Environ. Sci. Technol. **2009,** *43,* 7609–7613

Environmental Science & Technology
Feature

FerryMon: Ferry-Based Monitoring and Assessment of Human and Climatically Driven Environmental Change in the Albemarle-Pamlico Sound System†

HANS W. PAERL*
KAREN L. ROSSIGNOL
RODNEY GUAJARDO
NATHAN S. HALL
ALAN R. JOYNER
BENJAMIN L. PEIERLS
Institute of Marine Sciences, University of North Carolina at Chapel Hill

JOSEPH S. RAMUS
Duke University Marine Laboratory

Ships of opportunity afford ready study of marine environments so as to understand how they change.

ALAN R. JOYNER

North Carolina's (NC's) Albemarle-Pamlico Estuarine System (APES) is the U.S.'s second largest estuary and its largest lagoonal ecosystem at 1700 km^2. APES supports more than 80% of the Southeastern Atlantic U.S. fishery as a nursery and fishing ground (*1*), and it provides NC with a large share of its residential, recreational, and tourism income. Bounded by the Outer Banks barrier island system, APES experiences restricted water exchange (via 3 narrow inlets) with the Atlantic Ocean. This accounts for its lagoonal properties, including an average water residence time of 1 year (*2*). These hydrologic features enable APES to make efficient use of nutrient inputs, promoting high fertility and excellent fisheries. However, they also make the system highly sensitive to nutrient overenrichment and eutrophication (*1, 3–5*).

Despite its ecological and economic importance, and its sensitivity to growing nutrient inputs, APES has not been regularly monitored for water quality and habitat conditions. In the fall of 1999, floodwaters from Hurricanes Dennis, Floyd, and Irene greatly decreased the salinity of the APES, radically altering hydrologic, fisheries, and biogeochemical conditions (*6–8*). These events required rapid, comprehensive assessment of water quality and habitat impacts; information that is particularly relevant in light of a projected increase in hurricane activity impacting the U.S. Atlantic and Gulf coasts (*9, 10*). In response, NC's Division of Transportation's (NC DOT) ferries were instrumented in a program called FerryMon (*11*) to monitor water quality in APES; reflecting a global trend to use ferries as cost-effective monitoring platforms to support science-based management of coastal waters (*12–14*). In this overview, we provide examples of how FerryMon data are used to (1) establish a long-term data set of key environmental indicators of ecological change in APES; (2) intensively monitor the water quality effects of large scale meteorological perturbations, including hurricanes and droughts; (3) evaluate state water quality standards for chlorophyll *a* (Chl *a*), a commonly used measure of suspended algal, or phytoplanktonic, biomass; (4) calibrate remote sensing imagery of turbidity, Chl *a*, and diagnostic (of phytoplankton groups) photopigments (*15*); (5) provide data for models used to predict nutrient–algal growth relationships (*16–18*).

How Does FerryMon Work? Three NC DOT ferries (*19*) are equipped with flow-through systems for monitoring near-surface water. The Cedar Island-Ocracoke ferry crosses the southern Pamlico Sound and Ocracoke Inlet, and the Swan Quarter-Ocracoke ferry crosses the central Pamlico Sound, each 3 times per day (Figure 1). The Neuse River ferry makes 30 crossings per day on the APES's largest tributary estuary, the Neuse River Estuary (NRE) (Figure 1).

FerryMon's continuous-flow, automated system monitors surface water quality and links that data to a geographic (GPS) position. A Yellow Springs Instruments (YSI) model 6600 multiparameter water quality probe is equipped with sensors for specific water quality parameters: turbidity, temperature, conductivity (salinity), pH, and chlorophyll fluorescence (Figure 1). Newly calibrated probes are replaced weekly to biweekly to minimize fouling and drift. An automated, in-line refrigerated discrete sampler (ISCO) collects samples for measurements of nutrients, total organic carbon (TOC), and phytoplankton photopigments (*12, 13, 20*). Nutrient and TOC samples, besides being refrigerated, are preserved with dilute sulfuric acid (pH <2), immediately

† Editor's Note: To our delight at *ES&T*, we have started to receive Features and Viewpoints by independent author(s) coincidentally overlapping both in topic and review schedule. This manuscript was accepted within a week of another on risk assessment policy for Atlantic hurricanes. The choice was thus made to present both manuscripts in the same issue (October 15, 2009; 43[20]). Readers of this piece by Paerl et al. are therefore encouraged to read that by Grossmann (DOI 10.1021/es803533t).

