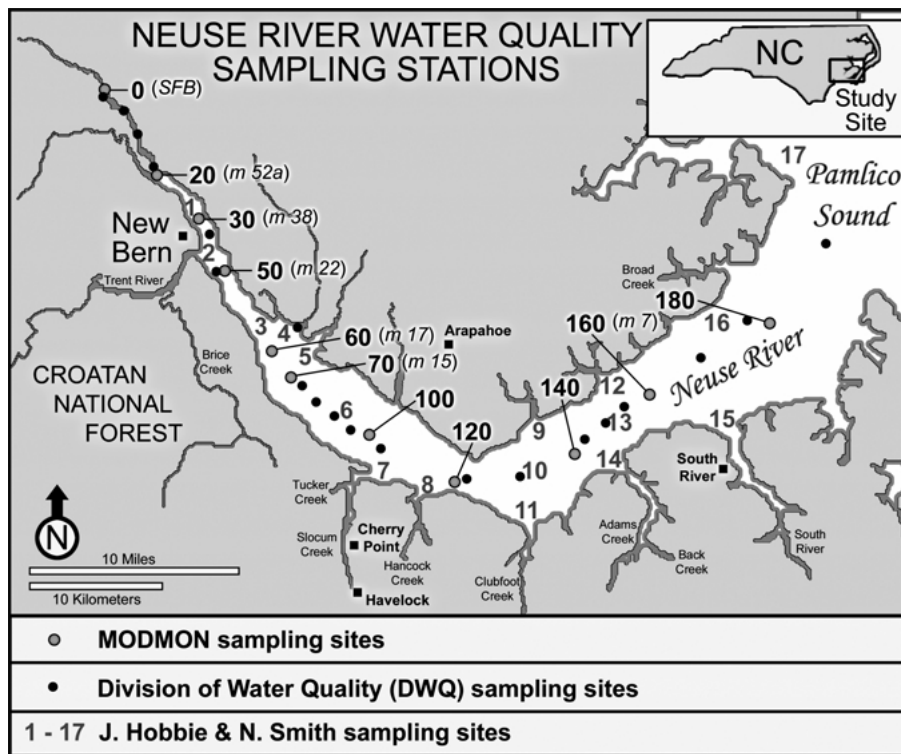
**Figure 1.** Map of the Neuse River Estuary, showing the locations of various monitoring and assessment sampling stations. Of these, only Streets Ferry Bridge (SFB) or Station 0 was included in this analysis. Shown are the stations occupied by Hobbie and Smith (1975), the State of North Carolina, Division of Water Quality, and the ModMon Program. Samples collected by the East Carolina University Group (Christian and others 1991) and Weyerhaeuser Co. (Lebo and others 2000) were from the same sites occupied by ModMon. The SFB location represented the upstream freshwater nutrient input source to the estuary. Nutrient concentration and chlorophyll *a* data from this location are shown in Figures 2, 3, and 6.

1995), the NRE is considered to be a meso- to eutrophic estuary ($\sim$350 g C/m$^2$/year) (Nixon 1995). The NRE watershed has undergone rapid agricultural and urban expansion, accompanied by accelerated N and P production (Copeland and Gray 1991; Dodd and others 1993; Stanley 1992; Stow and others 2001). In the past two decades, this system has experienced numerous symptoms of accelerated eutrophication, including increasing frequencies and intensities of phytoplankton blooms (Paerl and others 1995, 1998) as well as periods of summer and fall hypoxia and anoxia (Buzzelli and others 2002; Luettich and others 2000; Paerl and others 1998) accompanied by finfish and shellfish kills (Lenihan and Peterson 1998; Paerl and others 1998).

### Sources of Data on Nutrient and Water Quality in the NRE

Since the early 1970s, the NRE has been surveyed for standard water quality parameters including dissolved oxygen, temperature, salinity, pH, transparency/turbidity, nutrients (dissolved inorganic N [nitrate/nitrite] and ammonium, dissolved inorganic P [orthophosphate], total N, and total P), Chl*a*, and phytoplankton species composition.

Initially, periodic surveys were conducted to supplement particular research projects (Copeland and Gray 1991; Hobbie and Smith 1975; Kirby-Smith and Barber 1979; Paerl 1987; Stanley 1988). However, since the mid-1970s, the State of North Carolina's Department of Environment and Natural Resources, Division of Water Quality (DENR-DWQ), has monitored water quality on a monthly basis, with a focus on the more riverine portions and the mouth of the NRE where it flows into Pamlico Sound (Harned 1980; Tedder and others 1980). Since the late 1970s, state, university, and industrial water quality monitoring efforts have extended sampling throughout the estuary at monthly intervals (Boyer and others 1993, 1994; Christian and others 1991; Lebo and others 2000; Paerl and others 1990, 1995), increasing this to a biweekly frequency in 1994 (Buzzelli and others 2002; Luettich and others 2000; Paerl and others 1998). The number and

locations of sampling stations have varied over the 30 or more years of monitoring. However, key station features such as bridges, channel markers, and navigational buoys were continuous sampling sites during this period (Figure 1). These locations were used to construct long-term hydrographic (temperature, salinity, turbidity), dissolved oxygen, nutrient concentration, and biologic (Chl$a$) records for the NRE.

In this study, we focused on nutrient and Chl$a$ measurements from Streets Ferry Bridge (SFB) or Station 0, the most upstream long-term continuous sampling location in the NRE. As such, this station provides the most complete record of nutrient input to the estuary, before nutrients are assimilated and incorporated into phytoplankton biomass throughout the estuary (Figure 1). We also studied the Chl$a$ concentrations measured at a midestuarine region of the NRE, stations 60 through 120, to illustrate the response of phytoplankton biomass located further downstream of both the nutrient management efforts and the hydrologic variability that occurred in this system over the years (Figure 1). These midestuarine Chl$a$ concentrations were directly compared with the historical Chl$a$ concentrations measured at SFB. Other locations sampled in the NRE are not addressed in this particular analysis because of variability in sampling frequency, changes in station location, and lack of historical data.

The specific N and P forms studied were nitrate ($NO_3^-$), dissolved inorganic N (DIN), total Kjeldahl N (TKN), total N (TN), dissolved inorganic P (DIP), total P (TP), and the N:P molar ratios (DIN:DIP and TN:TP). Nitrate concentrations represented both nitrate and nitrite. Dissolved inorganic nitrogen concentrations were calculated by summing nitrate, nitrite, and ammonium. Total Kjeldahl N concentrations were either measured directly or calculated as total dissolved N (TDN) – nitrate + nitrite. Total N concentrations were calculated as either nitrate + nitrite + TKN or as TDN + particulate N, depending on which parameters were available.

