Site Profile of the

North Inlet - Winyah Bay National Estuarine Research Reserve

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Photo of F. John Vernberg by George Cathcart, taken at the dedication ceremony of the Hobcaw Barony Discovery Center, September 2009.

The North Inlet - Winyah Bay National Estuarine Research Reserve (NERR) Site Profile document is dedicated to Professor Emeritus F. John Vernberg, Director of the Belle W. Baruch Institute for Marine and Coastal Sciences from 1969 to 1996. Dr. Vernberg guided and inspired the development of an internationally recognized and respected research program centered in the North Inlet estuary. His success in establishing one of the first of the National Science Foundation's Long-Term Ecological Research sites (1980) and then the North Inlet -Winyah Bay NERR (1992) has enabled hundreds of scientists, staff, and students to conduct the studies that comprise the remarkable collection of scientific contributions described in this volume.

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Preface: Organization of the Profile

This comprehensive document covers the environmental setting, history of human use, and geology and ecology of the North Inlet – Winyah Bay National Estuarine Research Reserve (NI-WB NERR or the Reserve.) It has been prepared to increase awareness of the Reserve's spectacular natural resources, the successful private-state –federal partnership that assures continued protection of local lands and waters, and especially the internationally recognized base of scientific knowledge associated with the research conducted in the estuaries that comprise the Reserve. Literally hundreds of researchers, technical assistants, and students have contributed to this volume through their studies over more than 40 years. We could not list all of the published authors and successful graduate degree recipients in this profile, but references to almost all of their work can be found at the website of the Belle W. Baruch Institute for Marine and Coastal Sciences, University of South Carolina, which operates the Reserve: **www.baruch.sc.edu**. The website is also a good source of information about research and teaching facilities available at the Baruch Marine Field Laboratory, opportunities for visiting scientists, and on-going studies in the North Inlet – Winyah Bay NERR.

The site profile is designed primarily for investigators interested in conducting work in the NI-WB NERR and provides a summary of the current state of knowledge about North Inlet and Winyah Bay. We hope that students, teachers, coastal decision makers, and interested citizens will also find the maps, facts and figures, and references to further reading helpful in their study, enjoyment, and stewardship of these local estuaries and watersheds. Supplemental background information on some topics is included in **Appendix A** and is organized by sections as they appear in the main text of the document.

Initial efforts to develop a site profile began many years ago. Changes in priorities, schedules, and staff personnel slowed the process, but it was the sheer volume of relevant information about the local environment that had been generated by scientists over the decades that made this an especially daunting project. The resulting summary of that knowledge reveals that, although we know a great deal, much still needs to be understood and done before we achieve the goal of balanced environmental integrity and human needs, so critical to the mission of the NI-WB NERR. It is not enough to protect sections of the coast or conduct research. Success relies on the communication of useful information to citizens and those who make decisions that affect the environment at the home, city, county, state, regional, and federal levels. The education programs sponsored by the Reserve are often based on the results of studies conducted here and throughout the world's coastal systems. We encourage residents and visitors to the area to participate in our education programs and contribute to maintaining a long and balanced future for our estuaries and coastal communities.

Acknowledgements

Primary recognition and thanks goes to the Belle W. Baruch Foundation, which has carefully managed and defended the 16,000 acres of Hobcaw Barony to insure its outstanding ecological well-being and value for research and education in perpetuity. Their support of the NI-WB NERR and its programs has resulted in a productive partnership in conservation, environmental monitoring and research, and both academic and public education programs.

With the continued funding support of the Reserve by the National Oceanic and Atmospheric Administration (NOAA) and the oversight and collaboration we have enjoyed with the NOAA Estuarine Reserve Division (ERD) in the Office of Ocean and Coastal Resource Management, the NI-WB NERR has grown to be a productive and well-respected source of information and instruction within the state and region. We thank the South Carolina Department of Health and Environmental Control's Office of Ocean and Coastal Resource Management for all of their services and support since the late 1980's when establishment of a NERR at North Inlet- Winyah Bay was still only a concept. It was the initiative of the former University of South Carolina Baruch Institute Director Dr. F. John Vernberg and the support of Senator Ernest Hollings and Governor Carroll Campbell that resulted in the nomination and official designation of the Reserve in 1992. For the vision of these champions and the help from many others involved in creating the Reserve, we are grateful.

Much of the planning, writing, and editing of this document were accomplished by Drs. Dennis M. Allen and Robert J. Feller, with additional writing and editing provided by Reserve Manager Wendy Allen. Dr. Jennifer Plunket, Stewardship Coordinator for the Reserve, also contributed to the final editing and formatted the document for publication. The leadership and support of the Baruch Institute Directors, Dr. F. John Vernberg, Dr. Madilyn Fletcher, and Dr. James T. Morris, are also gratefully acknowledged. Significant input and contributions of text, figures and images were provided by several former and current NI-WB NERR, Baruch Institute, and Baruch Foundation staff members over the years including Lee Brockington, Dr. Chris Buzzelli, Dr. Bob Gardner, Paul Kenny, Anne Miller, Ginger Ogburn-Matthews, Jeffrey Pollack, Dr. Erik Smith, Laura Schmidt, Beth Thomas, Dr. Anna Toline, and Leigh Wood. We also gratefully acknowledge Dr. Marie Bundy and Bree Murphy for their careful review of this document on behalf of NOAA. This was truly a huge team effort and we thank all who helped along the way.

Researchers met at Hobcaw House in 2007 to share data and experiences in North Inlet and Winyah Bay. Some investigators have conducted studies in North Inlet for more than 40 years.

The NI-WB NERR Program: Genesis, Rational, and Mission

Pre-NERR Programs on Site: USC-Baruch Institute Research and Education

The establishment of a long-term agreement between the Belle W. Baruch Foundation and the newly formed Belle W. Baruch Institute for Marine Biology and Coastal Research at the University of South Carolina (USC) in 1969 marked the beginning of a productive partnership in education and research that continues today. The Institute's name was later changed to the Belle W. Baruch Institute for Marine and Coastal Sciences. In the 1960's, individual scientists from other South Carolina institutions explored and described some of the flora and fauna of what is recognized today as the NI-WB NERR near Georgetown, South Carolina. Multidisciplinary research and formal academic and continuing education programs were not organized until the early 1970's when the USC and Clemson University (which started a forestry program on Hobcaw Barony in 1968) established research-oriented facilities on site. With interests in estuarine ecology and coastal marine sciences, USC researchers began monitoring environmental conditions and conducting experimental research in North Inlet. Campus-based (in Columbia, SC) and resident scientists were successful in attracting funding from state, federal, and private programs. Large grants from the US Environmental Protection Agency (EPA) and the National Science Foundation (NSF) provided the opportunity to gain insights into how the estuarine-salt marsh ecosystem at North Inlet is structured and functions in relation to the surrounding watershed and coastal ocean. The Outwelling Study, conducted in the late 1970's, involved dozens of investigators from different disciplines and hundreds of students. This study demonstrated a net flux of dissolved and particulate materials to the ocean thus supporting the notion that much of the rich productivity of the estuary is exported and helps to nourish the relatively impoverished nearshore ocean (Dame et al., 1986) and generated several other hypotheses that were investigated in subsequent years. In

The Outwelling Study, conducted in the late 1970's, involved dozens of investigators from different disciplines and hundreds of students.

1980, the first estuarine site in NSF's Long-Term Ecological Research (LTER) Program was established in North Inlet. Long-term time series collections of physical features of the water and atmosphere, microbes, water chemistry, algae, marsh plants, benthos, zooplankton, fishes, birds and many other ecosystem variables were measured regularly, and process-oriented research and ecological modeling were conducted.

The North Inlet LTER program ended in the early 1990s as the NI-WB NERR was becoming established. In the years preceding the Reserve's designation, approximately $15M in research funding had supported more than 250 research projects and led to the publication of more than 900 scientific papers and books. Hundreds of USC and visiting investigators from all over the world conducted studies within the North Inlet portions of the Reserve, making this one of the most intensively studied and well-understood estuaries in the world. The significance of these contributions to science was enhanced by the recognition that measurements were made within a relatively pristine coastal system, thus reflecting natural variability in the patterns and processes being measured. As a consequence, the value of these multi-decadal databases is increasing as society seeks an understanding of the impacts of sea level rise and other aspects of global climate change. **Appendix B** lists USC Baruch and NI-WB archived and web published databases for biological, water chemistry and meteorological, and water quality data.

By 1992, more than 200 graduate students had completed Master's theses and PhD dissertations that involved research in North Inlet, and many hundreds of USC's undergraduate Marine Science Program majors had spent time at the site. Field trips and the use of materials and data in classrooms served to expand the value of the site for formal environmental education. Starting in the late 1970s, USC Baruch Institute staff organized community-based education programs such as coastal ecology classes for children, teacher training courses, public lectures by scientists, and discussions on environmental issues. Constituting the first public environmental education programs in the Georgetown area, these helped increase awareness of our coastal systems and the value of protected areas and research within them.

Professor Bruce Coull and one of the first of hundreds of USC marine science classes to study life in North Inlet.

Baruch scientists celebrate completion of cruise #150 as part of the LTER project.

National Estuarine Research Reserve System and the North Inlet – Winyah Bay NERR

The National Estuarine Research Reserve System (NERRS) was created by the Coastal Zone Management Act (CZMA) of 1972, as amended, 16 U.S.C. Sec. 1461, to augment the Federal Coastal Zone Management (CZM) Program. The CZM Program is dedicated to comprehensive, sustainable management of the nation's coasts. The reserve system is a network of protected areas established to promote informed management of the Nation's estuaries and coastal habitats. The reserve system currently consists of 28 reserves in 23 states and territories, protecting over one million acres of estuarine lands and waters (Figure 1).

As stated in the NERRS regulations, 15 C.F.R. Sec. 921.1(a), the National Estuarine Research Reserve System mission is:

> *The establishment and management, through Federal-state cooperation, of a national system of estuarine research reserves representative of the various regions and estuarine types in the United States. National Estuarine Research Reserves are established to provide opportunities for long-term research, education, and interpretation.*

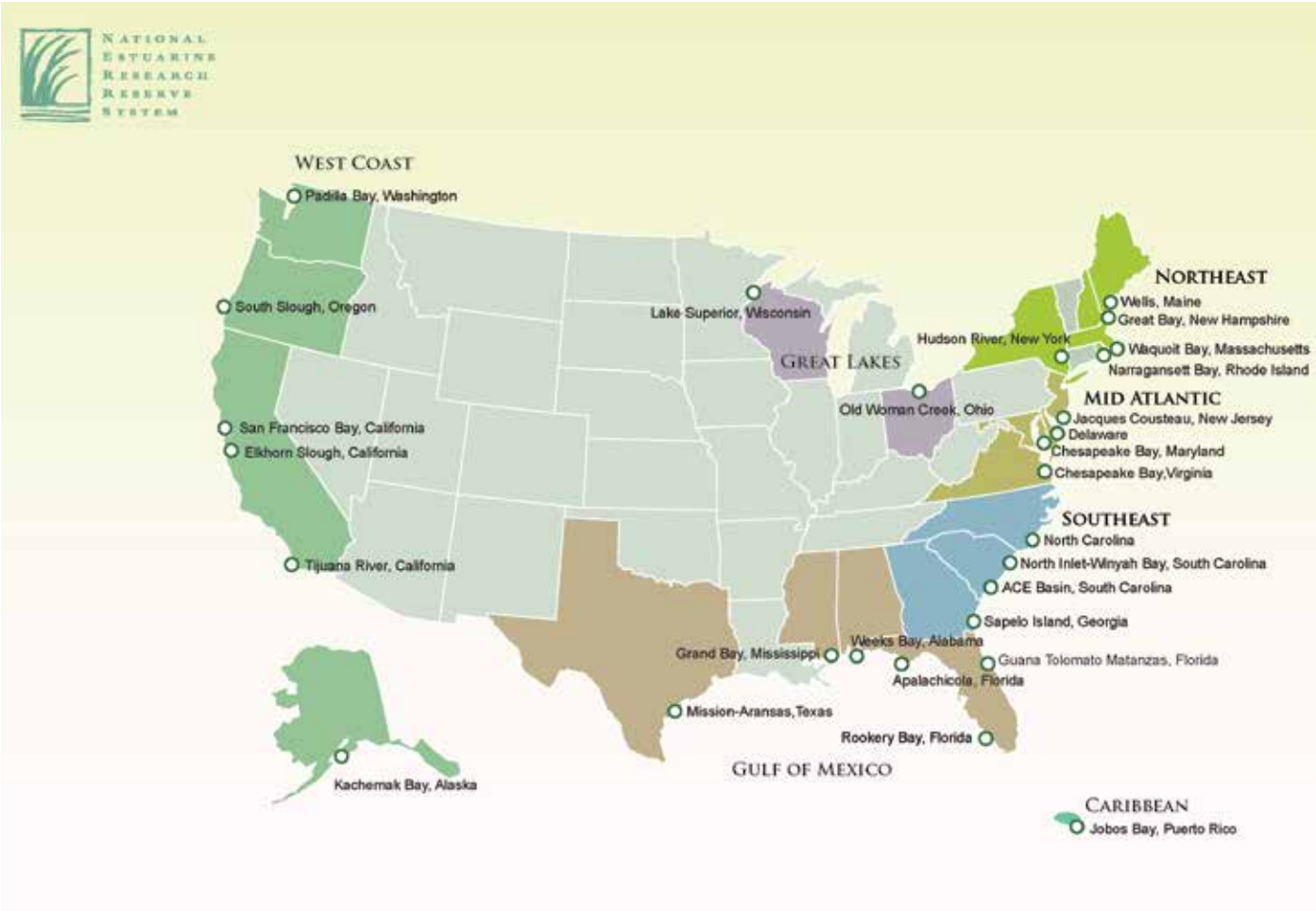

Figure 1. Location of the 28 Reserves in the National Estuarine Research Reserve System.

Federal regulations, 15 C.F.R. Sec. 921.1(b), provide five specific goals for the reserve system:

1) *Ensure a stable environment for research through long-term protection of National Estuarine Research Reserve resources;*

2) *Address coastal management issues identified as significant through coordinated estuarine research within the System;*

3) *Enhance public awareness and understanding of estuarine areas and provide suitable opportunities for public education and interpretation;*

4) *Promote Federal, state, public and private use of one or more Reserves within the System when such entities conduct estuarine research; and*

5) *Conduct and coordinate estuarine research within the System, gathering and making available information necessary for improved understanding and management of estuarine areas.*

The North Inlet – Winyah Bay National Estuarine Research Reserve (North Inlet – Winyah Bay NERR or NI-WB NERR or the Reserve) was designated in 1992 and is located in Georgetown County, South Carolina, about 30 miles south of Myrtle Beach and 50 miles north of Charleston (Figure 2). It encompasses 18,916 acres of tidal marshes and wetlands, much of which is on Hobcaw Barony, the 16,000 acre property of the Belle W. Baruch Foundation, a private, 501 (c) (3) operating foundation that manages its lands in perpetuity for conservation, research and education. The NI-WB NERR is administered by the Belle W. Baruch Institute for Marine and Coastal Sciences of the University of South Carolina that has facilities on the main university campus in Columbia, SC and on Hobcaw Barony.

The North Inlet – Winyah Bay NERR is in the South Atlantic subregion of the Carolinian biogeographic region in NOAA's Biogeographic Classification Scheme. The Reserve includes portions of two separate but connected estuaries: North Inlet, a small ocean-dominated estuary that is minimally impacted by human activities, and Winyah Bay, a classic estuary fed with freshwater by four major rivers. Both of these estuaries are described in more detail in other chapters of the site profile. The Reserve boundary has not changed since designation in 1992 (Figure 3). The core area of the Reserve is estimated at 11,173 acres and the buffer area is 7,743 acres, bringing the total acreage to 18,916 acres. A detailed description of these boundaries is contained the NI-WB NERR Management Plan (2011).

The University of South Carolina Belle W. Baruch Institute for Marine and Coastal Sciences operates the Baruch Marine Field Laboratory (BMFL) on Hobcaw Barony.

The Reserve wing of the BMFL houses a classroom, library, laboratory and offices. The NI-WB NERR is administered by the Belle W. Baruch Institute for Marine and Coastal Sciences of the University of South Carolina.

Looking south over North Inlet. Hobcaw Beach is in the forground. Image courtesy of Dr. Erik Smith.

Looking southwest over North Inlet and the Baruch Marine Field Laboratory. The bridges over Winyah Bay are in the upper left. Image courtesy of Dr. Timothy A. Mousseau.

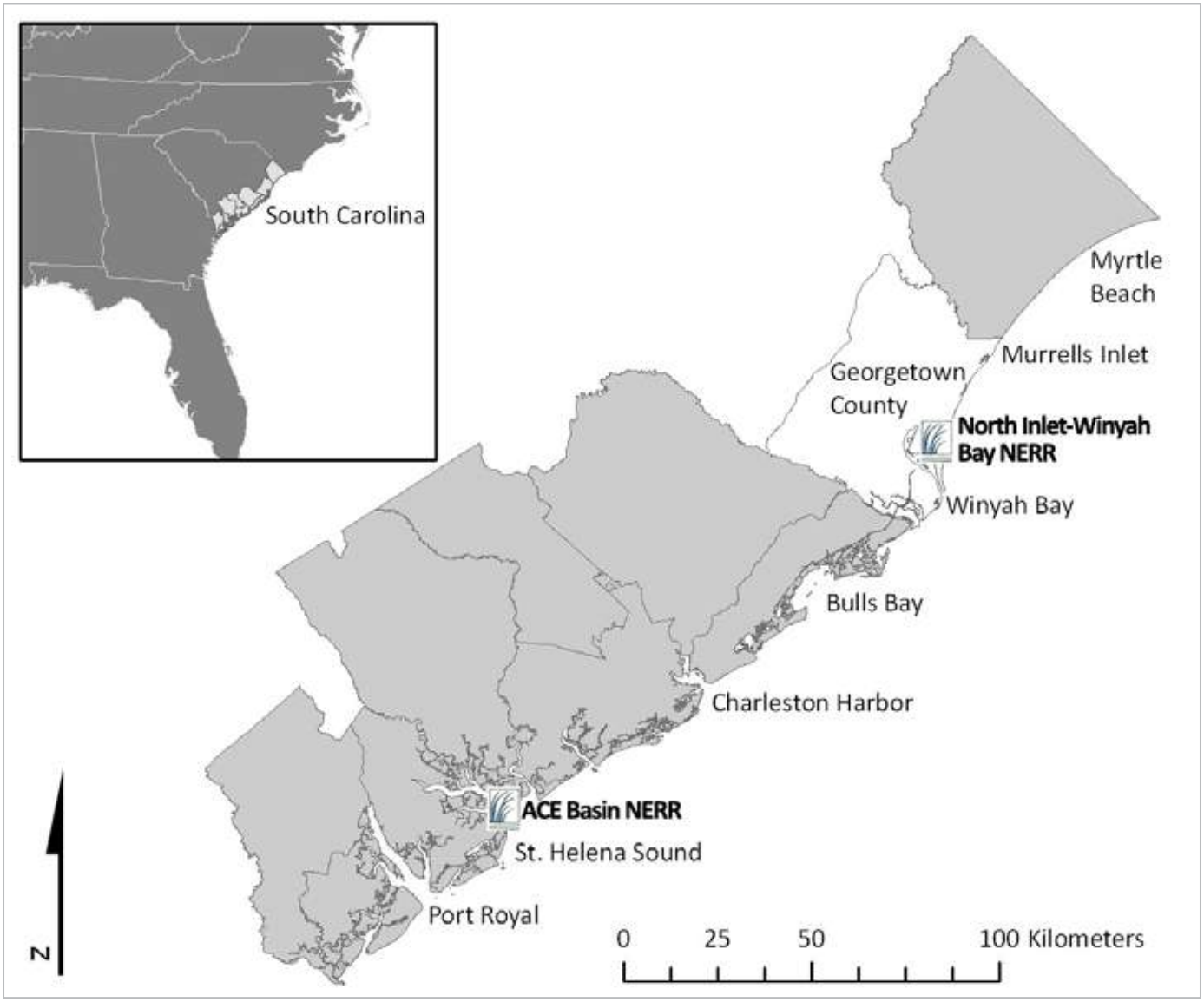

Figure 2. Location of the North Inlet-Winyah Bay National Estuarine Research Reserve in Georgetown County, South Carolina.

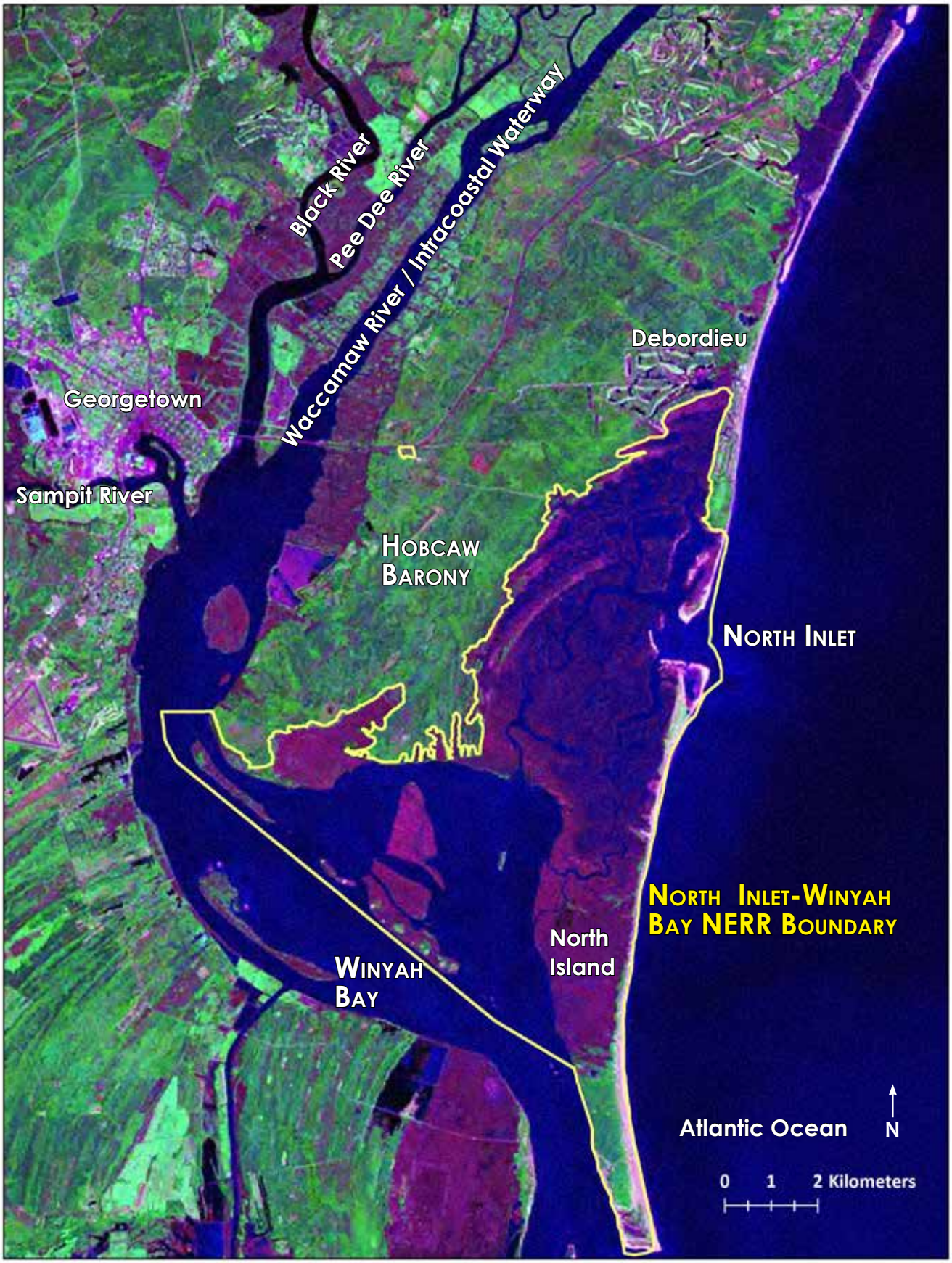

Figure 3. Boundary of the North Inlet-Winyah Bay National Estuarine Research Reserve.

» Reserve Milestones since Designation

There have been a number of significant milestones for the NI-WB NERR since it was established in 1992. The program has grown from a small staff of five individuals including a Manager, Research Coordinator, Education Coordinator and two research technicians to nine full-time and two part-time staff members. New positions were established over the years including a full-time Stewardship Coordinator (2001), a Coastal Training Program Coordinator (2003), and a full time Education Specialist (2007.) The research and monitoring program has also grown from a Research Coordinator and two technicians to a Research Coordinator and three full-time research specialists and one part-time research assistant. The Reserve also shares a system administrator with the Baruch Marine Field Laboratory and NERRS Centralized Data Management Office (CDMO).

Significant improvements to Reserve facilities have occurred since 1992. The NI-WB NERR was successful in securing a NOAA construction award to complete a 4,500 square-foot addition to the Baruch Marine Field Laboratory in 2002 that serves as the Reserve headquarters. NOAA construction funds were also used to enhance educational facilities on site including construction of a salt marsh boardwalk and renovations to the Kimbel Lodge, a conference building used for public education and Coastal Training Program events. Most recently, the Reserve received a series of NOAA construction awards to plan and build an education center in cooperation with the Belle W. Baruch Foundation. This joint-use facility, the Hobcaw Barony Discovery Center, was completed in 2009. It has approximately 12,000 square feet of space and includes a large exhibit area, classroom, audio-visual room and offices for Reserve and Baruch Foundation education staff. Staff members of the NERRS CDMO also occupy space in the staff wing of the center. A screened outdoor classroom adjacent to the Kimbel Pond and Lodge was also completed in 2009.

Although the North Inlet site was already well known for its research productivity before the Reserve was established, the NI-WB NERR has provided a stable platform for additional research and long-term monitoring. The Reserve's research and monitoring program has also experienced significant growth since 1992. Milestones include the successful establishment of the NERR System-wide Monitoring Program (SWMP) at our site (1993) and subsequent expansion of this program, including two monitoring sites that are linked via satellite for real time data transmission. While the Reserve has continued long-term biological monitoring for zooplankton, nekton and benthos, programs established prior to designation, it has also initiated new monitoring programs. In 2005, the Reserve established a series of permanent sampling transects in North Inlet for long-term biomonitoring of emergent marsh vegetation according to NERRS protocols; this was expanded in 2007 to include measures of sediment elevation change and porewater chemistry. These efforts position the Reserve to act as a sentinel site for salt marsh response to climate change and sea level rise in an area where marsh transgression of the uplands is not impeded by coastal development. In 2005 the Reserve also began routine monitoring of microplankton metabolism, designed to complement the SWMP nutrient monitoring program and track the ecological response of subtidal creeks to variability and change in salt marsh productivity. Within the broader watershed, the Reserve has been an active member of the multi-agency Long Bay Workgroup since its inception in 2004, examining the occurrence and mechanisms of hypoxia formation along the northern portion of the South Carolina coast.

The Reserve serves thousands of school aged children each year and provides a variety of classes, seminars and other public events to engage adults and families in learning about estuaries and the discoveries being made by scientists in the Reserve. The addition of the marsh boardwalk in 1997 and a salt marsh trail designed in 2011 provide increased access and opportunities for visiting groups to learn about salt marshes. Both access areas are used regularly by the Reserve in its education programs for K-12 students and members of the public and also by the Belle W. Baruch Foundation during public tours of the Hobcaw Barony property, conducted

2-4 times a week. The completion of the Hobcaw Barony Discovery Center in 2009 was a major milestone for the Reserve and enhances presence and visibility in the local community. The Reserve also enhanced its visibility with the creation of a website (**www.northinlet.sc.edu**) and an electronic newsletter, *Estuaries Illustrated*, that inform people about Reserve research, monitoring, stewardship and education activities.

The completion of the Hobcaw Barony Discovery Center in 2009 was a major milestone for the Reserve and enhances presence and visibility in the local community.

The midden tank is a popular exhibit at the Hobcaw Barony Discovery Center.

The transition of coastal issue workshops for decision-makers to a fully-implemented Coastal Training Program (CTP) in 2003 represented another significant milestone for the Reserve. The CTP addresses coastal information and management needs of local community leaders, environmental planners and engineers, and other coastal decision-makers. Current findings from scientific research and best management practices are shared during training events and field demonstration projects. This training program has been very well received by the local communities that it serves and has resulted in more informed decisions and actions being taken by planners and local governments such as using pervious alternatives for parking spaces.

The Reserve has also experienced success in the areas of resource management and stewardship. The Reserve worked with other conservation partners to develop the Coastal and Estuarine Land Conservation Program (CELCP) for South Carolina. One of the bigger success stories in this realm has been through working with the Beach Vitex Task Force. The Reserve helped form this group in 2002, remains an active member and maintains the task force website. Efforts of the task force have kept the invasive plant beach vitex from achieving its potential reputation as the "kudzu of the coast." Education efforts combined with research, town and county imposed ordinances prohibiting the planting of beach vitex, and voluntary and mandatory eradication efforts by individual property owners and communities, have contributed to this success story.

» Reserve Mission and Goals

The original Reserve management plan published in 1992 was updated in 2011 and provides a framework for the Reserve to continue to address NERRS and site-based priorities. The mission of the NI-WB NERR as defined in the 2011-2016 Management Plan is:

> *"To promote stewardship in the North Inlet and Winyah Bay watersheds through science and education"*

This mission supports the vision of sustainable and ecologically productive estuaries. The Reserve identified three goals on which to focus its research, education and stewardship efforts over the next several years that will help achieve this mission and vision. These goals, listed below, along with strategies to achieve them are also described in the NI-WB NERR Management Plan (2011).

- Understand and minimize the impacts of coastal growth on water and habitat quality and ecological communities
- Understand the impacts of naturally occurring short-term, stochastic and long-term, large-scale climate events on coastal ecosystems and human communities
- Understand and reduce the impacts of invasive species and habitat loss on biodiversity

» Resource Management and Responsible Authorities

The NI-WB NERR works in cooperation with the Belle W. Baruch Foundation (BWBF) and other partners to ensure that the resources in the Reserve are managed and protected to the fullest extent possible. Authority for resource protection within the Reserve resides with a number of different state and federal agencies. Public access and use of the upland portions of the Reserve is restricted by the BWBF. Visitors authorized by the BWBF, Baruch Institute or the Reserve, including scientists, students, and special groups, may enter through the electronic gate at the main entrance of Hobcaw Barony. Scientific permit requests are carefully reviewed through the system in place at the Baruch Institute of USC. The Baruch Institute obtains a permit each year from the SC Department of Natural Resources (SCDNR), Marine Resources Division, to collect biological samples in the North Inlet and Winyah Bay area. If new research projects are not covered by this permit, the investigator will have to obtain a special permit from the appropriate governmental agency such as the SCDNR, United States Fish and Wildlife Service (USFWS) or NOAA. Approved permits must be in possession of permit holders at all times when in the field sampling. In addition to state and federal permits, written permission must be obtained from the BWBF prior to conducting research on the Hobcaw Barony property. This system is in place to protect the environmental integrity of the Baruch Foundation's holdings and to ensure that new studies will not interfere with existing projects. These policies have not impeded research in any substantive manner but some lead time is required to process requests before research projects can begin. Persons interested in conducting new research should contact the Reserve for additional information on the approved policies and procedures.

NERR System-wide Monitoring Program and other Monitoring at the NI-WB NERR

The National Estuarine Research Reserve System (NERRS) provides a mechanism for addressing scientific and technical aspects of coastal management problems through a comprehensive, interdisciplinary, and coordinated approach. Research and monitoring programs, including the development of baseline information, form the basis of this approach. Reserve research and monitoring activities are guided by the research and monitoring plan 2006-2011 which identifies goals, priorities, and implementation strategies. This approach, when used in combination with the education and outreach programs, will help ensure the availability of scientific information that has long-term, system-wide consistency and utility for managers and members of the public to use in protecting or improving natural processes in their estuaries.

Prior to the mid 1990s each reserve operated its research and monitoring program independently. The NERR System-wide Monitoring Program (SWMP) was designed and implemented at all reserves in 1995 and provides standardized data on national estuarine environmental trends while allowing the flexibility to assess coastal management issues of regional or local concern. The principal mission of the monitoring program is to develop quantitative measurements of short-term variability and long-term changes in the integrity and biodiversity of representative estuarine ecosystems and coastal watersheds for the purposes of contributing to effective coastal zone management. The program is designed to enhance the value and vision of the reserves as a system of national references sites. The program also takes a phased approach and focuses on three different ecosystem characteristics, described below.

1) **Abiotic Variables:** The monitoring program currently measures pH, conductivity, salinity, temperature, dissolved oxygen, turbidity, water level and atmospheric conditions. In addition, the program collects monthly nutrient and chlorophyll *a* samples at four SWMP stations and monthly diel sampling at one SWMP station. The chlorophyll and nutrient data are collected by hand or, in the case of diel sampling, by automated instruments. These data are submitted to a centralized data management office.

2) **Biotic Variables:** The reserve system is focusing on monitoring biodiversity, habitat and population characteristics by monitoring organisms and habitats as funds are available.

3) **Watershed and Land Use Classifications:** This component attempts to identify changes in coastal ecological conditions with the goal of tracking and evaluating changes in coastal habitats and watershed land use/cover. The main objective of this element is to examine the links between watershed land use activities and coastal habitat quality.

These data are compiled electronically at a central data management "hub", the NERRS Centralized Data Management Office (CDMO) at the Belle W. Baruch Institute for Marine and Coastal Sciences of the University of South Carolina, located at the NI-WB NERR. The CDMO provides additional quality control for data and metadata and compiles and disseminates the data and summary statistics via the Web (**http://cdmo.baruch.sc.edu**) where researchers, coastal managers and educators can readily access the information. The metadata meet the standards of the Federal Geographical Data Committee.

» Implementation of the System-Wide Monitoring Program at the North Inlet –Winyah Bay NERR

Routine environmental monitoring within North Inlet has occurred, in some fashion, since 1980, when a National Science Foundation Long-Term Ecological Research Site was established (LTER; 1980-1993). Abiotic variable monitoring under the evolving NERRS SWMP auspices began at the NI-WB NERR in 1993, with the establishment of two long-term water quality monitoring sites, one in North Inlet (Oyster Landing site) and one in a tidal creek of Winyah Bay (Thousand Acre Marsh site). A third long-term monitoring site was added in 1998 (Debidue Creek), and the fourth site in 2001 (Clambank Creek site). The location of the four SWMP stations is shown in Figure 4. At each station, YSI 6600 EDS data loggers are continuously deployed to record pH, conductivity, salinity, temperature, dissolved oxygen, turbidity, and water level data at 15 minute intervals, as per NERRS SWMP protocols. The 15 minute data from Oyster Landing and Debidue Creek stations are transmitted on an hourly basis to the NOAA Geostationary Operational Environmental Satellites (GOES) to provide near real-time data.

Figure 4. Location of the four System-wide Monitoring Program (SWMP) stations, vegetation biomonitoring transects, and fauna monitoring sites in the North Inlet-Winyah Bay National Estuarine Research Reserve.

Four System-wide Monitoring Program (SWMP) stations are located in the NI-WB Reserve at Clambank Creek (top left), Oyster Landing (top right), Debidue Creek (bottom left) and Thousand Acre.

Routine nutrient and chlorophyll *a* monitoring was initiated at each of the four sites at the same time the stations were established for long-term water quality monitoring. Nutrients and chlorophyll *a* are sampled at exactly 20 day intervals, more frequently than the NERRS-recommended "approximately monthly intervals." This decision, approved by the NERR SWMP Oversight Committee and NERRS Data Management Committee, was made so as to minimize sampling bias with respect to spring – neap tidal periodicity over the annual cycle. On these 20 day intervals, both duplicate low tide grab sampling and diel sampling (2 hr and 4 min intervals over 26 hr) of water are conducted at each of the four stations. This sampling is accomplished through the deployment of ISCO model 3600 automated water samplers at each of the four stations. In addition to the currently the required dissolved inorganic nutrients (NH_4^+, NO_2^-, NO_3^- and PO_4^{3-}) and chlorophyll *a*, the Reserve has also been measuring a suite of elective nutrients. To date, this includes dissolved organic carbon, total suspended solids, organic and inorganic suspended solids (determined by difference before and after combustion at 450°C), as well as total nitrogen and total phosphorus in both the particulate and dissolved phases, which allow organic nitrogen and phosphorus fractions to be determined as the difference between total and inorganic fractions.

Meteorological conditions at North Inlet have been measured by the Baruch Marine Field Laboratory since 1982. In 1997, meteorological measurements were modified slightly to conform

to the newly established NERR SWMP protocols for meteorological data collection. The NI-WB weather station is located at Oyster Landing, adjacent to the long-term water quality and nutrient monitoring station. Air temperature, wind speed and direction, relative humidity, barometric pressure, rainfall, total short-wave global radiation (280 - 2800 nm wavelengths) and photosynthetically active radiation (400-700 nm wavelengths) are recorded. Sensors are all located on an electrically grounded aluminum tower at a height of approximately 3.5 meters. Sensors are connected to a Campbell Scientific CR-1000 data logger that records the meteorological conditions every 5 seconds continuously throughout the year, producing 15 minute, hourly, and daily averages of the data parameters.