10.1021/es900558f © 2009 American Chemical Society
Published on Web 08/05/2009

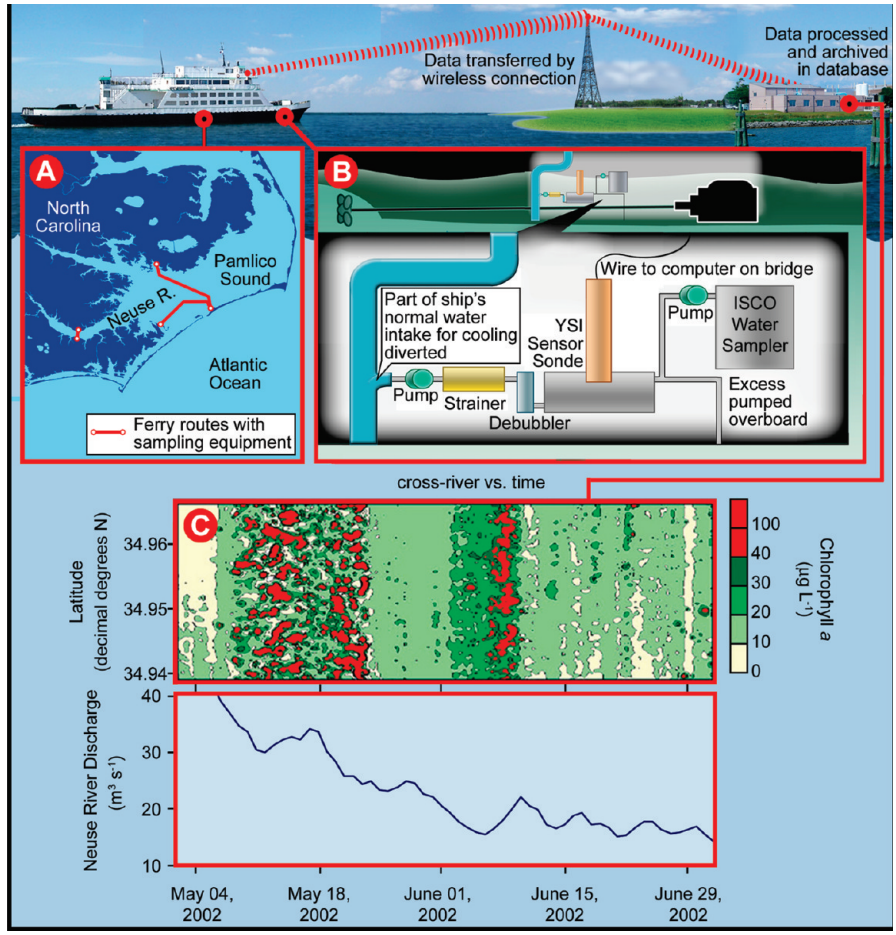

FIGURE 1. Schematic showing the routes (A), operation (B), and environmental data (C) obtained by FerryMon. Shown are concentrations of fluorescence-derived chlorophyll *a* (Chl *a*) obtained during 2 months of continuous sampling of the Neuse River estuary crossing. GPS-stamped cross-channel data were plotted against time. Note the patchiness of blooms (>40 μg L^{-1} Chl *a*). Also shown is freshwater discharge at U.S. Geological Survey (USGS) gauging station 02089500 at Ft. Barnwell, 30 km upstream from the head of the estuary. A 1.5 week lag was accounted for, which reflects the time for freshwater to travel to this estuarine location.

transported to the laboratory, and filtered along with photopigment samples.