Nutrient and Chl$a$ data were obtained from the following water quality monitoring activities and programs: (1) State of North Carolina (DENR-DWQ) Ambient Water Quality Monitoring Program, 1979–2002 (North Carolina Department of Environment and Natural Resources, 1998, 2002; Tedder and others 1980), (2) East Carolina University, 1980–1984 (Boyer and others 1994; Christian and others 1991), (3) Weyerhaeuser Co. Water Quality Monitoring Program, 1979–1997 (Lebo and others 2000), and (4) University of North Carolina–Chapel Hill Institute of Marine Sciences Neuse River Bloom Project and Neuse River

Estuary Modeling and Monitoring Study (ModMon), 1981, 1986–1988, 1994 to the present (Buzzelli and others 2002; Luettich and others 2000; Paerl and others 1998). The nutrient and Chl$a$ concentration data were compiled from the various sources and sorted by date to obtain a complete record of water quality at this station. If the station were monitored by more than one program on the same day, both values were used to obtain potential diurnal variability of water quality.

Respective collection and analytical methods, including detection limits for nutrients and Chl$a$ concentrations, have changed only slightly during the course of successive monitoring programs with the advent of more advanced techniques and equipment used to measure these parameters. These minor changes in methods did not impact our trend analysis because the large number of samples masked any minor deviations in parameter values and detection limits. Methodologies for nutrient and Chl$a$ concentrations can be found in Boyer and others (1994), Christian and others (1991), Mallin and others (1991), Paerl (1987), Paerl and others (1990, 1995, 1998), Pinckney and others (2001), Rudek and others (1991).

### Sources of Data on Nutrient Loading to the NRE

Nutrient loads to the NRE were estimated from streamflow and nutrient concentration data collected at Ft. Barnwell, NC, approximately 20 km upstream of SFB, below the confluence of the Neuse River and Contentnea Creek. Streamflow data were obtained from the U.S. Geological Survey gauging station (No. 02091814). Mean daily streamflow at this location has been measured only since October 1996. Thus, streamflow before October 1996 was back-estimated using a regression model that predicts streamflow at Fort Barnwell from upstream measurements in Contentnea Creek at Hookerton, NC, and in the Neuse River at Kinston, NC. Streamflow at these two locations has been measured, respectively, since December 1928 and March 1930.

Nutrient concentrations at Ft. Barnwell were measured by the DENR-DWQ approximately monthly from the late 1970s through 1995. In 1996, the sampling frequency was increased to almost daily in response to public and legislative concerns about eutrophication symptoms in the NRE. Sampling at this accelerated rate continued until 2003, when the frequency was reduced to approximately biweekly. Nutrient concentrations on days when samples were not collected were estimated using regression models predicting nutrient concentration from streamflow. Daily nutrient loading was calculated by multiplying

mean daily streamflow and nutrient concentration, then summing the daily calculations to provide annual estimates. Details pertaining to the regression models used to estimate Ft. Barnwell flow and nutrient concentrations can be found in Stow and Borsuk (2003).

### Statistical Analysis

Annual means of $NO_3^-$, TKN, TN, DIP, and TP concentrations; DIN:DIP and TN:TP molar ratios; and Chl*a* concentrations were calculated to determine the long-term temporal trends of N and P as well as the phytoplankton biomass at the SFB location. In addition, these data were averaged by three periods corresponding to the specific nutrient management and climatic events that occurred in the NRE during the 25-year period: (1) the period before implementation of the P reductions (1979–1986), (2) the period immediately after initiation of the P reductions (1987–1995), and (3) the period coinciding with the increased frequency of tropical storms and hurricanes and the implementation of N reduction practices (1996–2003). River discharge and nutrient loading rates at the Fort Barnwell location also were averaged by year and by the three periods.

All statistical tests were performed using the statistical package SPSS for Windows, version 11.5 (SPSS Inc., Chicago, IL). Initial assessment for the distribution of $NO_3^-$, TKN, DIN, TN, TP, DIN:DIP, TN:TP, and Chl*a* within years and within the three periods indicated that most of the data followed a nonsymmetric distribution (Shapiro–Wilk test for normality). Unequal variances and sample sizes also were observed for all parameters between years and periods (Levene's homogeneity of variance test). Normalizing transformations that have the potential to make the data follow a more defined Gaussian or normal distribution and that may reduce the inequality of variances between groups were unsuccessful, with the exception of the logarithmic transformation of TN:TP within years. Due to these violations of the assumptions for parametric statistical testing, nonparametric statistical analyses were performed for all parameters to account for the lack of parameter normality, unequal group variances, and unequal sample number between groups. For each parameter, Kruskal–Wallis or Mann–Whitney non-parametric tests were performed to test for significant differences between annual means and between the means of each time period. Nonparametric Spearman correlations also were performed to relate nutrient loading to river discharge rates at the Fort Barnwell location, and to relate Chl*a* concentrations to nutrient

concentrations at SFB. Values were significant at the 95% confidence level.

## Results

### Nutrient Concentration Dynamics at Streets Ferry Bridge

*1979–1986.* During the period before implementation of the P reductions (1979–1986), mean annual concentrations of TN, nitrate, TP, and DIP at the SFB location significantly increased from 1979 to 1986 (Figure 2A and B). Total N concentrations increased from 74 $\mu M$ in 1979 to 103 $\mu M$ in 1986, an increase of 39%, with a peak of 111 $\mu M$ in 1981, whereas nitrate concentrations increased by 97%, from 35 to 69 $\mu M$. During the same time, mean annual TP and DIP concentrations increased from approximately 6 to more than 12 $\mu M$ TP, and during 1979 to 1986, from approximately 2.5 to 7.5 $\mu M$ DIP, roughly 100% and 200% increases, respectively. Extreme drought conditions in 1986 led to a somewhat anomalous situation, in which TP and DIP mean annual concentrations were elevated relative to either the preceding (1985) or following (1987) years. Most likely, this reflected a sudden increase in P-enriched point sources (wastewater effluent) relative to the normally dominant non–point sources (agricultural and urban runoff), which tend to be more enriched by N (North Carolina Department of Environment and Natural Resources 1998, 2002).