» Other Monitoring Programs Conducted by the Reserve

ESTUARINE FAUNA MONITORING

Routine monitoring of dominant estuarine fauna in North Inlet began in the early 1980s with a grant from the National Science Foundation's LTER program. This monitoring was continued by the Reserve beginning in 1993. The on-going goals of this program are: to quantify the long-term composition and abundance of estuarine fauna within the Reserve in order to characterize and understand short-term variability and long-term changes in the abundance and community composition of both resident and transient estuarine species; to provide researchers and resource managers reference data from a relatively pristine estuary for comparisons with anthropogenically-impacted estuarine sites; and to provide baseline data for other faunal research conducted within North Inlet.

The components of the Reserve's fauna monitoring program include:

Zooplankton: Defined by two size fractions: a 153 micrometer mesh net towed obliquely through the water column collects copepods and small invertebrate larvae; and a 365 micrometer mesh net mounted on an epibenthic sled collects the larvae of fishes, shrimps and crabs as well as other large zooplankton. 153 micrometer tows are collected in duplicate. 365 micrometer tows are collected in triplicate. Samples have been collected biweekly since 1981 at mid-ebb tide in Town Creek and have been identified to lowest practical taxa and life stage.

Nekton: Comprised of resident and transient fishes, shrimps and crabs greater than 20 mm long. From 1984 until fall 2011, biweekly (spring, summer and fall) or monthly (winter) collections were made using a combination of seining a drainage pool at low tide and/or enclosing a one acre area of flooded marsh at high tide and collecting all fauna leaving the area with the ebbing tide in a 0.25 inch mesh net. Sample catches were processed for species richness, individual species abundance and biomass, individual species lengths, and total catch abundance and biomass. This very labor-intensive sampling was conducted in the Oyster Landing basin, adjacent to the Reserve's long-term water quality, nutrient and weather monitoring station. Since fall 2011, the project was scaled back to examine phenology and growth of transient species to this basin through a biweekly seining effort conducted April – November.

Benthos: Two size fractions of animals that live in the sand or mud have been made at the same locations in North Inlet since 1972 (meiofauna) and 1981 (macrofauna). Biweekly samples of macrobenthos (> 0.5 mm) were collected from 1981-1992, and then quarterly from 1992 to the present. Meiofauna (<0.5 mm > 0.063 mm) samples were collected at two sites and analyzed through 1994. Although macrofauna continue to be sampled on a quarterly basis to maintain continuity in the dataset, neither the Reserve nor the Baruch Marine Field Laboratory currently has the personnel and resources needed to process the archived samples.

SALT MARSH EMERGENT VEGETATION MONITORING

As part of the biological component of the NERR System-Wide Monitoring Program, the Reserve initiated a long-term vegetation monitoring program

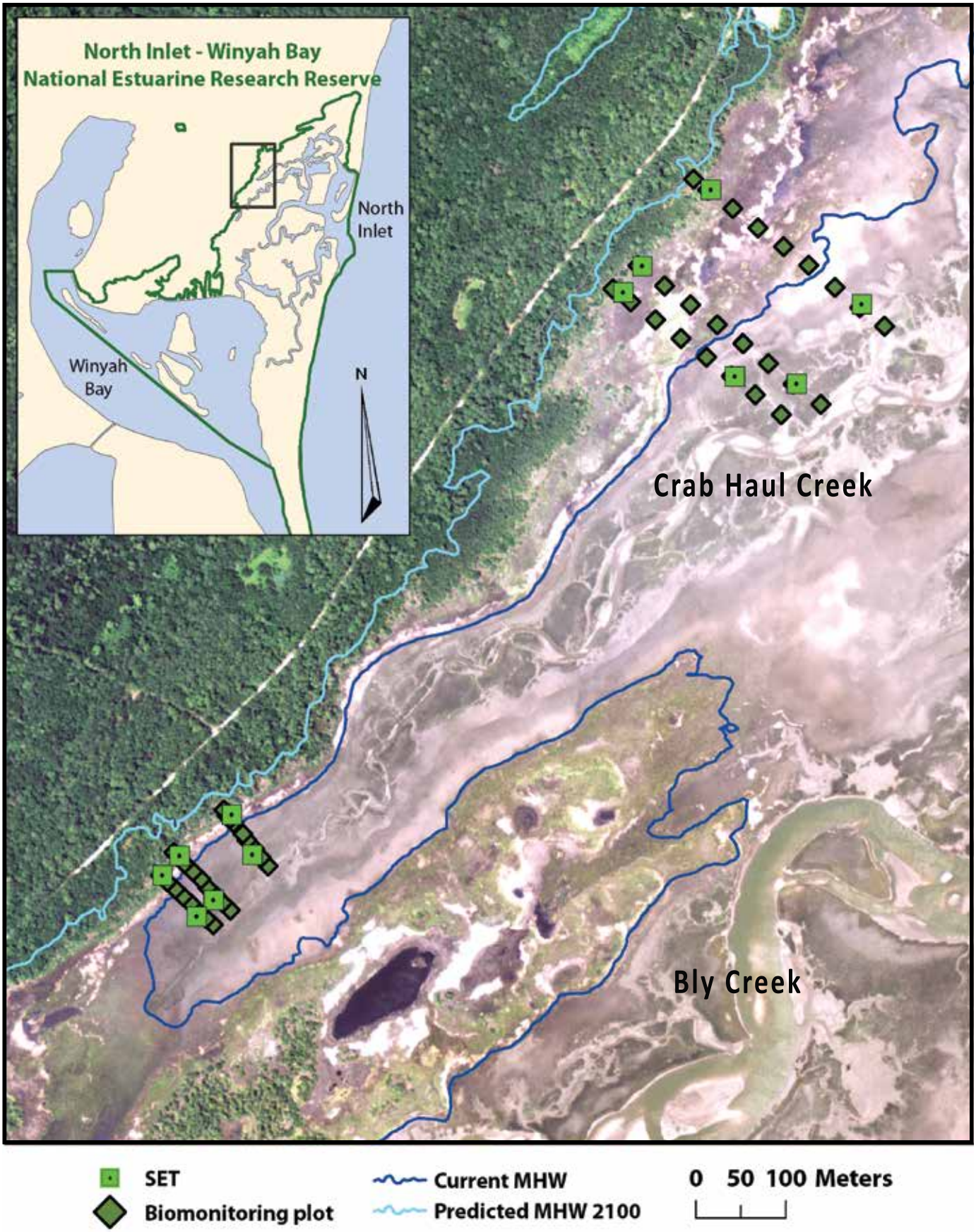

Figure 5. Long-term emergent vegetation monitoring plots and infrastructure in the Crab Haul Creek basin in North Inlet.

in 2005. The long-term goal of this program is to assess the effects of rising sea level on the spatial dynamics of emergent vegetation communities within the salt marshes of the North Inlet –Winyah Bay NERR. Specifically, this project seeks to quantify how salt marsh macrophyte community structure (species composition, relative abundance) varies along an elevation gradient, from creek bank to upland forest edge, in response to long-term changes in tidal height and flooding frequency due to sea level rise. In accordance with established NERRS protocols, a stratified sampling approach using fixed transects and repeated measurements within permanent sample plots are employed. Two segments have been established along the central axis of upper Crabhaul Creek, upstream of the Oyster Landing long-term water quality, nutrient and weather monitoring station and NOAA/NOS tide gauge (Figure 5). Within each segment, 3 fixed transects were randomly established from creek bank to the western, upland edge of the marsh platform. Each segment delineates a total of 25 permanent sampling plots. Groundwater wells and porewater equilibrators are installed adjacent to each permanent plot. Sediment Elevation Tables (SETs) have been installed adjacent to plots at the lower and upper ends of each transect. Vegetation sampling includes: percent cover for each species or cover category; species' shoot/stem density; species' maximum canopy height, which is conducted annually at the end of the growing season. Water table height and salinity at low tide is sampled biweekly, porewater chemistry (nutrients, dissolved organic carbon, and sulfide concentrations) is sampled monthly during summer, SET measurements are conducted bimonthly.

A long-term monitoring program will help to assess the effects of rising sea level on the spatial dynamics of emergent vegetation communities within the salt marshes of the North Inlet –Winyah Bay NERR.

MICRO-PLANKTON METABOLISM MONITORING

The Reserve conducted a program to quantify and understand the short-term variability and potential for long-term change in water column respiration and heterotrophic production rates through a combination of routine field measurements and manipulative experiments during the period July 2005 – December 2012. The focus of this effort was on the tidal creeks and open-water portions of the estuary because these represent the conduit for material exchanges between the land-margin and coastal ocean. Routine sampling was conducted on both ebbing and flooding tides at the Oyster Landing site in conjunction with the 20-day water chemistry sampling. The goal of this program was to quantify the role of the pelagic microbial community in the biogeochemical dynamics of carbon, nutrients and oxygen in the creek waters of North Inlet. This information will help improve understanding of how key ecological processes within the ecosystem respond to long-term changes associated with climate change, salt marsh productivity and organic export associated with sea level rise.

Geographic and Cultural Setting

The Region and South Carolina Coast

North Inlet-Winyah Bay NERR is located in Georgetown County, SC, about 50 km (30 mi) south of Myrtle Beach and 80 km (50 mi) north of Charleston (see Figure 2 presented in an earlier chapter). The entire length of the South Carolina coastline stretches approximately 300 km (180 mi) and includes more than 4,800 km (nearly 2,900 miles) of shoreline. Approximately 80,000 ha (200,000 acres) of marshes occur along this coast. A full range of Southeast coastal systems, including river-dominated estuaries (e.g., Winyah Bay, Santee), coastal lagoons and sounds (e.g., Bulls Bay, Port Royal), and ocean-dominated salt marsh systems (e.g., North Inlet and Murrells Inlet) can be found along the South Carolina coast.

South Carolina has four major watersheds that terminate at the coast, the Savannah, the Santee, the A.C.E. and the Pee Dee. Winyah Bay is in the northernmost Pee Dee watershed (Figure 6). The main rivers in central South Carolina meet the ocean at Charleston Harbor Estuary. Several smaller rivers drain through the ACE Basin NERR. The Savannah River Basin drains some of southern SC. Although the most conspicuous estuaries on the SC map are associated with major rivers, tidally-dominated estuarine waterways and marshes are far more numerous on the SC coast than those which receive most of their water from rivers.

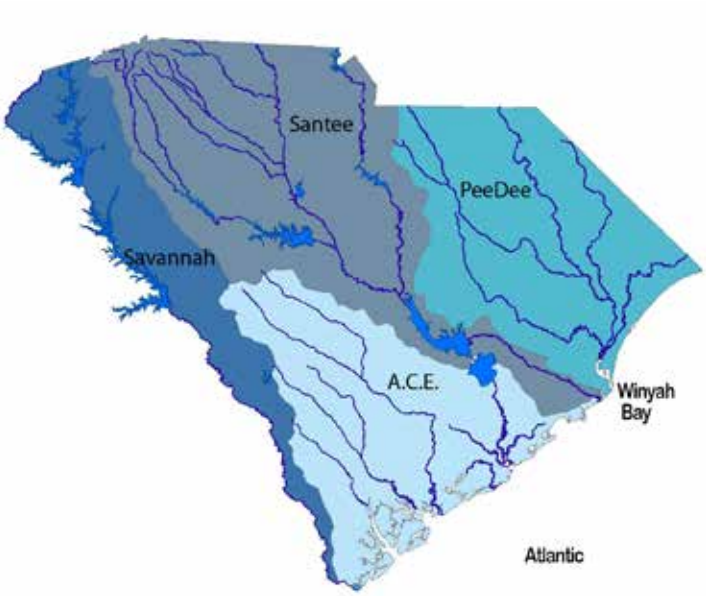

Figure 6. The four major watersheds of South Carolina.

According to NOAA's Biogeographic Classification Scheme, the NI-WB Reserve is in the South Atlantic subregion of the Carolinian biogeographic region. Other southeastern NERR sites include the NC NERR, the ACE Basin NERR about 150 km (90 mi) south of the NI-WB NERR in SC, the Sapelo Island NERR near Brunswick, GA, and the GTM NERR near St. Augustine, FL (Figure 7).

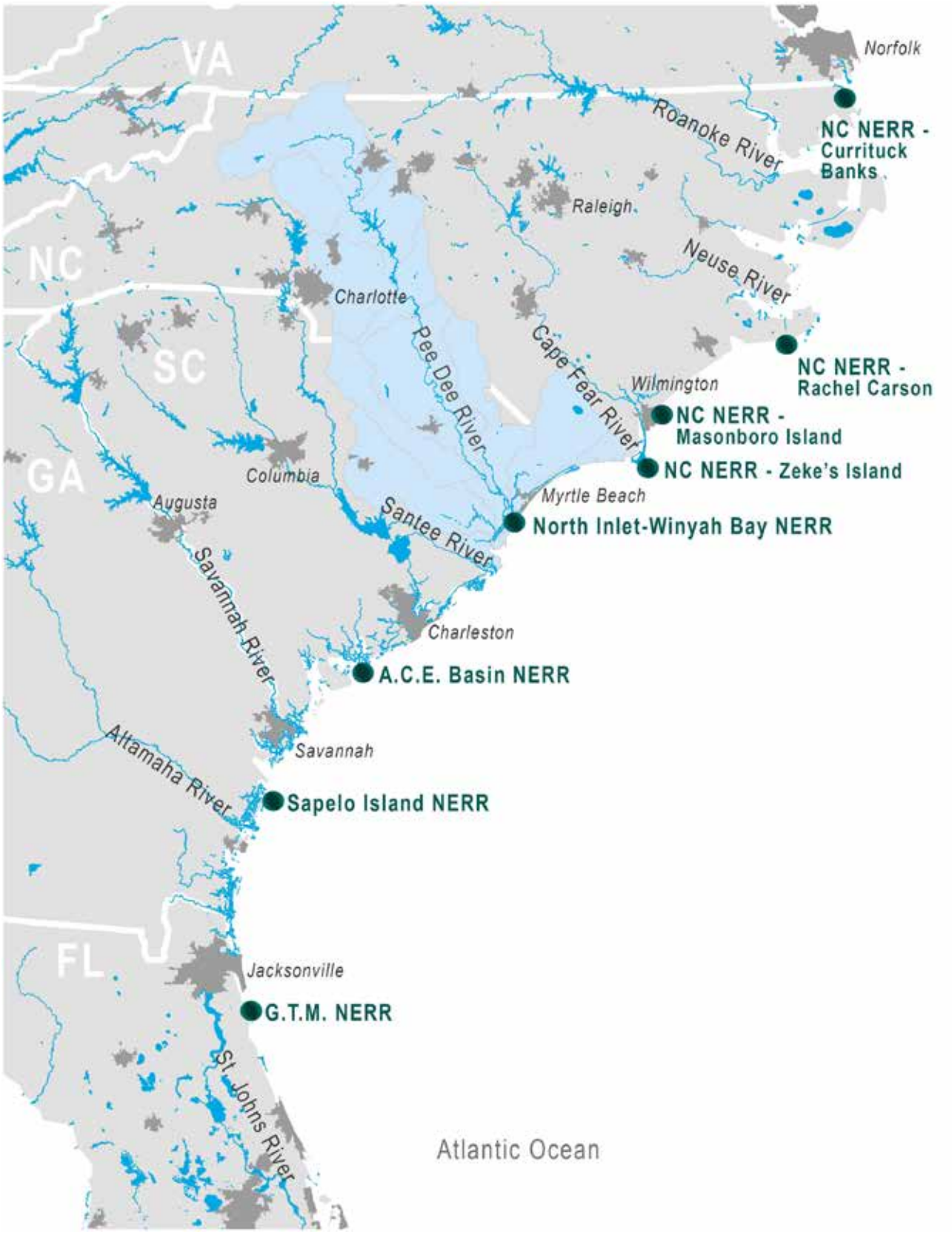

Figure 7. Southeast Reserves and major rivers and urban areas of the southeast. The Winyah Bay watershed is highlighted in blue.

The North Inlet and Winyah Bay Estuaries

The Winyah Bay watershed lies mostly on the coastal plain of South Carolina (Figure 7). The sloped landscape accounts for a steady movement of riverine waters towards the sea. In terms of watershed size, Winyah Bay is the third largest estuary on the east coast of the US after the Chesapeake Bay (VA) and Pamlico-Albemarle (NC) complexes. The entire Winyah Bay watershed is approximately 18,000 square miles (4.7 million hectares or about 12 million acres). It accounts for about 20% of North Carolina's and 25% of South Carolina's land areas. The watershed is mostly rural forested and agricultural lands. Five primary river systems comprise the basin (Figure 8). With origins in the Blue Ridge Mountains of North Carolina, the Pee Dee – Yadkin River system drains the largest portion of the watershed (>85%); the (Great) Pee Dee is the largest river associated with Winyah Bay. The Lynches River lies to the west of the Pee Dee and drains a portion of east central SC. The Black and Sampit Rivers, which merge with the Pee Dee further downstream, drain coastal SC counties. The Little Pee Dee lies to the east of the Pee Dee and drains a portion of northeastern SC. The Waccamaw River originates from Lake Waccamaw in eastern NC and parallels the coastline. All of the rivers merge within 50 km (30 mi) of the coast and form an expanse of forested wetlands and marshes at the headwaters of the open water body known as Winyah Bay.

Winyah Bay is oriented along a northwest-southeast axis. The estuary is about 30 km (18 mi) long and ranges in width from 1 to 7 km (0.6 – 4.2 mi) (Figure 8). The surface area is approximately 15,500 ha (about 40,000 acres). Mean depth is 4.2 m (14 ft) and the deepest areas are associated with the shipping channel that traditionally was maintained at 8.2 m (27 ft). This federally-authorized channel extends from the Port of Georgetown about 29 km (17 mi) to jetties at the mouth of Winyah Bay. Various types of tidal wetlands and impounded marshes border Winyah Bay downstream of the US Highway 17 bridges.

The North Inlet watershed is comparatively small, comprising approximately 38 square kilometers (3800 ha or just under 15 square miles). Most of the uplands are forested and only about 2% of the watershed is developed (Figure 8). Freshwater runoff into the tidally-dominated North Inlet is through numerous small streams and groundwater. The bar-built type estuary at North Inlet encompasses approximately 3,300 ha (8,250 acres). Salt marsh cordgrass (*Spartina alterniflora*) dominates the system, but other types of marshes occur around the upland borders and on the southern border where North Inlet intersects with the Mud Bay section of Winyah Bay (Figure 8). Mud Bay is an expansive shallow lagoonal area north and east of the main axis of Winyah Bay. Several large marsh islands and historic dredge spoil islands lying along the navigation channel separate Mud Bay from the rest of the open water of Winyah Bay.

The Black and Pee Dee Rivers (left) and the Waccamaw River (right) enter Winyah Bay just north of Georgetown.

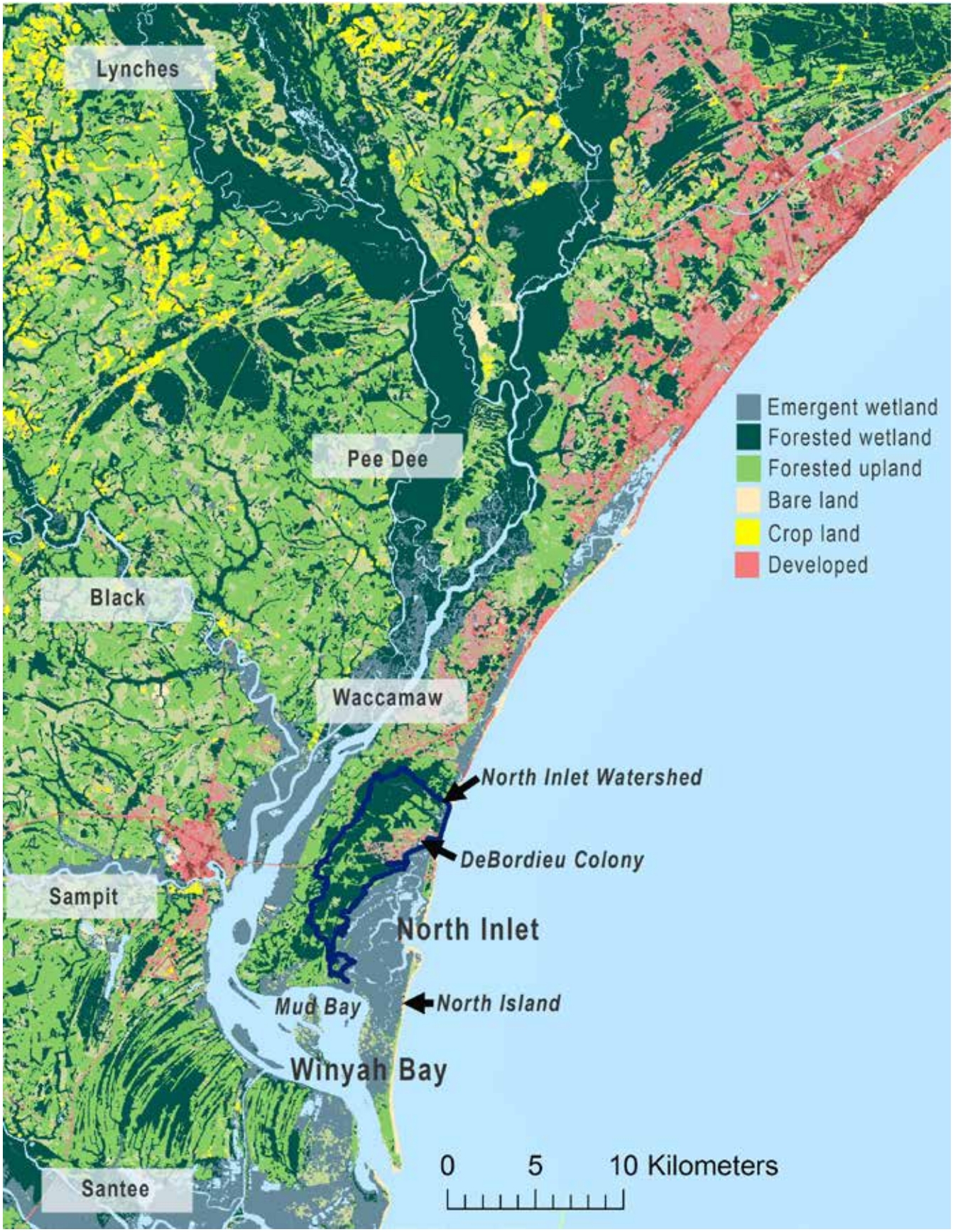

Figure 8. Rivers and landcover in the Winyah Bay and North Inlet watersheds.

Historic Land and Water Use

The peninsula where the North Inlet – Winyah Bay NERR is located was called "hobcaw" by local Native Americans. Meaning "between the waters," the term refers to the forested uplands being bordered by the Waccamaw River and Winyah Bay on the west and by the Atlantic Ocean on the east. The land supported the seasonal villages of the Waccamaw tribe. They hunted whitetail deer, black bear and wild turkey in the forests and harvested fish, oysters, clams, shrimp and crabs from the marshes.

The first contact with Europeans was most likely in 1526 when Spanish voyagers arrived with families, slaves and livestock and, according to most scholars, created a settlement on the shores of Hobcaw. The Spanish were unsuccessful. The English established the colony of Carolina in 1670 with Charleston as its capital and by 1700 had created Indian trading posts on the rivers of present day Georgetown County, one of which was located on Hobcaw's bluff overlooking Winyah Bay.

In the 18th century, Englishmen sought and were awarded land grants. Native Americans were displaced into present day Horry County, SC, and North Carolina. Hobcaw Barony was granted by King George to Lord Carteret, one of South Carolina's eight Lords Proprietors. The grant, called a "barony," stretched from the river to the sea and included swamps, marshes, woods and dunes. As the colony prospered, the tract was sold and subdivided into 14 separate, individually named plantations which first produced timber and naval stores, such as pitch, tar and turpentine, and within a few more years, high yields of indigo and rice.

By the time of the Civil War, Georgetown County grew more rice than any other place in the world except the area around Calcutta, India. At Hobcaw Barony, the plantations were owned by men whose names are prominent in local history, and the land was worked by slaves whose descendants still live in the area. Remnants of the plantation era survive as extant slave cabins, ruins of a rice mill and cemeteries. Maps, deeds and plats provide evidence of main houses, churches, summer cottages, boundary ditches and rice fields.

The rice era changed significantly following the emancipation of slaves and with growing competition from rice growers in western states. A series of unusual storm events at the turn of the 19th century ended rice production, and landowners sought to create revenue by harvesting timber and leasing their land to hunters.

In 1904, Bernard M. Baruch, a native South Carolinian and Wall Street financier, hunted over the rice fields and salt marshes of Hobcaw Barony with a group of northern hunters. He spontaneously offered to purchase the land. By 1907, Baruch was able to buy 11 of the original 14 tracts from various

Above: Friendfield Village Cabins, circa 1905 - courtesy of the Belle W. Baruch Foundation. Right: Friendfield church 2013.

The original Baruch winter home, the Old Relick (top), burned to the ground in 1929, and was replaced by Hobcaw House (bottom). Photos courtesy of the Belle W. Baruch Foundation.

owners to reassemble most of the original barony. He established a winter retreat for his family at Hobcaw, away from the pressures of city life in New York and away from the decisions he had to make as a presidential advisor in Washington. Each winter between Thanksgiving and Easter, family and guests hunted the land for duck, deer, turkey, quail, dove, and wild hog. Local men were hired as plantation managers, hunting guides and maintenance supervisors and moved their families to live on the barony. Freed slaves, their children and grandchildren continued living in four remaining slave villages and were hired by Baruch as boatmen, farmers, stable hands, cooks and maids. Goods and equipment were bought locally and boats ran regularly between Georgetown and Hobcaw Barony.

The Baruchs entertained hunting parties regularly and guests included congressmen, military officers, Broadway and Hollywood personalities, journalists, poets and musicians. In 1932, Winston Churchill arrived by yacht and in 1944, President Franklin D. Roosevelt stayed nearly a month for a much-needed health vacation. In addition to hunting, the guests enjoyed fishing, riding, oyster roasts, wild game dinners, drinking and storytelling.

In December 1929, a fire burned the Baruch winter home to the ground, leaving only ashes and fire-scarred live oaks that still overlook Winyah Bay today. Hobcaw House, a brick, concrete, and steel structure, was constructed on the same site the next year. Mr. Baruch sold the northern half of Hobcaw to his eldest child, Belle, in 1935 and by 1956, Belle had acquired all of Hobcaw Barony.

As a young child, Belle had enjoyed the forests and the waters of the family's winter retreat and became a sailor and equestrian, competing internationally in the 1920's and 30's. She became a pilot at age 40 and regularly flew from New York to Hobcaw. While in residence, she flew over the marshes of Hobcaw and guarded them against poachers. Through her protection of the fauna and habitats, Hobcaw was transformed from a hunting locale to a wildlife refuge. She entertained on a small scale and shared the property with a close circle of friends.

When Belle became very ill at age 64, she focused on the future of her property. She created a trust and directed trustees to hold the property in perpetuity for the purposes of research and education in the fields of forestry, wildlife and marine science. Her further stipulation was that the property should serve as an outdoor laboratory for researchers from universities and colleges located in South Carolina. Her death in 1964 began an era of long-term research that continues today. The Belle W. Baruch Foundation owns and operates the private tract and encourages its use by researchers, educators, students, and historians. An excellent summary of Hobcaw Barony history that includes historic photographs is found in *Plantation Between the Waters – A Brief History of Hobcaw Barony* by Lee G. Brockington (2006).

Belle and her father Bernard Baruch at the Old Relick, circa 1925 - courtesy of the Belle W. Baruch Foundation

Current Land and Water Use

South Carolina is among the fastest growing states in the nation. Population projections calculated by the SC Budget and Control Board's Office of Research and Statistics indicate that South Carolina's population will increase by over one million new residents by 2015, with rapid development at the periphery of the state's larger metropolitan areas and coastal resort/tourism centers (South Carolina Population…[cited 2010]). The state has roughly 182 miles of beaches and 200,000 acres of saltwater marshes that attract almost 30 million tourists annually.

A National Resource Inventory report released in 2000 indicated that between 1992 and 1997, 15.8 million acres of South Carolina's land were converted from farms and woodlands to a developed land status (U.S. Department of Agriculture, 1997). Land was converted at six times the rate of population growth during that period, a rate of development that was the 9th fastest in the nation despite ranking only 40th among states in land area. Development directly affects habitat quality and ecological communities as buildings and infrastructure replace natural areas, and also has indirect effects which are often overlooked and may be difficult to quantify. Runoff from impervious surfaces carries sediment and toxic chemicals into ditches and small streams that feed into the waterways. The infilling of isolated wetlands compounds the runoff problem as the water-holding and filtration capacity across the landscape is reduced. Development also forms barriers to the movement of species and materials between protected natural areas, creating a fragmented landscape which may diminish ecosystem functioning.

The North Inlet watershed is currently largely undeveloped. The land within the watershed is classified by the NOAA Coastal Change Analysis Program (C-CAP) as estuarine emergent wetland (29%), palustrine forested wetland (25%) and evergreen forest (18%). Only about 2% of this watershed is classified as low or medium intensity development. DeBordieu Colony is a gated residential community just north of the NERR, with high-end residential homes, condominiums, an 18-hole golf course, private docks and a boat ramp. Also in the North Inlet watershed is the gated community Prince George with properties both east

and west of Highway 17. This development includes beach front and riverfront home sites and a private access boat slip and ramp on the Waccamaw River. The University of South Carolina Development Foundation also owns about 1,200 acres of forest, former rice fields and tidal marsh within the Prince George tract. An additional planned development just north of DeBordieu, Bannockburn, will also be within the North Inlet watershed. Clemson University's Baruch Institute for Coastal Ecology and Forest Science has initiated a pre- and post development impact study on this property.

Calculations of land cover based on the C-CAP data show that the majority of land in the 18,000 square mile Winyah Bay watershed is palustrine forested wetland (23%), evergreen forest (22%), cultivated land (19%), and scrub/shrub (12%). Approximately 3% of the land area is classified as low to high intensity development (Figure 9).

Within the City of Georgetown and Georgetown County, land use is much more diverse (with associated anthropogenic impacts), including large industries such as International Paper Company, 3V Chemical, a cargo port facility, a steel mill,

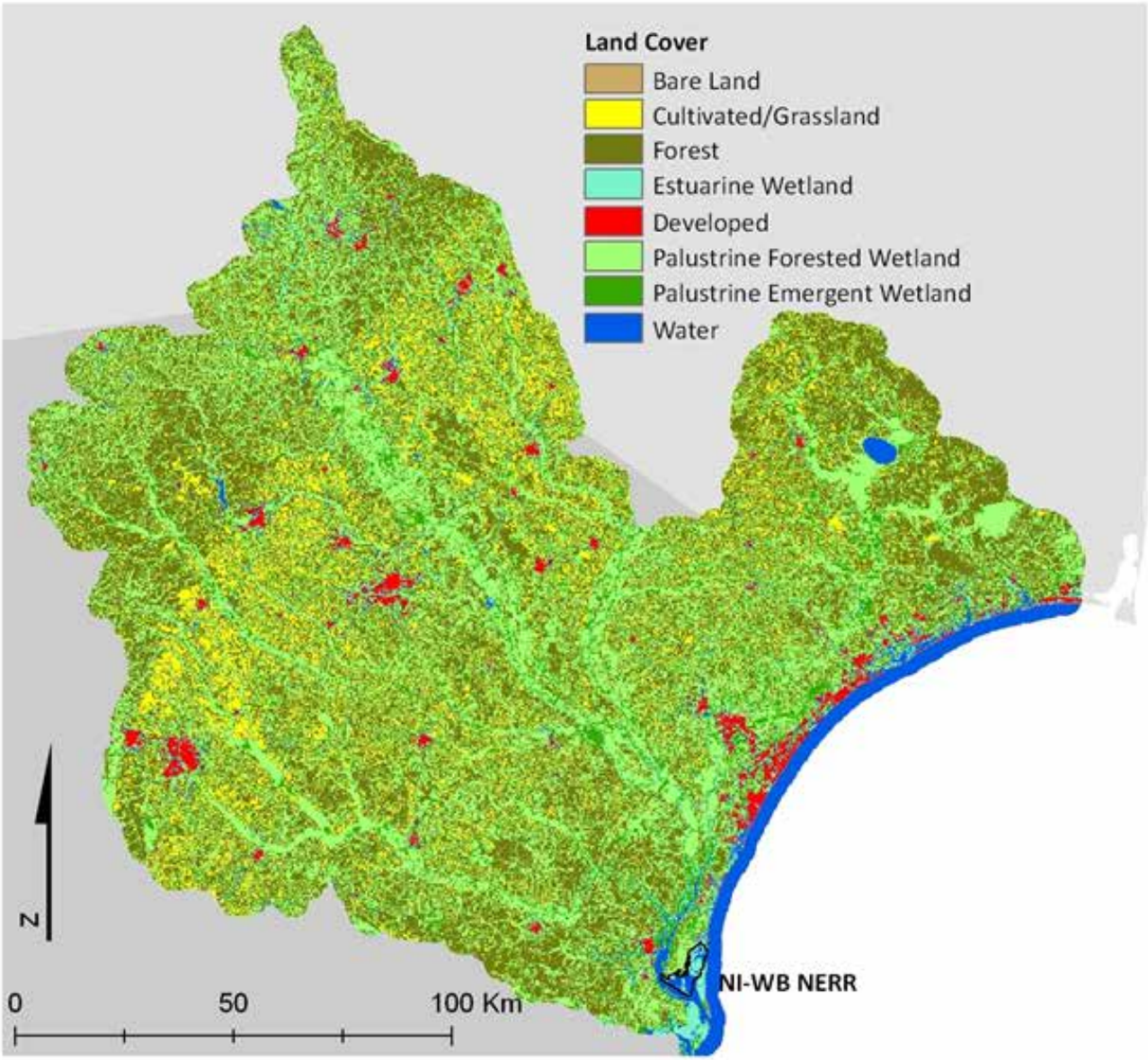

Figure 9. Coastal Change Analysis Program land use/land cover classification in the Winyah Bay watershed.

several marinas, and municipalities and associated infrastructure - including a variety of mixed-use businesses and single and multi-family residences. The Atlantic Intracoastal Waterway follows a portion of the Waccamaw River and maintenance dredging of this waterway and also the shipping channel for the Port of Georgetown is conducted on a periodic basis.

The population of Georgetown County reached 63,520 in 2010 according to the U.S. Census Bureau. The population of the county increased by 9.5% between 1980 and 1990, by 20.5% between 1990 and 2000, and by 13.8% from 2000 to 2010. Current projections by the Waccamaw Regional Council of Governments anticipate that the County of Georgetown will increase its 2000 population an additional 30.1% by the year 2030 (Waccamaw Regional … [cited 2010]). The Waccamaw Neck, the narrow strip of land between the Waccamaw River and the Atlantic Ocean which includes the resort towns of Pawleys Island, Litchfield Beach, and Murrells Inlet, is one of the fastest growing areas of Georgetown County. A 2003 population estimate of the Waccamaw Neck included 16,000 residents, a number that has tripled in the past 30 years.

NOAA C-CAP data were used to generate land cover changes from 1996 to 2001 within the Winyah Bay watershed. The majority of changes were from evergreen forest to shrub/scrub (21% of total change), from shrub/scrub to evergreen forest (14% of total change), from palustrine forested wetland to palustrine shrub scrub wetland (13% of total change) and from evergreen forest to grassland (11% of total change). These changes probably reflect forestry practices. About 3% of the total land change in the Winyah Bay watershed was undeveloped land to developed land. In comparison, within the Waccamaw Neck area adjacent to the NI-WB NERR, about 39% of the total land cover change was from undeveloped land to developed land.

Land management activities on Hobcaw Barony are designed to maintain a diverse and mixed age forest and conserve the rich historic sites. The pine and hardwood forest is managed by the Belle W. Baruch Foundation (BWBF) for research, long-term health, and wildlife. The BWBF harvests timber on Hobcaw periodically to improve forest health and to generate some revenue to support its operations including the continued protection and maintenance of the property. Buildings on Hobcaw Barony include research and education facilities associated with the Baruch Institutes of the University of South Carolina and Clemson University, the Hobcaw Barony Discovery Center and Baruch Foundation office, the Kimbel Conference Center, and several dormitories and visiting scientist cottages. Historic buildings including Hobcaw House, Bellefield House, numerous historic cottages, cemeteries, earthen fortifications, a rice mill, slave villages, and other sites are associated with Hobcaw Barony's designation as a registered National Historic Site.

Much of the history and current culture and economy of Georgetown County is associated with its abundant and diverse water resources. The City of Georgetown was one of the first ports in the Southeast region. Large volumes of lumber, cotton, rice, and other coastal products were exported, especially during the 1700's and 1800's. Today, the ship channel in Winyah Bay and the Sampit River provides a corridor for the movement of large commercial ships between the ocean and city of Georgetown. The Intracoastal Waterway provides protected access for commercial barges and recreational boats into Winyah Bay from the north and south.