Initially stored on the shipboard computer, geographic and water quality data are downloaded daily via the Internet and screened for quality assurance and quality control (QA/QC) before entering into comprehensive databases. All data are archived and shared as part of the NSF-supported Consortium of Universities for the Advancement of Hydrologic Sciences Water and Environmental Research Systems Network (CUAHSI) (*21*). FerryMon is linked to several local, regional, and national observational programs: (1) the Neuse River Modeling and Monitoring Program (ModMon) (*22*) and the NC Department of Environment & Natural Resources-Division of Water Quality (NCDENR-DWQ) ambient water quality program (*23*), and (2) the U.S. Southeastern Regional Coastal Ocean Observing Systems (SeaCOOS) (*24*).

Figure 1 shows the response of a key water quality indicator, Chl *a*, to variable freshwater discharge from May until early July 2002 in the NRE. During this period, spring elevated rainfall, followed by summer dry periods and thunderstorms, led to variations in freshwater discharge and water residence time. This "fueled" periodic algal blooms, as elevated Chl *a*, which formed when relatively dry periods followed rainy periods during which elevated freshwater discharge introduced new nutrient supplies. When flow decreased, phytoplankton growth rates caught up with decreasing flushing rates, promoting re-establishment of blooms (*5, 6*). Blooms are not homogeneously distributed in the estuary. They appear as patches of relatively high Chl *a*, at times exceeding the Chl *a*-based criterion for acceptable water quality conditions (<40 μg L^{-1}), as part of a total maximum daily (nitrogen) load (TMDL) mandated for the NRE (*25*). Localized circulation features and differential vertical migration patterns among major phytoplankton groups likely affect this patchiness (*5, 26, 27*).

Evaluating Event Scale and Longer-Term Environmental Impacts. Event-scale impacts include significant discharge and wind events from major storms and droughts that influence freshwater and nutrient inputs, flushing, mixing, and circulation.

Impact of Hurricane Isabel on APES Hydrography. Category 2 Hurricane Isabel made landfall near Drum Inlet on the Outer Banks on September 18, 2003. Hatteras Island was overwashed between Hatteras Village and Frisco, creating a breach in the barrier island of ~600 m wide and 6.5 m deep. Within a week, the NC DOT and U.S. Army Corps of Engineers began filling the breach with sand to restore NC Hwy 12, connecting villages on the Outer Banks. By November 18, the breach was filled. FerryMon salinity data were used to characterize the hydrographic effects of opening and closing of the new inlet.

The Pamlico Sound is separated into two basins by Bluff Shoal (Figure 2). We hypothesized that Bluff Shoal limits water exchange between the two basins, and that the basins exchange water with the coastal ocean somewhat independently. We expected the breach to primarily affect the east basin, which is directly connected with the coastal ocean. The ferries pass between the two basins by traversing the