Significant differences in mean annual TN, TP, and DIP concentrations between consecutive years during the 1979–1986 period were observed only between 1979 and 1980 and between 1985 and 1986, and characterized by significant increases in concentration. Mean annual nitrate concentrations during this period were significantly different only between the consecutive years of 1982 and 1983, with a significant increase in concentration, and between 1984 and 1985, with a significant decrease in concentration.

Concentrations of TKN, which comprise the ammonium and DIN fractions, did not significantly change from 1979 to 1986 at the SFB location. However, there was a significant increase in mean annual TKN concentration between 1979 and 1980. This increase was masked by the significant decreases in TKN concentration that occurred between the consecutive years of 1982, 1983, 1984, and 1985.

The mean annual dissolved inorganic molar N:P ratio (DIN:DIP) did not change significantly from 1979 to 1986 (Figure 2C). Therefore, DIN and DIP concentrations appeared to have increased proportion-
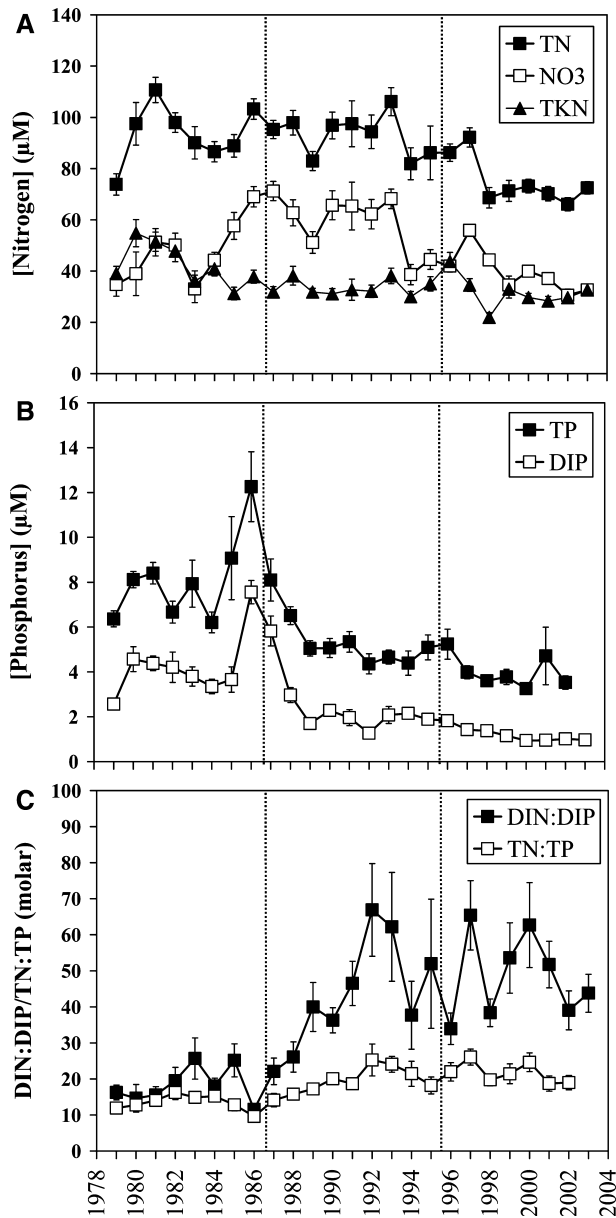
**Figure 2. A–C.** Mean annual concentrations of total nitrogen (TN), nitrate (nitrate plus nitrite), total Kjeldahl nitrogen (TKN), total phosphorus (TP), and dissolved inorganic phosphorus (DIP), as well as the dissolved and total N:P molar ratios (DIN:DIP and TN:TP) at the upstream Streets Ferry Bridge location for the 1979–2003 period. Total phosphorus and TN:TP data were not available for 2003. Error bars represent standard error. Each panel is divided into three periods that correspond to the period before the P input reductions (1979–1986), the period after the P reductions (1987–1995), and the period characterized by an increase in the occurrence of tropical storms and hurricanes.

ately from 1979 to 1986. Mean annual DIN:DIP molar ratios were significantly different only between the

consecutive years of 1985 and 1986, when the DIN:DIP ratio significantly decreased. Unlike the mean annual DIN:DIP ratios, the mean annual TN:TP molar ratio in 1986 was significantly lower than the TN:TP ratio in 1979, indicating that TP increased at a greater rate than TN from 1979 to 1986 (Figure 2C). Mean annual TN:TP ratios were not significantly different between consecutive years during the 1979–1986 period.

*1987–1995.* During the 1987–1995 period, mean annual TN and TKN concentrations at the SFB location did not change significantly (Figure 2A). However, mean annual nitrate concentrations did decrease significantly, by 58%, from approximately 71 $\mu M$ at the beginning of this period in 1987 to near 45 $\mu M$ nitrate at the end of the period in 1995. All three N forms (TN, nitrate, and TKN) decreased significantly in mean annual concentration between the consecutive years of 1993 and 1994. In addition, there was a significant decrease in mean annual TN concentrations between the consecutive years of 1988 and 1989. These results appear to underscore the importance of river discharge as a driver of concentrations, as 1989 proved to be one of the highest discharge years during the entire 25-year data period. Other consecutive years were not significantly different from one another with respect to the mean annual concentration of these three N forms.

The results of the P reduction efforts that began in the mid- to late-1980s with the reduction of P concentrations in wastewater discharge, and in January 1988 with the P detergent ban were observed immediately at the SFB location during the 1987–1995 period. Mean annual TP and DIP concentrations at SFB significantly decreased from 1987 to 1995 (Figure 2B). During this time, significant decreases in mean annual TP concentrations between consecutive years were observed from 1986 to 1987 and from 1988 to 1989, whereas mean annual DIP concentrations differed significantly between the consecutive years of 1987 and 1988 and between 1988 and 1989. Specifically, mean annual TP and DIP concentrations dropped rapidly from an annual mean of approximately 12 $\mu M$ TP in 1986 to 5 $\mu M$ TP by 1989, and from 7.5 $\mu M$ DIP in 1986 to near 1.7 $\mu M$ DIP by 1989, equivalent to a 140% decrease in mean annual TP and a 77% decrease in mean annual DIP concentration. After 1989 and through 1995, mean annual TP and DIP concentrations did not change significantly between consecutive years.