The Harborwalk connects businesses in historic downtown Georgetown to the waterfront on the Sampit River. The harbor is also a popular stop over for boaters traveling the Intracoastal Waterway.

Local boaters use the extensive rivers and tidal marsh systems within Georgetown County for fishing, hunting, and general recreational enjoyment. In Winyah Bay and North Inlet, recreational fishers enjoy catching a variety of fishes, especially red drum, speckled sea trout, and flounder. Oysters, clams, shrimps, and blue crabs are also sought after resources by area residents and visitors. The recreational fishing industry in South Carolina was valued at over $441 million in 2009 (NOAA, 2011). The commercial shellfish industry in South Carolina contributed over 14 million dollars to the economy in 2010, with white shrimp being the most important in terms of value, followed by blue crabs and then oysters (National Ocean and Economics Program, 2012).

Belle Baruch's vision for preserving a large tract at the southern end of the Waccamaw Neck was noteworthy in the 1960's, and her legacy becomes more remarkable with each passing year as more and more of the coastal area becomes developed. Although Hobcaw Barony is one of only a few protected properties on the north side of Winyah Bay, a contiguous set of large tracts of land south of North Inlet are also protected and provide additional opportunities for research and education. Immediately adjacent to Hobcaw is the Tom Yawkey Heritage Preserve managed by SCDNR that includes North Island, South Island and Cat Island. Other properties in the protected chain include Santee Coastal Reserve, the Cape Romain National Wildlife Refuge, and Capers Island. Together, these properties comprise more than 50 miles of protected coastline.

There is a delicate balance between managing growth, development and tourism that drive South Carolina's economy while sustaining the natural resources that support these economic activities. Faced with this rapid growth scenario, the NI-WB NERR is committed to better understanding the impacts of coastal growth and to promoting stewardship of the resources in the North Inlet and Winyah Bay watersheds.

Shrimping continues to be an important part of the economy in coastal South Carolina.

Environmental Setting

Climate and Weather Patterns

General descriptions of climate, weather, storms and hurricanes for the state of South Carolina and the state's Lowcountry (coastal plain), including Georgetown County, were derived from the South Carolina State Climatology Office's website unless otherwise noted.

» Climate Controls

South Carolina's climate is classified as warm temperate – subtropical. Geographical features that most strongly influence the state's climate are its southerly latitude, low elevation, near proximity to warm waters of the Gulf Stream, and the blocking effect of the Appalachian Mountains which reduce the eastward flow of cold air from the interior of the United States during winter. Four seasons are recognized. Summers tend to be hot and humid whereas winters are short and mild. Variance in day length causes distinct differences in daytime heating and nighttime cooling among seasons. At the summer solstice, the sun is nearly overhead at solar noon, and the maximum zenith angle is approximately 79.5°. At winter solstice, the sun is low in the southern horizon at solar noon, and the maximum zenith angle is approximately 23.5°.

Coastal South Carolina has less extreme summer and winter temperatures than inland areas. Because land and water heat and cool at different rates, sea breezes cool the coast during the summer and warm the coast during the winter. During summer, the weather is dominated by a maritime tropical air mass known as the Bermuda High which brings moist air inland from the ocean waters of the Gulf Stream. At the land-sea interface, the air rises and forms a "sea-breeze front" where thunderstorms may extend up to 30 kilometers (20 mi) inland. This convergence zone is where the cooler air mass from the sea meets the warmer air from the land.

» Temperature

Along the coast, the onset of the spring warming is usually evident by mid-March, and warm temperatures (25 – 32 °C (77 – 90 °F)) are typical by mid-May. Summer humidity and heat commonly persist through September and into October. November brings relief from high temperatures. From December through March, daytime maximum temperatures (1981 - 2010) were about 15 °C (60 °F) in Georgetown (Station 2E). Freezing nighttime temperatures are not unusual from December through March but sustained periods that create ice are unusual. Surface ocean temperatures range from about 7 - 30 °C (45 – 85 °F) during the year.

The 'Valentines' storm on February 13, 2010 blanketed the marsh and boardwalk near the Baruch Marine Field Laboratory.

» Precipitation and Drought

In South Carolina, there is no discernible wet or dry season; alternating periods of heavy and light precipitation occur throughout the year with averages of two inches or more typical for every month. The state also has high year-to-year variability in precipitation; the main cause of high seasonal and interannual variability is the strength and geographic placement of the Bermuda High. As high pressure continues over the area, solar radiation increases, which in turn increases the temperature, which then decreases the cloud cover, thereby reducing the probability of substantial precipitation. When precipitation occurs during periods of drought, however, it is highly localized with low accumulation and the rainfall generally evaporates within 24-hours (Guttman and Plantico, 1987).

There is approximately a one in four probability of a drought somewhere in South Carolina at any time. Droughts are sometimes alleviated by a tropical cyclone. In 1954, Hurricane Hazel ended an extreme drought in eastern South Carolina, although drought conditions continued in western sections. In 1990, the remnants of Hurricane Klaus and Tropical Storm Marco ended an extreme drought. Historically, severe droughts have had adverse impacts on the people and economy of South Carolina. Periods of dry weather have occurred in each decade since 1818 (Hirschboeck, 1991). The most damaging droughts in recent history occurred in 1954, 1986, 1990, and 1998-2002, 2007-2008, 2011-12. The 1986 drought was severe and was accompanied by weeks of record or near-record high temperatures and record high demand for water in July. Less severe droughts were reported in 1988, 1993, and 1995. The adverse impacts on the people and economy were made especially clear during the drought of 1998-2002 that impacted agriculture, forestry, tourism, power generation, public water supplies, and freshwater fisheries. More recent detailed drought information for the Georgetown area comes from the SC State Climatology Office: Georgetown County was in a moderate drought in June 2007; drought status continued and was upgraded to severe in September 2007 through January 2008. The next moderate drought in Georgetown County lasted from June 2011 through April 2012.

In coastal South Carolina, precipitation tends to be greater in summer than in winter, but the pattern varies considerably from year-to-year. This is, in large part, due to the frequency and intensity of "sea-breeze front" thunderstorms, tropical storms or hurricanes during summer and autumn, and the frequency and intensity of El Niño/Southern Oscillation (ENSO) events (known as El Niños) during the winter and spring. In the Lowcountry, short-lived snowfall events are rare, occurring on average once every three years.

» Wind

Wind directions and velocities vary with the passage of weather systems, but the prevailing directions for the state and coast tend to be either from the northeast (during the cooler months) or southwest (during the warmer months). Upper air winds (those more than 1500 meters above mean sea level) are usually southwest to northwest in winter and spring, south to southwest in summer, and southwest to west in autumn. Average surface wind speeds for all months range between 6 and 10 miles per hour. The Appalachian Mountains have a strong influence on the prevailing surface coastal wind direction during all seasons but have a more pronounced effect in the winter, summer, and autumn. During winter, most low pressure

cyclones that affect the state pass to the south of the mountains. As these systems move around the mountains, the winds are generally southwest. As the low pressure moves over the Atlantic Ocean, the winds shift to the northeast. During summer, air flows north along the western edge of the Bermuda High from the Gulf of Mexico. Quite often the mountains form the western extent of the Bermuda High. The Bermuda High also contributes to air stagnation, especially during the summer. Stagnant air is caused by very light winds that tend to be rather disorganized in direction. During autumn, winds are from the northeast because the mountains form the southern edge of the predominant continental high pressure pattern known as a "wedge". This circulation generates northeast winds as the air wraps around the center of the high pressure in a clockwise fashion.

» Evaporation

The rate of evaporation of moisture from the ground influences weather, and the highest rates in South Carolina (> 65 inches, 1650 mm per year) are found along the lowcountry. Georgetown County's annual rate is approximately 60 inches (data from 1961-1990). Evaporation measurements are expressed as the number of inches of water that evaporate from an evaporation pan per day, month, or year. Rate of evaporation is strongly influenced by wind velocity. With the increased frequency and intensity of droughts in the low country, evaporation rates are very important to estuarine ecosystems. With high evaporation rates and low rainfall, porewater salinity and geochemistry of marsh soils can change so dramatically that large expanses of saltmarsh cordgrass die-offs have been observed (Brown and Pezeshki, 2007). These dies-offs or diebacks have been observed more frequently and along the entire east coast within the last decade.

A former NI-WB NERR Research Coordinator stands next to what remains of an old loblolly pine which was impacted by a tornado formed from TS Gordon in 2000.

» Lightning

Thunderstorms and associated lightning are regular occurrences in the lowcountry, especially on warm afternoons and evenings from May to November. As of 2011, the National Weather Service (NWS) ranks South Carolina 18th in the number of reported lightning deaths (total of 99) since 1959 (Holle, 2012). The majority of lightning injuries and deaths occur on small boats without cabins.

» Tornadoes

In the period from 1950 through 2012 South Carolina saw 924 confirmed tornadoes, an average of 15 tornadoes per year. From 1994 to 2012 the annual average was 28 tornadoes per year. This dramatic increase is primarily attributable to the implementation of the National Weather Service's advanced NEXRAD Doppler radar system which is able to pinpoint state-wide tornadic vortex signatures, unlike previous NWS radar systems. The majority, 81%, of South Carolina's tornadoes are short-lived EF-0 and EF-1 tornadoes. Stronger more destructive EF-3 and EF-4 tornadoes are rare, but occur with a consistent annual frequency of 2-4 per year. There is no record or evidence of an EF-5 tornado, the strongest and most devastating on the EF scale, ever touching down in South Carolina.

Tornadoes have touched down in South Carolina during every month of the year; however, they are most likely in the spring and fall. During spring, tornadoes result from active cold fronts and pre-frontal squall lines. During November and December, active cold fronts can spawn tornadoes. Tornado frequency is at a minimum from October

to January. In South Carolina, tornadoes are more likely to touch down during the afternoon and early evening; but, they can also touch down late at night and during the early morning hours. Fortunately, the strongest tornadoes occur in the afternoon and early evening when television and radio warnings are most effective. Many late season tornadoes are triggered by decaying tropical storms that make landfall in or near South Carolina. These tropical tornadoes can significantly add to the annual tornado average. Although tornadoes are rare in eastern Georgetown County, water spouts are not uncommon in the coastal ocean adjacent to the NI-WB NERR. Most are small and short-lived; however, a large water spout in Winyah Bay made landfall on the western side of the Hobcaw peninsula (just west of the North Inlet – Winyah Bay Reserve) during Tropical Storm Gordon in 2000 and destroyed more than 30 acres of old growth forest.

» Winter and Coastal Storms

The most intense winter storms generate high northeasterly winds and extreme high tides along the coast. They can occur anytime from autumn through early spring. Wave action, flooding, and beach erosion peak during this period. An especially severe storm system on January 1, 1987, produced gale force winds and abnormally high tides that caused an estimated $25 million worth of damage to South Carolina barrier island properties. In December 1989, the lowcountry experienced its first white Christmas on record, with more than six inches (15 cm) of snow that lasted for several days.

» Hurricanes (Tropical Cyclones)

In the western Atlantic basin, hurricane season is typically from June through November, with peak activity in August and September. Tropical cyclones are infrequent along the South Carolina coast. Depending on the storm's intensity, speed, and proximity to the coast, tropical cyclones can be disastrous. The major coastal impacts from tropical cyclones are storm surge, winds, flooding, precipitation, and tornadoes. Storm surge refers to the increase in the level of the ocean as water is pushed forward in front of the advancing wind field. Hurricanes can have lasting impacts on the geomorphology of local barrier islands, forests, crops, and local economies.

Hurricanes are characterized by wind speeds exceeding 64 knots (74 miles per hour) and central

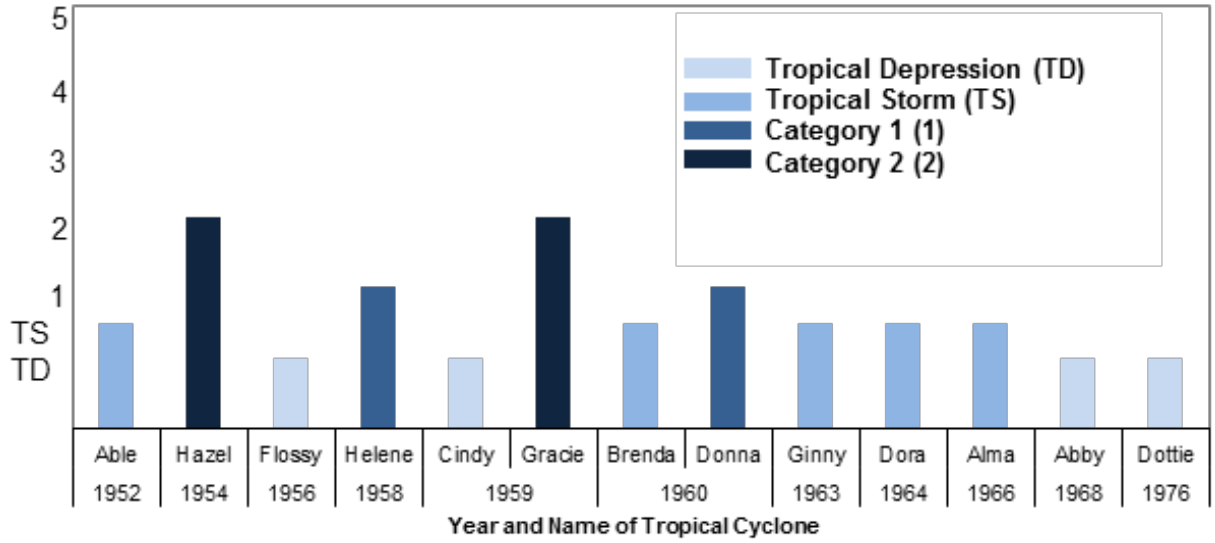

Figure 10. Classification of tropical depressions, storms, and hurricanes that occurred in the North Inlet- Winyah Bay area between 1952 and 1976. Classifications of storms in this figure are based on their category when they hit the North Inlet – Winyah Bay (Georgetown County) area, not on their full core intensity when they were offshore or hit other areas first.

pressure usually less than 980 millibars (mb) (28.94 inches of mercury). Less intense, but more frequent, are tropical storms (winds over 34 knots and under 64 knots: greater than 980 mb central pressure) and tropical depressions (winds under 34 knots). In the period 1901-2009, only 27 tropical cyclones made landfall on the South Carolina coast. Of these, only eight were of Category 2 to Category 4 intensity. Since 1900, no Category 5 hurricanes have hit South Carolina. There have been two Category 4 hurricanes (Hazel, 1954, and Hugo, 1989) and two Category 3 hurricanes (September 17th, 1945, and Gracie, 1959). It is possible that the "Great Storm of 1893" that struck the southern coast on August 20 of that year was at least a Category 4 storm, but there was no way of accurately measuring tropical-cyclone intensity before 1900.

» Lowcounty and NI-WB NERR Tropical Cyclone Impacts

Accounts of major hurricanes are prominent in the history of Georgetown County. According to historical newspaper records, North Inlet was hit by a devastating hurricane in 1822. It made landfall near Charleston and moved up the coast to Virginia before moving out to sea. With the arrival of the hurricane, tides were unable to ebb and then flooded with overwhelming violence, killing more than 300 people who were living on North Island. By 1893, major population centers could be telegraphically alerted to storms moving along the coast, but there were no warnings for the Sea Islands and other isolated areas. The "Great Storm of 1893" struck the south coast at high tide on August 28th, pushing an enormous storm surge ahead of it that swept over and submerged whole islands. Maximum winds in the Beaufort area were estimated to be 125 miles per hour; those in Charleston were estimated near 120 miles per hour. At least 2,000 people lost their lives, and an estimated 20,000-30,000 were left homeless and with no means of subsistence. Notable and historical storms which impacted the NI-WB Reserve from the 1950s to the late 1970s are shown on Figure 10.

In the last 60 years, hurricanes Hazel (October 14th, 1954), Gracie (September 29th, 1959), and Hugo (September 22nd, 1989) have been the most severe storms to impact the northern South Carolina coast. Hazel, a Category 4, made landfall near Little River, S.C., with 106-mph winds and a storm surge of 16.9 feet. Damage was estimated at $27 million. Hurricane Hazel moved parallel to the coast before making landfall; the heaviest damage in South Carolina was from Pawleys Island northward (Pawleys Island is just a few miles north of the North Inlet – Winyah Bay Reserve). Gracie, a Category 3, made landfall between Charleston, SC, and Savannah, Georgia, on St. Helena Island and continued toward the north-northwest, maintaining hurricane strength for more than 100 miles inland. Winds reached 140 mph and tides reached 8 ft. Damage of disaster proportions occurred along the coast from Beaufort to Charleston, and was estimated at $20 million (1959 dollars). These storms did considerable damage to the forests surrounding the North Inlet salt marsh. Heavy rains caused flooding through much of the state and crop damage was severe.

In more recent years, meteorological data have been recorded during the passage of tropical storms and hurricanes by the Baruch Marine Field Laboratory and the North Inlet-Winyah Bay NERR (Table 1). The amounts of rain recorded for the various storms varied and were not related to the classification (category) of the event. Amounts were related to the location of the Reserve relative to the core of the cyclone, the precipitation potential of the storm, and the rate at which it moved across the landscape. The greatest rainfall was recorded during Fran (1996, 12-15 inches) and Floyd (1999, 12-18 inches). Hurricane Floyd (September 1999) did not make landfall in South Carolina but was a very large storm that came ashore near Cape Fear, NC. Heavy rain of more than 15 inches fell in parts of Horry County, SC, causing major flooding along the Waccamaw River (which feeds into Winyah Bay) in and around the city of Conway, SC, for a month. The year 2004 was a particularly active summer for tropical storms with Alex, Bonnie, Charley, Gaston, Frances, and Jeanne affecting the Georgetown area and lowcountry. These six storms occurred within a two-month period (shaded area of Table 1).

Table 1. Tropical systems and their main impacts on the North Inlet – Winyah Bay and Georgetown area between 1981 and 2010. Rainfall amounts recorded at Oyster Landing (OL) Pier are indicated for each named storm; *Hugo rain gauge amount is not correct as the entire pier was uprooted and laid on its side in the marsh. Other noted effects of each storm in nearby counties or along the SC coast are also discussed. The shaded area of the table highlights six storms that occurred within a two-month period.

Storm Name	Year	Dates in SC	Storm's Center of Landfall or Track in SC	OL Rain Gauge(s) Inches	NIW Daily Ave & Max Wind mph	Other Noted Effects to Georgetown Area, lowcountry, or State of SC
Dennis	1981	Aug 19-20	Up and along SC Coastline, then into Myrtle Beach, SC	7.62	No data	Heavy rains with significant flooding
Sub-tropical Storm#1	1982	Jun 18-19	Along SC Coast, but Offshore	4.63	No data	No Information
Diana	1984	Sep 9-14	Along SC Coast, but Offshore	4.10	No data	Heavy Rains; gusty winds
Isidore	1984	Sep 29-30	Along SC Coast, but Offshore	2.70	No data	Heavy rains along the SC Coast
Bob	1985	Jul 23-25	Savannah, Ga North and Inland through Columbia, SC	5.00	18mph Jul 25 daily ave	Heavy rains, flooding, gusty winds
Kate	1985	Nov 22	Across SC: Aiken to Myrtle Beach	3.20	15 daily ave	Primarily heavy rain
Charley	1986	Aug 13-15	Along SC Coast, but Offshore	1.60	No data	Heavy rains along the SC Coast
Hugo (see text)	1989	Sep 21	Isle of Palms	*1.70	22 daily ave	Storm surge, tornados, flooding, winds, not much rain (2.5" in Georgetown)
Marco	1990	Oct 10-13	Up through GA then to Columiba, SC	7.00	No data	Rain with significant flooding
Bob	1991	Aug 18-19	Offshore of SC	2.40	9mph daily ave	1 SC storm-related death, rain
Gordon	1994	Nov 21	Up and along the SC coast	0.95	17mph Nov 20 daily ave	Higher than Normal tides, storm surge, flooding
Allison	1995	Jun 4-6	Across SC: Aiken to Florence	1.79	16mph Jun 6 daily ave	Heavy rains with street flooding in Georgetown, minor wind damage
Jerry	1995	Aug 23-27	Huge storm covered entire state; tracked through the upstate from GA	7.90	14mph Aug 26 daily ave	Heavy rains with street flooding in Georgetown
Arthur	1996	Jun 18-19	75 miles offshore of Cape Romain, SC	4.65	No data	Slow Rain event, no flooding
Bertha	1996	Jul 10-12	Offshore of Northern Coastal Counties	2.15	No data	other rain gauges in area: 3.5"; just below 60mph max wind gust in Charleston
Fran	1996	Sep 1-9	Offshore of Northern Coastal Counties	10.83	No data	Heavy rains with flooding
Josephine	1996	Oct 6-8	Up and along SC Coastline, then into Myrtle Beach, SC	3.69	No data	Heavy rain, gusty winds, flooding
Danny	1997	Jul 23-24	Across upstate SC east to around Lumberton, NC	1.23	No data	Weather station up and down in July; rain amount questionable
Bonnie	1998	Aug 26	70 miles offshore of Horry Co., SC	0.45	23 daily ave	More rain than our gauge measured (2 to 4"), at the Myrtle Beach Paviliion highest wind gust was 76mph

Table 1 continued.

Storm Name	Year	Dates in SC	Storm's Center of Landfall or Track in SC	OL Rain Gauge(s) Inches	NIW Daily Ave & Max Wind mph	Other Noted Effects to Georgetown Area, lowcountry, or State of SC
Earl	1998	Sep 3-4	Across SC: Aiken to Florence	4.66	14mph Sep 3 daily ave	Tornado in Georgetown, gusts in county were 50-60mph, rain event with flooding
Dennis	1999	Aug 29-30	Offshore of SC: Closest to Horry & Georgetown Counties	2.79	16mph Aug 29 daily ave	Rain and wind event, 6" rain with wind gust of 48mph in Horry County
Floyd	1999	Sep 14-16	Offshore of SC: Closest to Horry & Georgetown Counties	10.29	24mph Sep 15 daily ave; max gust 24.6 on Sep 17	Huge Rain and wind event with flooding of roads & buildings, over 15 inches of rain from other gauges, beach erosion, with 15' waves at Cherry Grove Pier, gusts in Georgetown were 50-60mph
Irene	1999	Oct 16-17	Offshore & Parallel to SC coast	5.66	18mph Oct 17 daily ave	Large rain event with minor street flooding, gust in Charleston was 48 mph with beach erosion
Gordon	2000	Sep 18	Across SC: Savannah, GA to Florence, SC	5.60	11mph Sep 18 daily ave	Large rain event, other gauges > 8" of rain, tornado on Hobcaw Barony (see photograph), wind gust in Charleston 37mph
Helene	2000	Sep 21-23	Across SC: Aiken to Florence	3.83	10mph Sep 23 daily ave	Tornadic event in low country, wind damage, heavy rain in Berkeley County
Allison	2001	Jun 14-15	Across SC: Aiken to Florence	0.16	No data	Tornadic event in low country with wind damage
Kyle	2002	Oct 10-11	Up and along SC Coastline, brushing McClellanville, SC	0.67	12mph Oct 10 daily ave	F-2 Tornado in Georgetown, Beaufort to Goose Creek experienced 3-6 inches of rain with flooding of roads & homes
Alex	2004	Aug 1-2	90 mi SE of Charleston	0.27	13mph Aug 2 daily ave	Heavy rainfall with damaging river flooding occurred primarily upstate
Bonnie	2004	Aug 12-13	Up and along the SC coastline	5.60	7mph Aug 13 daily ave	Tornadic events across the state, including low country with wind damage, severe thunderstorms, heavy rainfall
Charley	2004	Aug 14-15	Offshore of SC: Brushing Horry & Georgetown Counties	4.24	10mph Aug 14 daily ave	Tornados in Georgetown and other nearby lowcounty counties, max wind gust in Georgetown 57mph & 100mph in Surfside, power outages, 5.71" Rain from another gauge, minor coastal erosion
Gaston	2004	Aug 26-31	Northward up through Bulls Bay, SC	4.52	27mph Aug 29 daily ave	Wind Damage in the lowcountry, with tornados and heavy rain, max wind gust at the Isle of Palms was 73mph, flooding and some coastal erosion
Frances	2004	Sep 6-9	Across upstate SC northeast to West Virginia	0.64	19mph Sep 8 daily ave	Tornadic events across the state, including low country with wind damage
Jeanne	2004	Sep 26-28	Upstate mountains	0.79	19mph Sep 26 daily ave	F1 Tornado 27 Sep 2004 in Georgetown, primarily a wind event in the lowcountry, max gust in downtown Charleston 41mph, 1.9" another local rain gauge

Table 1 continued.

Storm Name	Year	Dates in SC	Storm's Center of Landfall or Track in SC	OL Rain Gauge(s) Inches	NIW Daily Ave & Max Wind mph	Other Noted Effects to Georgetown Area, lowcountry, or State of SC
Cindy	2005	Jul 7-9	Upstate mountains	3.82	12 & 26 on jul 7	Heavy rain, gusty winds, tornados, flooding statewide, locally wind and rain
Ophelia	2005	Sep 12-14	Offshore; closest to Horry and Georgetown Counties	2.31	17 & 37 on sep 13	In Georgetown and Horry Counties: High surf and severe beach erosion, minor coastal flooding and wind damage, Myrtle Beach Airport max gust 44mph
Tammy	2005	Oct 5-8	South of State: Georgia and Florida; strongest effects north of Center	9.00	19.5 & 44 on oct 6	Major beach erosion along the coast, street & building flooding and damage in Georgetown, 14.88 & 15.14" other local rain gauges, wind damage, max gust at Edisto Beach of 59 mph
Alberto	2006	Jun 13-15	Across SC: Aiken to Florence	1.31	21.5 & 40 on jun 14	Wind Damage in the lowcountry, with tornados and heavy rain, most effects felt south of Charleston
Ernesto	2006	Aug 31 - Sep 1	Offshore of SC: Closest to Horry & Georgetown Counties	4.07	23 & 39 on aug 31	Heavy rain, flood and wind event, especially in Horry and Charleston Counties, North Myrtle Beach Airport 7.20" rain with 44 peak gust
Andrea	2007	May 8-13	Offshore of SC	1.39	17 & 40 on may 8	Primarily wind event with heavy surf
Barry	2007	Jun 2-3	Up and along the SC coastline	1.90	15.5 & 44.5 on jun2	Rain and wind event in lowcountry, minor storm erosion, local gauges in Georgetown 3.81" & 2.07, 51 mph gust at Edisto Beach
Cristobal	2008	Jul 17-20	Offshore & Parallel to SC coast	0.57	13.7 & 28 on jul 17	Very little rain along the coast, no damaging winds
Fay	2008	Aug 20-26	South of SC: East Coast of Florida tracked west through FL panhandle	1.47	20 & 33 on Aug 21 & 22	Heavy rains over SC, tornados upstate, 3.57" Rain in local gauge
Hanna	2008	Sep 4-6	Offshore of SC: Closest to Horry & Georgetown Counties	3.61	17 & 40 on Sep 5	Minor beach erosion, 4.12" & 4.48" other local rain gauges, peak gust in North Myrtle Beach 59mph
Ida	2009	Nov 10-12	South of SC: Alabama east to FL panhandle	3.38	15 & 28 on Nov 12	Heavy rainfall across SC, local gauges 4.08" & 4.2" rain

Tropical storms, tropical depressions and hurricanes affect North Inlet and Winyah Bay in many different ways. Rain, flooding, wind damage, and storm surge can cause severe destruction. Not all tropical storms and hurricanes impart the same type of damage. For example, Hugo had extremely intense winds with a large storm surge, but very little rain. On the other hand, a relatively minor tropical system can cause devastation with its slow movement and heavy rainfall and flooding.

Hurricane Hugo was the most significant storm in recent history to impact the North Inlet – Winyah Bay NERR. Hugo made landfall on September 21st, 1989 as a Category 4 near the Isle of Palms just north of Charleston with winds of 138 miles per hour and gusts over 160 miles per hour and storm surge of 20+ feet. It continued on a northwest track at 25-30 miles per hour and maintained hurricane force winds (gusts up to 109 miles per hour) as far inland as Sumter. Hugo exited the state southwest of Charlotte, N.C., before sunrise on September 22nd. The hurricane caused 35 related deaths, and it injured several hundred people in South Carolina. An estimate of more than 50,000 people were left homeless. Damage in the state was the costliest in history. Damage was estimated to exceed $7 billion, including $2 billion in crop damage. The forests in 36 counties along the path of the storm sustained major damage.

Hugo struck The NI-WB Reserve near high tide and created a storm surge of 12 to 14 ft at the USC Baruch Marine Field Laboratory. Wind-driven waves of up to 5 ft were superimposed on the heighted level of the ocean. Storm surge traversed the barrier islands and salt marshes and caused ocean water to flood over a large area of coastal forest adjacent to the estuary. The surge retreated within a few hours after the storm moved inland. In general, physical impacts on the tidal system were minimal and short-lived. There were no major changes to the saltmarsh creek network or to the size or shape of sand bars in the estuary (Gardner, et al., 1992a). The oyster reefs and lower-lying mud flats were sufficiently buffered by the high tide when the most violent part of the storm and waves arrived, so little evidence of physical disturbance was evident. Wave action and the retreating surge scoured the marsh surface of most of its soft sediments leaving exposed roots on a sandy base. Tidal creek waters remained very turbid for at least 6 weeks. Resuspended sediment was deposited on the vegetated intertidal marsh during the following weeks, but it was months to more than a year before the inner marshes and intertidal creek bottoms and pools were as muddy as they were before the event. Much coarse organic debris remained in the deeper channels for weeks to months. Large volumes of *Spartina* wrack and woody debris from marsh islands were deposited in the forest.

The front of Baruch Marine Field Laboratory the morning after Hurricane Hugo surged through it.

The impact of Hugo's wind and surge was mainly on the uplands. Evidence that saltwater penetrated more than 0.75 km into the Hobcaw forest was found on roads and in forested wetland swales. Many mature pines and hardwoods were blown down or severely damaged. In the months and years following the storm, low-lying forests were killed by saltwater intrusion.

The pier and weather station at Oyster Landing were destroyed and debris was deposited in the forested uplands. The pier and boat shed at Clambank were also destroyed. Hugo flooded and fractured the 14,000 sq ft. USC Baruch Marine Field Laboratory, moving the original building off its foundation, rendering all of the structure too damaged to be repaired. Total losses of buildings, piers, equipment, and contents were about three million dollars. Pre-storm preparation saved all data and all light-weight equipment that could be transported to higher ground at the Kimbel Center, which sustained wind but not flood damage. The loss of the facilities, major analytical instruments, and refrigerated/frozen collections that were awaiting processing were a setback, but post-storm water and biological sampling began within hours of the storm's passing. Results of some of these studies are reported in sections on water chemistry and fauna assemblages.

Coastal Observer
Thursday, September 28, 1989 21

Lab destroyed, research saved

By Zane Wilson

Baruch Marine Lab was destroyed by Hurricane Hugo, but almost all the research was saved, and the facility will be rebuilt, says Dr. Dennis Allen, director at the site.

"There's no question we're out of business down there for the near future," he said.

But the lab was insured, and adjusters visited on Tuesday. The building will cost "better than a million dollars to repair," if it can be fixed, and more than $2 million if it has to be rebuilt farther inland, which is what Allen said he prefers to do.

The lab "took a beating on the back of the building" from the storm surge. The lab is on a creek off North Inlet, and even in locked rooms, he said there was "just short of four feet of standing water" on the floors.

Allen said 95 percent of the research records were saved. Many were on computer disks. Others were hauled out Thursday, when staffers spent the day trying to get the most valuable items to safety.

Lab workers are using Kimbel Center off Highway 17, which was undamaged. Bellefield Nature Center was also unscathed, as were the dorms and homes on Hobcaw Barony.

"We really haven't broken stride," Allen said.

Most of the research data can be run on University of South Carolina's mainframes, and much of the lab testing can be done on campus as well.

"It was quite a blow to our operation in terms of being a functional analytical laboratory," he added.

However, there is a bright spot. Allen thinks it's an unprecedented opportunity to study the effect of a major storm on North Inlet's ecosystem.

It will take six months to a year to replace the lab, Allen said, but he added everyone there feels fortunate compared to the losses of some of the community.

Meanwhile, the research continues; workers were out Friday collecting their usual samples, he said.

Workers at the Belle W. Baruch Institute try to clean the boat maintenance shed, which had parts of the wall facing the marsh knocked out by the force of Hurricane Hugo

Baruch lab lost, but research continues

By Nicole Parker

Despite the destruction ravaged upon the University of South Carolina marine research laboratory by Hurricane Hugo, researchers at the Belle W. Baruch Institute say the storm also created enormous research opportunities with the effects of hurricanes.

"The hurricane increased the research potential of the tidal area immediately," said Dr. Dennis Allen, assistant director of the Belle W. Baruch Institute for Marine Biology and Coastal Research. "It was the biggest natural disaster that could occur in a coastal area."

Allen said proposals were already being developed for research into the immediacy of the storm. He said for the first time, scientists will be able to conduct research on hurricanes where it is possible to know exactly when and where a hurricane will hit.

Although the storm was a setback in terms of damage, Allen said "most things are replaceable."

"We all anticipated this from the day we started here," he said. "We knew that sooner or later there was going to be a physical disturbance."

Dr. George Adams, director of the Belle W. Baruch Forest Science Institute of Clemson University, said the opportunities for research into Hugo's effect were also numerous.

He said one area that will be closely studied is the long and short-term effects of salt water on the trees in the upland areas. Some of the trees on the 8,000 acres of forest were standing in two-to-four feet of salt water.

Although there was little structural damage to the majority of buildings on the property, the USC marine science lab, located on the edge of the marsh, was completely gutted by the storm surge. Allen said damage estimates to the building and its contents, which included valuable equipment, is estimated at roughly $1 million.

However, only 5 percent of the data collected over the years at the lab was lost due to evacuation measures taken the week a complete lab with the USC campus in Columbia.

Looking to the future, Allen said it will probably be six months to a year before he and the rest of the research staff can get back to normal. But in the meantime, they are able to carry out a vast majority of research they were doing before the storm while working out of home which judges on the property, packing any specimens collected in dry ice and sending them to Columbia.

Although the property damage to the marine research lab and its surrounding buildings was extensive, Adams said other buildings on the property were not significantly damaged with the exception of an office building, one the Bellefield Plantation house, which had roof damage.

Hobcaw House, the office for the Clemson operation, received no significant damage and neither did any of the other historical buildings on the property. However, the front deck of Hobcaw House on Waccah Bay was destroyed.

The area forest science office, currently under construction on the property, was protected, yet somewhat with the insurance of a new roaring struggle.

In the aftermath of the hurricane, Baruch school researchers are still trying to get a handle on the extent of damages to the forests, marsh and marine stocks of juvenile fish or fishery and some fish stocks were hard or fishery and some fish stocks were completely blown away. The area in portions of the upland areas there were damage but not present a hand of the most fish are stocks of land and marine trees.

"It will a need to cut our area for the property," he said.

Allen said there wasn't a great deal of research or physical damage to the marsh areas. Accordingly and Adams agree it will be several years before the effects of Hurricane Hugo are completely known.

But he is sure of one thing. Hugo has left a mark on the marsh. Adams said he has seen no dead animals with the exception of one bird in Georgetown. Yet he said he has seen no dead animals during over the present.

Adams and most of the animals living in the marsh came through the storm safely. Yet he said some of the smaller animals living around the marsh had probably not fared as well. He said he saw some burrows and signs living in the marsh and that the storm's fall and power has been so much.

Because of the wind velocity and strength, crashing waves, the force of the property and storm surge have been totally catastrophic and a most Friday, October 13, Hurricane Hugo Research Institute

Hurricane Hugo destroyed the Baruch Marine Field Lab building and weather station in 1989, but pre-storm preparation saved all data and all light-weight equipment that could be transported to higher ground.

» North Inlet Climate and Weather Data Summary

In this section, weather patterns and trends based on long-term data from the NI-WB NERR are provided. The data were collected at Oyster Landing pier starting in 1982. These detailed observations and analyses should be particularly useful to researchers analyzing other long-term time series from the area and to investigators planning new field studies. The frequency, magnitude, and variability associated with physical factors that influence chemical and biological processes provide context for studies that are based on measurements made over short periods.

Aerial view of Oyster Landing pier, the location of the NI-WB NERR weather station.

All summary graphics and findings are based on daily averaged data. The 1983-1996 daily averaged data are derived from hourly averages (n=24) based on one second instantaneous observations (3600 per hour). The 1997-2004 daily means are derived from hourly averages (n=24) based on five second instantaneous readings (720 per hour). The 2005-2010 daily averaged data are derived from 15 minute averages based on five second instantaneous readings (180 readings per 15 minute interval). If there were less than 64-15 minute data (67% of the data per day), then the values were not averaged for the day and the daily average value was listed as missing. If there were less than 20 days of daily averages for the month (less than 67% of the daily values for the month), then the values were not calculated, and the monthly value was listed as missing. Years and variables which had less than 250 days (67% of the year) of daily mean data were not used in annual summary or long-term analysis; years which had less than 310 air temperature, barometric pressure, or wind speed daily values (or less than 85% of the year) are used with caution.