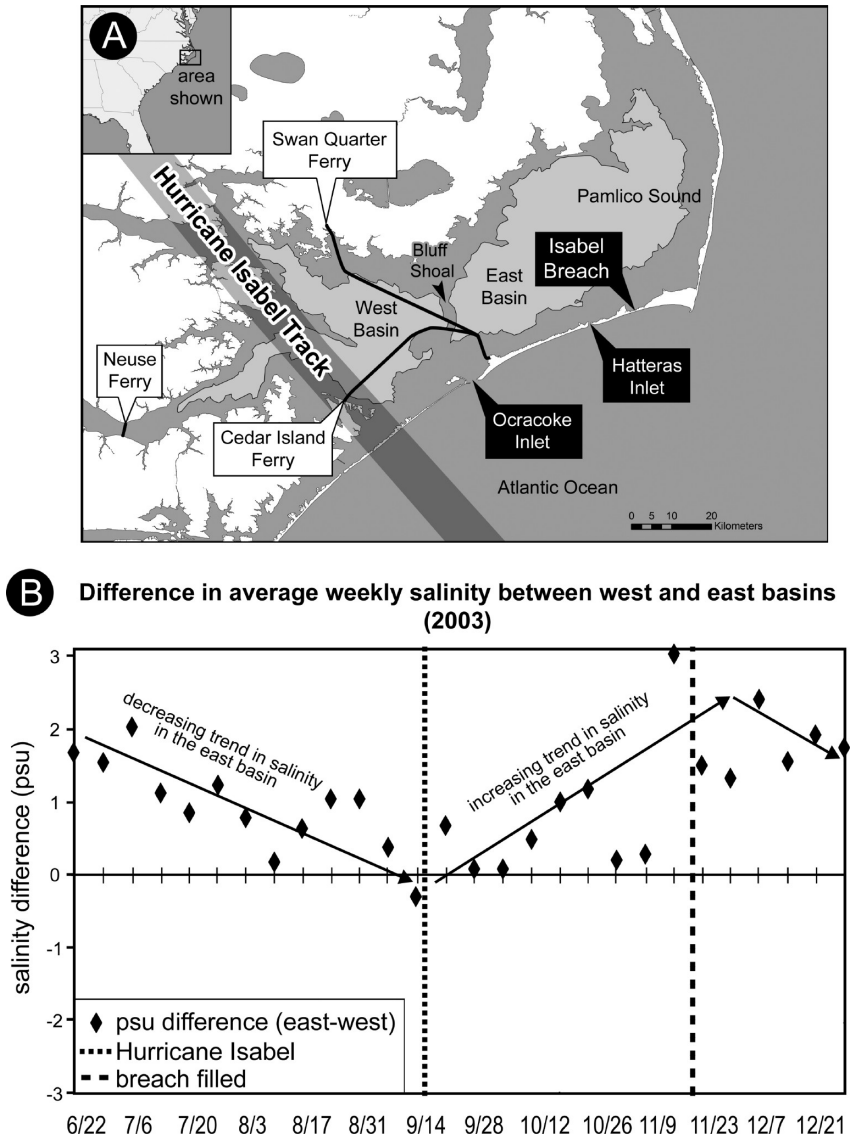

FIGURE 2. FerryMon's monitoring of the effects of a breach in APES's Outer Banks, following landfall of Hurricane Isabel (Sept. 2003). Shown are the breach location, track of Isabel, and ferry-based results of salinity differences between east and west basins of the Sound, before, during, and following Isabel's landfall, and after the closing of the breach.

Bluff Shoal (Figure 2). We delineated 40 km^2 areas on either side of the Bluff Shoal (east and west), which the ferries transect several times daily. Salinity was logged every 3 min and the data were binned on a weekly basis for the 4 months preceding and following Hurricane Isabel. The water column is almost always vertically mixed by wind and lunar tides, thus the 1m data are representative of the shallow water column in the sampling areas.

During the months prior to Hurricane Isabel's arrival, the east basin received a much greater volume of fresh water (Roanoke and Chowan River discharge) than the west basin (Neuse and Pamlico River discharge) (*28*). As a result, the relative salinity (east minus west segments of the basin) showed a steady decline prior to the hurricane's arrival (Figure 2). The high degree of variability between contiguous weeks is likely attributed to wind advection, which strongly affects the hydrology of APES (*2*). The freshening trend in the east basin relative to the west basin reversed upon the opening of the new inlet, which allowed greater exchange with higher salinity oceanic water. Relative salinity in the east basin continued to increase until the inlet was closed and the relative freshening of the east basin resumed. Salinities are highly variable in space and time due to watershed runoff, basin circulation, interbasin and coastal ocean transfer, astronomical and wind tides. Nevertheless, the time-and-space intensive data produced by FerryMon captured the sudden opening and slow closure of the new inlet which resulted in a statistically significant change ($p < 0.002$) in this important hydrologic indicator.

The Spring Bloom of 2007 in the Neuse River Estuary. Winter−spring of 2007 had a higher than average rainfall and nutrient discharge period. Chl *a* concentrations measured by the NRE ferry were also elevated, starting in late winter and peaking in late March (Figure 3). The spring bloom showed lateral variability, with relatively high Chl *a* concentrations occurring on the northern side of the estuary (Figure 3) further illustrating phytoplankton "patchiness" and the need for spatially and temporally intensive monitoring to accurately assess this important water quality parameter.

Interannual Hydrologic Variability. Examples of the impacts of longer-term interannual hydrologic variability included the effects of two hydrologically contrasting years, 2002 and 2003. Due to a persistent drought, 2002 showed unusually low freshwater discharge compared to the 50 year mean (Figure 4). In contrast, 2003 proved to be an extremely wet year, with higher than normal late winter−early spring rains, a rainy summer, and near-normal fall rainfall conditions.