The mean annual DIN:DIP molar ratio increased significantly from 1987 to 1995, indicating that DIP concentrations decreased to a greater extent than DIN concentrations (Figure 2C). Significant differences in the DIN:DIP molar ratio between consecutive years during the 1987–1995 period were observed only be-

tween 1988 and 1989, with a significant increase, and between 1993 and 1994, with a significant decrease. Unlike mean annual DIN:DIP molar ratios, TN:TP mean annual ratios were not significantly different between 1987 and 1995, nor were there significant differences in the TN:TP ratio between consecutive years during the 1987–1995 period.

*1996–2003.* Coinciding with the increased frequency of tropical storms and hurricanes that impacted coastal North Carolina, the 1996–2003 period demonstrated some interesting patterns in mean annual concentrations and molar ratios of N and P at the SFB location. Total N, nitrate, TKN, and DIP mean annual concentrations significantly decreased from 1996 to 2003, whereas a significant decrease in mean annual TP concentrations was observed from 1996 to 2002 (TP data during 2003 at SFB was not available) (Figure 2A and B). Significant decreases in mean annual nutrient concentrations between consecutive years during the 1996–2003 period occurred for TN during the 1997–1998 period, for nitrate during the 1997–1998 and 1998–1999 periods, for TKN during the 1997–1998 period, and for DIP during the 1996–1997 and 1998–1999 periods. Significant increases, however, also occurred during this period between consecutive years. These included a significant increase in mean annual nitrate between 1996 and 1997 and in mean annual TKN concentrations between 1998 and 1999. No other consecutive years demonstrated significant changes in mean annual concentrations for TN, nitrate, TKN, or DIP. Mean annual TP concentrations were not significantly different between any of the consecutive years in this period. These results indicate that significant changes in mean annual nutrient concentrations between consecutive years have not been observed since 1999.

Annual means of the DIN:DIP molar ratio significantly increased from the beginning of this period in 1996 to the end of the study period in 2003, from 34 to 44 (29% increase) (Figure 2C). During this period, however, the mean annual DIN:DIP ratio significantly peaked in 1997 to 65 DIN:DIP from 34 in 1996, with another peak of 63 observed in 2000. These years coincided with reduced river flow rates, as compared with the other years (1996, 1998, and 1999). Unlike the mean annual DIN:DIP molar ratio, the TN:TP molar ratios did not significantly change between 1996 and 2002. However, there was a significant decrease in the mean annual TN:TP molar ratio between the consecutive years of 1997 and 1998.

*Period Comparisons.* Mean concentrations and molar ratios of N and P at the SFB location for each period (period 1: 1979–1986; period 2: 1987–1995; period 3:
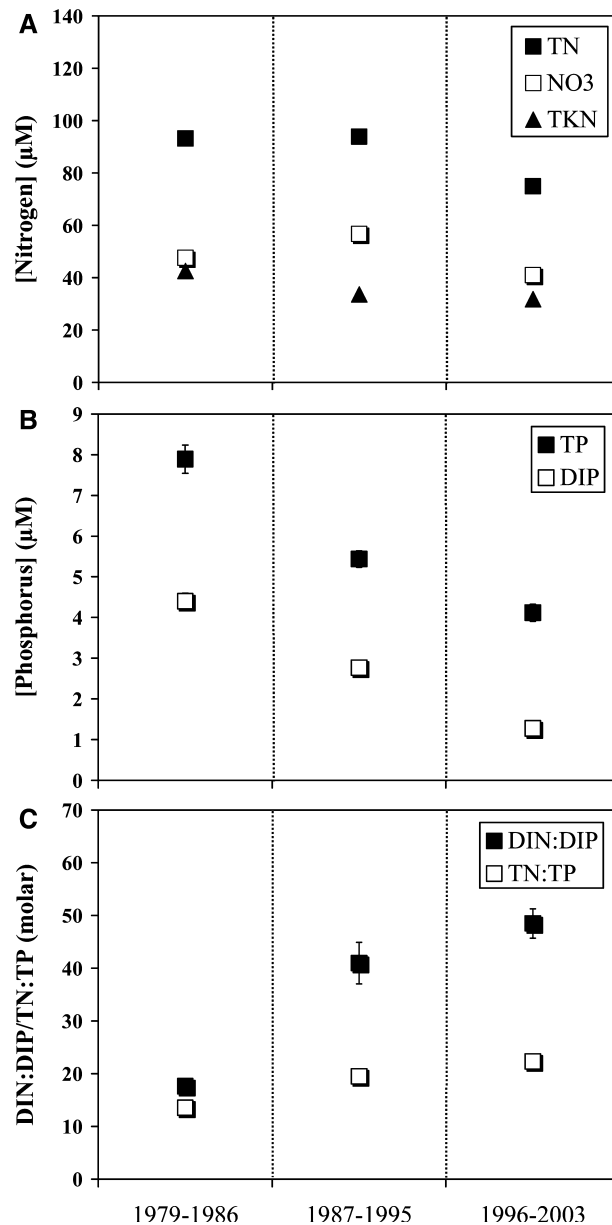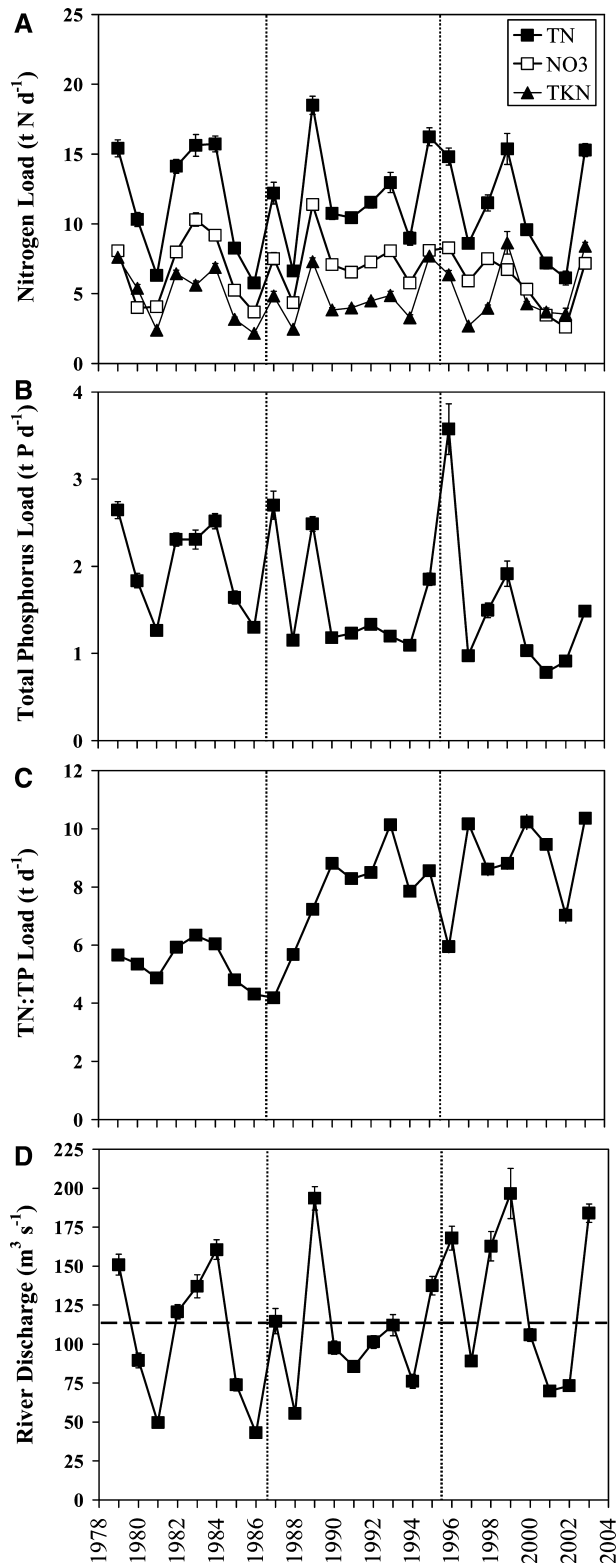
**Figure 3. A–C.** Mean total nitrogen (TN), nitrate, total Kjeldahl N (TKN), total phosphorus (TP), and dissolved inorganic P (DIP) concentrations as well as the mean dissolved inorganic N (DIN):DIP and TN:TP molar ratios.