AIR TEMPERATURE

Measurements of air temperature have been made at the North Inlet – Winyah Bay Reserve since June of 1982. Over the 28-year period from 1983 through 2010, mean annual air temperature at North Inlet remained fairly consistent, ranging from a low of 16.7°C (62°F) in 1989 to the hottest yearly average of 19.0°C (66°F) in 1998 (Figure 11). The overall mean based on annual averages from 1985-2010 (excluding 1986, 1987, 1996 & 1997) was 17.8°C (64°F). The five years with the greatest range or variability in daily air temperature during the year were: 1989 (range of 36.6°C (98°F)) and 1994, 1999, 2003, and 2005 (range of about 34°C (93°F)). The five years with the lowest range in daily air temperature were: 1990 (range of 28.5°C (83°F)) and 1987, 1992, 1993, and 1998 (range of about 29°C (84°F)). Fifteen degrees Fahrenheit separated the largest (1989) and the smallest (1990) air temperature ranges; oddly, these were in two consecutive years.

The hottest average daily air temperature of 32.5°C (90.5°F) occurred on August 1st, 1999. The next hottest was 1986 (not graphed) with 31.6°C (88.9°F) on July 10th. July and August 2005 and 2007 also had daily average temperatures of over 31°C (87.8°F). The coldest daily temperature occurred on January 21st, 1985 when the average was -9.3°C (15.3°F). December 25th and 23rd of 1983 and 1989, respectively, averaged below -8.2°C (17.2°F). Figure 11 illustrates that the maximum daily temperatures for each year varied little over the 28 years. However, the minimum daily temperatures warmed by an average of about 5°C (41°F) between the 1980s and the 2000s.

The monthly average air temperatures in North Inlet followed a bell-shaped curve, with the coldest air temperatures averaging between 8°C and 10°C (46°F and 50°F) in the fall & winter months. The hottest average air temperatures of over 25°C (77°F)

occurred in summer (July and August), with July having the hottest average temperature of 26.5°C (79.7°F) (Figure 12). Ranges between minimum and maximum daily temperatures were greatest from December through February (26.5 - 31°C or 79.7°-87.8°F), and daily variability was least during June, July, and September (13 - 15°C or 55.4-59.0°F).

The coldest monthly mean with an air temperature of 4.4°C (39.9°F) was recorded in January 1988. January of 1985 and 2010 were the next coldest months/years of the 28 years with an average monthly temperature of 5.8°C (42.4°F). The hottest monthly mean air temperature was 27.9°C (82.3°F) in July 1986. Following very close to this high were July 1993, 1998, 1999, and 2005 which had average air temperatures at or slightly above 27.5°C (81.5°F). 1990, 1991, and 1992 also had average highs of over 27°C (80.6°F) in July.

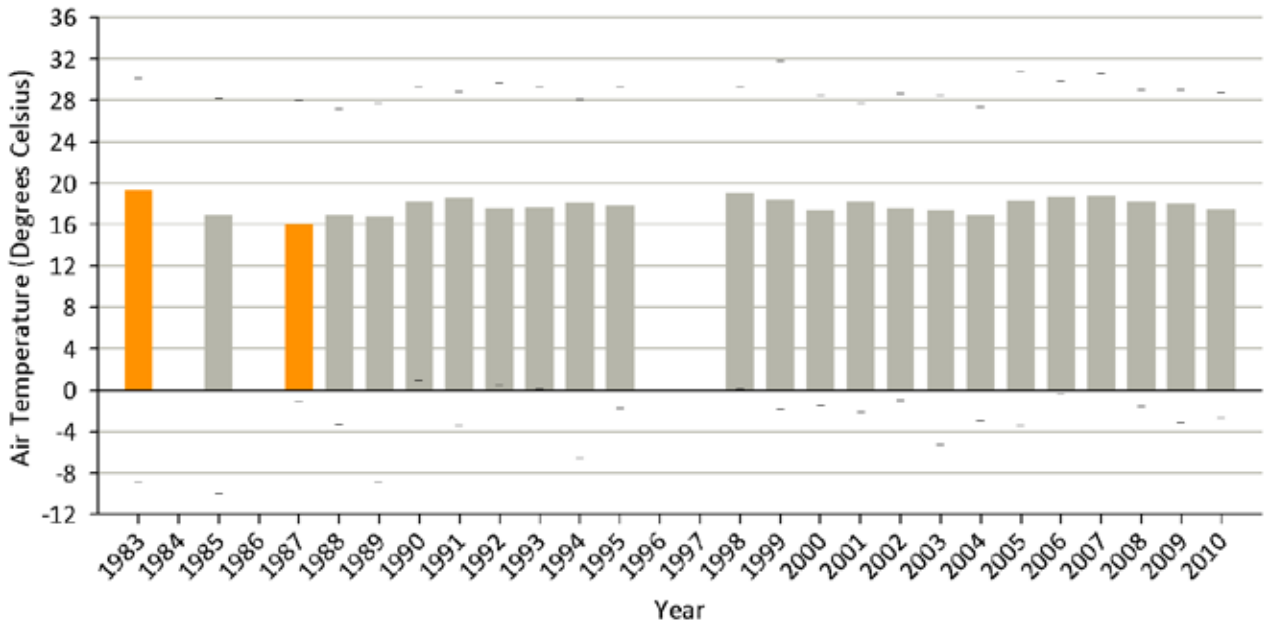

Figure 11. Annual average air temperatures in North Inlet. Minimum and maximum daily temperatures for that year are indicated with a dashed line below and above each bar. Years which did not have enough data for annual temperature summaries were 1982, 1984, 1986, 1996 and 1997. Note: 1983 and 1987 (colored orange) had less than 85% air temperature data for the year, so were graphed here, but not used in annual statistics.

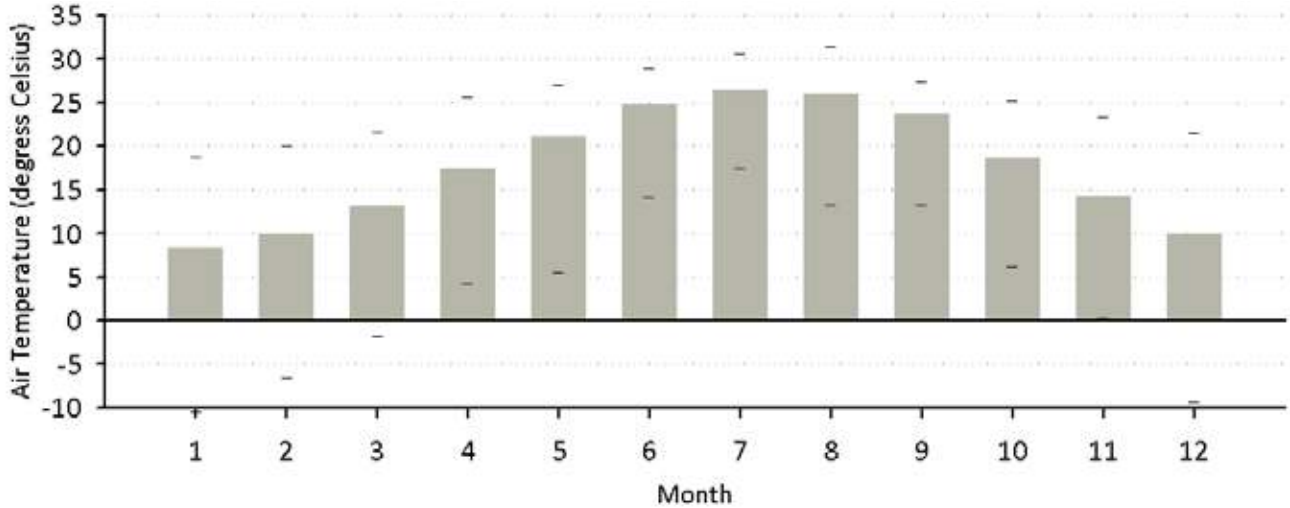

Figure 12. Monthly average air temperatures in North Inlet. Minimum and maximum daily temperatures for the month are indicated with a dashed line below and above each bar. Not all months from all years are included in this graphic, as some years were lacking enough data.

PRECIPITATION

According to 30 years (1981-2010) of rainfall measurements at North Inlet, the overall annual average was 49.14 inches. The seven wettest years were 2003 (66.13 inches), 2005 (62.94 inches), 1992 (59.51 inches), 1998 (59.32 inches), 1994 (59.19 inches), 1982 (58.81 inches), and 1995 (57.87 inches) (Figure 13.). These years coincided with El Niño events that brought unusually high precipitation to the southeastern U.S. from December through April. Two of the strongest El Niño events in 100 years were in 1982 and 1998. Above average precipitation in North Inlet was not always associated with El Niño events. Other wetter than average years (1989, 1996, 1999, and 2008) were due to winter storms (Nor'easters), spring and summer thunderstorms, and/or summer and autumn tropical disturbances. Due to increasing frequency of El Niños and tropical storms during the 1990s, the long-term trend for the North Inlet area was one of increasing precipitation. Severe drought conditions in the 2000s ended this trend (Figure 13).

The six driest years in North Inlet from 1981-2010 were 2007 (31.61 inches), 2001 (33.30 inches), 1993 (33.98 inches), 1990 (34.80 inches), 1988 (38.72 inches), and 1986 (38.99 inches) (Figure 13). A number of these dry years were associated with La Niña events (red bars). Documented severe droughts occurred statewide during the years of 1986, 1990, 1998-2002, and 2007-08. The 1986 and 2001 droughts were two of the most severe droughts in South Carolina. The 1986 drought was accompanied by weeks of record or near-record high temperatures and record high demand for water in July. Less severe droughts were reported in 1988, 1993, and 1995. Adverse impacts on the people and economy were made especially clear during the drought of 1998-2002 which impacted agriculture, forestry, tourism, power generation, public water supplies, and freshwater fisheries. A moderate drought was declared in June 2007 and its status was upgraded to severe from September 2007 through January 2008.

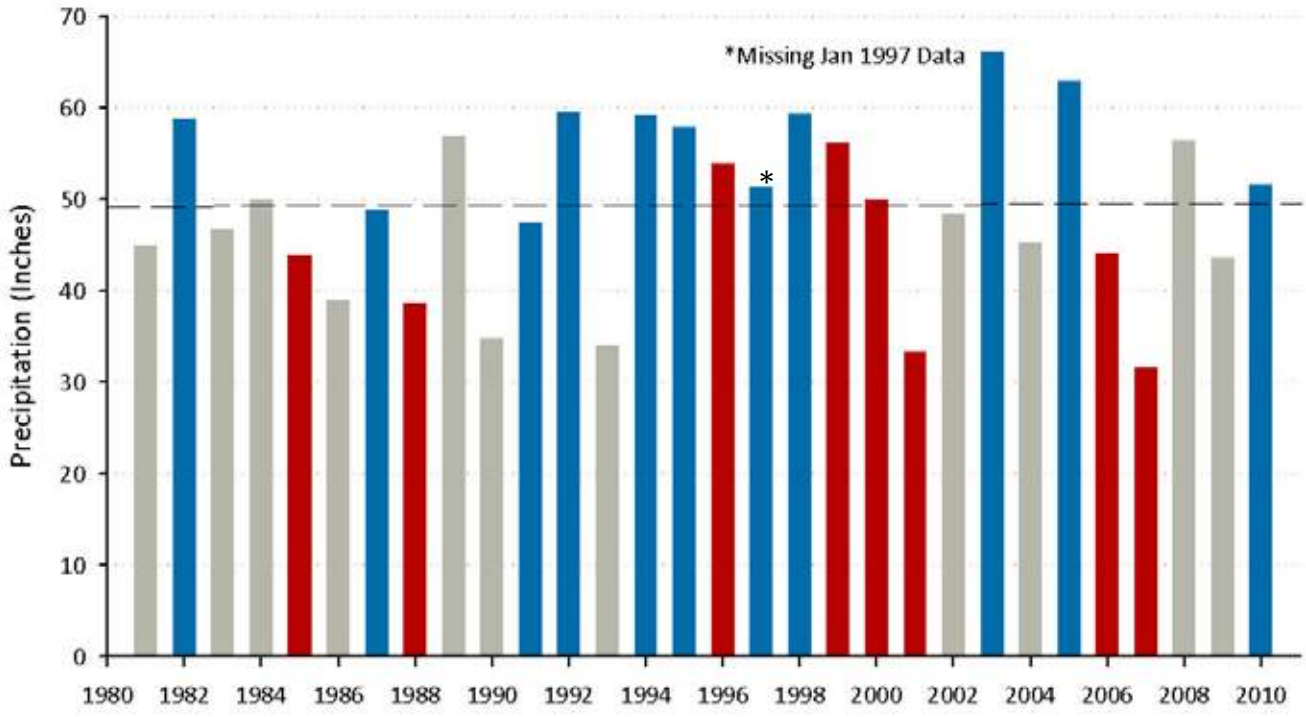

Figure 13. Total annual precipitation measured at Oyster Landing, North Inlet for 1981 through 2010 (30 years). Blue bars indicate years in which El Niño events occurred; red bars denote years when La Niñas were present. El Niño and La Niña events are based on NOAA's monthly NINO 3b Index. The dashed line indicates the 30 year average total rainfall of 49.14 inches.

During the 30 year period, overall monthly average for rainfall in North Inlet was 4.11 inches. Monthly average precipitation was highest in August (6.43 inches), with average rainfall in September and July closely following with 5.91 and 5.81 inches, respectively (Figure 14). The maximum monthly precipitation of 15.33 inches was recorded in August 2004, the greatest monthly rainfall in the 30 years of observations. Other peak monthly values above 14 inches were August 1981, September 1996, 1999 and 2000, and July 2003. The typical high variability observed during the summer and early autumn months (Figure 14) is due to intense thunderstorms and tropical disturbances. Table 1 lists some of the tropical systems that produced large amounts of rain in the Georgetown area. The largest single total daily rainfall of 8.94 inches occurred on September 15th, 1999.

The months with the least amount of rainfall were November, April, and May, with a monthly average of less than 3 inches per month (Figure 14). Some rainfall was recorded for every month during the 30 year period. October 2000 was the driest month with a trace recording of 0.06 inches; the next lowest month/year total rain was November 2007 with 0.10 inches. Other month/years with a monthly total of less than or equal to 0.5 inch of rain were November and December 1984, July 1993, April 1994, August 1997, and April 2001.

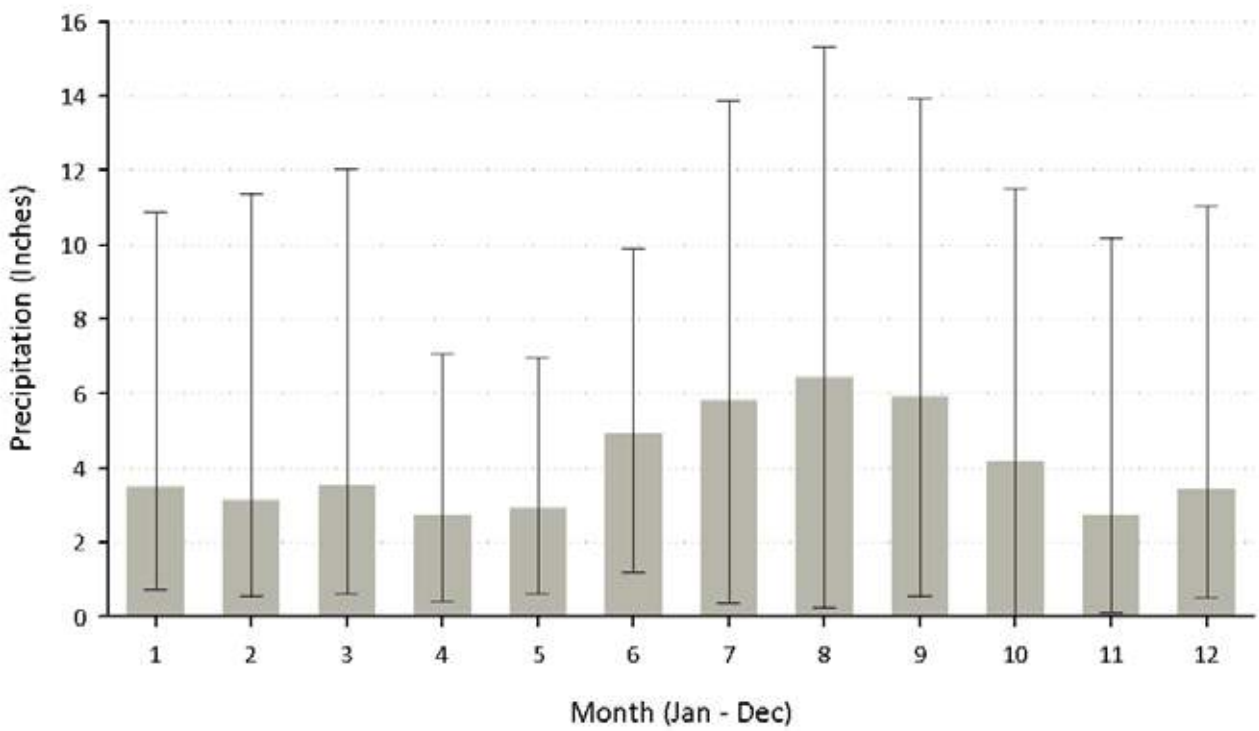

Figure 14. Monthly average precipitation for North Inlet from 1981 through 2010. The minimum and maximum monthly total rainfall recorded over the 30 years are denoted with the vertical range line in each bar.

WIND

The general direction of wind in North Inlet during spring and summer is from the south and west, but wind is more evenly distributed around the compass during autumn and winter. Southwest is the most frequently recorded direction during all seasons. Prevailing wind direction has been consistent from year to year. Data from 1982 through 2004 were analyzed for the following summary and shown in Figure 15.

Spring winds (both low and high velocity) were primarily from the south and west (180 to 270 degrees) direction, but the dominant spring wind pattern was from the southwest. However, both calm and strong episodic wind events from the northeast and southeast directions occurred during spring. Winds from the northwest are uncommon in May and June. In June, the flow from the southwest was more prevalent, although low velocity southeast winds became more common.

During July and August, light winds from the southwest especially dominated, with some from the southeast. In August and September, the pattern changed with an increasing frequency and higher velocities of winds from the northeast. Some southeast winds were recorded but northwest winds were unusual during July and August.

Autumn winds were from all directions, but southwest was still the prevailing direction. Northeast events became more frequent with higher velocities and the frequency and speed of northwest winds increased in December.

Winter winds were from all directions, but southwest continued to be a dominant direction. In January, northwest winds are also common. The strongest winds were from the northeast during all three winter months, and in March strong winds occurred from the southwest as well. In March, very little wind originated from the north.

Average monthly wind speeds remained fairly constant over the year, with the greatest difference being less than 1 ms^{-1} between the highest and lowest average monthly velocities (Figure 16). Based on daily values for the 28 year period, the mean wind velocity for North Inlet Estuary was 3.6 ms^{-1} or 8.1 miles per hour (mph). The highest average monthly wind velocities of greater than or equal to 4 ms^{-1} or 8.9 mph occurred in March, April and May. March, July, August, and October all had the most variable daily wind velocities of over 12 ms^{-1} (26.8 mph). June and November had the least monthly variation, with less than 8 ms^{-1} (17.9 mph) between the highest and lowest daily wind speed. August through January had the lowest daily wind speeds of less than or equal to 0.5 ms^{-1} (1.1 mph). The highest average daily wind velocity was recorded on August 29th, 1990 of 13.70 ms^{-1} (30.7 mph). Other windy days were March 13th, 1993, October 3rd, 1994, July 18th, 1984, and August 29th, 2004 with average winds over 12 ms^{-1} (27 mph). The March wind event was due to a Nor'easter and the other wind events were due to tropical disturbances. Maximum wind gusts from tropical systems and hurricanes can be found in Table 1. Like the monthly average wind speeds, average yearly wind speeds remain fairly constant over the 28 years; the greatest difference was less than 1 ms^{-1} among the years.

The weather station at Oyster Landing

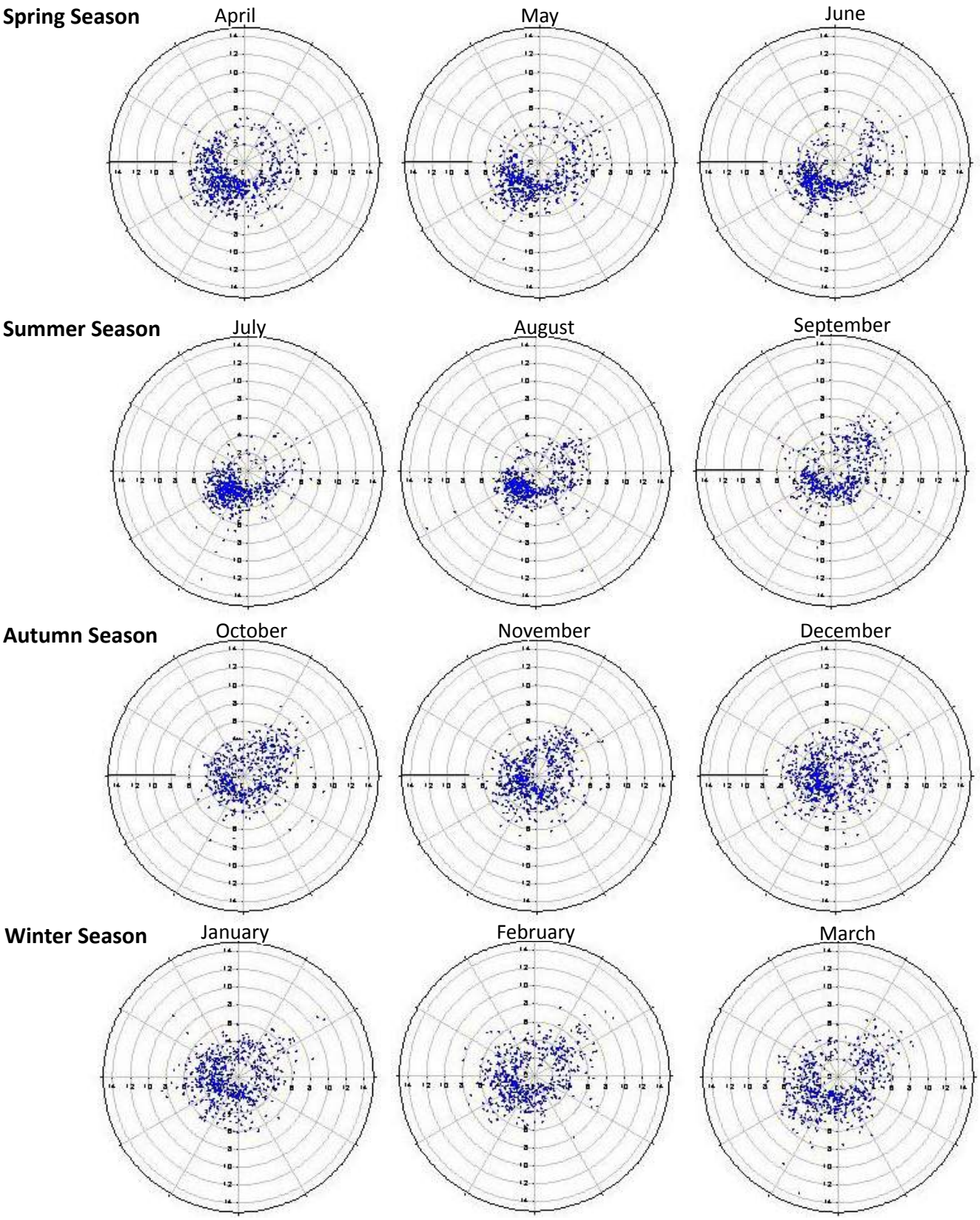

Figure 15. Average daily wind direction and velocity (ms-1) for each month from 1982 through 2004. These data were recorded at the Oyster Landing Pier in North Inlet. Direction of the wind that is coming at you is indicated by the position of the data point (dot) relative to North at the very top edge or 0 degree position of the compass rose. Due east is 90 degrees, south is 180, and west is 270 degrees. Velocity of the wind data point increases with distance from the center and is measured in meters per second.

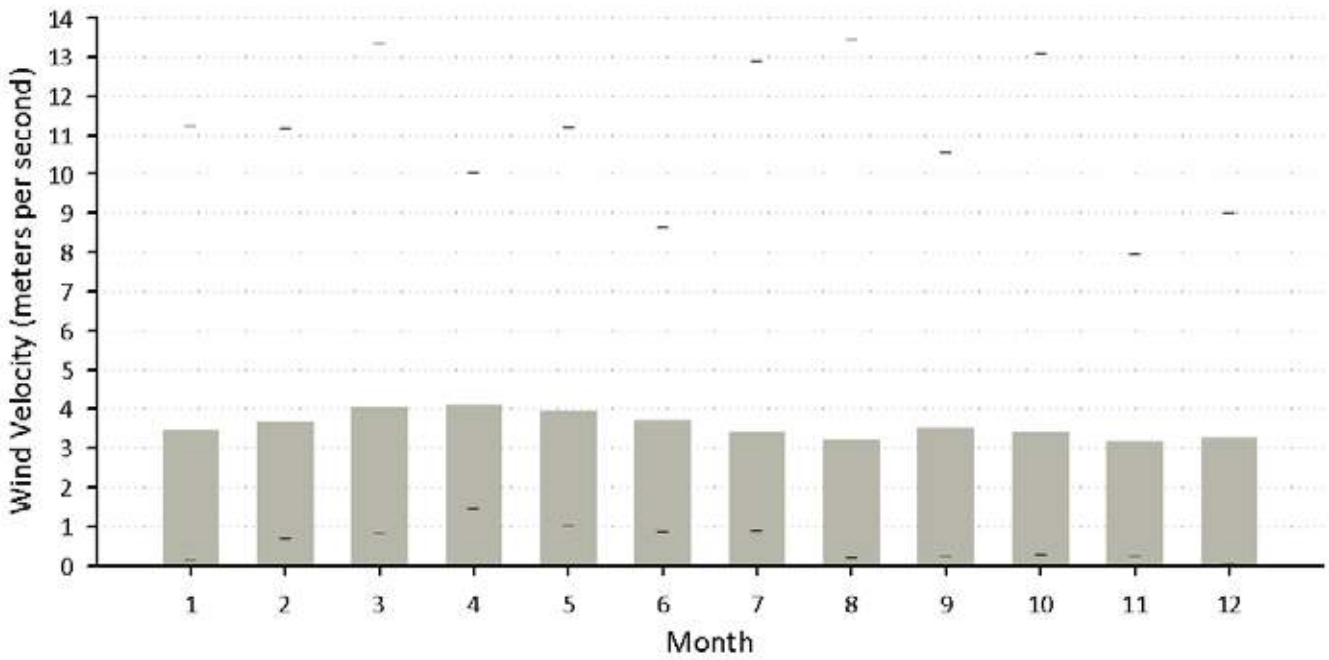

Figure 16. Monthly average wind velocities recorded in North Inlet from mid-1982 through 2010. Minimum and maximum daily wind speeds for the month are indicated with a dash below and above each bar. Values are in meters per second.

BAROMETRIC PRESSURE

The average monthly barometric pressure (BP) in the North Inlet area varied little between January and December (only about 5 millibars (mb)), although the spring and summer months had somewhat lower than average pressures than the winter and autumn months (Figure 17). The overall average barometric pressure for the 28-year period was 1017.3 mb. Day-to-day variation was smallest in July, August, and September. May and June also had the lowest maximum daily pressures (less than or equal to 1029 mb). October through April had the highest monthly average barometric pressures (1033 - 1040 mb) of the year along with the greatest daily variation. These seasonal patterns can be attributed to large weather patterns such as the Bermuda High, continental and oceanic high and low pressures, tropical storms, and large thunderstorm systems.

The highest average daily pressure was recorded on February 26th, 1990 with 1040.00 mb; ten other daily averages of over 1036 mb occurred over the 28 year period; seven of these days were during the month of January in the years of 1998, 2000, 2004, 2005, and 2008. November and December of 2004 and February of 1990 were the other months which had a daily average BP over 1036 (Figure 18).

The lowest average daily pressure of 985.25 mb occurred on May 16th, 1985; six other dates in this month/year also had daily average BPs of 990 mb or less. February 4th, 1998 also had a very low daily average BP value of 988.28 mb; this was the year of the strongest El Niño in 100 years. The weather station instruments at Oyster Landing recorded the lowest daily minimum reading on March 13th, 1993 of 975 mb due to an intense winter cyclone (average daily value was 987.79). The highest daily maximum values of over 1040 mb occurred on February 26th, 1990 and December 1st and 19th, 1991.

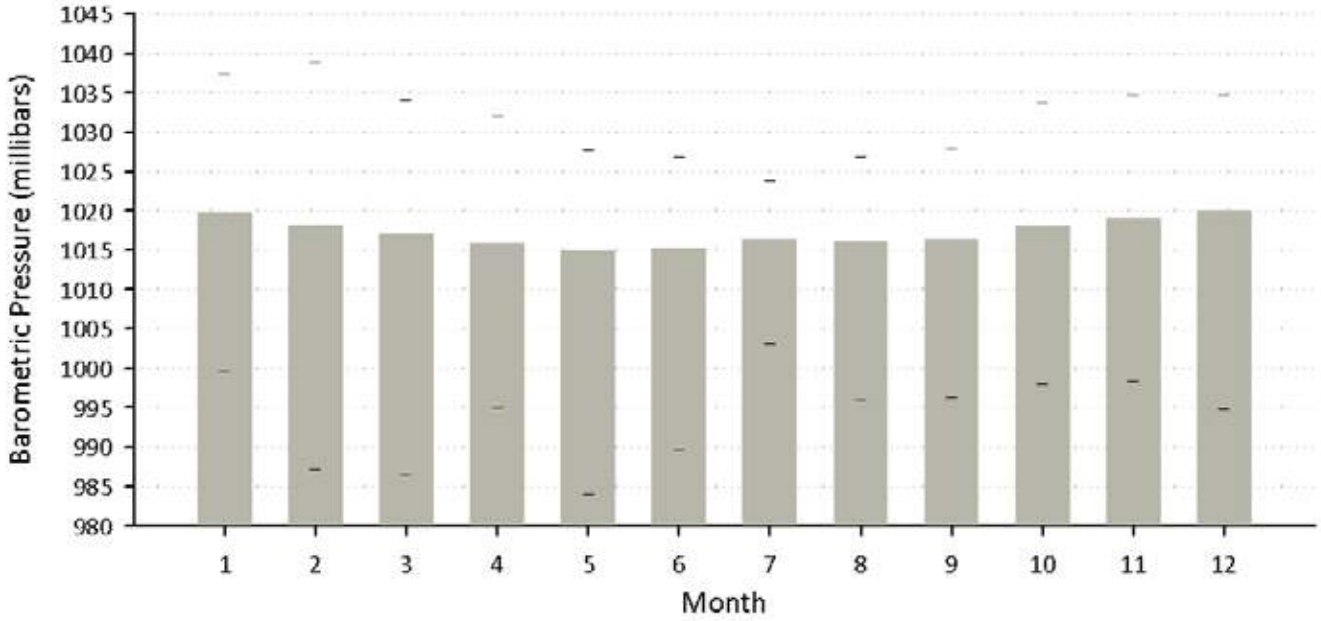

Figure 17. Monthly average barometric pressure recorded in North Inlet. Minimum and maximum daily barometric pressures for the month are indicated with a dash below and above each bar.

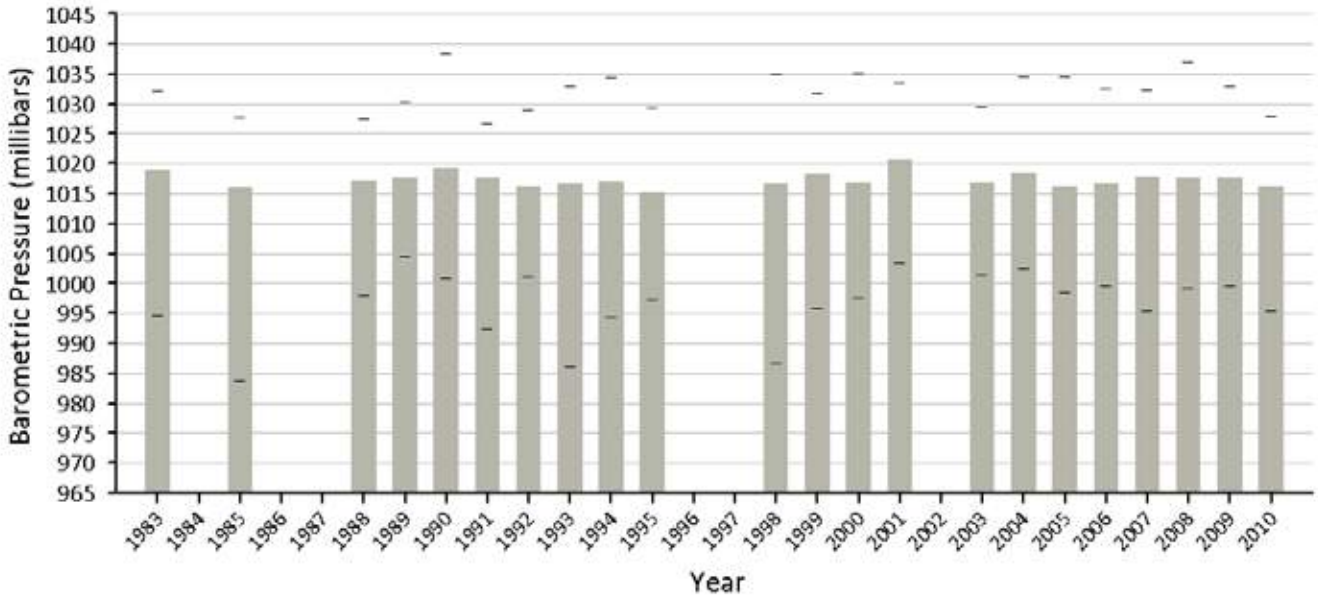

Figure 18. Yearly average barometric pressure recorded in North Inlet. Minimum and maximum daily barometric pressures for the year are indicated with a dash below and above each bar.

General Physical Characteristics and Justification for Treating the Two Estuaries Separately

There are large differences in the physical structure and water properties of the North Inlet and Winyah Bay estuaries, including their water chemistry, ecological functions, and their flora and fauna. These differences are profound enough that we decided to provide separate descriptions of the physical, chemical, and biological characteristics of the two partially-connected estuaries.

Estuaries are broadly defined as coastal areas where freshwater from the land meets the ocean. One extreme type of estuary is so strongly dominated by tidal exchanges from the ocean that the influence of freshwater runoff from the surrounding watershed on the salt content of the major waterways is small. North Inlet is an example of such an ocean- (tidally) dominated estuary. At the other extreme, an estuary may be so strongly dominated by river inflow and drainage from the surrounding watershed that the penetration of seawater with the incoming tides is limited to the area close to the inlet. An example of this kind of estuary is found just south of Winyah Bay where the North and South Santee Rivers flow into the ocean. Because more mixing of freshwater and seawater occurs outside of the inlet than within it, this area has been referred to as the only major delta on the east coast of the US.

Winyah Bay is intermediate between these two extreme types of estuaries. The influence of its rivers is strong but, except under periods of high freshwater outflow, much of the mixing between freshwater and seawater takes place within the estuary, with the area closest to the inlet typically having higher, oceanic salinities. Table 2 highlights many of the gross differences between Winyah Bay and North Inlet that should be kept in mind while reading the subsequent sections of this document. There are also many similarities between portions of both estuaries, but the major functional differences that exist between these two portions of the NERR outweigh their similarities, hence our decision to treat them separately.

In the next two sections, we describe the geology, geography, patterns of water movement, and water quality/chemistry. In the chapter that follows, the habitats common to both estuarine systems are presented. This is followed by a section on the algae, vascular plants, microbes, and animals of North Inlet, then by a section on the same biotic components in Winyah Bay. Figure 19 shows the names and locations of waterways and landmarks mentioned in the many research studies presented in these sections that help characterize the NI-WB NERR.

A final comparative section presents similarities and contrasts differences between the two estuaries. By treating these two estuarine systems independently, the disparity in the extent of our knowledge of the two estuaries becomes even more apparent. Compared to North Inlet and despite its being one of the largest estuaries on the east coast, relatively little research has been conducted in Winyah Bay.

The lighthouse on the southern end of North Island marks the entrance to Winyah Bay.

Table 2. Comparison between the North Inlet and Winyah Bay portions of the North Inlet-Winyah Bay NERR: differences in key features and other characteristics.