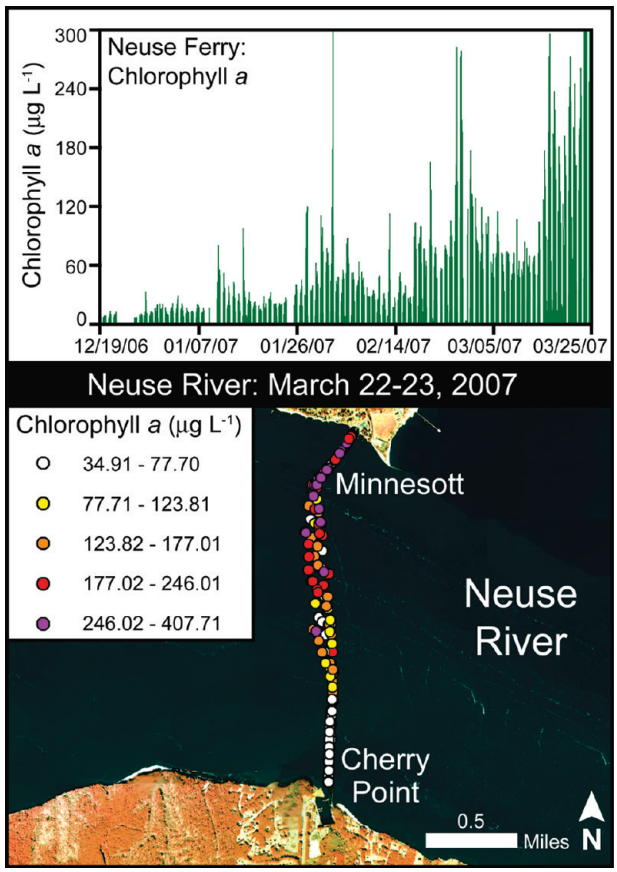

FIGURE 3. Top: Development of the 2007 spring phytoplankton bloom monitored by the Neuse River Estuary ferry. Data show daily mean values for discrete water samples for Chl *a* along the ferry crossing. Bottom: The cross-estuary distribution of Chl *a* during March 22–23, 2007. During this period, consistent southerly winds prevailed in the region, causing a surface-dwelling dinoflagellate bloom (*Prorocentrum minimum, Heterocapsa triquetra*) to concentrate on the northern shore of the estuary. Note that Chl *a* concentrations varied from <50 to >200 μg L^{-1} between the southern and northern shores of the estuary.

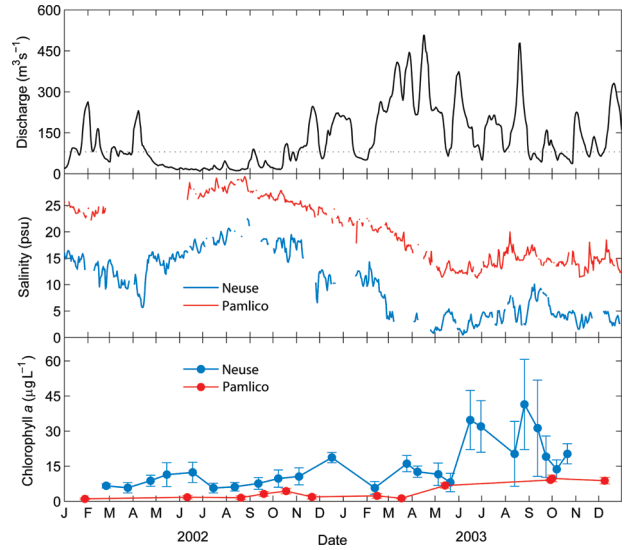

FIGURE 4. Effects of interannual variability in Neuse River discharge on salinity and high-performance liquid chromatography (HPLC) derived Chl *a* in the Neuse River Estuary and Pamlico Sound. (a) Daily average Neuse River discharge at Fort Barnwell, NC (solid line). Dashed line is the 50 year mean discharge. (b) Daily mean salinity and (c) transect mean Chl *a* from the Neuse River Ferry (blue) and the Cedar Island-Ocracoke Ferry crossing of the Pamlico Sound (red). Error bars indicate the standard deviation of the transect means.