1996–2003) were significantly different, demonstrating the effects of both nutrient management and hydrologic variability. Variable trends were observed among the N forms studied (TN, nitrate, and TKN) between the three periods (Figure 3A). Whereas the mean TN concentrations were not significantly different between periods 1 and 2, the mean TN concentration during period 3 was significantly lower than that observed during periods 1 and 2. Mean nitrate concentrations

**Figure 4. A–C.** Total nitrogen (TN), nitrate, total Kjeldahl N (TKN), total phosphorus (TP), and TN:TP loading to the Neuse River Estuary at the Fort Barnwell location for the 1979–2003 period. **D.** Freshwater discharge to the Neuse River Estuary measured at the U.S. Geological Survey gauging station (No. 02091814) located at Fort Barnwell, NC, approximately 20 km upstream from Streets Ferry Bridge. Error bars represent standard error.

nitrate concentration during period 1 was significantly greater than that of period 3. Mean TKN concentrations decreased significantly with each successive period because the mean TKN in period 1 was significantly greater than the mean TKN concentration in periods 2 and 3, and the TKN mean for period 2 was significantly greater than for period 3.

Unlike the N forms, both TP and DIP mean concentrations for each period demonstrated a similar trend (Figure 3B). Effects of the P reductions were clearly evident because mean TP and DIP concentrations significantly decreased with each successive period, whereas the mean DIN:DIP and TN:TP molar ratios for each period significantly increased with each successive period.

### Nutrient Loading Dynamics at Fort Barnwell, North Carolina

Substantial year-to-year variability in mean annual river discharge and nutrient loading rates were observed at Fort Barnwell. The mean annual river discharge and the mean annual TN, nitrate, TKN, TP, and TN:TP loading rates were significantly different between the majority of consecutive years from 1979 to 2003. In fact, the mean annual TN:TP loading ratio was significantly different between all the consecutive years studied.

The mean river discharge rate at Fort Barnwell from 1979 through 2003 was 114 $m^3/s$ (Figure 4D). In particular, large peaks in mean annual river discharge rates (>160 $m^3/s$) were observed in 1984, 1989, 1996, 1998, 1999, and 2003. These years coincided with large rainfall amounts associated with either spring rains or the passage of several tropical storms and hurricanes in the vicinity of coastal North Carolina, specifically tropical storm Diane in 1984, hurricanes Bertha and Fran and tropical storm Josephine in 1996, hurricane Bonnie and tropical storm Earl in 1998, and hurricanes Dennis, Floyd, and Irene in 1999. Hurricane Isabel, which impacted coastal North Carolina in the fall of 2003 did not have a significant effect on river discharge rates because there was relatively little rainfall associated with this storm. Instead, 2003 proved to be a significantly wet year, with high river flow rates observed
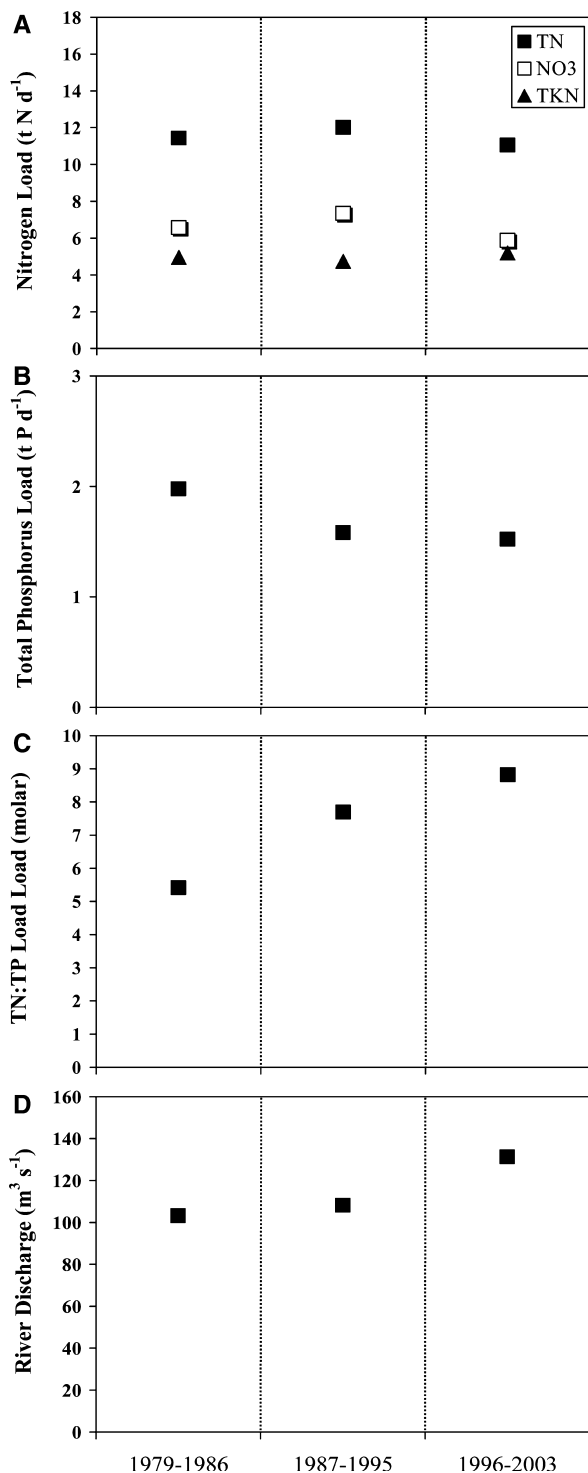
were significantly greater in period 2, after the P reductions, than in periods 1 and 3, whereas the mean