Characteristic	North Inlet	Winyah Bay
Watershed size	Small	Very large
Hydrographic regime	Tide-dominated	River-dominated
Circulation shallows	Well-mixed	Stratified channel, mixed
Sources of freshwater	Precipitation	Rivers, precipitation, agricultural runoff, non-point source
Influence of precipitation	Small	Large
Salinity range	High/narrow	Wide/variable
% open water vs. edge	Small	Large
Fetch/current velocity	Short/moderate	Long/strong channel-moderate shallow
Sediment input/turbidity	Small/moderate	Large/high
Depth regime	Shallow	Deep rivers and channels/shallow flanks
Nutrient load	Low	High
Pollutant load	Very low	Moderate-high
Pollutant source	Aerial deposition, creeks connecting Winyah Bay	Aerial, agricultural, municipal, industrial
Dissolved oxygen	High in major waterways	Low-moderate in channels, hypoxia occurs
Dominant marsh plants	*Spartina alterniflora*	*S. alterniflora* near ocean, *S. cynosuroides*, *Juncus* mid-upper bay, *Phragmites* in upper bay
Fauna diversity/structure	High/oyster reefs	Moderate near ocean, low upper bay
Commercial fisheries	Blue crab	Penaeid shrimp, blue crab, shad
Shipping traffic	None	Moderate-high

Figure 19. Waterways and landmarks in the North Inlet-Winyah Bay NERR

North Inlet

Sunset over North Inlet viewed from the fire tower at Clambank Landing

» Geology and Geomorphology

The NI-WB NERR lies on the Coastal plain geological province which consists of a tectonically inactive wedge of largely unconsolidated sedimentary strata that began to accumulate about 100 million years ago (Late Cretaceous). More than one half mile (~ 1000 m) of accumulated sediments occur beneath the SC coast. Present topography, bathymetry, and geology reflects changes in climate, sea level, and riverine discharge during the past 15,000 years. Since that time, sea level has increased by about 120 m. The North Inlet and Winyah Bay areas were entirely upland areas located 100 km or more from the ocean. Increasing sea level resulted in the encroachment of the ocean into the present day North Inlet area about 5000 years ago. As the level of the ocean increased, it extended over a series of old shorelines and beach ridges left from when sea level retreated during the Wisconsin Glaciation (>15,000 years ago). Around North Inlet, freshwater marshes and swamps (that had developed between sandy ridges during the time sea level was low) eventually became inundated by tidal water and became salt marshes. Radiocarbon datings of roots of cedar trees collected below the North Inlet salt marsh show that the Crabhaul Creek area was forested about 2600 years ago (Gardner and Porter, 2001).

Tidal creek networks and marshes are the result of spatial and temporal variations in patterns of erosion and deposition over millennia and centuries (Gardner and Bohn, 1980). Rising sea level converted small terrestrial streams to major tidal creeks. Ancient valleys between high sand-ridges were eroded by tidal flow, resulting in the widening and deepening of channels. A net seaward transport of forest sand nourished inlets and barrier islands. At the same time, a net landward transport of clay and mud (probably as suspended material) built new marshes and mudflats within the estuary (Gardner et al., 1992b). Larger, sandier, older, and temporally more stable creek systems occur closest to the ocean whereas more recently formed and more dynamic tidal creeks and marshes occur closer to the forest.

» Tidal Regime/Hydrology

North Inlet is a high-salinity, well-mixed coastal lagoon harboring typical southeastern US salt marsh with an area of 32 km^2 (3,200 ha). It is a bar-built, class C estuary (Pritchard, 1956) and usually has salinities between 30-34 in its main basin. The inlet has an open connection to the sea through which semidiurnal tides flood and ebb twice each tidal day (about 24 h 50 min). Each successive high or low tide occurs about one hour later the following day. Mean tidal range is 1.4 m and average water depth in the basin is about 3.5 m at high tide. Maximum depth is about 8 m. Tidal range is greatest during new and full moons (spring tides, range = 2.1 m) and least during 1st and 3rd quarter moons (neap tides, range = 1.0 m). Maximum tidal range, about 2.5 m, occurs when the moon, sun, and Earth are aligned. Approximately half the water in the North Inlet basin flows to the Atlantic Ocean during ebb tides. The mouth of the inlet is part of an active subtidal sediment transport system driven by net southerly alongshore currents. As water moves in and out of the inlet, depositional deltas form both outside (seaward) and inside (landward) the mouth, constricting flow into deeper channels that change location when storms reconfigure the bottom contours (Blood and Vernberg, 1992).

Flooding tides enter North Inlet with velocities that are slightly slower than the velocity of ebbing tides. Flood duration can last up to 1.5 h longer

than ebb duration. This asymmetry in the tidal regime results in seaward transport of suspended sediments, but hurricanes in the summer and fall and other fall storm events can shift huge amounts of sand along the coastal beaches, greatly altering the configuration of the inlet's mouth. Depending on season, much of the water that leaves North Inlet re-enters on the next flooding tide. The net result is that enough sediment is retained within the basin for the marsh surface to maintain its position relative to the local rate of sea level rise, 1.5 – 3.0 mm per year. Water levels within the basin are greatly influenced by the wind. With prevailing and persistent easterly and northeasterly winds, water can be pushed into or held within North Inlet to such an extent that, for instance, the next predicted low tide is higher and later than predicted. It is rare that southwesterly winds are so strong as to affect entry of a flooding tide, but the predicted arrival times of flood tides can be delayed by such winds. Strong westerly winds can result in lower tide levels than those predicted. The combination of spring tides and strong westerly winds on April 15-16th, 2007 resulted in some of the lowest tides in a decade, with low tides being about 0.7 m (about 2 ft.) below mean low tide. Persistent southwesterly winds often result in increased penetration of Winyah Bay water into North Inlet, especially when river discharge is high during winter and spring.

Freshwater input to North Inlet comes primarily from the surrounding forested watershed and is on the order of 10 m^3s^{-1}(Dame et al., 1991). Following heavy precipitation events; however, salinities can temporarily decrease to nearly freshwater values in the shallowest tidal creeks. With prolonged periods (days) of runoff from the surrounding forest, salinities can remain depressed for several days at a time, with salinities on the order of 10 in surface waters of the inlet, but these are rare events.

Tidally-driven currents in the main channels of North Inlet (e.g., Town Creek) can reach 2.3 ms^{-1} and have been known to move heavy equipment moored or anchored to the bottom. Ebbing flows are substantially faster than floods, so the ebb-dominance must be taken into account whenever time-integrated volume flux measurements are made in North Inlet. Current velocities are typically slower in creeks near the forest border than near the inlet, and velocities are also lower near the bottom than at the surface of creeks. Throughout North Inlet, water flow into smaller creeks is, of course, tidally-driven, but when water level exceeds the height of the creek banks, sheet flow from adjacent creeks will enter the marsh. Compared to creek flow, however, sheet flow is minor, accounting for only about 1% of the tidal prism (Eiser and Kjerfve, 1986). Sheet flow may be very significant as a conduit for movement of organisms between the marsh surface and the creeks within North Inlet, especially during spring tides when 50% of the volume of water that enters smaller basins inside North Inlet can be a result of sheet flow over the grassy flats of the marsh (Miller and Gardner, 1981).

Besides the Atlantic Ocean entrance, there are three other outlets/inlets for water in the North Inlet basin. No Man's Friend and Haulover creeks are minor in this regard compared with Jones Creek, a well-defined channel that also opens into the Mud Bay portion of Winyah Bay to the south of North Inlet. Jones Creek accounts for about 80% of the exchange of water between North Inlet and Winyah Bay. Jones Creek meanders 8 km in a N-S direction from just inside the mouth of North Inlet to the eastern side of Mud Bay. It averages <3 m deep and 50-80 m wide. Flow in the creek is unidirectional at all depths. The creek has a 2 km long stretch at its northern end where water is warmer and higher in salinity than the southernmost 3 km stretch with fresher and cooler water. Between these two water masses lies a transition zone having sharp longitudinal gradients of temperature and salinity. In the transition zone is a region where a nodal point exists such that tidally-driven water simultaneously floods Jones Creek from North Inlet and from Winyah Bay. Likewise, water north of the nodal point leaves Jones Creek via North Inlet and water to the south of the nodal point travels toward Winyah Bay (Traynum and Styles, 2008). Tidal flows within Jones Creek can be half a tidal cycle out of phase (Schwing and Kjerfve, 1980).

» Water Quality in North Inlet

Good water quality is essential for the health of our nation's estuaries. Reduced water quality can result from elevated nutrient levels (harmful algal blooms), low levels of dissolved oxygen (anoxia, fish kills), chemical contaminants (toxins, oil spills, heavy metals), and elevated fecal coliform bacteria or viruses (shellfish harvesting closures, skin infections, diarrhea). Any of these problems may be a sign of poor estuarine ecosystem health because they subvert and disrupt natural biogeochemical cycles that normally insure high water quality. Conflicts often arise between economic concerns and resource use that can be deleterious to water quality, e.g., dredging, industrial discharges, resource harvesting methods, and accidental spills. Monitoring water quality therefore has important implications far beyond local concerns and thus remains a critical element guiding and informing regulatory services imposed by local, state, and federal levels of government.

The NERR system was designed in part to monitor many of these measures of coastal ecosystem health (Wenner and Geist, 2001; Kennish, 2004). The NI-WB NERR conducts a water monitoring program – System Wide Monitoring Program (SWMP) - to provide high-quality data to researchers and coastal decision makers. The same instruments and methods are used at all NERR sites and hence the water quality data from all locations are directly comparable. Data from all 28 Reserves nationwide are compiled and certified at the Baruch Marine Field Laboratory by personnel in the NERRS Centralized Data Management Office (CDMO). Porter et al. (1994, 2004) describe how the estuarine data management process is organized, and Fletcher et al. (2006) describe data collection and management for the system of offshore sensors in the South Atlantic Bight. These water quality data are used to examine tidal, seasonal, and annual changes and trends in water quality parameters.

Until such time as additional sampling stations for broader spatial coverage and more reliable offshore monitoring capabilities can be established, the NERR's System Wide Monitoring Program will remain at the forefront for monitoring estuarine health in the U.S. Local scale, individual NERR site monitoring becomes regional and/or national when the SWMP database is considered *in toto*. In addition to the non-regulatory SWMP programs in South Carolina are other state level, regulatory, water quality monitoring efforts under the Department of Health and Environmental Control (DHEC) and the Department of Natural Resources that are beyond the scope of this overview (e.g., Van Dolah et al., 2008).

Monitoring of water characteristics has occurred at least somewhere in North Inlet for several decades, and at Oyster Landing since 1981 under aegis of the National Science Foundation's Long Term Ecological Research (LTER) program (Wolaver et al., 1984). These long-term data provide an infrastructural capacity that is uncommon in most other U.S. estuarine waters. They are exceedingly valuable for researchers making predictions about climate change or for understanding the impacts of sea level rise, drought, weather events (tropical storms and hurricanes), or human-caused alterations to drainage basins under the constant pressures of coastal development.

At the NI-WB NERR, one SWMP station exists at Oyster Landing, a location that has also served as the original water quality and meteorological station for North Inlet since the LTER program started in 1980. Two additional SWMP stations are located in Debidue Creek (Lohrer and Wetz, 2003) and at Clambank Landing. Another SWMP station is located in a small creek in central Winyah Bay. This is Thousand Acre marsh, an old rice field that undergoes regular tidal flooding. Details about the overall SWMP sampling program can be found in Wenner and Geist (2001), Sanger et al. (2002), and Kennish (2004). Details about the sampling protocol here are found in the Baruch database metadata descriptors (**www.baruch.sc.edu**) or more briefly in Buzzelli et al. (2004).

Research on water quality in the NI-WB NERR has been conducted at a variety of spatial and temporal scales, but most studies have sampled only a very few stations and have been directed at questions related to sources and sinks, variability of

concentrations over tidal, seasonal, and interannual periods of time, exchanges between subsystems within the estuary, and fluxes of dissolved materials to and from the adjacent coastal ocean or fluxes between subsystems within the marsh. Calculations of material and chemical fluxes require knowledge of an entities' instantaneous concentration and the volume and flow rate (discharge) of the water carrying those concentrations, whether in natural creeks and channels or in experimental flumes (Wolaver et al., 1985). Overviews of physical and chemical factors in North Inlet and Winyah Bay can be found in the earlier synthesis works by Blood and Vernberg (1992) and Vernberg (1993), while overviews of inter-estuary comparisons between many of these same factors can be found in Vernberg (1981, 1996) and Blood and Smith (1996).

The four strategically located SWMP stations are adequate to characterize water quality to the degree that is currently needed in the NI-WB NERR. The long-term data that exist are generally continuous but occasionally interrupted by a variety of short-term equipment malfunctions and/or faulty instrument calibrations. Regular long-term sampling in tidal systems can be problematic in the face of a stochastically or periodically changing landscape. Sampling water at a single fixed time of day can result in data aliasing with a semidiurnal tide regime, but Hutchinson and Sklar (1993), by grouping data into lunar periods, found an efficient way to remove short-term cycles in a long-term data set for analysis of longer-term trends, spatial patterns, and unusual events. Considerable effort has been put into solving many of the logistical and statistical sampling problems that have arisen in this regard (Kjerfve et al., 1981, 1991; Childers et al., 1994). Wilde et al. (2007) have used data from five different NERR sites in the southeastern US region and a variety of statistical methods to separate signal from noise in the long-term water quality monitoring data sets.

In the following sections, water quality studies are compartmentalized according to their physically- and analytically-measured foci. Additional information on each topic (e.g., salinity) can be found in other sections of this document that address hydrology, phytoplankton, animal communities, and water chemistry.

SALINITY

Salinity used to be expressed as parts per thousand (ppt or ‰). The correct expression in use today is the Practical Salinity Scale which has no units – salinity is a ratio between the measured salt concentration and that of a standard salt solution (UNESCO, 1985). Because both numerator and denominator have the same units, they cancel each other mathematically and the resultant measure has no units. Some investigators have reported salinity using the term "psu" (practical salinity unit), but this unit has lost favor in the literature and is only used when the term 'salinity' does not precede it in a sentence (Millero, 1993). The values of the newer, dimensionless measures are very close to the old parts per thousand values.

North Inlet is a high-salinity estuary with little freshwater input. The concentration of dissolved salts in the water is altered by precipitation, surface and underground runoff, evaporation, riverine inputs during flood events, drought, freezing (extremely rare here), and tidal fluxes. Most of the time salinity of the water column in North Inlet falls between about 29 and 34, but occasionally up to 37 or down to about 20, but after rain, it can get down to about 4 in the tidal creeks closest to the forest.

Salinity varies spatially and can change rapidly but has some regular temporal variations. Creeks close to land drainage or to exchanges with Winyah Bay have lower salinities than those closer to the mouth of the inlet. Generally speaking, however, salinities are spatially homogeneous in North Inlet because so much of its volume is exchanged with each change of the tide (approximately 40%) and because the water is well-mixed from top to bottom and has a hydrodynamic residence time of only about 15 hours (Kjerfve, 1986). Tropical storms and hurricanes can lower the entire estuary's salinity dramatically. The resultant freshwater discharges and prolonged runoff from watersheds surrounding the North Inlet salt marsh can keep surface salinities low for periods of days if rainfall persists. Waters closest to the uplands have much higher variability

in salinity than those near the inlet. Groundwater in the uppermost several meters of upland soils moves very slowly under gravity toward the tidal system and discharges at various points in the marsh surface and especially from the banks and bottoms of creeks. On the salt marsh, sediment pore water (= interstitial water in marsh soils) salinities are generally invariant with depth in the sediment down to 30 cm but salinities in the uppermost 1 cm can reach nearly 60 in the high marsh in summer during times of intense insolation and high evaporation at low tide (Morris, 1995).

Short-term patterns for salinity are similar at the two North Inlet stations located in creeks near the uplands borders. The dataset from Oyster Landing is useful for describing the salinity record for North Inlet as a whole, and a general description of the results based on the monitoring there is presented below.

Figure 20 shows the salinity track during a typical 48 hour summer period during which there was no dilution of the water from rain. Salinities over multiple tidal cycles were near the 35 levels found in the coastal ocean. Even though this site is near the forest border, high tidal flushing in the North Inlet estuary maintains high salinity throughout the system most of the time. After a runoff event, salinity at Oyster Landing is depressed especially during the ebbing tide and especially at low tide before saltier water from the ocean pushes the introduced freshwater back up the creek toward the forest. During both longer (days, weeks) and major (high amounts) periods of rain, salinities can drop to very low levels, even depressing salinities in the flood tide waters until the input ceases and the tides re-establish high salinity conditions. The runoff signal is much dampened closer to the ocean origin of salty water.

The pattern seen in Figure 21 compresses 15 minute data for a full year of measurements. Although salinities remained above 32 for most of 2010, periods of lowered salinity were evident in all seasons. Summer low salinity events reflected short rain events (e.g., thunderstorms) of various intensities; salinities returned to high levels within days. During the fall, and especially in winter, low salinity persisted for longer periods due to extended periods of runoff and recovery following the last rain events.

Mean salinity values based on all measurements made during the fall season for each year from 1994 -2010 show that salinity remained at high levels, dipping below 30 on only a few years (Figure 22). The short-lived periods of major salinity fluctuations seen in fall 2010 (Figure 21) had a relatively small overall impact on the salinity regime at Oyster Landing. The year 2010 was part of an extended period of drought on the SC coast. Even though 1997 and 2005 had wetter falls, the mean salinity for the innermost area of the North Inlet estuary was still high.

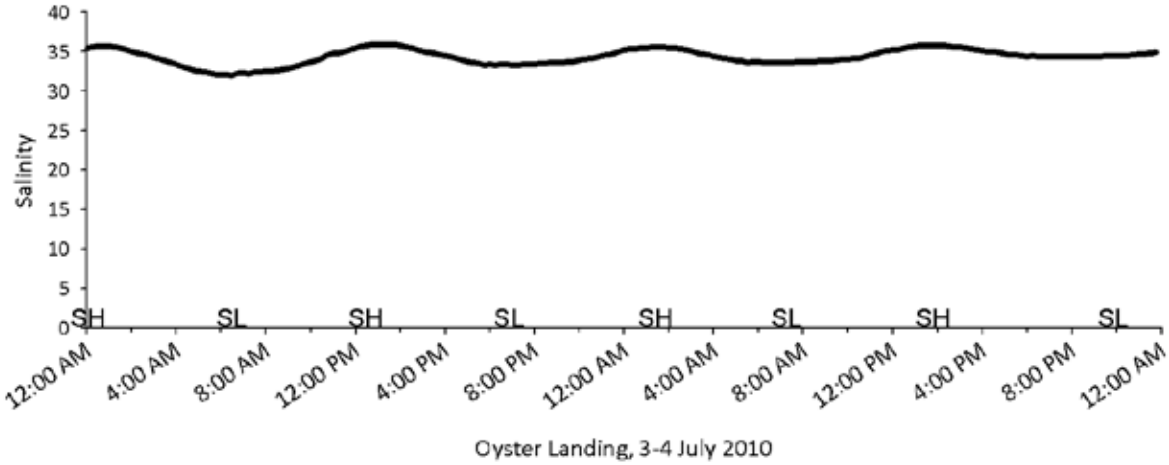

Figure 20. Salinity values recorded every 15 minutes over a 48 hour period at the NI-WB NERR SWMP station at Oyster Landing July 3-4, 2010. Slack high and slack low tides are indicated.

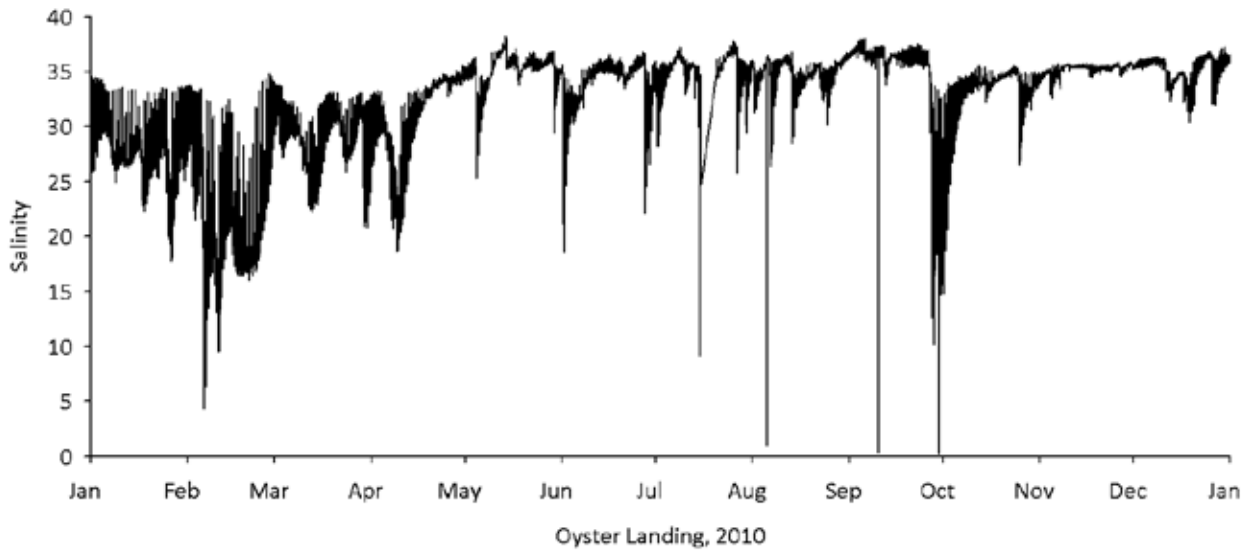

Figure 21. Salinity values recorded every 15 minutes over a 12 month period at the NI-WB NERR SWMP station at Oyster Landing January 1 – December 31, 2010.

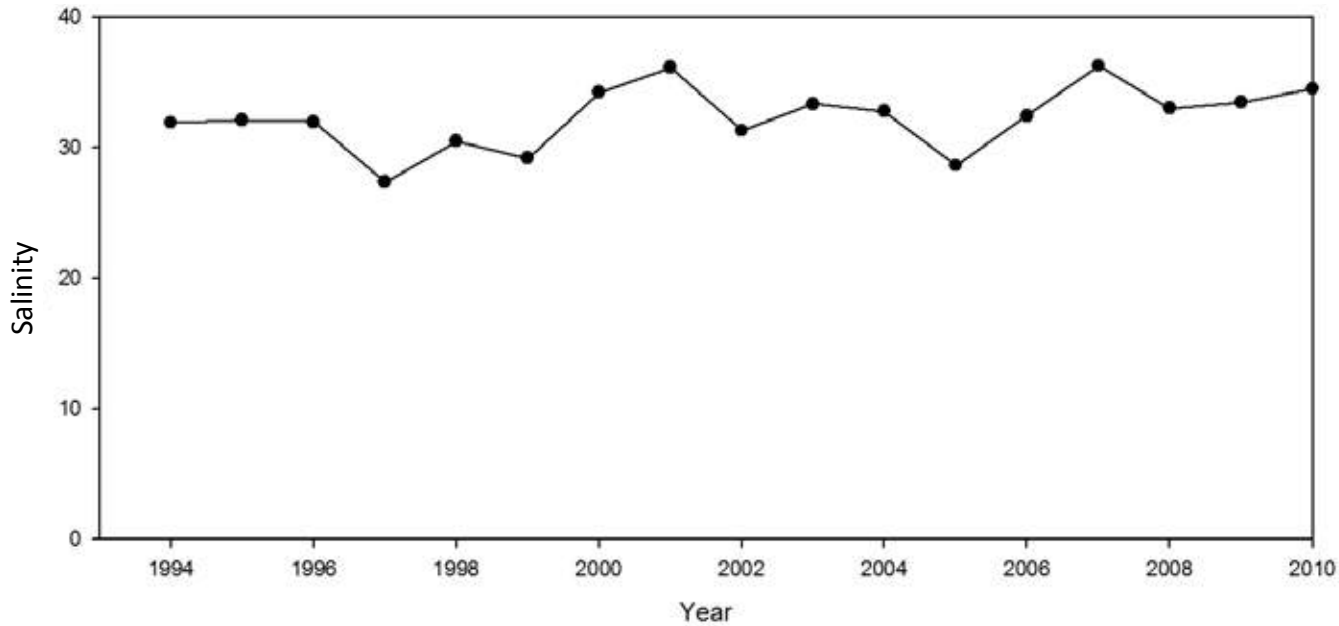

Figure 22. Mean salinities for measurements made during the fall season from 1994-2010 at the Oyster Landing NI-WB NERR SWMP site.

An independent time series of measurements at Oyster Landing from 1984 (pre-SWMP) - 2011 shows a significant long-term increase in the surface salinity (Figure 23). The biweekly measurements used to generate these seasonal means were made at low tide in an intertidal creek pool adjacent to the SWMP measurement site at the pier in the intertidal channel. Measurements made at low tide reflect the lowest salinities that occur in the intertidal basin, because runoff from the watershed is not affected by the flooding tide. Unlike the high mean salinities based on data from all tide stages in the nearby subtidal channel (shown in the preceding graphs), the average low tide salinity is close to 20. Salinities below 10, which are the result of particularly rainy seasons, occurred periodically throughout the

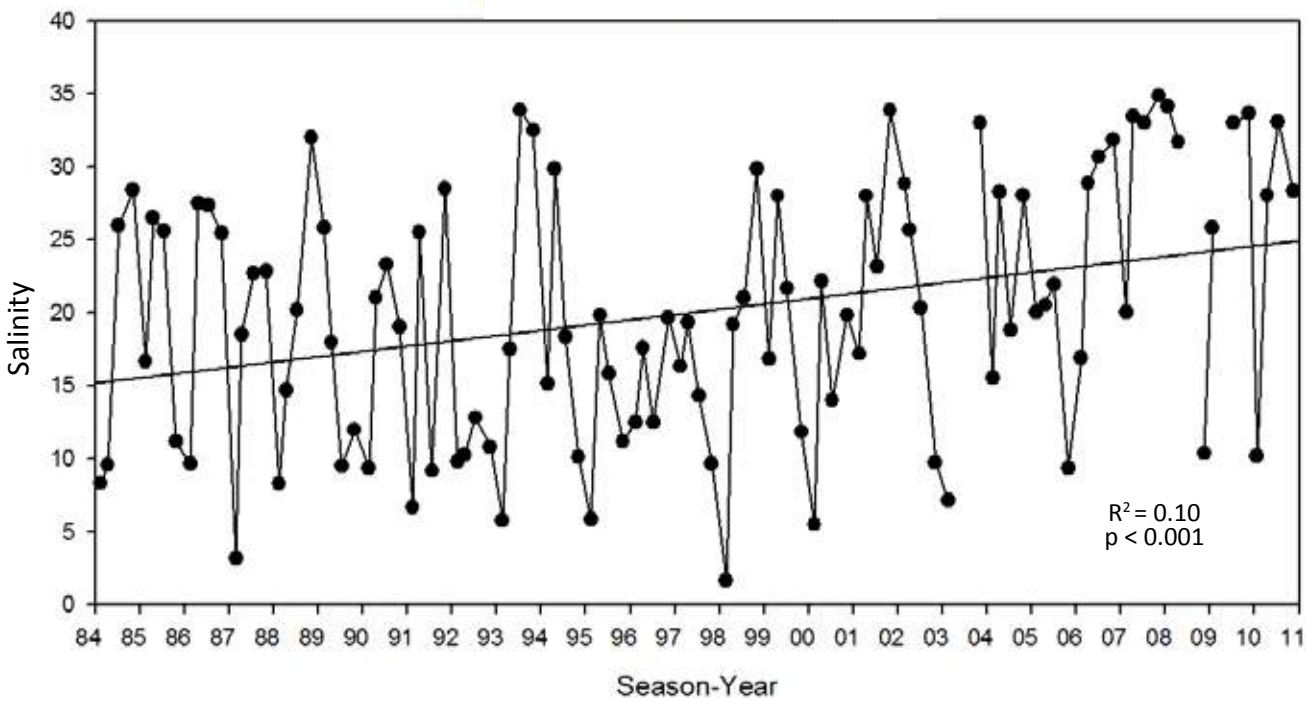

Figure 23. Mean seasonal salinities for measurements made from 1984-2010 at the Oyster Landing Creek intertidal pool near NI-WB NERR SWMP site. Note that although the SWMP series did not start until 1994, historic data from the same location are available for the previous ten years, providing an opportunity to determine whether a long-term trend could be detected with linear regression (shown here as a diagonal line).

27-year period. Despite seasonal variations, the frequent occurrence of El Niño-driven wet years in the 1990s is evident in Figure 23 and so is the much drier period through the 2000s. A long-term trend with significant increase in salinity was determined for the time series with salinities in recent years being higher than at the beginning of the period of measurement.

SUMMARY OF SALINITY STUDIES IN NORTH INLET

While measuring microbial biomass in two intertidal creeks in North Inlet, Erkenbrecher and Stevenson (1975) took water samples over five tidal cycles. These data were reported separately by Erkenbrecher and Stevenson (1977). The salinity in one of the two creeks sampled, near Clambank Landing, varied between 15 and 34, while at Crab Haul Creek much nearer the forest, it varied between 2 and 34. This illustrated how dramatically physical conditions in tidal creeks can change over relatively short periods of time.

Weiland et al. (1979) examined the effects of freshwater intrusion in five different tidal creeks, including one in Mud Bay, on microbial biomass. They encountered a gradient of salinity that ranged from 11.5 to 32.7 over an 8 month period. Salinity and other variables explained different percentages of the variability in microbial biomass, depending on which creek was sampled. They cautioned that no two creeks were similar enough that extrapolations of their conditions could be applied to other unsampled creeks.

Gardner and Gorman (1984) measured specific conductance every 30 minutes over 65 tidal cycles in spring and summer during 1976 and 1977. Automated measurements were taken from the Oyster Landing walkway over the creek. The net salt transport was an amount of 57,000 kg over a tidal cycle, but this is only about 2% of the mean amount of salt held in the Oyster Landing basin at high tide.

An examination of groundwater salinity (conductivity) was conducted by Powell (1985) in summer 1984. On transects across Goat Island,

piezometers were used (14 on one, 11 on the other transect) and water samples were collected to measure transmittance to test for the presence of discoloring from dissolved organic constituents in the groundwater. They found salinities ranging from zero to 83, with the highest values always associated with the presence of *Salicornia* plants. They found that the water table was often exposed at the ground surface in the *Salicornia* zone and that groundwater was actively discharged upward in this zone.

Kjerfve (1986) characterized the complex hydrodynamics of tidal flow in North Inlet as part of the Outwelling Study mentioned earlier. His estimates of salt flux suggested that water velocity and hence volume transport had a greater impact on the salt balance of the estuary than did slight changes in its concentration, and that the net salt balance in the system results from advective ebb transport and flood-directed transport due to tidal sloshing, the dominant dispersive flux mechanism. Because North Inlet is so well-mixed and lacks a pycnocline, shear fluxes are negligible. Kjerfve suggested that measurements of export of materials to the adjacent coastal ocean should be made at the coastal boundary front outside the estuary rather than at its entrance.

Childers et al. (1994) measured chlorophyll and salinity with transect data taken at North Inlet during ebbing and flooding tides in winter, spring, and summer 1991. They found total dissimilarity in the magnitude of salinity data from one season to the next, but inter-seasonal similarity in spatial patterns over both hourly and monthly scales.

Blood et al. (1991) and Gardner et al. (1992a) studied the effects of the tidal surge that came ashore with Hurricane Hugo in September, 1989. Soil salinities increased dramatically, causing extensive tree defoliation, with the most salt-induced mortality at the forest's edge next to the saltmarsh. Soil chemistry changed dramatically as well. Conner (1995) and Conner and Inabinette (2003) followed what happened in the forest over time after the hurricane.

Morris (1995) used measures of salt concentrations as a conservative tracer of porewater turnover. He had measured the salinity of porewater to depths of 30 cm at Goat Island and at Oyster Landing since 1987 and then modeled the mass balance of salt and water in a representative portion of the marsh. The model found that of the three ways salt is moved in the marsh (drainage, diffusion across the marsh surface, uptake and excretion by plants), only drainage accounted for a significant flux.

Gardner and Reeves (2002) examined the fluxes of water at the forest-marsh edge, an input to the system that measurably dilutes salinity of soil porewater, especially during winter. They suggest that this dilution is good for *Spartina* growth in the following spring. Deeper examination of the juncture between the flow of fresh groundwater into North Inlet was performed by Carter et al. (2008) who used resistivity probes to measure salinity at sediment depths of up to 4 m monthly during 2005 in Crabhaul Creek. The interface between the fresh and saline water belowground in this margin moves on a time scale of months but is not well correlated with either rainfall or tidal cycles as one might expect.

Although their main focus was on some other aspect of North Inlet, the following papers also included salinity measurements or measured the effects of salinity: Agosta (1985) – runoff and groundwater dilution of nutrient-rich pore water; Apple et al. (2008) – salinity effects on auto- and heterotrophy; Gardner et al. (1992a) – seawater intrusion into shallow groundwater after a hurricane; Nelson et al. (2005) – comparison of long-term data in North Inlet and Murrells Inlet; Weiland et al. (1979) – effects of salinity on microbial biomass (ATP) in North Inlet tidal creeks; and White et al. (2004) – comparative aspects of nutrients in Murrells and North Inlets.

The most important aspects of salinity in North Inlet are that it is generally much higher than in Winyah Bay and that it exhibits modest fluctuations with the tide. Greater variations in salinity occur as weather-driven events, and the long-term trend is towards higher average salinities over time.

WATER TEMPERATURE

In North Inlet, water temperature follows a regular seasonal pattern, coolest in winter (January) and hottest in mid-to-late summer (July-August). Because of vigorous semi-diurnal tidal mixing even into the shallowest reaches of the estuary, neither thermoclines nor pycnoclines form on a regular basis in North Inlet. When they do form, they are weak and not persistent. The average low is about 8 °C and the average high is about 27 °C, although at times greater extremes are reached, especially in the shallow creeks of the inlet. Those who work in the intertidal portions of the marsh have encountered temperature extremes in standing pools of water that reach into the mid 40 °C range, and ice formation has been observed on the exposed marsh surface on rare occasions. Temperature has not been a focus for research activity in the NI-WB NERR, but it has been monitored almost daily since the start of the Long Term Ecological Research program in 1980. Water and air temperatures are included as part of the SWMP protocol. For modeling purposes, the annual change of water temperatures in North Inlet is typically represented as a sinusoidal function over time.

Short-term fluctuations in water temperature are shown in Figure 24. Even during the summer, water temperatures tend to rise in the afternoon and drop overnight; however, diel fluctuations are much lower in summer than during fall and spring, times when exposed intertidal areas warm or cool faster than the water column before they are inundated on the next flooding tide.

Diel and diurnal variations in water temperature can be seen on the curve showing the annual pattern in 2010 (Figure 25). Temperatures are typically lowest from December to February, increase sharply from March to June, and remain fairly stable from June to September before decreasing sharply in the fall.

When seasonal mean values from Oyster Landing are plotted for the entire 27-year time series, a very symmetric pattern is evident; mean seasonal water temperatures appear to be very similar from year to year (Figure 26). However, when the annual mean temperatures are plotted, an increasing trend becomes apparent. Linear regression indicates a significant long-term increase (Figure 27). The increase predicted by linear regression over the period 1982-2010 was about 1.4°C. Trend analyses for each month also revealed significant increases during winter (January, Figure 27 B) and summer (August, Figure 27 C); the increase estimated for January was about 1.8°C and for August was about 2.3°C. Note that measured values and estimated amounts of change vary between monitoring stations in North Inlet, but all indicate increasing trends for temperature.

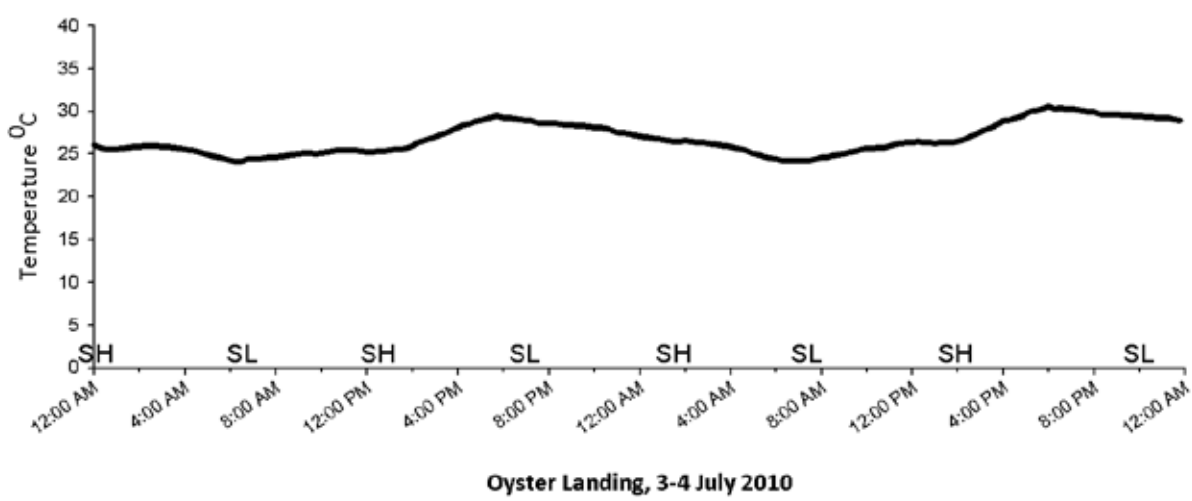

Figure 24. Water temperature values recorded every 15 minutes over a 48 hour period at the NI-WB NERR SWMP station at Oyster Landing July 3-4, 2010. Slack high and slack low tides are indicated.