Ferry-based Chl *a* and salinity data revealed the effects of interannual variability of flow, with much lower Chl *a* concentrations and higher salinities in 2002 than in 2003 (Figure 4). In APES, nutrient loading trends (data not shown) closely parallel those for discharge (*3*), and phytoplankton biomass is largely determined by nutrient loading (*3, 5*). As a result, 2003 was a much more productive, higher phytoplankton biomass year than 2002 in both the Neuse River and Pamlico Sound (PS) (Figure 4). However, the timing and magnitudes of responses differed between systems. Volume-wise, the NRE is much smaller than the PS, and thus more profoundly affected by changes in freshwater discharge and nutrient loads. In general, Chl *a* concentrations in the NRE were more responsive to fluctuations in nutrient loading than those in the PS (Figure 4). This illustrates how "new" nutrients supplied via freshwater discharge are "stripped" by sub-estuaries like the NRE. Thus, the NRE serves as a "nutrient filter", removing a significant fraction of the nutrient load before it enters the PS, and converting it into phytoplankton biomass. Given excessive nutrient loading and relatively long residence times, undesirable accumulations of biomass occur as potentially harmful blooms (>40 μg Chl *a* L^{-1}) (*5, 26, 27*). When very large discharge events following major "wet" storms (e.g., Hurricane Floyd, 1999) impact the NRE, exceedingly high flushing rates prevent the stripping of nutrients because phytoplankton growth rates cannot keep up with flushing rates (*5, 6*). Under these conditions the PS is an increasingly important phytoplankton response component of APES (*6–8*).

Subsiding discharge following flood events allows residence time and salinity to become more favorable for phytoplankton growth in the tributaries and often leads to blooms. This scenario unfolded following Tropical Storm Ernesto (Aug. 31, 2006), resulting in a bloom of the icthyotoxic dinoflagellate *Karlodinium veneficum*, which was subsequently linked to several fish kills in the NRE (*27*). FerryMon can capture these differential responses and, through coupled water quality models, provide predictability as to where, when, and how long algal bloom responses are likely to impact water quality. This has improved our understanding of phytoplankton growth responses to simultaneous nutrient enrichment and hydrologic forcing in APES. FerryMon data are also being used to calibrate various remote sensing platforms (aircraft-based SeaWiFS, MODIS, MERIS), characterizing surface water temperature, turbidity, and chlorophyll of APES (*5, 15*).

Serving Ecosystem and Regional Research and Management Needs. The examples provided above illustrate the utility of ferry-based water quality monitoring in clarifying the way estuarine (and coastal) ecosystems "work" and respond to environmental perturbations and change. From research, management, and decision-making perspectives, FerryMon can detect and characterize ecological and biogeochemical impacts that may not be captured by conventional environmental monitoring programs. Space-time intensive FerryMon data provides the "ground truthing" calibration source for remote sensing and modeling that enable researchers and managers to "scale up" to ecosystem and regional levels for comprehensive evaluations of the impacts of external stressors on these systems. The added dimensionality provided by these vessels plays a crucial role in better assessing estuary status, natural variability, and trends in response to how increasing anthropogenic- and climatically induced environmental changes impact coastal regions. Lastly, it provides science-based support of water quality management through accurate assessments of Chl

a-based criteria for acceptable water quality conditions (<40 μg Chl *a* L^{-1}). The increased vigilance and comprehensive assessments that are provided by programs like FerryMon will translate into improved management and conservation of our estuarine and coastal resources.