**Figure 5.** **A-C.** Mean total nitrogen (TN), nitrate, total Kjeldahl N (TKN), total phosphorus (TP), and TN:TP loading rates to the Neuse River Estuary at the Fort Barnwell location for each of the three time periods: 1979–1986, 1987–1995, and 1996–2003. **D.** Mean river discharge rates at the Fort Barnwell location for each of the three time periods. Error bars represent standard error.

throughout the year. At the other extreme, several years exhibited significantly reduced mean annual river discharge rates ($< 75$ m$^3$/s). These dry years included 1981, 1985, 1986, 1988, 2001, and 2002.

Significant differences also were observed for mean river discharge and TN, nitrate, TP, and TN:TP loading rates between the three periods studied: period 1 (1979–1986), period 2 (1987–1995), and period 3 (1996–2003) (Figure 5). The mean TN loading rate was significantly greater in period 2 than in periods 1 and 3. However, there was no significant difference between periods 1 and 3 with respect to TN loading. The mean loading rate of nitrate also was significantly greater during period 2 than during periods 1 and 3. Nitrate loading also was significantly greater during period 1 than during period 3. The mean of TP loading significantly decreased with each successive period from period 1 to period 2, from period 2 to period 3, and from period 1 to period 3.

The means for both river discharge and TN:TP loading rates significantly increased with each successive period from period 1 to period 2 and from period 2 to period 3. River discharge rates and TN:TP loading rates also were significantly greater during period 3 than during period 1. Mean TKN loading rates were not significantly different between the three periods.

### Streets Ferry Bridge and Midestuarine Chlorophyll *a* Concentrations

*1980–1986.* During the 1980–1986 period, the mean annual Chl*a* concentrations at the SFB location significantly decreased, from 24 μg/l in 1980 to 9.5 μg/l in 1986, or by 60% (Figure 6A). Significant year-to-year variability in SFB Chl*a* concentrations during this period were observed only between the years of 1981 and 1982, 1982, and 1983, and 1983 and 1984. In contrast to the Chl*a* concentrations at SFB, mean annual Chl*a* concentrations in the midestuarine segment of the NRE increased from 1980 to 1986. However, this increase was not significant. In addition, there was no significant year-to-year variability in Chl*a* concentrations in the midestuarine segment of the NRE during this period.

*1987–1995.* During the period coinciding with and immediately after the P reductions, mean annual Chl*a* concentrations at SFB continued to decrease significantly, from 13 μg/l in 1987 to 3 μg/l in 1995, a decrease of 77% (Figure 6A). These decreases paralleled decreases in TP and DIP that occurred during this time (Figure 2B and 6A). In fact, significant positive Spearman correlations were observed between Chl*a* concentrations and both DIP (0.201) and TP (0.206) concentrations. Streets Ferry Bridge Chl*a* concentra-
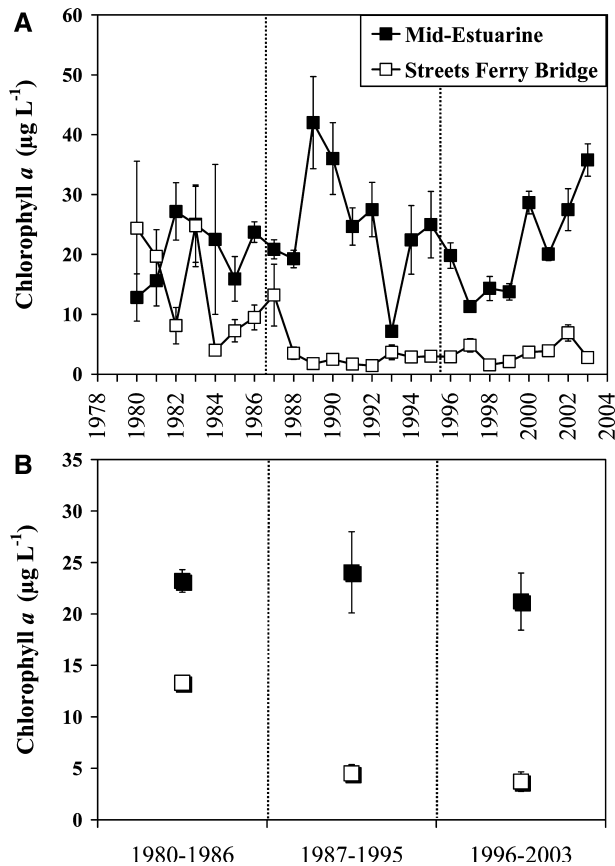
**Figure 6.** Mean annual chlorophyll *a* concentrations in micrograms per liter (μg/l) at the Streets Ferry Bridge location and a midestuarine region (stations located in between ModMon sampling stations 60 and 120 shown in Figure 1) during the 1980–2003 period. Error bars represent standard error.

region began to decrease to pre-1989 levels. In fact, there was a significant decrease in mean annual Chl*a* in the midestuarine segment between the consecutive years of 1992 and 1993. This decrease was followed by significant increases in Chl*a* between 1993 and 1994 and between 1994 and 1995. No other consecutive years were significantly different from one another with respect to mean annual midestuarine Chl*a* concentrations.

*1996–2003.* In contrast to the previous two periods, Chl*a* concentrations did not significantly change from 1996 to 2003 at the SFB location. However, year-to-year variability in SFB Chl*a* concentrations was observed during this period between the consecutive years of 1997 and 1998, 1999 and 2000, and 2002 and 2003. Whereas mean Chl*a* concentrations at the SFB location remained decreased during this period, Chl*a* concentrations in the midestuarine region increased significantly during this time of increased hurricane frequency, from 19.8 μg/l in 1996 to near 36 μg/l in 2003, an increase of 82%.