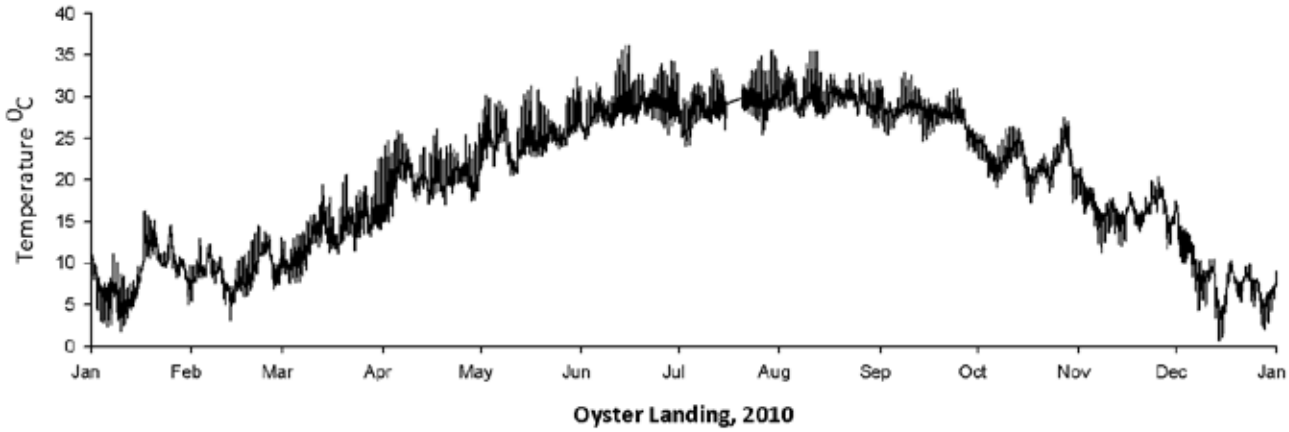

Figure 25. Water temperature values recorded every 15 minutes over a 12 month period at the NI-WB NERR SWMP station at Oyster Landing January 1 – December 31, 2010.

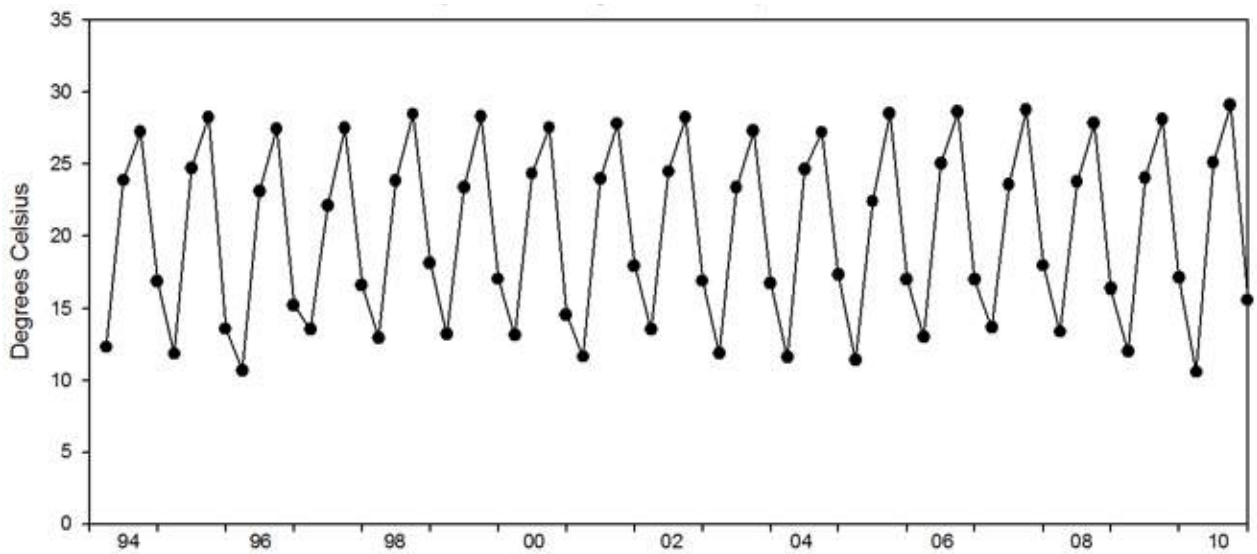

Figure 26. Mean seasonal water temperatures at the NI-WB NERR SWMP station at Oyster Landing from January 1994 – December 2010.

SUMMARY OF STUDIES ON WATER TEMPERATURE IN NORTH INLET

Wilde et al. (2007) analyzed a multi-year record of temperature from Debidue Creek (see their Figure 8). Gardner and Gorman (1984) measured temperature and calculated the net transport of heat (as kilocalories) over 65 tidal cycles in late spring and summer in Oyster Landing creek. A slightly greater amount of heat is exported in the volume of water leaving the Oyster Landing basin during ebb tides, with a little less imported during flood tides, yielding a net discharge of heat of about 129 kcal per square meter of basin area per day. This heat amounted to less than 2% of the heat added to the basin daily by the sun.

Kratz et al. (1991) addressed temperature patterns and its variability at different LTER sites, including North Inlet, and Apple et al. (2008) compared a variety of water quality parameters collected at 21 different NERR sites. Using principal components analysis, they found that temperature and salinity were the primary variables that differentiated the reserves. Both of these properties were also identified as most important in generating a balance between heterotrophic and autotrophic processes in the water. They suggested using site-specific temperature and salinity regimes to classify the different NERR sites for comparative purposes in the future.

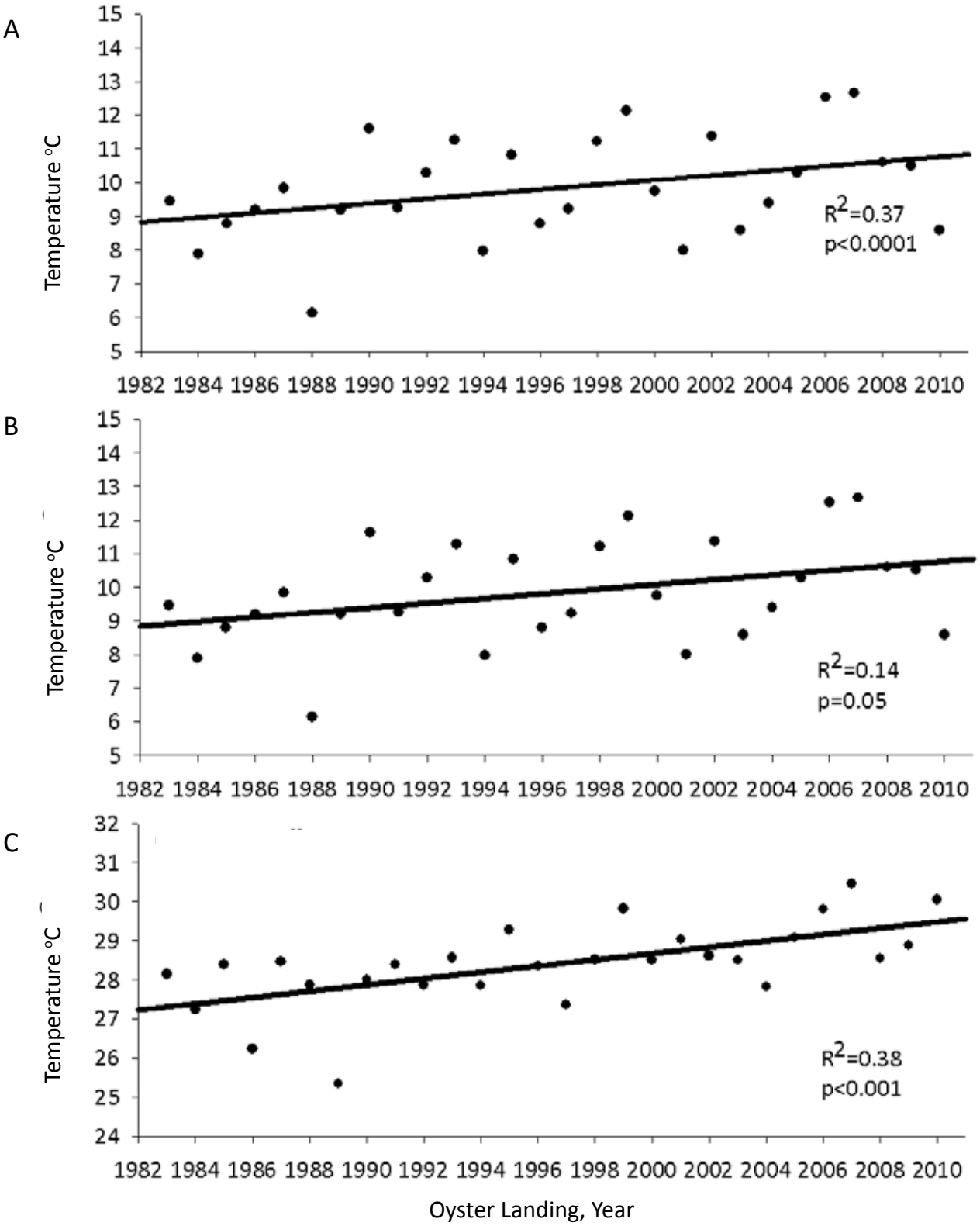

Figure 27. Yearly, winter and summer water temperature trends. A) Mean annual water temperatures at the NI-WB NERR SWMP station at Oyster Landing from 1994 –2010. B) Mean water temperatures for the month of January at the NI-WB NERR SWMP station at Oyster Landing from 1994 –2010. A significant increasing trend was determined by linear regression. C) Mean water temperatures for the month of August at the NI-WB NERR SWMP station at Oyster Landing from 1994 –2010. A significant increasing trend was determined by linear regression.

In summary, water temperatures in North Inlet are rising slowly over the long term. They fluctuate on a variety of temporal and spatial scales, but the most obvious differences in temperature occur as seasonal changes. North Inlet is so well mixed that thermoclines do not usually develop. As a fundamental driver of many ecological and physiological processes, water temperature has great importance in long-term monitoring efforts.

pH AND REDOX POTENTIAL

Having a high buffering capacity, the pH of seawater in the open ocean typically changes very little in response to additions of acids or bases and thus stays within a narrow range of values. In estuaries, however, the close proximity of chemical-laden discharges from land and biogeochemical reactions within the marshes and shallow waterways makes changes in pH considerably greater and more frequent than in the open sea. In estuaries, pH and redox potential (Eh) are usually measured by investigators who study sediment chemistry, diagenesis of organic matter and sediments, and the vertical distribution of living organisms in the sediment (e.g., *Spartina* roots, bacteria, meiobenthos, macrobenthos).

The NI-WB NERR SWMP water quality instruments measure pH in the water column at the same location and frequency as the other variables. Tidal variations of up to one pH unit are common, but the long-term average is between 7 and 8. Although a characterization of the SWMP data is not included in this section, these data (and all SWMP data) are available at the NERR CDMO web site.

SUMMARY OF STUDIES ON pH AND REDOX POTENTIAL IN NORTH INLET

Gardner (1973a, 1975) found that North Inlet interstitial waters had pH values in the range of 6.4 to 7.8, with an average of 6.8. He found that surface waters were usually around 8.0. Erkenbrecher and Stevenson (1977) found that tidal creek surface water pH averaged 7.5 over the range 7.1 to 7.9 during five tidal cycles. Gardner et al. (1988) measured pH in sediment porewater along three transects in North Inlet and found decreasing values from the creek banks (7.3) to the high marsh (6.5). Eh showed similar trends, being slightly oxidizing (+100 mv) at the creek bank and reducing (-200 mv) in the high marsh.

Duncan and Shaw (2003) measured concentrations of rare earth and redox sensitive elements from groundwater wells along a transect across the forest-marsh interface in North Inlet. They found concentrations of iron, manganese and uranium that were consistent with the reducing conditions belowground along the entire transect and calculated a net export of dissolved rare earth elements to the tidal creek system and ultimately to the coastal ocean. This export results from diagenetic mobilization of organic rich carbon phases where the saline wells were located, and they suggested that degradation of relic organic carbon and rare earth elements that are exported is on a scale equal to or even exceeding those from river inputs in this region.

A few other studies in which pH and/or redox measurements were reported as key variables include Agosta (1985), Aller and Aller (1998), Aller and Yingst (1985), Aller et al. (1983) and Gardner (1973a, 1975).

The pH of water within North Inlet varies mostly with changes in the tide, but porewater pH and Eh variations have rather well-defined spatial characteristics. Changes in water chemistry are also temperature-dependent and affect the distributions of both chemical and biological species, particularly within sediments.

SEDIMENTS AND TURBIDITY

Measurements of turbidity with the SWMP water quality data loggers have revealed patterns on various time scales. A repeatable tidal pattern occurs at Oyster Landing with highest levels of suspended sediments occurring when currents are strongest near the middle of the ebbing tides (Figure 28). Resuspension of sediments is typically lower during the mid-flood tide and lowest around slack high tides. Peak and low levels were separated by a factor of about three during July 2010.

The background level of turbidity is highest from

April to November, but large short-lived spikes can occur at any time of year (Figure 29). The higher levels seen during the warmest months are attributed to the increased numbers and activity of benthic invertebrates and nekton, particularly those associated with the bottom. Bioturbation results from feeding, burrowing, and other activities that suspend sediment in both the intertidal zone and subtidal channels. Changes in other physical properties and chemical processes during the warmest period of the year factor into the elevated levels of turbidity in the creeks. Superimposed on this source of resuspension are major spikes caused by strong rain/runoff and wind events that result in large amounts of sediment being resuspended. Recovery usually occurs within a tide cycle or two after the rain or wind stops. The higher incidence of these events during summer and fall is probably related to thunderstorms and the resulting runoff from the marshes and exposed lower intertidal flats. For this reason, summer or fall are consistently the highest points on a plot of seasonal mean turbidity over a 15 year period (Figure 30). The long-term pattern is irregular, but winter lows were higher during the 1990s, the decade of frequent El Niño events and associated wet winters and springs. A very high, weather-related, spike was observed during the spring of 2000.

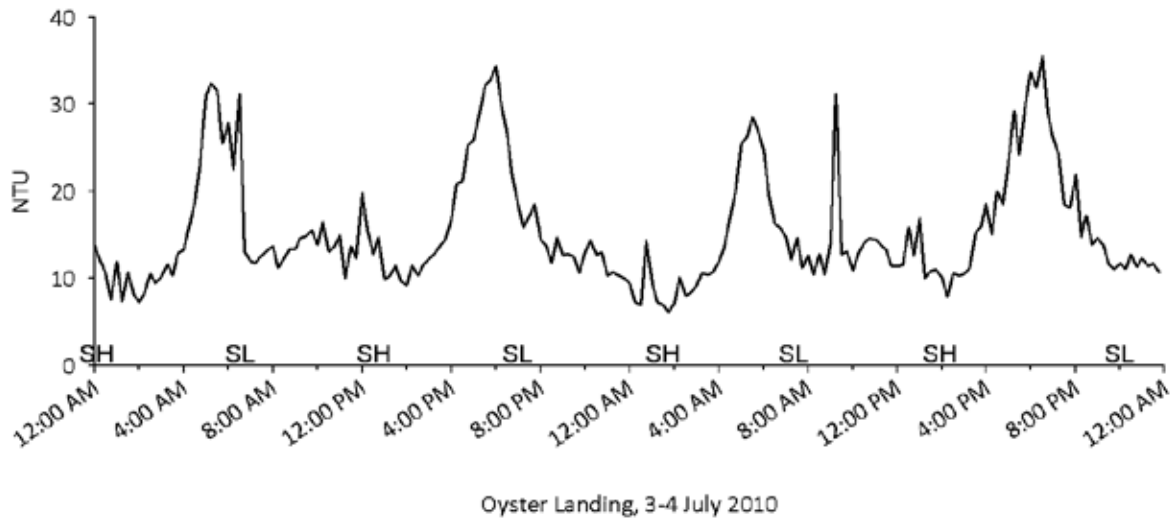

Figure 28. Turbidity values (Nephelometric turbidity units) recorded every 15 minutes over a 48 hour period at the NI-WB NERR SWMP station at Oyster Landing July 3-4, 2010. Slack high and slack low tides are indicated.

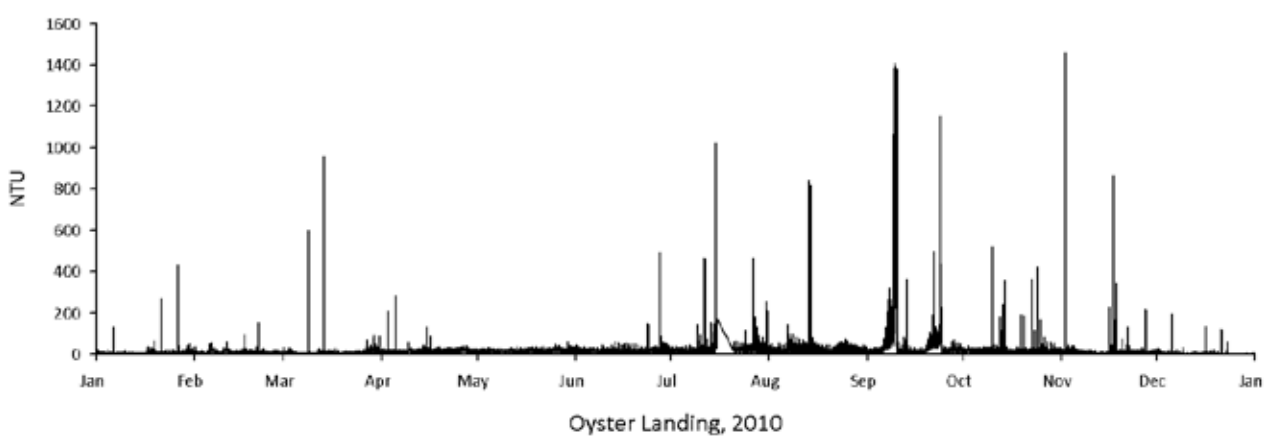

Figure 29. Turbidity values (Nephelometric turbidity units) recorded every 15 minutes over a 12 month period (2010) at the NI-WB NERR SWMP station at Oyster Landing.

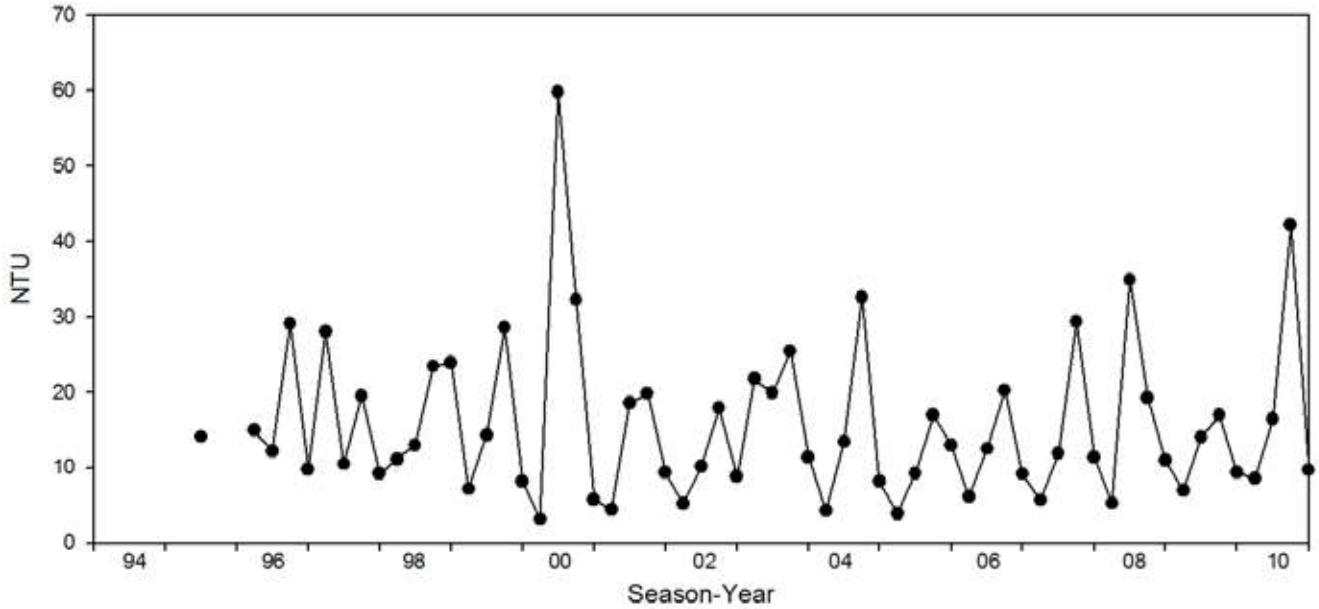

Figure 30. Mean seasonal turbidity (Nephelometric turbidity units) values from January 1995 to December 2010 at the NI-WB NERR SWMP station at Oyster Landing.

SUMMARY OF STUDIES OF SUSPENDED SEDIMENTS IN NORTH INLET

The earliest mention of sediment dynamics in North Inlet is a result of quarterly studies of beach and inlet morphology by Finley (1976). Wave observations, wind measurements, storms, and a series of beach profiles at 11 locations showed that erosion is primarily due to northeastern storm events directed to the south. A 7 m (22 ft) foredune retreat was measured in 1972-73 that contributed sediments to the ebb tidal delta in the inlet. The beach on the south side of the inlet was not eroding because the ebb tide delta afforded it some protection from wave energy.

Gayes (1991) used side scan sonar to show what happened to sediments in the nearshore zone just outside coastal SC inlets after Hurricane Hugo passed. Stauble et al. (1991) provide an additional overview of the storm's effects on shore protection structures and dunes such as exist near the mouth of North Inlet. Kjerfve et al. (2002) provided a macroscale comparison between the Atlantic coastlines of North and South America and highlight how muddy sediments dominate the coastal landscapes of both.

The first systematic examination of suspended sediment concentrations took place as part of the Outwelling Study that measured fluxes of material across the mouth of North Inlet (Dame et al., 1986). Fluxes were calculated based on the volumes of water transported and the concentrations of materials the water carried. Over the year, there was a net export of suspended sediments from North Inlet. Sediments were imported during spring tides and exported on neap tides. Imports occurred mostly during fall and winter, while exports took place in spring and summer. Suspended sediments were comprised of 20% organic and 80% inorganic particles by weight. In winter the concentration of suspended particulates declines, leaving the clearest water of the year and the deepest Secchi depth readings. In the spring, turbidity increases along with the activities of bioturbating organsisms (e.g., by fiddler crabs - McCraith et al., 2003; by benthic fishes and invertebrates – Grant, 1983). Total suspended sediments comprised the greatest flux of particulate material in the Outwelling Study. Dame et al. (1986) suggested that the salt marsh is a sink for inorganic sediment particles but that organic sediment flux varied with every change of the tide.

Gardner et al. (1989) analyzed suspended sediment data, both organic and inorganic. High turbidity was associated with high water temperature more so than with tide height or salinity. They proposed that sediment enters the marsh through the ocean inlet rather than from freshwater river intrusions and that sediment reworking by organisms, bioturbation, is the main source of suspended sediments in North Inlet. Wolaver et al. (1988a) looked at net organic and inorganic suspended sediment data collected for 34 tidal cycles at a flume constructed in Bly Creek. They measured net sediment exchange during tidal inundation and during marsh runoff through the flume at low tide exposure (including during storms). Highest concentrations occurred in summer, and they found that the marsh is a net sediment sink, exporting only about 35% of what comes in with the tide, sufficient for the marsh surface level to keep pace with the rise of sea level. In the Wolaver et al. (1988b) Bly Creek Study, inorganic suspended sediment concentrations varied seasonally and ranged between 6.5 in winter and 85.1 mg L^{-1} in summer. Freshwater input of inorganic suspended sediments was negligible, and sediment accumulation in the marsh was, again, found to be keeping up with sea level rise.

As for marsh elevations relative to sea level rise, Childers et al. (1993a) measured them seasonally in North Inlet at six locations using a clever, mechanical leveling-arm device. They found elevations increasing at the greatest rates, two to three times the rate of apparent sea level rise, at the sites closest to freshwater influence. However, marsh elevations at the dead ends of tidal creeks without freshwater input increased only at the same rate as apparent sea level rise.

Pillay et al. (1992) compared three different methods for calculating suspended sediment transport rates in Town Creek. These investigators found high correlation coefficients between the three methods, suggesting that the LTER daily water sample data can be used confidently to estimate instantaneous discharge from continuous tide data, provided an accurate hypsographic model of basin volume change can be developed.

Sediment traps were used by Hutchinson et al. (1995) in two areas (Mud Bank (MB) and Sixty Bass (SB)) where there is a close connection to the oceanic inlet (SB) and where the influence of input of brackish water from Winyah Bay is significant. They also measured sediment concentrations (both organic and inorganic), salinity, carbon and nitrogen in adjacent creeks. Because the Mud Bank site was 27 cm (about 1 ft) higher than the Sixty Bass site, it was inundated only about half as long per day, yet sediment deposition rates were higher at this higher site (MB) than at Sixty Bass (5.3 mg/d/cm^2 vs 4.2 at SB). They found essentially no correlation between water sediment concentrations or tidal inundation duration and the sedimentation rates measured, suggesting that bioturbation activities are important to sediment dynamics.

Mobilization and redistribution of sediments by rain drops falling on the exposed intertidal marsh surface was studied by Mwamba and Torres (2002). They also simulated tidal flow with a flood irrigation experiment. Sediment concentrations were up to 1000 times higher in the sprinkler runoff plots than in the flood irrigation water. Most of the sediment mobilization took place within the first 5 minutes following raindrop impact detachment of sediments from the marsh surface and subsequent transfer via sheetflow. Even though rainfall volume is very small compared to the tidal prism, rainfall effects can be disproportionately large in moving and redistributing sediments. Additional data analysis from these experiments measured how much organic matter was entrained by the rainfall effect (Torres et al., 2003). Compared to their abundances in the surrounding substratum, the rainfall carried considerably higher amounts of organic matter, organic carbon and nitrogen, suggesting that rainfall events can deplete the marsh surface of these constituents. Most of the organic matter mobilized was a mixture of algae and vascular plant detritus.

In response to an application to dredge the Debordieu Channel and Debidue Creek for boat access to homes at the northern edge of the NI-WB NERR boundary, a long-term monitoring station was established there in spring 1998. Its purpose was to provide a record of pre-dredging water

quality conditions, because this disturbance to the creek bottom was expected to release nutrients that normally leach slowly from sediments into the overlying water, with concerns that turbidity and DO would also be impacted. The long canal was dredged in fall/winter 2001-2002, and the creek leading into the canal was dredged in October 2001. In addition to the long-term water quality station, a set of synoptic samples was taken in Debidue Creek during the dredging operation. This study reports the results found for total suspended solids (TSS) and nutrient concentrations. TSS was highest in summer and highest at slack tides and lowest when tidal currents were swiftest, on both ebb and flood. Samples taken within the cloud of sediments during dredging operations revealed higher concentrations of TSS than occurred about 700 m downstream. TSS declined rapidly when dredging ceased for the day. Samples taken along the creek transect while it was being dredged failed to find any significant temporal or spatial gradient in TSS that could be ascribed to the downstream effects of dredging. TSS impacts were tightly localized to an area within 10 m of the dredge and water cleared to background levels within 10 min after dredge cessation. The coarse sandy sediments from the creek bottom settled rapidly. Lohrer and Wetz (2003) concluded that there was essentially no impact to water quality realized from the dredging activity but cautioned that the timing, duration and spatial scale of such activities in the future might have greater consequences for the environment. Monitoring of dredging activity in the future should include measures of water flux so that nutrient fluxes can be estimated rather than just the instantaneous concentration measurements made in this study. Caine and Hull (1981) summarized many of the expected effects of dredging salt marsh creeks.

Buzzelli et al. (2004) compared SWMP data from 1994-2001 for suspended solids at the Oyster Landing (OL) and Thousand Acre (TA) marsh long-term sampling sites. Mean concentrations were twice as high at TA, as was turbidity during all seasons. Turbidity was, in fact, the most variable of all the parameters measured during that time, especially at Oyster Landing. Inorganic particles comprised between 66 and 80% of the total suspended solids, with organic particles the rest.

Sedimentation was also investigated by Voulgaris and Meyers (2004a) using a laser diffraction system, acoustic Doppler velocimeters and optical backscatter sensors in a tidal creek. They found that sediments suspended in tidal creeks exist primarily as flocs with a mean particle size between 25 and 75 micrometers and with settling velocities of between 0.02 and 0.2 mm per second. During spring tides, the flocs were larger and had larger average grain sizes. Their time series of measurements revealed that erosion occurred only during the ebb stage of spring tides, with essentially no bed erosion during flood tides. They also found that sedimentation onto the marsh surface occurs mostly in the form of flocs that settle to the bottom at the same rates (0.24 mm/s) during both neap and spring tides. They suggest that marsh sedimentation is controlled by availability of sediment flocs for deposition and inundation time, both of which are higher during spring tides.

In their evaluative overview of the three past outwelling-related studies conducted in the North Inlet basin (entire basin: Dame et al., 1986; Bly Creek sub-basin and Bly Creek flume study: Dame et al., 1991), Gardner and Kjerfve (2006) examined whether the water chemistry data collected with the SWMP protocol at Oyster Landing can be used to estimate fluxes of nutrients and sediments. Their study was prompted by the lack of precision with which these three earlier studies estimated fluxes of materials on a diurnal, seasonal, or long-term basis. By examining the SWMP's half-hour data collection protocol, they hoped to make recommendations for protocol changes that might improve measurements that could provide a better understanding of outwelling processes.

Using instantaneous concentrations of various water constituents measured at Oyster Landing and flow discharges from Crab Haul Creek, Gardner and Kjerfve (2006) were able to estimate instantaneous fluxes of nutrients, sediments and salt. Everything measured, except salt, had mean long-term advective fluxes significantly less than zero, i.e., they are exported. None of the particulate materials, including inorganic and organic sediments, had

statistically significant dispersive fluxes, while all of the dissolved constituents did. Movements and redistribution (dispersive flux) of materials that exist in the basin were balanced by their import and export due to changes in the tidal height.

Sediment resuspension in a tidal channel in North Inlet was examined by Traynum and Styles (2007). The deployed an acoustic Doppler current profiler onto the bottom of a mid-marsh shallow channel of Town Creek for measurements during a spring tide cycle when river discharge into Winyah Bay was great. Suspended sediment concentrations were highest during the late stages of the ebbing tide, indicating net particulate transport from Winyah Bay to North Inlet through this creek despite the fact that the creek channel is flood-dominated. Flow asymmetries along the bottom caused higher concentrations of suspended sediments during ebb when bottom friction created the highest stresses near the time of low water, even though stronger currents existed during flood tide. A rigorous description of the current variations that exist in the creek study area around its nodal point from data collected with an acoustic Doppler current profiler over a 35 day set suggests that winds are heavily involved in tidal asymmetries in the area (Traynum and Styles, 2008).

Another view of short-term sediment dynamics under flow conditions was constructed by Wargo and Styles (2007) along the deep channels just inside the mouth of North Inlet. They measured currents, bed sediment, salinity, and suspended sediment concentrations plus particle size distributions over a complete tidal cycle. Bed elevation and channel width variability, i.e., changing bathymetry, caused many changes in tidal current velocity, shear stress, with highest values observed in the narrowest section of the inlet throat. At stations closer to the marsh, channel "geometry" and branching results in a reduction of flow energies. They found higher currents and associated sediment transport during ebb tide. Interestingly on this particular tide cycle in 2005, they found that depth-integrated transport of sediments is directed towards the marsh on the landward side of the intersection between Town and Debidue Creeks. Seaward of this intersection, transport was out of the inlet. Examination of changes in the size spectrum of particles as it changed during the tide cycle suggested that there was a net transport of fine-grained sediments landward.

Styles and Teague (2007) made current velocity measurements in tidal creeks and over the marsh surface using an ultrahigh-frequency radar system that transmits from an antenna set up next to the marsh. The return signal's Doppler shift is calibrated to be proportional to surface current velocity. The ability to make current measurements in the marsh at high tide was complicated by the radar reflections from *Spartina* grass.

Summarizing sediment dynamics in North Inlet is difficult because studies have been conducted at various locations and at different spatial and temporal scales. Suspended inorganic sediments enter North Inlet from offshore and once inside they settle out and get redistributed with wave action and changes in the tide. Summertime bioturbation resuspends large amounts of sediment. Water turbidity is thus highest in summer but is minimal in winter when waters are clearer than at any other time of year. The rate of sediment supply to the system has been sufficiently high to keep pace elevationally with the rate of sea level rise. Whether this will continue in the future, especially with predicted accelerated rates of sea level rise, remains to be determined.

DISSOLVED OXYGEN

Dissolved oxygen (DO) is measured at the SWMP datalogger sites in North Inlet. DO exhibits high short-term variability with typically higher levels during the day when photosynthetic phytoplankton and microbenthic algae produce oxygen. The cessation of photosynthesis at night results in reductions in DO levels in the water column especially before daybreak; this may be due to continuing activity of microbes which consume DO while decomposing organic material. This pattern can be seen in Figure 31 where DO was about twice as high on daytime low than on night low tides on July 3rd-4th, 2010. Little difference was observed between the nighttime high and low tides.

These diel and tidal patterns of DO variation are evident in the 12-month track of DO shown in Figure 32. More short-term variability is evident during the warmest months when overall DO is at the lowest levels of the year. In summer DO can vary from 2 to 7 mg/L within a week or even a few days. DO is least variable during winter when values of 7-11 are typical.

Interannual variations in DO are shown in Figure 33 where the seasonal mean values are plotted. Summer DOs are lower than winter's, and spring values are usually higher than fall's. No long-term trend was evident for the 16 year period.

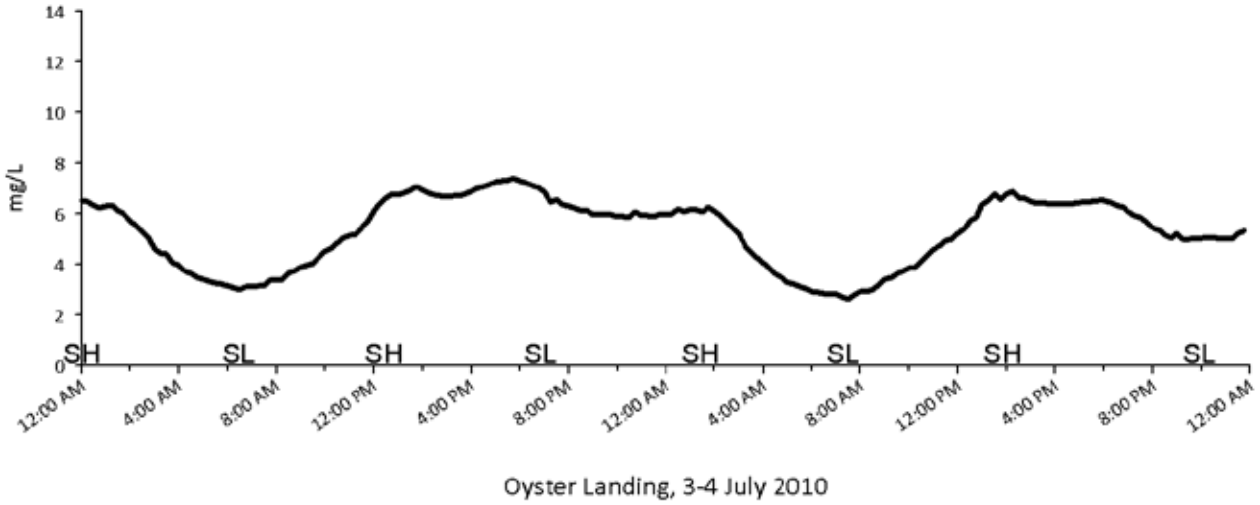

Figure 31. Dissolved oxygen values recorded every 15 minutes over a 48 hour period at the NI-WB NERR SWMP station at Oyster Landing July 3-4, 2010. Slack high and slack low tides are indicated.