Hans Paerl is the William R. Kenan Professor of Marine and Environmental Sciences at the University of North Carolina at Chapel Hill (UNC-CH) Institute of Marine Sciences in Morehead City, NC. He is coprincipal investigator of the FerryMon Project. Karen Rossignol is a research technician and laboratory manager at the UNC-CH Institute of Marine Sciences. Rodney Guajardo is the data manager for the FerryMon Project. Nathan Hall is a recent Ph.D. recipient in Marine Sciences at UNC-CH and a postdoctoral researcher at the Institute of Marine Sciences. Alan Joyner is a graphics arts illustrator at the Institute of Marine Sciences who designed and maintains the FerryMon website. Benjamin Peierls is a recent Ph.D. recipient in Marine Sciences at UNC-CH and a postdoctoral researcher at the Institute of Marine Sciences. Joseph Ramus is Professor of Biological Oceanography, Marine Science and Conservation at the Duke University Marine Laboratory/Nicholas School of the Environment and coprincipal investigator of the FerryMon Project. Please address correspondence regarding this article to hpaerl@email.unc.edu.

Acknowledgments

We appreciate the assistance of T. Boynton, J. Braddy and P. Wyrick. FerryMon is funded by the NC Dept. of Environment and Natural Resources and the National Science Foundation's Environmental Engineering & Technology and Chemical Oceanography Programs. Additional support was provided by North Carolina Sea Grant and the U.S. Environmental Protection Agency.