*Period comparisons.* Mean Chl*a* concentrations at the SFB location were significantly different between the three periods studied, as the mean Chl*a* concentration of period 1 was significantly greater than that of periods 2 and 3 (Figure 6A). Periods 2 and 3 were not significantly different with respect to mean Chl*a* concentrations. Mean Chl*a* concentrations in the midestuarine segment of the NRE were not significantly different between the three periods.

## Discussion

Chlorophyll *a* has been used widely as an indicator of phytoplankton biomass and eutrophication in a wide range of aquatic ecosystems (Jeffrey and others 1997), including the NRE (Luettich and others 2000; Pinckney and others 1999). When examined in parallel with nutrient data for the upstream freshwater segment of the estuary (SFB), P concentrations were shown to decline along with Chl*a* concentrations in the late 1980s, and were positively correlated. Therefore, nutrient reduction has been successful in reducing upstream freshwater algal biomass. In fact, nuisance algal (cyanobacterial) blooms that were a regular feature of this riverine segment in the 1970s and early 1980s (Tedder and others 1980) have been arrested. In particular, the P reductions associated with the detergent ban and improved wastewater treatment in the mid- to late-1980s have largely brought this segment of the estuary below the bloom threshold, defined by the state of North Carolina as 40 μg/l. This was an outcome consistent with nutrient dilution bioassays con-

tions remained reduced (< 4 μg/l) for the remainder of this period. In effect, SFB Chl*a* concentrations between consecutive years during this period were not significantly different, with the exception of the significant decrease that occurred between the consecutive years of 1987 and 1988. Although mean annual Chl*a* concentrations in the midestuarine segment of the NRE were not significantly different between the beginning of this period in 1987 and the end of this period in 1995, a significant increase in mean annual midestuarine Chl*a* concentration occurred between the consecutive years of 1988 and 1989. This large increase in mean annual midestuarine Chl*a* concentrations coincided with the decrease in Chl*a* at SFB, suggesting a reduction of upstream phytoplankton biomass in response to the P reductions, followed by an increase in midestuarine Chl*a* concentrations. After 1989, the mean annual Chl*a* in the midestuarine

ducted before the actual reduction (Paerl and Bowles 1987). Sustained P and N reductions throughout the 1990s appear to have been effective at keeping this part of the system bloom free. However, this cannot be said for the lower, more mesohaline segments of the NRE, in which N inputs appear still sufficiently high to support periodic dinoflagellate and cryptomonad blooms that supply the ''fuel'' for extensive hypoxic and anoxic events (Paerl and others 1998, 2004).

Hydrologically, the post-1995 period of reduced nutrient concentrations coincided with a sudden and sustained increase in tropical storms and hurricanes that severely impacted the NRE watershed. At least eight hurricanes, magnitude 2 or greater on the Saffir-Simpson scale, have affected this system since 1996, starting with hurricanes Bertha and Fran in the summer of 1996; and followed by Bonnie in the early fall of 1998; Dennis, Floyd, and Irene in the summer–fall of 1999; Isabel in the late summer of 2003; and most recently, Alex and Charley in the summer of 2004. These storms have caused large-scale, cumulative environmental destruction, including downed trees; washouts of wetlands, swamps, and croplands; and lengthy periods of flooding. Hurricanes Fran (1996) and Floyd (1999) left major segments of the NRE watershed under water for several months (Bales 2003; Paerl and others 1998, 2001). The record rainfall associated with hurricanes Dennis, Floyd, and Irene, which struck within a 6-week period in 1999, triggered a 100- to 500-year flood event, causing major hydrologic and geomorphologic modifications in the NRE watershed (Bales 2003). There also were large-scale biogeochemical alterations associated with this event, including massive washouts of wetlands, swamps, and forests, causing a large amount of previously stored organic matter, soils, and vegetation to be washed into Pamlico Sound and the adjacent coastal ocean (Bales 2003; Paerl and others 2001). The N discharged with the floodwaters of the 1999 hurricanes equaled the annual N input for this system (Paerl and others 2001).

The dramatic increase in hurricane frequency and intensity led to post-1995 decreases in total and soluble mean annual nutrient concentrations. In particular, rather sharp decreases in TN, nitrate, TKN, TP, and DIP concentrations occurred in the wake of hurricane Fran, which rivaled Floyd in terms of rainfall and flood potential (Bales 2003)). This was most likely because of dilution by the large amounts of freshwater discharged to the NRE and APES after these large storms. Furthermore, although the runoff accompanying these events transported large amounts of N and P to the NRE and APES, the total annual loads to these systems did not dramatically exceed those reported for pre-hurricane years.

Therefore, despite the large magnitude and increased frequency of these discharge events, no more N and P appear to have entered the NRE and APES than in earlier, hurricane-free years. On the contrary, it appears that N and P loads to the NRE are continuing to decrease during the current high-frequency hurricane period. To help clarify these results, the following possibilities were considered: (1) the data collected were incomplete and did not accurately reflect hydrologic and/or nutrient concentrations/loading conditions, including storm-driven discharge, at the entrance to the NRE (i.e., some nutrient loading events were missed); (2) the loading of nutrients, especially N, has been stabilized and potentially reduced in the NRE watershed through improved nutrient management practices; and (3) the NRE watershed nutrient dynamics, specifically nutrient cycling, retention, and release characteristics, have changed during the period of elevated hurricane activity and flooding. These alternative explanations are examined and evaluated in the following sections.

## Critical Event-Scale Data Are Missing

It is possible that biweekly nutrient monitoring could have missed changes in nutrient concentrations associated with short-term rainfall events. However, it is unlikely that larger, more protracted periods of rainfall and discharge associated with thunderstorm activity, tropical storms, and hurricanes went undetected and escaped quantification. Studies have shown these events to be major, multiweek drivers of nutrient delivery to the estuary (Paerl and others 1998; Peierls and others 2003). Furthermore, sampling was not confined to the SFB location of the NRE, but rather was distributed among 13 locations spanning the entire length of the estuary. Thorough examination of the data sets used for this analysis and in companion studies (Paerl and others 1995, 1998, 2004) have indicated that, given the length and relatively long travel/residence time along the axis of the NRE, such events were not likely to be missed. In addition, Bales (2003) and Peierls and others (2003) have pointed out that in the aftermath of hurricanes Fran (1996) and Floyd (1999), elevated discharge entering the NRE continued for several months after the event. Finally, the quantitative ramifications of a few missed events were insignificant in the context of mean annual values (Luettich and others 2000; Paerl and others 1995, 1998). Therefore, it seems unlikely that potential omissions of events explain the observed trends.