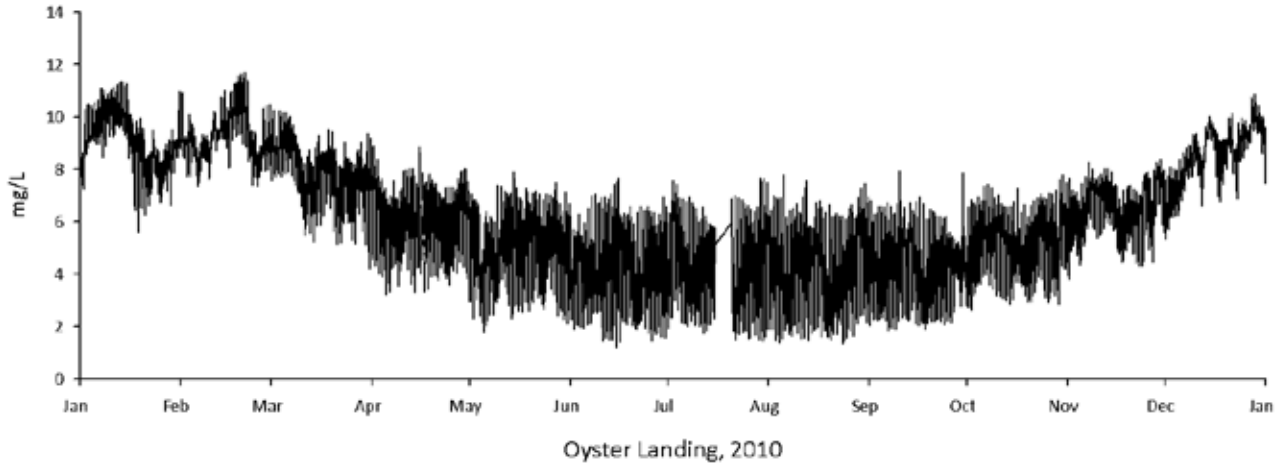

Figure 32. Dissolved oxygen values recorded every 15 minutes over a 12 month period (2010) at the NI-WB NERR SWMP station at Oyster Landing.

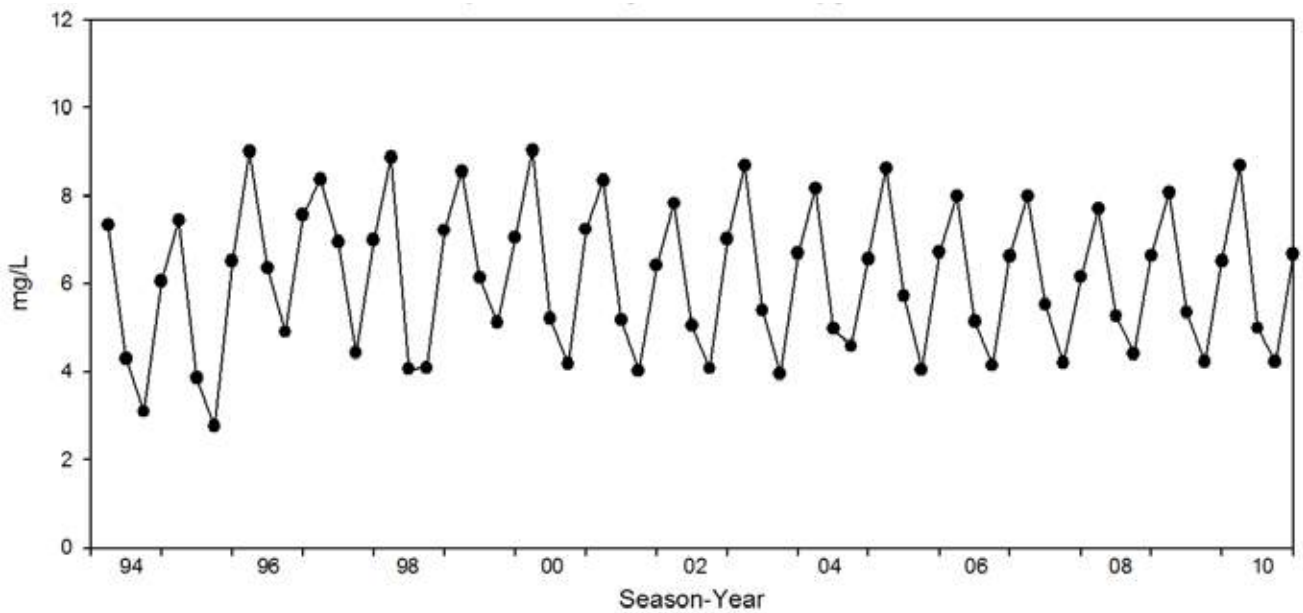

Figure 33. Mean seasonal dissolved oxygen values from January 1994 to December 2010 at the NI-WB NERR SWMP station at Oyster Landing.

SUMMARY OF OTHER STUDIES ON DISSOLVED OXYGEN IN NORTH INLET.

Wenner et al. (2004) examined the incidence of hypoxia at 55 sampling locations within 22 different NERR sites based on SWMP data collected up to that point in time. Their study illustrated the value of high frequency sampling in the SWMP protocol because it allowed detection of many hypoxia situations that would otherwise have gone undetected. Wenner and Geist (2001) also examined hypoxic events and found that natural processes affecting dissolved oxygen concentrations differ among NERR sites depending on tidal amplitude, a measure of the difference between high and low tide water levels. Both of these studies involved analysis of other water quality parameters as well.

Because DO was not measured during the Outwelling Study, it was measured every 30 min during spring and summer over 65 tidal cycles at the Oyster Landing boardwalk in a separate study by Gardner and Gorman (1984) to see if DO was exported or imported in this portion of North Inlet. They also measured biological oxygen demand (BOD) over 14 tidal cycles as part of their study. They found that the principal determinants of the DO flux over a tidal cycle were the amount of sunlight received and the volume of water flowing in and out of the Oyster Landing basin. There was a direct correlation between net heat transport and net DO transport as a consequence. Interestingly, the times when DO was exported from the basin occurred only when high tide happened within 2 hours of local noon, i.e., between 10 am and 2 pm. Maximum exports of DO from photosynthesis took place during spring tides that started at sunrise. The BOD study was inconclusive, but the investigators felt that most of the BOD, either imported or exported, was a water column phenomenon that happened on a much faster time scale than the export of particulate organic carbon that may impose the oxygen demand. They suggested that excess loads of oxygen demanding materials (e.g. bacteria-laden detritus) could produce anoxia in the headwaters of marsh tidal creeks.

Aelion et al. (1997) measured the concentration of dissolved oxygen in groundwater collected from deep wells in the edge of the forest near Oyster Creek in North Inlet. This was a study examining the rate of denitrification in coastal aquifers, so the DO measurements were made in that context. They found between 0.4 and 1.0 mg/L concentrations and described this DO level as “microaerophilic”.

Using SWMP data collected at Oyster Landing from November 1993 and April 1996, Gardner et al. (2006) examined DO to see whether Crab Haul Creek exported or imported oxygen, a further test of the outwelling hypothesis. Their Figure 1 provides a concise overview of "DO dynamics in aquatic ecosystems". Up to 40% of total oxygen uptake can be due to sediment oxygen demand where organisms and biogeochemical reactions utilize DO from the water column while plankton and nekton consume the rest. Tidal fluxes of water to and from the creek were estimated using current velocity and depth measurements, so that the volume of water in the basin could be calculated based on tidal height. Some error is inherent in this method due to sheet flow across the entire marsh at high tide, i.e., basins are isolated only when water is confined within the creek's banks during lower tides (Miller and Gardner, 1981). Their methods assumed that the concentrations of DO measured at the Oyster Landing pier were the same as those occurring in the channel cross section of Crab Haul Creek. A separate study confirmed that it was, i.e., DO is spatially uniform there. Concentrations of DO were described as having a "sawtooth pattern", with January peaks at about 10 mg L^{-1} and July troughs at about 3 mg L^{-1}. Tide cycle-to-tide cycle fluctuations averaged about 2.0 mg L^{-1}. For the entire study period of 30 months, there was a small net export of DO from the creek, indicating that there was, on average, slightly more oxygen produced by photosynthesis and diffusion from the air than was consumed by biological and chemical processes.

Buzzelli et al. (2004) synthesized SWMP data from Oyster Landing and Thousand Acre marsh from 1994-2001. DO concentrations varied seasonally at both sites but were higher at the TA site in winter and spring. Concentrations ranged from zero to 17.6 mg L^{-1} at TA and from 0.9 to 23.7 at OL. Comparing average monthly values for the water quality parameters measured, DO had a highly significant negative correlation with water temperature (r2 = 0.91) over the range of 9 to 29 ºC. DO was also negatively correlated with dissolved organic nitrogen and chlorophyll-*a*.

Caffrey (2004) analyzed dissolved oxygen records from 42 sites within 22 NERRs from 1995 to 2000. DO concentrations, taken every 30 min, were mathematically converted to production gains and respiratory losses while accounting for air-sea exchanges. Caffrey's goal was to determine whether the types of environments represented by NERR sites were sources or sinks for carbon. All but three sites were net heterotrophic over a year's time. Trends in production and respiration were consistent at all sites, with rates higher in summer and lower in winter. Both the Thousand Acre and Oyster Landing sites were net heterotrophic, i.e., oxygen consumption exceeded production on average.

The results of the study by Gardner et al. (2006) conflicts with the results found above by Caffrey (2004) who estimated that the same basin imported oxygen because respiration exceeded gross primary production. Neither study found great differences between the basin's being in DO balance (import flux = export flux), and both methodologies had enough error that they were probably not that different. Thus outwelling of DO, if it exists at all, is not great enough to affect the trophic status of continental shelf communities. In contrast, outwelling of carbon contributes significantly to the net heterotrophy of shelf waters.

These DO budgeting studies demonstrate the types of analyses that are afforded by the existence of long-term SWMP data, their power for making it easier to detect changes in these shallow coastal ecosystems and, through careful statistical comparisons, their utility for making rigorous generalizations about how these ecosystems are regulated. Differences in nutrient inputs explained most of the variability that existed in DO concentrations between sites.

Dissolved oxygen is one of the more dynamic chemical species in North Inlet. DO concentration varies considerably at all temporal scales that have been measured. North Inlet is usually so well mixed that DO levels remain high except during periods of stagnation in summer in shallow portions of the estuary. DO is negatively correlated with water temperatures and responds quickly to changes in organic matter loadings.

» Water Chemistry in North Inlet

The term 'water chemistry' is used here to refer to dissolved and particulate inorganic and organic materials in the water. These include the various forms of nitrogen and phosphorous as well as many other important building blocks for synthesizing organic compounds such as carbohydrates, lipids, and proteins. Microbial decomposers remineralize organic materials in complex biogeochemical cycles.

NITROGEN AND PHOSPHORUS

The most comprehensive studies of nutrient cycles in North Inlet were conducted as part of the Long-Term Ecological Research (LTER) project's daily water sampling program starting in 1978 at Oyster Landing, Clambank Creek, and Town Creek. To better understand the contributions and fluxes of materials and nutrients to and from Winyah Bay, many water samples have been taken at No Man's Friend and in Jones Creek (at both its north and south ends), the two major connections between the two estuaries. Movement of nutrients within the marsh via exports to creeks and from creeks to the coastal ocean (the Outwelling Study) dominated most of the early research on chemical species. More recently there have been a number of studies using the quality of North Inlet waters as the natural, undisturbed, baseline against which nearby anthropogenically-impacted coastal bodies of water have been compared. Nutrient budgets have been proposed and several models constructed to explain how the complex biogeochemical nutrient cycles work and change under various stressors in both North Inlet and Winyah Bay.

Water samples were collected at the same time daily, 1979-1993, prior to the NERR becoming established.

The NI-WB NERR 20-day water chemistry monitoring database, initiated in June 1993 and continued to the present (2014), is a continuation of the (LTER) Daily Water Sample 1978-1993 database. Because the LTER daily water sampling collections were taken every day at 10:00 am EST, it was determined that those nutrient data are biased for spring high tides; therefore, not all tide levels would be represented. The NI-WB NERR water chemistry collection protocols sample all tidal stages (day and night) over the years. Thirteen 1000-mL samples are collected every 20 days at 2 hour and 4 minute intervals, for 2 complete tidal cycles (24:48 hours). Samples are collected from 0.5 m below the water's surface into one-Liter sampling bottles by an automated water sampler. Samples are collected at each of the four water-quality/chemistry monitoring stations: Oyster Landing (OL), Debidue Creek (DC), Clambank Creek (CB), and Thousand Acre Marsh (TA). Sampling events always begin and end on predicted slack low tide (SL) and cover two tide cycles, one in the day and one at night. The timing of SL for the North Inlet sites (DC, CB, OL) is different than the timing of SL for the Winyah Bay site (TA), due to differences in runoff, river flow, and distance from the ocean. Therefore, sample times for each site do not match exactly within a sample event, but tide stages or levels do match.

The Oyster Landing monitoring site is used in this document to represent nutrient levels which have been recorded and analyzed in short- and long-term time frames in North Inlet. A 20-day sampling event in July 2010 showed that nitrate+nitrite (NN), ammonium (NH_4^+), and orthophosphate (PO_4^-) concentrations are influenced by tide and time of day (Figure 34). For this particular sampling event, nutrient levels were typically higher from about midnight to 8:00 am and then dropped off sharply during the noon-time slack high tide. Values remained low until the nighttime hours when they began to increase again.

A 2010 yearly plot of these nutrients at the OL site puts the July 3-4 values in context with the rest of the 20-day data for that year (Figure 35). Lower July 2010 NN concentrations, which range from 0.0 to about 0.6 micromoles per liter, are similar to the

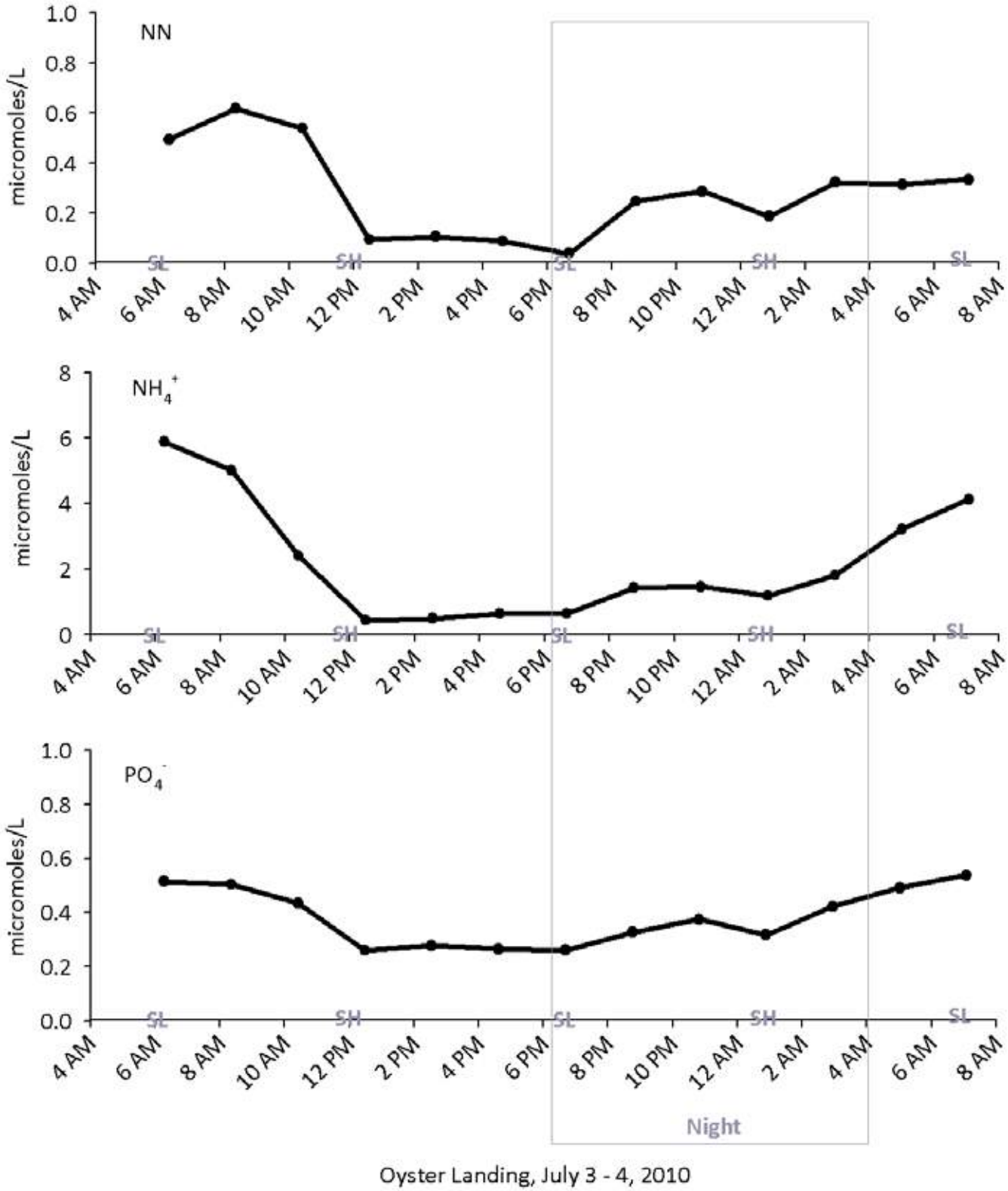

Figure 34. Oyster Landing nitrate+nitrite (top graph), ammonium (middle graph) and orthophosphate (bottom graph) concentrations during July 3-4, 2010 (a 20-day sampling event which last about 25 hrs). Water samples are collected every 2 hours and 4 minutes. SL= slack low tide; SH=slack high tide.

rest of the summer and early fall values. Winter, spring, and late fall have comparable low levels of NN, but the variation within each 20-day event is much greater (up to 3.0 micromoles per liter – see February's data in Figure 35). Figure 35 demonstrates that NH_4^+ and PO_4^- have the highest values (NH_4^+ with 16 and PO_4^- with 1.1 micromoles per liter) and variability from about April/May through December. Winter NH_4^+ and PO_4^- levels are much less variable and lower in concentration during these months. Seasonally averaging the nutrient data illustrates differences within and among years, and long-term trends are also elucidated. Figure 36 demonstrates seasonal differences within years with most winter NN values being the lowest of each year (about 0.2 or less micromoles per liter), and with spring and summer concentrations typically the largest. The rainy El Niño years 1998 and 2003 have the highest NN values. The drought years' (latter part of 1999 through the summer of 2001 and about 2007-2010) values are lower and less variable. If the drought trend continues over the next decade, it could be expected that the long-term trend of NN concentrations in North Inlet may decline and continue to have less variation. NH_4^+ seasonal averages from 1994 through 2010 show similar characteristics to NN, although the latter three seasons in 2010 are increasing in concentration (Figure 36). There is no apparent long-term trend for NH_4^+ in North Inlet. In all the above-mentioned graphs, NH_4^+ is about an order of magnitude greater in concentration than either NN or PO_4^-, both of which have very low levels (usually <1.0 micromoles per liter). The most obvious feature in Figure 36 is the increasing trend for PO_4^- values, and, like NN and NH_4^+, PO_4^- has seasonal low values in the winter and highs in the spring and summer.

SUMMARY OF OTHER STUDIES ON NITROGEN AND PHOSPHOROUS IN NORTH INLET

Gardner (1975) collected drainage from small tidal rivulets at Goat Island at low tide to examine the contribution of diffusion to the release and discharge of nutrients from interstitial waters in the marsh. Diffusion from the sediments was the most important process in this translocation of nutrients into tidal waters. An earlier preliminary study found

Water samples are anaylzed at the Baruch Marine Field Lab.

that, compared to the receiving creek water, this water was enriched in silica, phosphate, alkalinity, calcium and possibly ammonium as well as having a reduced pH (Gardner 1973a). Because salinities did not change appreciably over time in the interstitial water samples, it was concluded that there was no freshwater input from subsurface groundwater or terrestrial sources. Compared to freshwater runoff along the coast of SC, marsh drainage as detected here supplied less than 10% (by volume) of total runoff from the land. But because the concentrations of SiO_2 and PO_4^- are so much higher in marsh runoff, this mechanism supplies a disproportionate amount of nutrient runoff. Gardner (1975) concluded that "the impact of marshlands on silica and phosphate concentrations in coastal waters may equal or perhaps even exceed that of freshwater runoff."

Wolaver et al. (1984) reported data collected during the first 15 months of the LTER daily water sampling program at the Town Creek transect. Ammonium, orthophosphate, and nitrate+nitrite concentrations (the labile fraction) all had a tidal signature: highest at low tide and lowest at high tide. This tidal signature was less evident in winter. Orthophosphate and nitrate + nitrite were highest in fall and low in winter and spring. Because all the dissolved inorganic species had high concentrations at low tide, this suggested their source must lie within the inlet. Possible sources included the vegetated marsh surface during tidal inundation, runoff and seepage from the marsh surface during low tide exposure, diffusion from the sediments within the

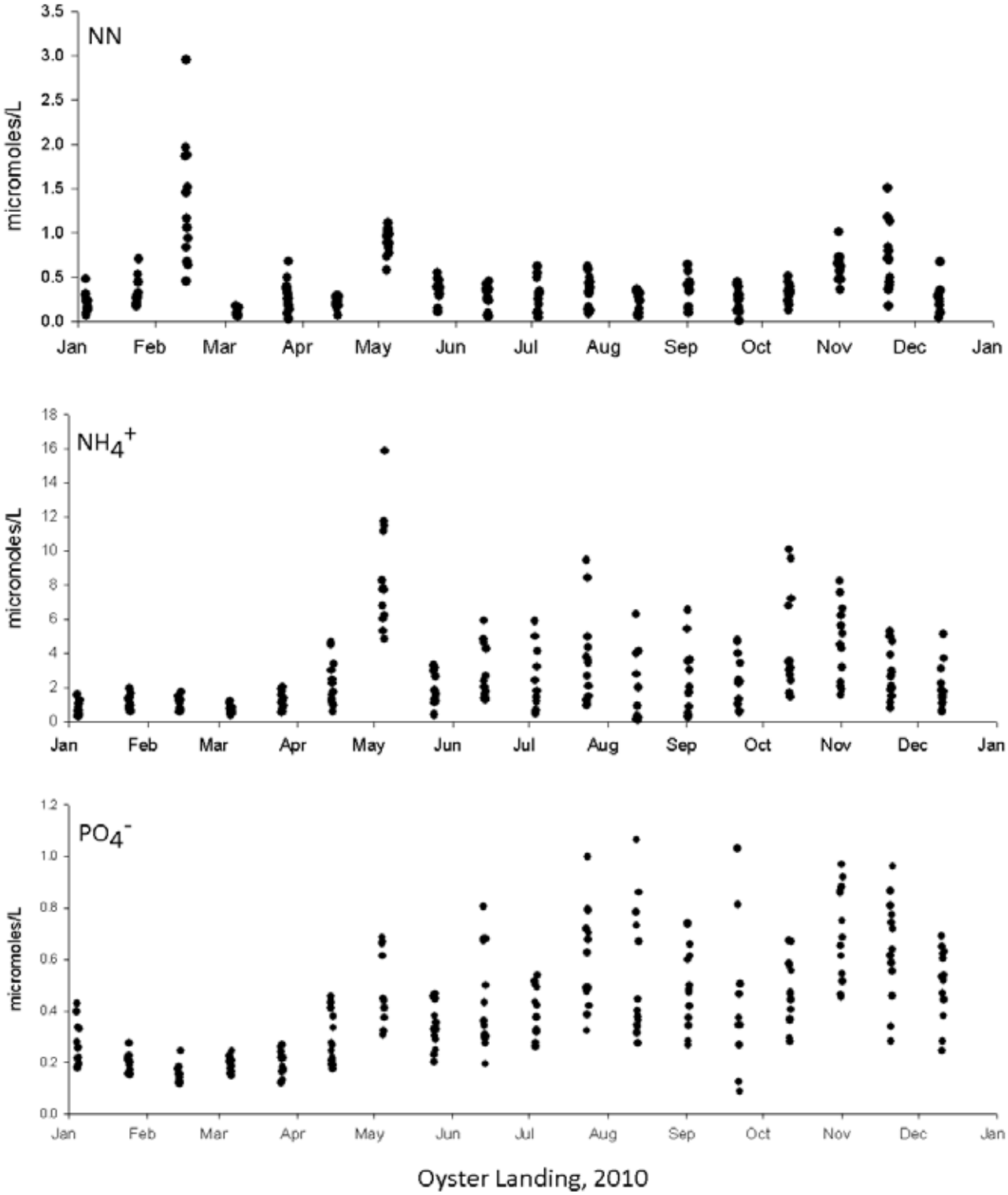

Figure 35. Oyster Landing nitrate+nitrite (top graph), ammonium (middle graph) and orthophosphate (bottom graph) concentrations for all 20-day sampling events during 2010. Water samples are collected every 2 hours and 4 minutes during each 25 hour event.

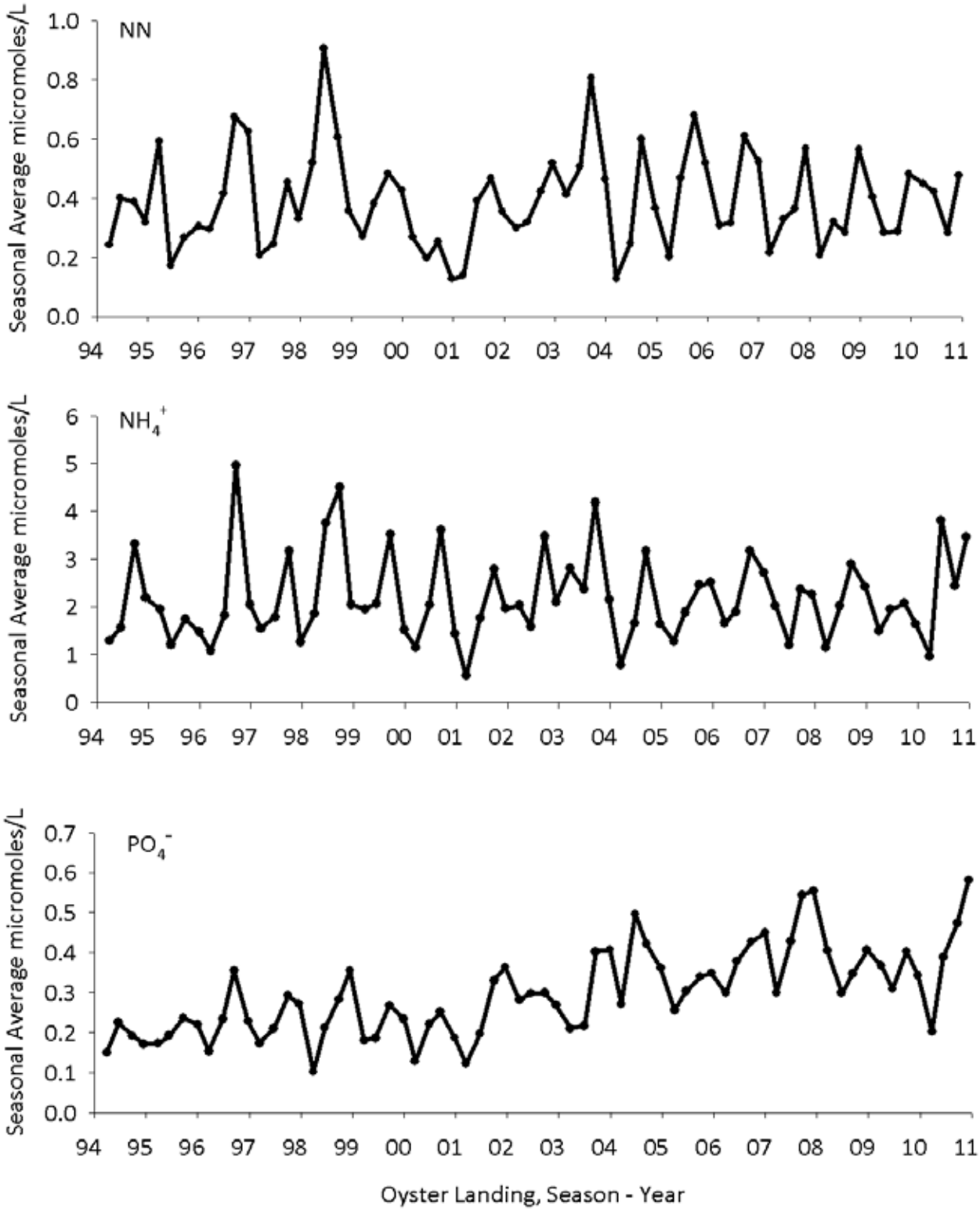

Figure 36. Oyster Landing nitrate+nitrite (top graph), ammonium (middle graph) and orthophosphate (bottom graph) concentrations for all 20-day sampling events from Winter 1994 through Fall 2010. Seasonal averages include all 2 hour and 4 minute data from each event. January through March = Winter, April through June = Spring, July through September = Summer, and October through December = Fall.

tidal creeks, possibly coupled with groundwater flow, and excretion from organisms. Sources and sinks for the dissolved organic phases of N and P were unclear, but on a seasonal basis DON and DOP had different sources. DOP is generated within the system, whereas DON enters via freshwater inputs. Neither particulate P nor particulate N had a tidal signature. Both were low during the winter. Tidal scour of creekbanks, rainfall-driven erosion, and tidal scour of creek bottoms when flow velocities are high (resuspension) pointed to sources for these particulate phases of N and P. These refractory constituents (DON, DOP, PN, and PP) get moved rapidly through the system, while the labile species had dynamic behavior within the system.

The focus of nutrient cycling research in the 1980s in North Inlet was the question of whether coastal marshes act as sources or sinks for nutrients and whether nutrients and materials are exported to coastal oceans by outwelling. Major funding was obtained in the late 1970s to examine the outwelling hypothesis and a coordinated series of studies was performed across the major outlets from North Inlet to the ocean and Winyah Bay. The basic sampling design for the North Inlet Outwelling Study was to measure various waterborne constituents at stations along a transect across the narrowest connection between the inlet and the ocean. Kjerfve and McKellar (1980) provided a scheme for calculating flows and fluxes across the transect. Transects were established that also took into account cross-sectional variability in tidal flow patterns and asymmetrical flow velocities (Whiting et al., 1985; Kjerfve and Medeiros, 1989). Water samples were taken at intervals over several tide cycles at near-surface, mid- and near-bottom depths for measurements of nutrient concentrations. Other constituents were measured as well, including macrodetritus, chlorophyll-*a*, zooplankton, sediments, ATP, and physical properties of the water like temperature and salinity. Many of these details have been mentioned above and the overview of the Outwelling Study was reported by Dame et al. (1986). Water input as runoff from the surrounding forest, precipitation, and input from Winyah Bay was exported to the coastal ocean. This water exported everything measured except for total sediments (imported in fall and winter) and chl-*a* and zooplankton that were imported in summer and fall. Carbon, nitrogen and phosphorus export was high compared to other places where similar outwelling has been measured. It was suggested that some of the nutrients (ammonium and orthophosphate) exported fuel phytoplankton production offshore that is later imported back into the marsh where it is consumed, decomposes and gets remineralized. Many of the questions raised by the Outwelling Study gave impetus for examination of nutrient cycling processes within various portions of the salt marsh itself, and chief among these efforts was the Bly Creek Study.

Bly Creek runs between Goat Island and is an intermediate-aged intertidal system that connects to the mouth of North Inlet via Town Creek. Once again, the task of estimating nutrient fluxes within the creek required a sophisticated modeling technique and experimental sampling design (Spurrier and Kjerfve, 1988). Once this was established, 34 tidal cycles were sampled between 1983 and 1984 and nutrient inputs from rainwater, stream flow and groundwater were balanced against those resulting from changes of the tide as well as the flux of materials transported via the marsh, oyster reefs, and the tidal creek (Wolaver et al., 1988c; Dame et al., 1990). Spurrier and Kjerfve (1988) found that nitrate+nitrite was exported to the ocean out of Town Creek, but there was an increased concentration of these constituents in the water flowing into South Jones Creek on flooding tides. Despite the higher concentrations,

Flumes were used in Bly Creek to examine the transport of nutrients in the marsh.

the flux of water out to Winyah Bay on ebb tides negated the existence of any flux into North Inlet. Orthophosphate data suggested a source of this species inside the marsh, consistent with what Gardner (1975) found in marsh runoff. Spurrier and Kjerfve (1988) also cautioned that variations in concentrations and water flux imbalances can complicate the calculations of nutrient fluxes.

Groundwater flow and nutrient concentrations were measured from a grid of 108 piezometers arrayed around the site (Wolaver et al., 1988c). Rainfall N was measured nearby. There was a net tidal flux of NH_4^+ into the basin during late summer and early fall, with export the rest of the time. The total N exported from the basin was statistically insignificant. That is, the Bly Creek basin was neither source nor sink, but ammonium nitrogen was actively recycled within the basin during the year. Nitrate and nitrite dynamics suggested that these species were produced during periods of maximum tidal flow and turbulence, perhaps from nitrification in the sediments. Streamwater from the forest (as blackwater) carried DON to the creek from March to July. This source combined with other sources in the marsh resulted in a net export of DON throughout the year. PN loads increased during storms and from marsh runoff at low tide, but the basin was neither a source nor a sink for PN. The data on N suggested a net balance between production and utilization of the various species measured such that N is retained in the system via recycling.

As for phosphorus in the Bly Creek Study (Dame et al., 1990), the area was a sink for particulate P and for orthophosphate. The annual net flux of water from the creek was less than 2.4% of the basin capacity at high tide, but this estimate was fraught with measurement error from sheetflow (Eiser and Kjerfve, 1986). PO_4^- concentrations were highest in summer and lowest in fall and winter. Particulate P was highest in summer and lowest in winter, suggesting that bioturbation released PP to the system. Net flux of PP and TP was zero across the Bly Creek transect. Concurrent with the Bly Creek basin transect measurements, a flume study was conducted near the head of the creek (Wolaver and Spurrier, 1988), and an Oyster Reef Study in the lower reach of the creek seaward of the transect across the creek (Dame et al., 1989).

Wolaver and Spurrier (1988) conducted a flume study to measure phosphorus exchange between the vegetated marsh and the upper reaches of Bly Creek. They also collected runoff from the marsh surface using a weir system. The flume, 140 m long, was two parallel walls set 2 m apart that crossed from the short *Spartina* zone to the edge of the tidal creek. It channeled water on a rising tide into the marsh and from it on an ebbing tide. The walls were removable to prevent any longer term effects of its presence (see Wolaver et al., 1985 for specifics about the flume design). Between April 1983 and June 1984, 40 tidal cycles were sampled every 11.8 days on average to capture lunar and diel cycles within each season. Orthophosphate was removed from the water as it flooded the marsh surface. The marsh surface was also a sink for particulate P, especially in summer, and most of it was removed from flooding tidal water in the low marsh. Total P followed the same trends as particulate P. Some of these constituents left the marsh at low tide, but overall their uptake exceeded loss, hence the marsh surface was a net sink for P.

A 10 m long portable tunnel was used by Dame et al. to study nutrient flows over an oyster reef in Bly Creek.

Dame et al. (1989) also participated in the Bly Creek Study with a separate study of nutrient flows over an oyster reef downstream from the main transect. They deployed a 10 m long portable tunnel that was placed over an oyster reef. Materials were either taken up by organisms in the tunnel or released by them. Net annual fluxes of constituents were estimated using a regression model (Spurrier and Kjerfve, 1988). Over the

33 observed tidal cycles that included neaps and springs, total and particulate nitrogen were taken up on flooding tides and released on the ebb. Only ammonium showed both uptake and release during all changes of the tide (ebbs and floods). Other dissolved N constituents were also taken up and released by the reef. The measured net uptake of N (189 g N m^{-2} yr^{-1}) was not statistically different from zero. Total and particulate P were taken up by the reef during about 90% of the flooding tides and released on the ebb. Overall annual uptake was 98 g P m^{-2} yr^{-1}. The reef serves as a nutrient retention mechanism that processes them rapidly, converting particulate forms to dissolved forms, consistently releasing ammonium. Thus oyster reefs, depending on their size and distribution within the marsh and on how much water flows over them, can have a significant role in nutrient cycling. As presaged by Dame et al. (1980), it is clear that benthic filter feeders affect many aspects of biogeochemical cycles in North Inlet. Childers (1994) provides an overview of the Bly Creek Study in the context of other similar flume-based studies.

Dame and Gardner (1993) reviewed multiple lines of evidence that parts of North Inlet's marsh are much older geologically (Pleistocene versus Holocene) and suggested that this age difference is reflected in the manner in which nutrients are processed in the different-aged marsh. They constructed a map (their Figure 1) identifying sites at different stages of evolutionary maturity. Immature marsh to the west of Bly Creek exports N and imports P and C. Intermediate stage marsh like Bly Creek imports particulates and exports dissolved phases of most nutrients. The Town Creek opening to the Atlantic Ocean is the most mature part of North Inlet. The Dame and Gardner paper is a "must read" for potential marsh investigators who may be perplexed by the high spatial variability documented in so many published studies about nutrient cycles in North Inlet. It provides context for the hypotheses of Odum (1969) about coastal ecosystem development and Vitousek and Reiners (1975) about ecosystem succession and nutrient retention. In a young developing ecosystem, nutrients are stored to support a growing biomass, whereas in a mature one with lower growth, fewer nutrients are needed. Much the same is seen across the marsh age spectrum in North Inlet, though sampling variability at all spatial and temporal scales often clouds some of these gradations.