Literature Cited

(1) Copeland, B. J.; Gray, J. *Status and Trends Report of the Albemarle-Pamlico Estuary* (Ed. By Steel, J.);Albemarle-Pamlico Estuarine Study Report 90-01; NC Department of Environment, Health & Natural Resources: Raleigh, NC, 1991.
(2) Pietrafesa, L. J.; Janowitz, G. S.; Chao, T.-Y.; Weisberg, R. H.; Askari, F.; Noble, E. *The Physical Oceanography of Pamlico Sound*; UNC Sea Grant Publication UNC-WP-86-5; Raleigh, NC,1996; 125 pp.
(3) Paerl, H. W.; Mallin, M. A., Donahue, C. A.; Go, M.; Peierls, B. L. *Nitrogen Loading Sources and Eutrophication of the Neuse River Estuary, NC: Direct and Indirect Roles of Atmospheric Deposition*; UNC Water Resources Research Institute Report 291; Raleigh, NC, 1995; 119 pp.
(4) Paerl, H. W. Coastal eutrophication and harmful algal blooms: Importance of atmospheric deposition and groundwater as "new" nitrogen and other nutrient sources. *Limnol. Oceanogr.* **1997**, *42*, 1154–1165.
(5) Paerl, H. W.; Valdes-Weaver, L. M.; Joyner, A. R.; Winkelmann, V. Phytoplankton indicators of ecological change in the nutrient and climatically-impacted Neuse River-Pamlico Sound System, North Carolina. *Ecol. Appl.* **2007**, *17* (5), 88–101.
(6) Paerl, H. W.; Valdes, L. M.; Joyner, A. R.; Peierls, B. L.; Buzzelli, C. P.; Piehler, M. F.; Riggs, S. R.; Christian, R. R.; Ramus, J. S.; Clesceri, E. J.; Eby, L. A.; Crowder, L. W.; Luettich, R. A. Ecological response to hurricane events in the Pamlico Sound System, NC and implications for assessment and management in a regime of increased frequency. *Estuaries Coasts* **2006**, *29*, 1033–1045.
(7) Bales, J. D. Effects of Hurricane Floyd inland flooding, September-October 1999, on tributaries to Pamlico Sound, North Carolina. *Estuaries* **2003**, *26*, 1319–1328.
(8) Peierls, B. L.; Christian, R. R.; Paerl, H. W. Water quality and phytoplankton as indicators of hurricane impacts on a large estuarine ecosystem. *Estuaries* **2003**, *26*, 1329–1343.
(9) Webster, P. J.; Holland, G. J.; Curry, J. A.; Chang, H. R. Changes in tropical cyclone number, duration, and intensity in a warming environment. *Science* **2005**, *309*, 1844–1846.
(10) Elsner, J. B.; Kossin, J. P.; Jagger, T. H. The increasing intensity of the strongest tropical cyclones. *Nature* **2008**, *455*, 92–95.
(11) North Carolina Ferry-Based Water Quality Monitoring Program, FerryMon; technical support information can be viewed at www.ferrymon.org.
(12) Buzzelli, C. P.; Ramus, J. R.; Paerl, H. W. Ferry-based monitoring of surface water quality in North Carolina estuaries. *Estuaries* **2003**, *26*, 975–984.
(13) Ensign, S. H.; Paerl, H. W. Development of an unattended estuarine monitoring program using ferries as data collecting platforms. *Limnol. Oceanogr. Meth.* **2006**, *4*, 399–405.
(14) Ainsworth, C. Ferryboxes begin to make waves. *Science* **2008**, *322*, 1627–1629.
(15) Lunetta,; R, S; Knight, J. F.; Paerl, H. W.; Streicher, J. J.; Peierls, B. L.; Gallo, T.; Lyon, J. G.; Mace, T. H.; Buzzelli, C. P. Measurement of water color using AVIRIS Imagery to assess the potential for an operational monitoring capability in the Pamlico Sound Estuary, USA. *Inter. J. Remote Sens.* 2009 (in press).
(16) Borsuk, M. E.; Stow, C. A.; Reckhow, K. H. Integrated approach to total maximum daily load development for Neuse River Estuary using Bayesian probability network model (Neu-BERN). *J. Water Res. Plan. Manage.* **2003**, *129* (4), 271–282.
(17) Bowen, J. D.; Hieronymous, J. W. A CE-QUAL-W2 model of Neuse Estuary for total maximum daily load development. *J. Water Res. Plan. Manage.* **2003**, *129* (4), 283–294.
(18) Arhonditsis, G. B.; Paerl, H. W.; Valdes-Weaver, L. M.; Stow, C. A.; Steinberg, L. J.; Reckhow, K. H. Application of Bayesian structural equation modeling for examining phytoplankton dynamics in the Neuse River Estuary (North Carolina, USA). *Estuar. Coast. Shelf Sci.* **2007**, *72*, 63–80.
(19) The North Carolina Department of Transportation Ferry Division; general information can be viewed at http://www.ncdot.org/transit/ferry/.
(20) Paerl, H. W.; Valdes, L. M.; Pinckney, J. L.; Piehler, M. F.; Dyble, J.; Moisander, P. H. Phytoplankton photopigments as indicators of estuarine and coastal eutrophication. *BioScience* **2003**, *53* (10), 953–964.
(21) Consortium of Universities for the Advancement of Hydrologic Sciences Water and Environmental Research Systems Network; technical information can be viewed at http://www.watersnet.org/wtbs/.
(22) The Neuse River Estuary Modeling and Monitoring Project (ModMon); technical support information can be viewed at www.unc.edu/ims/neuse/modmon.
(23) The North Carolina Department of Environment & Natural Resources-Division of Water Quality (NCDENR-DWQ); data summaries can be viewed at http://h2o.enr.state.nc.us/.
(24) US Southeastern Regional Coastal Ocean Observing Systems (SeaCOOS); technical support information can be viewed at www.seacoos.org.
(25) North Carolina Dept. of Environment and Natural Resources-Div. Water Quality (NCDENR-DWQ). Phase II of the Total Maximum Daily Load for Total Nitrogen to the Neuse River Estuary, NC; Raleigh, NC, 2001.
(26) Valdes-Weaver, L. M.; Piehler, M. F.; Pinckney, J. L.; Howe, K. E.; Rossignol, K. L.; Paerl, H. W. Long-term temporal and spatial trends in phytoplankton biomass and class-level taxonomic composition in the hydrologically variable Neuse-Pamlico estuarine continuum, NC, USA. *Limnol. Oceanogr.* **2006**, *51* (3), 1410–1420.
(27) Hall, N. S.; Litaker, R. W.; Fensin, E.; Adolf, J. E.; Place, A. R.; Paerl, H. W. Environmental factors contributing to the development and demise of a toxic dinoflagellate (*Karlodinium veneficum*) bloom in a shallow, eutrophic, lagoonal estuary. *Estuaries Coasts* **2008**, *31*, 402–418.
(28) Surface Water Data for North Carolina: USGS Monthly Statistics; database can be viewed at http://nwis.waterdata.usgs.gov/nc/nwis/monthly.

ES900558F