### Watershed Nutrient Loading Has Decreased as a Result of Nutrient-Reduction Strategies

This is a potentially attractive scenario, especially as nutrient-reduction steps have been mandated for the NRE watershed since 1998, the successful results of which have been demonstrated with the particular decreases in mean annual TN concentrations at SFB since 1998. In fact, mean annual TN concentrations at SFB have remained decreased since these N reduction practices have taken place. In addition, agricultural, urban, and industrial sectors have increasingly adapted non–point-source nutrient-reduction strategies, including control of urban storm water runoff and agricultural best management practices such as the construction of riparian buffers zones, more timely and prudent fertilizer applications, and improved techniques for handling and processing animal wastes (Osmond and others 1997). Indeed, N and P loadings in some tributaries of the Neuse River (e.g., Contentnea Creek) have recently declined (Harned and Caire 2003). However, whereas urban, industrial and agricultural nutrient management have led to nutrient loading decreases in certain sectors of the NRE basin (Osmond and others 1997), we note that, on the larger basin scale, both the human population and livestock inventories have continued to increase dramatically in the NRE basin during the 1990s and into the new millennium. During this time, the NRE basin's human population increased by nearly 17%, from 1990 to 2000, and by 14% during the critical 1996–2000 period (North Carolina Department of Environment and Natural Resources 1998). Livestock inventory more than doubled during the 1990s, with numbers of hogs alone increasing from fewer than 500,000 to more than 1,500,000 head in the NRE basin. Estimates of annual N sources in the NRE watershed, which included cropland, animals, and point sources (mostly wastewater treatment plants), during the 1990–2000 period indicate continued increases, although the rate of increase has declined since the 1980–1990 period (Stow and others 2001). In concert, these findings indicate that an increase rather than a decrease in N loading to the NRE should have been expected throughout the 1990s, extending well into the post-1996 period of elevated hurricane activity.

### Watershed Nutrient Cycling and Retention Characteristics Have Changed as a Result of the Hurricanes

The increased frequency and intensity of hurricanes has had profound impacts on hydrology and nutrient cycling in the NRE and its watershed (Bales 2003; Paerl and others 2001; Peierls and others 2003). These events have altered the physical and chemical forms of nutrients as well as their mobility, transport, and transformations. One obvious effect of large storms is their ability to flush previously deposited and stored nutrients rapidly and effectively from wetlands, swamps, forests, and agricultural lands (Bales 2003). During hurricanes Fran and Floyd, the sheer volume and force of rapidly surging floodwaters dislodged vegetation, organic debris, and sediment organic matter deposits that had accumulated since the last major spate of hurricanes, at least 40 years ago (mid-1950s). Although these hurricanes scoured sediment organic matter deposits and transported sediments into downstream estuarine and sound waters, they also left exposed wetland, swamp, and soil surfaces free to adsorb, retain, and process (e.g., denitrification) new nutrient sources. Mechanistically, we envision this potential nutrient replacement scenario operating like a giant sponge. First, the sponge is saturated by floodwaters. Then it is ''wrung out'' by the flushing and scouring of the more nutrient-rich organic matter, leaving behind less organic-rich material that would leach fewer nutrients and contribute less to the baseline nutrient load. This also would leave numerous sites on the sponge ready to adsorb and retain new nutrients from subsequent runoff and depositional events. The overall effect would be increased retention of nutrients after storms and a decrease in base flow nutrient discharge to the estuary.

In addition, flooding from hurricanes leads to waterlogged wetlands, swamps, and soils. This tends to enhance the development of anoxic conditions in which denitrification can proceed and be stimulated (Groffman 1994), promoting within-watershed N losses. The net effect is a reduction in dissolved N (mainly as nitrate) concentrations and N loading to the estuary. The combined effects of increased nutrient retention and promotion of denitrification in flooded soils and wetlands would help to explain how hurricane-prone periods might enhance within-system retention and losses of fixed N.

The proposed mechanisms underlying the observed decreases in N and P concentrations and loading during the hurricane-prone years need not be exclusive of each other. It is conceivable that scenarios 2 and 3 could be operating simultaneously and synergistically. According to this scenario, increased hurricane activity helps to accelerate ecosystem recovery in response to a nutrient management strategy that includes (1) agricultural practices emphasizing best management practices, (2) simultaneous optimization of nutrient retention and denitrification by promotion of vegetative buffers, and (3) maximization of water

retention times and extension of the beneficial functional roles of wetlands, swamps, and forests. The promotion and maintenance of these important hydrologic and nutrient-cycling features represent a unique ''adaptive'' nutrient management strategy in the face of climatic changes, whether they be hurricanes or droughts. As such, it is recommended that wetlands, swamps, riparian buffers, water retention ponds, and devices (i.e., flashboard risers) be a highly integrated, functionally important and essential feature of a long-term nutrient management strategy that best accommodates elements of climatic change in the NRE basin and other hydrologically variable coastal watersheds.

It is imperative that we recognize both the complications and benefits that large-scale tropical storm and hurricane events might provide to ecosystems undergoing nutrient reduction strategies aimed at arresting eutrophication of downstream waters. There are numerous lessons to be learned from such events. Among them is the lesson that periodic floods and flushing of watersheds are not necessarily detrimental on the longer decadal scale, especially when accompanied by long-term nutrient reduction strategies. Perceptible improvement in the water quality of the NRE in response to currently formulated nutrient input reductions may require several decades (North Carolina State Senate 1996). However, the predicted time frame for recovery and improvement in water quality conditions may be accelerated significantly in the presence of an elevated frequency of such storm events. The key to a successful long-term nutrient management strategy is to stay the course with dual nutrient (N and P) reductions, the effects of which can be either accelerated or retarded by climatic variability and trends. In this regard, scientists and managers must educate decision makers, stakeholders, and the public at large to understand that estuarine ecosystem responses to nutrient manipulations should be accompanied by long-term monitoring and modeling efforts capable of capturing and assessing the impacts of short-term hydrologic variability and longer-term climatic change in order to evaluate the effectiveness and success of these strategies. The lesson learned for the NRE is that at least a multidecadal monitoring program that incorporates high temporal and spatial resolution sampling is needed to assess anthropogenic and climatic drivers of ecologic change.

## Acknowledgments

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