It was not until 30 years after his 1975 work above that Gardner (2005) published a model describing pore water seepage from salt marsh sediments into tidal channels. This interesting numerical boundary integral equation model showed water movement dynamics that clustered within only a few meters from the creek bank into the marsh, with much less flushing out from the creek bottom. Water moves from this bank area rather quickly and thus has a relatively short residence time (1-2 years) there. He suggested that this flushing action between draining at low tide and recharging during flood tides might enhance *Spartina* productivity in creek bank areas of the marsh.

Because nitrogen is generally regarded as a major limiting nutrient for coastal marshes, and because so little work had been done on N transport in southeastern salt marshes, Whiting et al. (1987) conducted a detailed study of net fluxes and tidal concentration patterns for total N, ammonium, and nitrate+nitrite in North Inlet. They sampled four consecutive tidal cycles at three locations: Town Creek, North Jones Creek, South Jones Creek. These locations are the major passages through which North Inlet water is exchanged with the coastal ocean and Winyah Bay. The calculated fluxes showed consistent export of dissolved inorganic N (DIN) to the coastal ocean. Ammonium and nitrate+nitrite showed increasing values during ebbing tides as marsh processes released these forms to the water. Ammonium export was greatest during the summer. Interestingly, these forms increased in concentration during the flood tide at South Jones Creek as lower salinity enriched bay water entered this gateway into North Inlet. Their measures of water export and changes in salinity suggested that neither freshwater inputs from the forest nor imports of Winyah Bay water were a factor in the export fluxes. Ammonium export was significant during all seasons, being greatest through Town Creek during summer. Nitrate+nitrite export was also significant during all seasons, but greatest out

Town Creek in winter. Trying to balance exports with utilization (uptake) of N in the marsh suggested that much of the N uptake was from N-fixation in the marsh itself. They also suggested that the ratio of marsh surface to tidal creek surface (3:1 for North Inlet) could play a role in explaining differences in N dynamics seen by researchers in other marshes.

To optimize future sampling efforts and information return at Bly Creek, Kjerfve and Wolaver (1988) undertook a calibration study of water flow, particulate organic carbon, and nitrate+nitrite at the 53-m wide Bly Creek transect over two tidal cycles in October 1982. The concentrations of POC and nitrate+nitrite did not change appreciably, and water discharge explained over 90% of their variability. Thus their recommendation for future flux measurements was to measure water flow most carefully.

Whiting et al. (1989) examined several aspects of nitrogen exchange between the vegetated marsh and an adjacent tidal creek using the Bly Creek flume (Dame et al., 1990). A regression model correlated with relevant measures of tidal, weather, and plant biomass predictor variables was used to estimate a net annual N flux. During inundation by the tide, the marsh surface imported ammonium, nitrate + nitrite, and particulate N and exported dissolved organic nitrogen (DON) on an annual basis. The low marsh had higher exchange rates than the high marsh. During the time between late ebb and early flood when marsh surface drainage occurred, both particulate and dissolved organic N were lost in substantial amounts to the tidal creek , but drainage loss of dissolved inorganic nitrogen (DIN) was small. Rainfall increased runoff drainage from the marsh surface when it was exposed, and particulate N export to the tidal creek increased by a factor of 40. They estimated that the vegetated marsh exported about 4.5 g N m^{-2} yr^{-1}, mostly as DON. Their findings also suggested that when seasonal imports of N occurred to the marsh, they were dependent on the concentration of nitrogenous compounds in the flood waters.

Other locations of nutrient enrichment sources were studied by Whiting and Childers (1989) who examined the advection of water from creek sediments, a process that is also known as seepage (Agosta, 1985). Seepage from Bly Creek (14 L m^{-2} tide $cycle^{-1}$) was three times greater than at Clambank. Nutrient concentrations in the advected water were 5 times higher than in the overlying creek water, but there was great spatial variation depending on which transect site was measured. NH_4^+ concentrations in seepage from the creek bottom exceeded overlying creek water by an order of magnitude, while interstitial water contained 4X that in seepage. Orthophosphate concentration in seepage was 4X that of overlying waters and about equivalent to interstitial porewater concentrations. Drainage water collected in the weir had inorganic nutrient concentrations at least 5X higher than in overlying creek water. This so-called "tidal pumping" of interstitial porewater and subsurface water through the creek bottom contributes very significant amounts of dissolved nutrients to tidal creek waters and occurs via three mechanisms: 1) remineralization and diffusion from creek sediments; 2) direct advection (seepage) of interstitial water from the marsh sediments out through the creek bottom; and 3) diffusion of nutrients from the marsh surface into water draining off the marsh at low tide. Of the three, direct advection through the creek bottom was most important for exporting ammonium, NH_4^+ , but about the same as marsh runoff for phosphate export to creek waters. Low tide drainage delivered more oxidized inorganic nitrogen (NO_3^- and NO_2^-) to creek waters than benthic advection. Because nutrient concentrations in the tidal creek water column are enriched at low tide compared to high tide, it is clear that these advective and diffusive processes are the source of this enrichment. Once again, their data indicated that discharge of groundwater into these processes did not occur.

Krest et al. (2000) had difficulty accounting for the amounts of nutrients outwelled by North Inlet (Dame et al., 1986) and proposed a different source for the surplus nutrients. They suggested that the amounts outwelled simply could not be accounted for from remineralization of detritus in the estuary or of phytoplankton imported to the estuary. Nutrient inputs from Winyah Bay were also deemed insufficient to account for the excess. Marsh mud

serves as an impermeable cap on top of a subsurface porous sandy layer (found with vibracores) within which the coastal groundwater aquifer exists. As tidal creeks cut across the marsh, their deepest parts intersect the aquifer. Previous work by Rama and Moore (1996) used radium isotope data during the summer to estimate groundwater discharge in the inlet, but the amounts calculated were deemed to overestimate the actual discharge. Ammonium and dissolved reactive phosphorus were measured in the samples along with radium. Groundwater contained up to two orders of magnitude greater concentrations of radium and both nutrients than was found in the inlet water.

Moore (1999) had found winter nutrient concentration in North Inlet to be twice that in summer, and winter radium concentrations were likewise double those of summer. This suggested a linkage between radium and nutrients. Based on previous estimates of nutrient export, Krest et al. (2000) eliminated all possibilities other than groundwater discharge as being too small, i.e., surficial freshwater input, diffusion from sediments on the marsh surface, and import of sediments were insufficient to account for the magnitude of the export. They determined that there was more than enough groundwater input to account for the shortfall from nutrients that are converted to biomass during the growing season.

Moore (1999) proposed that this groundwater input derives from seawater intrusion much like seawater, because of its greater density, moves under fresher water into estuaries on a rising tide. He coined the term “subterranean estuary” to describe this long-neglected zone of mixing in the aquifer that drives a major input of dissolved nutrients to coastal marshes and the nearshore coastal ocean itself. Because empirical measurements of seepage and drainage and all the other ways that nutrients reach the inlet are considerably out of balance with this groundwater input, Gardner (2005) suggested that there is really no conclusive evidence for existence of a subterranean estuary beneath the North Inlet basin. Research on this issue will continue, of course.

Building on the earlier modeling efforts of Wilson and Gardner (2006) and the model of Gardner and Wilson (2006) that showed the importance of incorporating sediment compressibility as a relevant variable that affects seepage from the marsh, Wilson and Morris (2012) provide a summary overview of the role of groundwater in the nutrient cycles of North Inlet. They used a new numerical model to demonstrate how changes in water level due to both the tide and to relative sea level affects porewater and groundwater flux into tidal creeks. Based on empirical nutrient concentration data collected over many years at Goat Island and Oyster Landing, the model accurately depicted the magnitude of nitrogen and phosphorus exchanges between the salt marsh and tidal creeks as water level changes. Because nutrient concentrations in porewater are basically always higher than in the water brought to the marsh by the tide, it is clear that biogeochemical processes in the upper meter or two below the marsh surface generate nutrients that are then flushed into tidal creeks by deeper groundwater moving upward in response to hydraulic pressure from the overlying water. Compared to the amounts of nutrients from tidal exchanges, runoff, precipitation, and other sources, this porewater-fluxed source is biologically significant, is much greater, and is perhaps the dominant fuel for what eventually gets exported to the coastal ocean from North Inlet. What remains to be determined is how this belowground nutrient-generating system will respond biologically and elevationally to future changes in sea level.

Blood and Smith (1996) compared Murrells Inlet and North Inlet with respect to the impacts of urbanization. North Inlet has less than 6% urbanization, while Murrells Inlet is over 50% urbanized. Water samples at 30 stations throughout each inlet were analyzed for salinity, oxygen, inorganic nitrogen, and inorganic phosphorus and examined for both spatial and temporal distribution patterns. When averaged over seasons and tides, nutrients (ammonium, nitrate, orthophosphate) showed no significant differences between estuaries. Ammonium concentrations were highest near land in both estuaries, but the highest concentration found (> 60 microgram-atoms per

liter) was in the upland drainage area of North Inlet. Nitrate concentrations did not differ between near-land and near-ocean stations in either inlet, but there were several times when concentrations were quite different. Orthophosphate concentrations had no regional differences within either estuary overall, but were different for certain tidal stages and seasons. Only ammonium concentrations varied significantly with tidal stage, being higher at low tide in both estuaries. Water exchanges with Winyah Bay provided higher concentrations of nitrate in North Inlet at high tides. Highest nutrient concentrations occurred in both estuaries during the summer. Surface water drainage impoundments were successful in retaining nutrients in Murrells Inlet. In both inlets the amount of tidal flushing is great, and this contributes to the minimization of runoff effects and lack of eutrophication problems in each. However, continued nutrient loading could become a problem in the future.

Tufford et al. (2003) compared nitrogen and phosphorus concentrations in nonpoint source runoff in Murrells and North Inlets. Surface water samples were collected at low tide monthly during 1999. Total, dissolved inorganic, and dissolved organic forms were analyzed from 8 small drainage basins in Murrells Inlet and two in North Inlet. The landscape was partitioned into forested creeks, urban creeks, and urban ponds. DON and ammonia were highest in forested streams, while nitrate and total phosphorus were highest in urban streams. Their major finding was that land use was not a reliable indicator or predictor of nutrient concentrations.

White et al. (2004) compared concentrations of nutrients in North Inlet with those in the developed Murrells Inlet estuary. They hypothesized that greater non-point source runoff in Murrells Inlet would cause elevated nutrient levels and more chlorophyll-*a* as a result. When salinity declined (from runoff after rain storms), inorganic nutrients increased more in Murrells Inlet than in North Inlet. Lowest nutrient concentrations occurred in November 1998 and July 1999 in both estuaries. Two hurricanes (Floyd and Irene) brought high precipitation with subsequent increases in nitrate concentrations in both inlets, but more so in Murrells Inlet. Ammonium concentrations were negatively correlated with salinity in Murrells Inlet, but there was no correlation between these variables in North Inlet. Dissolved organic nitrogen concentrations were highly variable in both inlets with no distinct seasonal trends. DON was highest in North Inlet after passage of hurricane Irene. Orthophosphate was positively correlated with temperature in both study areas. Reactive silicate followed a similar trend, higher in summer, lower in winter. There were indications of eutrophication in Murrells Inlet, but overall the system there seemed able to respond quickly to stochastic runoff events. Both North Inlet and Murrells Inlet have high rates of water turnover as the tide changes, hence their response to nutrient inputs is not as dramatic compared to estuaries with much greater freshwater inputs of nutrients and less tidally-driven exchanges with the coastal ocean.

Nelson et al. (2005) screened historical (1967-1995) records of rainfall and fecal coliform bacteria concentrations measured in the waters of North Inlet and at Murrells Inlet. They focused on major interventions – jetty construction and sewage diversion from septic tanks to municipal treatment at Murrells Inlet, construction of the Baruch Marine Field Laboratory and development of homes at Debordieu Colony for North Inlet – to see what effect they had on water quality in the two areas. The interventions at Murrells Inlet resulted in decreased fecal coliform counts, especially from elimination of septic tanks, but the jetty completion probably kept the decreases from being even greater because the jetty restricted the flow of clean coastal water into the inlet there. At North Inlet, neither intervention was detectable, most probably because they were such small scale, but also because of the greater contribution of fecal coliforms from wildlife there masked any small increase that might have been due to human activities. More data will be needed to measure impacts of future changes in land use at the coast.

Aelion et al. (1997) examined water quality in groundwater wells dug in North Inlet in the forested headwaters of the Oyster Landing basin and another

in nearby urbanized Murrells Inlet for comparison. Rates of denitrification were also measured on 1 m deep sediment samples collected from adjacent creeks at both sites. Nitrate concentrations were higher in the urbanized site, but ammonium concentrations were considerably higher in the forested site where leaf litter is abundant. Nitrate additions to the sediments altered the rates of denitrification and its efficiency.

In another comparative study between denitrification rates at North Inlet and at Kiawah Island, SC, a developed barrier island with golf courses and residential areas adjacent to the marsh there, Aelion and Engle (2010) found significant differences in the two study areas. Both core sampling sites had typical dark, sulphidic marsh sediments. The impacted site had more active denitrification and faster NO_3^- removal than the unimpacted site, North Inlet. Based on ^{15}N measurements, the impacted site had more active participation of ammonium in its nitrogen cycling than North Inlet. This suggested that the impacted site had responded better to episodic N inputs.

BIOTIC ELEMENTS IN NUTRIENT CYCLES

Bildstein et al. (1992) calculated nutrient transport of the white ibis, a colonial nesting bird that had established springtime breeding colonies on Pumpkinseed Island in Mud Bay for many years. Annual fluxes of N, P, K, and Ca to North Inlet due to white ibis activities were compared to those from tidal input of nutrients from Winyah Bay for two years, 1984-85. Their calculations included many assumptions about bird ingestion, caloric content of food, assimilation efficiencies of adults and nestlings, etc. Bird census counts differed greatly each year, with about 85% fewer nesting pairs on the island in 1985 compared to 1984; i.e., 12,973 in 1984 to 1,976 in 1985. Despite the large year-to-year difference in the census, compared to nutrient inputs from a nearby watershed, precipitation, and flow from Winyah Bay, the ibis population contributed at most (in 1984), 33% as much P, 9% as much N, and <1% as much K and Ca. Thus these and possibly other birds that take up residence in the area for any appreciable amount of time can translocate significant amounts of nutrients, especially to localized areas like their nesting grounds where excreta are differentially and perhaps preferentially deposited.

Haertel-Borer et al. (2004) examined the role that excretions from motile species of fishes and shrimps play in the biogeochemical cycling of nitrogenous materials (urea and ammonium) and phosphorus as orthophosphate in tidal creeks of North Inlet. There are over 700 such intertidal creeks in the estuary that feed into the marsh from 15 larger subtidal creeks. Collections of fauna from 8 intertidal creeks were made over all seasons for this study. Animals were collected and placed in bags of filtered creek water and suspended for 2 hr in the creek to maintain ambient temperatures. DO and nutrient concentrations were measured before and after incubations, with controls. In spring the fauna were representative of the community that utilizes the creeks (e.g., silversides, mullet, spot, grass shrimp, mummichogs) and in summer the fauna included a few additional species. Mass-specific excretion rates were calculated based on faunal biomass and container volumes. Other experiments were done in tanks containing natural creek sediments to separate the effects of bioturbation from excretion on changes in nutrient concentrations in both spring and summer trials of 6-hr duration during which animals were fed *ad libitum*. Data from these and many other studies done in North Inlet were used to calculate nutrient input to the system expressed as hourly rates per square meter of intertidal channel surface at high tide. In the bag experiments, ammonium excretion rates were higher in summer than in spring as temperatures were higher then. Urea excretion rate was always much lower than for ammonia, depending on species, as were orthophosphorus excretion rates, but these were higher in spring than in summer. Summer N:P ratios for excretory products were higher than in spring. Nutrient production rates in the tank experiments followed the same patterns as in the bag experiments, and bioturbation inputs were about 40% of excretory inputs alone. Using nekton biomass and other faunal component data from other studies, nutrient inputs to the creek were spread equally across nekton, oyster reefs, and sediment, with the zooplankton and atmospheric contributions much smaller. The effect

of nekton was mostly translocation of nutrients among subsystems of the marsh, but the amounts of ammonium released were significant enough to have an important impact on water column primary production. This and the Allen et al. (2013) studies evaluated the magnitude of the nektonic, biotic component of nutrient cycles in saltmarsh-dominated coastal ecosystems.

Oyster reefs in North Inlet also participate in nutrient cycles. Dame et al. (1985) constructed a plastic tunnel for emplacement over a reef to measure input/output concentrations and flow velocities over several tidal cycles in summer. They found elevated concentrations of ammonia, with its release greater on the ebb than on flood tides. N uptake through oyster feeding was the source of this ammonia return to the water. Dame (1984) and Dame et al. (1989) also pertain to the role of oysters in nutrient cycles in North Inlet. Dame and Libes (1993) used oyster removal manipulations in tidal creeks to deduce that oyster reefs act as nutrient retention reservoirs. Dame et al. (2000a) reviewed the impacts of benthic-pelagic coupling, both passive and active, on nutrient cycling and other processes within marsh ecosystems as well as within coastal oceans.

In summary, the essential nutrients N and P in North Inlet have been investigated in several different modes. First, their short-term concentrations in the water are higher during low than during high tides. Second, quantitative estimates of their source and sink dynamics within the estuary were evaluated as part of the Outwelling Study which showed export of these constituents to the coastal ocean. Third, the Bly Creek Study found how nutrient concentrations change as water flows over the marsh. Nutrients, particularly N, are basically retained and recycled within the marsh while P is taken up by the marsh sink. Fourth, oyster reefs both take up and release significant amounts of N and P as the tide changes. Fifth, marsh porewaters serve as a source for nutrients by leaking N into the tidal creeks. Sixth, groundwater flux also contributes dissolved nutrients to the system. Seventh, rainfall redistributes nutrients when the marsh surface is exposed at low tide. Eighth, long-term monitoring has shown that nitrate N increases during years with higher precipitation and declines during droughts. Seasonal changes were also apparent. Orthophosphate is trending to higher concentrations over time. How nutrients will respond to future changes in sea level and marsh elevation and how continued coastal development in the NI-WB NERR watershed will impact water quality remains to be seen.

SULFUR

Wolaver and Gardner (1983) used interstitial water samplers along transects at three sites in North Inlet to measure a variety of water quality parameters, including total dissolved iron, total dissolved sulfide and sulfate. Out in the old marsh at Bread and Butter Creek, porewater sulfides were negligible in the mud flat and on the creek berm by the tall *Spartina*. In the high marsh transect, iron and sulphide profiles increased in concentration during late summer and fall and underwent dissolution in winter. Along the Goat Island and Town Creek transects, no such seasonality was found. Regardless of site, however, sulphides increased from lows in winter to higher values in late summer and fall.

King (1988) took sediment cores at Goat Island and Oyster Landing, injected them with radio-labeled sulfate, incubated the cores for 72 hr, and then froze them to stop metabolic processes. Sulfate reduction rates (micromoles per cubic cm per day) varied seasonally and spatially over the 30-mo study, with lowest rates in January and highest in August. Rates were proportional to temperature as expected and were about twice as high in short *Spartina* as in the tall form zones. Rates were about 5-10 times greater in the uppermost 2 cm of the cores than in the 8-10 cm sections, correlating with carbon content. The labeled sulfate was also traced to its end products, pyrites and acid-volatile pools, for instance. Sulfate reduction was inversely proportional to *Spartina* productivity.

The only other major study of sulfur chemistry in North Inlet was conducted by Gardner et al. (1988). This study emphasized spatial differences by the examination of samples along three different transects: Goat Island, Bread and Butter, and Town

Creek. This study produced too much data for presentation here, but they found that downward movement of iron oxide via fiddler crab burrowing activities played a large role in the mechanism by which pyrite was moved to the surface and oxidized there. Most of the sulfur compounds increased in concentration, as did carbon, with distance from tidal creeks, although acid volatile sulfur (FeS) decreased with distance. Interactions between reactive iron oxide and sulfur compounds dictated much of the spatial variability found.

Remaining questions about how decomposition of organic matter is related to the process of sulfate reduction and sulfide oxidation led Gardner (1990) to construct a model of how carbon, sulfur, and dissolved oxygen contribute to generating the observed vertical profiles at different locations in the salt marsh. He hoped to achieve a greater understanding of how the oxygen, sulfur, and carbon cycles intersect within saltmarsh sediments. The numerical model has many compartments and non-linear differential equations, but conclusions from many experimental simulations revealed the following conclusions: 1) oxygen supply to the sediments prevents the buildup of excessive amounts of reduced sulfur, with plant root exudates playing a greater role than simple diffusion of oxygen into the sediments: 2) in the mid-marsh areas, root oxidation is much more important than fiddler crab bioturbation and pore water movement in preventing reduced sulfur buildup; 3) the stable carbon isotope signature of sediments is influenced more by fiddler crab burrowing in the creek bank sediments than in the back marsh; and 4) future work is required on the mechanisms involved in root oxidation of sediments and processes making *Spartina* decomposition products. The genesis of this 1990 model began with some of the earliest studies of nutrient chemistry and sulfate reduction in North Inlet (Gardner 1973b, 1975).

Though little research has focused directly on sulfur and sulfurous compounds in North Inlet, their role in moderating marsh productivity suggests that process studies of the role of microbes in the sulfur cycle will be a future focus. Sediments and sulfur are inextricably linked in the diagenesis of organic matter and its decompositional fate.

CARBON

The NI-WB NERR 20-day water chemistry monitoring database, described earlier in the section on nitrogen and phosphorous also collects and measures dissolved organic carbon (DOC). These collections and results are not formally required in the NERR System-Wide Monitoring Program (SWMP), but are a part of USC Baruch Institute's long-term monitoring program. The NI-WB NERR water chemistry collection protocol is to sample all tidal stages (day and night) over the years. Thirteen 1000-mL samples are collected every 20 days at 2 hour and 4 minute intervals, for 2 complete tidal cycles (24:48 hours).

The Oyster Landing monitoring site is used in this document to represent DOC levels which have been examined in both short- and long-term time frames in North Inlet. A 20-day sampling event in July 2010 shows that DOC concentrations are influenced primarily by tide (Figure 37). DOC levels during slack low tides were about twice as high as those at slack high tide. The tidal water ebbing out to sea carries higher concentrations of DOC than the ocean waters entering North Inlet. Time of day appears to have no influence on DOC values.

Figure 38 illustrates that the winter months had the highest levels and variation of DOC; spring months had the next highest. Summer and Fall had similar concentrations, ranging from about 2 to 4 milligrams per liter.

Figure 39 demonstrates seasonal differences within and among years. The El Niño years 1998 and 2003, which had large amounts of rain, had the highest DOC values. The drought years' (latter part of 1999 through the summer of 2001 and about 2007-2010) values were lower and less variable. DOC concentrations in North Inlet have declined since 2004.

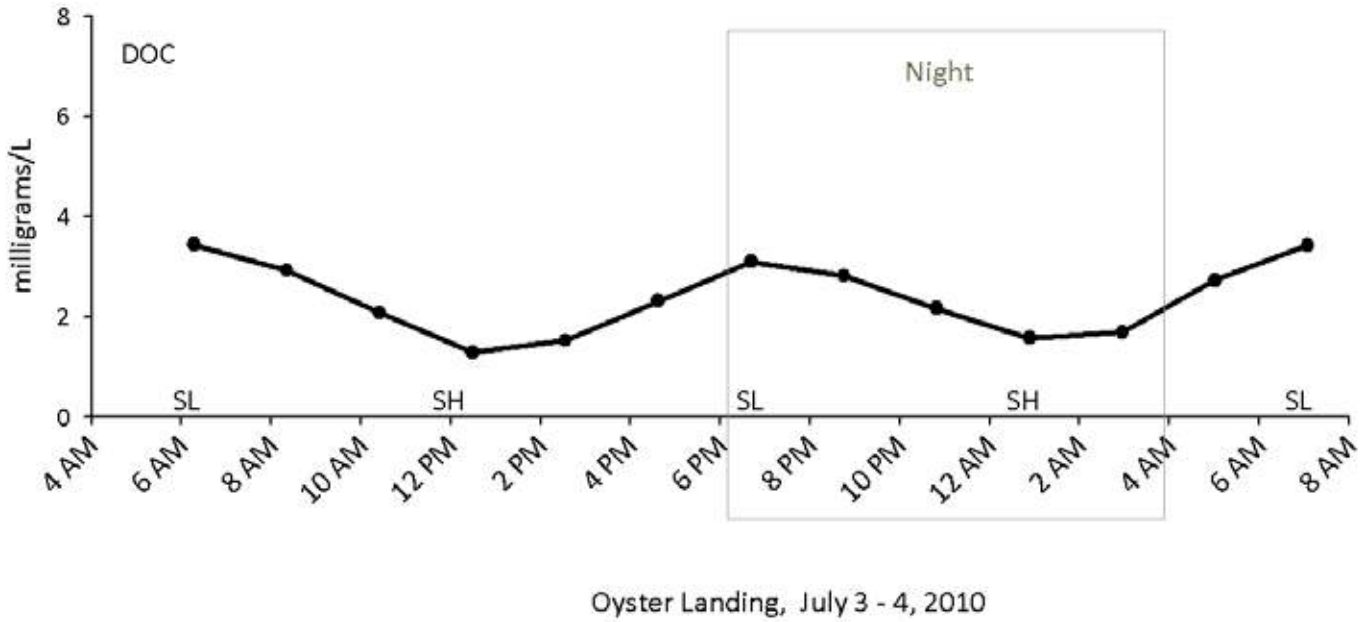

Figure 37. 25hr. Oyster Landing dissolved organic carbon (DOC) concentrations during July 3-4, 2010 (a 20-day sampling event which last about 25 hrs). Water samples are collected every 2 hours and 4 minutes. SL= slack low tide; SH=slack high tide.

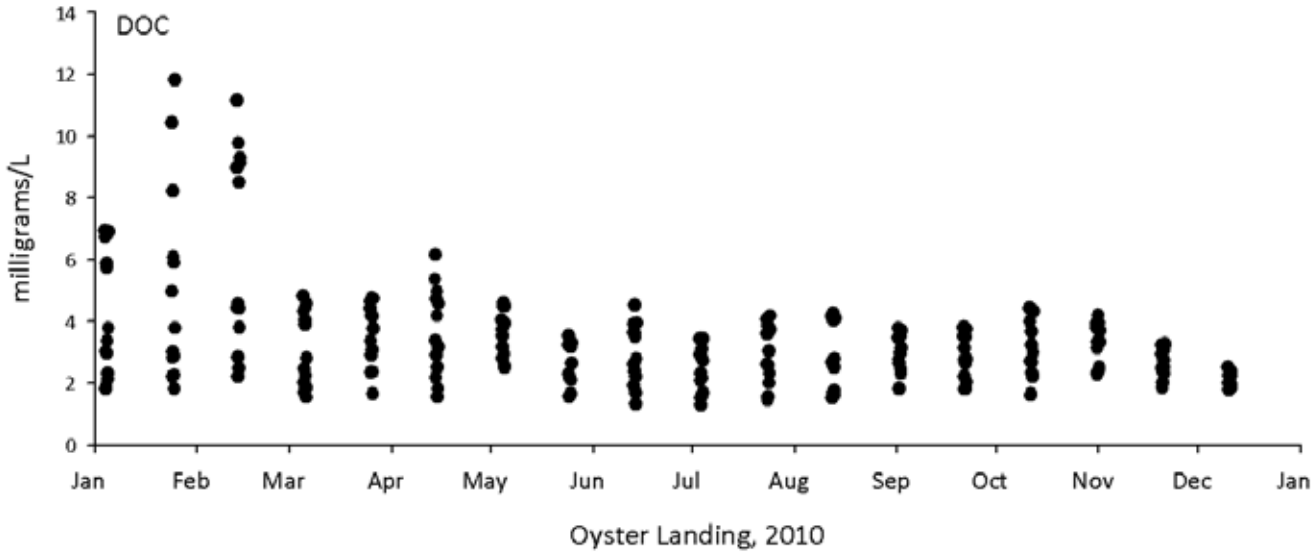

Figure 38. Oyster Landing dissolved organic carbon (DOC) concentrations for all 20-day sampling events during 2010. Water samples are collected every 2 hours and 4 minutes during each 25 hour event.

SUMMARY OF OTHER STUDIES ON CARBON IN NORTH INLET

Early studies related to carbon fluxes were done by Erkenbrecher and Stevenson (1975) who sampled water for particulate organic carbon (POC) over a 12-hr tidal cycle in a small creek near Clambank Landing and in Crab Haul Creek during May 1973. Throughout the sampling period, about 2-5% of the total POC was living carbon, presumably mostly microbial. POC at low tide was twice the concentration found at high tide at the Clambank station and three times higher (low vs high tide) in Crab Haul Creek. An additional sampling at Crab Haul Creek in August 1973 again found POC highest at low tide and lowest at high tide but, averaged over the 12-hr tidal cycle, POC was 2.5 times higher than in May. Another interesting finding was that

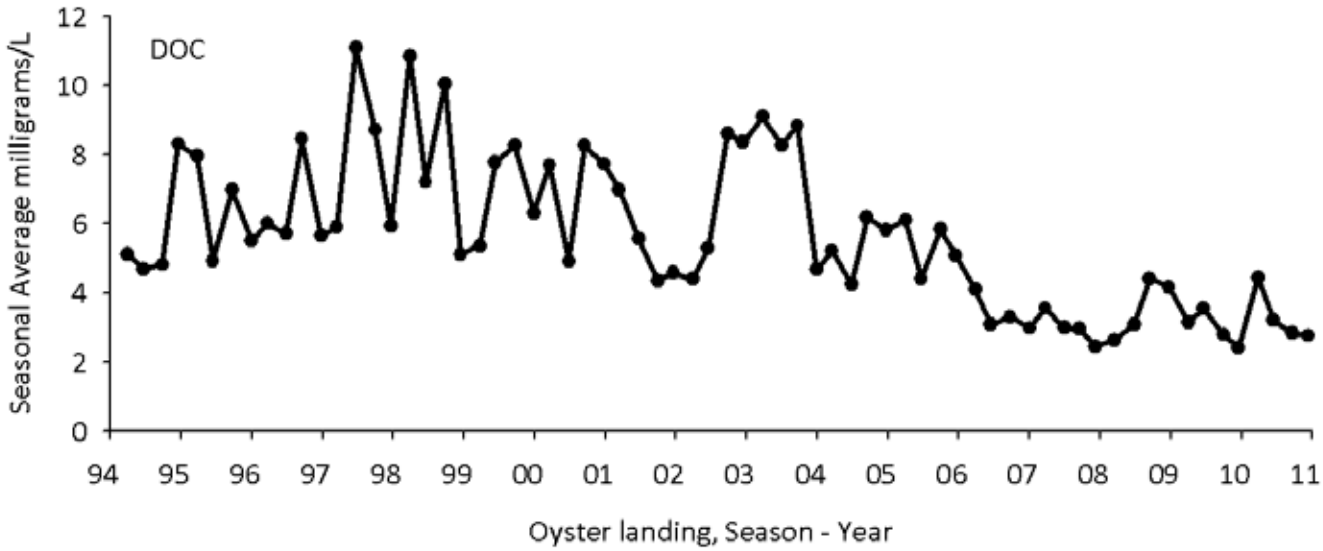

Figure 39. Oyster Landing dissolved organic carbon seasonal average concentrations for all 20-day sampling events from Winter 1994 through Fall 2010. Seasonal averages include all 2 hour and 4 minute data from each event. January through March = Winter, April through June = Spring, July through September = Summer, and October through December = Fall.

the low marsh station near Clambank Landing had a considerably higher proportion of non-living detrital carbon than in Crab Haul Creek. The lessons learned here were that organic carbon in marsh creeks is neither static nor homogeneous over a tidal cycle, making extrapolations to other areas tenuous at best.

Sampling 5 tidal cycles at the same two tidal creeks (Clambank and Crab Haul) as in their 1975 study, Erkenbrecher and Stevenson (1977) measured POC as one of many variables used to correlate with their measures of microbial biomass. POC varied over two orders of magnitude during the study, as the creeks experience wide temperature fluctuations (10-34ºC). POC correlated positively with bacteria numbers. POC had an inverse relationship with water depth and positive correlations with water temperature, pH, and dissolved oxygen concentrations. POC variations accounted for 55% of the variation in microbial biomass (ATP) during ebb tides but only 1% during floods. Several regression techniques were used to examine relationships between all 10 variables measured, but POC seemed to always be most important during ebbing tides. Single variable regressions (e.g., A vs B) were commonly low, but multiple variable regressions (e.g., A, B, C, and D vs F) explained more of the variation measured in any given variable.

Erkenbrecher and Stevenson (1978) took water samples and measured the fluxes/transport of materials (bacterial biomass, total microbial biomass, ATP, POC, chl-*a*, and suspended matter that was categorized as total suspended material, TSM, fixed, FSM, and volatile, VSM) in Crab Haul Creek, the same site as in their two earlier studies cited just above. Water discharges were net seaward, suggesting that there should have been net export of virtually every constituent measured, but this was not the case. There was no "agreement" between either the direction or the magnitude of transport of TSM and POC. POC was exported on 75% of the tides measured, with influx on the rest. Highest mean concentrations of POC occurred in August, the same for chlorophyll, ATP, and TSM. Net flux of POC for the study was an export of 31 kg per tidal cycle. This material contained about 19% living matter based on ATP biomass estimates. There was no apparent correlation between transport of POC and movements of suspended material.

To study the impact on microbial biomass and POC of freshwater or brackish intrusions into North Inlet from Winyah Bay, Weiland et al. (1979) established 5 sampling stations southward along Clambank

Creek as it meanders and empties into Mud Bay. Presumably sampling took place around high tide, as this is the only time when that particular creek is easily navigable from their northernmost station in the central marsh all the way southward to their Mud Bay station. High tide is also when water from Winyah Bay would have already moved northward into the marsh. POC concentrations almost always explained a significant portion of the variability measured in ATP along the transect. Compared to data on POC and microbial biomass in other North Inlet studies, they found no appreciable effect of Winyah Bay water intrusions on microbial biomass in this creek during the study. Intrusion may have affected the species composition of the microbial community, but this was not examined, just ATP. As found by Erkenbrecher and Stevenson (1978), no single variable explained much about the other variables. They closed with an emphatic admonition against extrapolations from one site to another.

Other early studies in North Inlet involving the carbon cycle were carried out by Chrzanowski and Stevenson (1979) on the flux of POC, TSS and organics (total volatile material, microbial ATP, fungi) through one tidal creek for one tidal cycle. This and other smaller studies provided fodder for larger, whole-estuary flux POC and DOC studies conducted by Chrzanowski et al. (1982, 1983) as tests of the prevailing outwelling hypothesis regarding transport of organic matter from inlets to the coastal ocean. The Outwelling Study established 3 sampling transects across choke-points into North Inlet from the ocean near its mouth across Town Creek and across North Jones Creek, and also across South Jones Creek where brackish Winyah Bay water enters the system from Mud Bay. The majority of the POC was small detrital particles that moved with the water. Trends for POC transports were different in winter and summer. In winter at the two inlet transects, POC concentrations fluctuated in phase with the tides (higher on rising, lower during falling tides) but out of phase in summer. Highest concentrations coincided with highest flow rates during both ebbs and floods. Concentrations dipped during slack waters. At the brackish transect, no transport patterns emerged – they were "erratic". In-phase transports suggested imports of POC from ocean to inlet during times when biological activity is depressed in the inlet. This did occur at North Jones Creek, but not at the larger Town Creek where net water export was measured. POC exports took place when marsh productivity and "activity" were highest in summer and into the fall. Calculations showed net annual POC export through Town Creek, import into North Jones, and exports from South Jones. These three creeks account for about 95% of the water flow through North Inlet – TC 81%, NJ 16%, and SJ 3% of that 95%. The rest flows to and from and between creeks and the surrounding forest and Winyah Bay and cannot be accounted for with this method of sampling. Because of the volume transport from Town Creek, overall net export of POC from North Inlet was estimated to be 87 g m^{-2} yr^{-1}. This was estimated to be between 9 and 16% of net annual aboveground primary production in the marsh.

A platform used in the Outwelling Study

Their analysis of DOC during the Outwelling Study was confined to the data from Town Creek (Chrzanowski et al. 1983), because about 85% of tidal flow volume is through Town Creek. Contrary to the POC data above, the DOC data fluctuated greatly throughout the year, but not in any regular manner. Variations in concentration were great even on an hourly basis during a single tidal period as well as during other longer sampling time intervals. Thus calculations of net imports and exports were somewhat tenuous. Net transports of DOC on an annual basis were as high as 7.5 x 10^9 g C, corresponding to 416 g DOC m^{-2} yr^{-1}. What emerged from the study was that the amounts of

TOC (the sum of POC and DOC) and DOC exported were much higher than expected, suggesting that primary productivity was not the sole or majority source of this dissolved constituent. Other sources of DOC must exist, and the most likely of these was suggested to be forest runoff and belowground seepage of water into tidal creeks. This suggestion stimulated much additional research.

Floating macrodetritus flux and subsequent export to the coastal ocean is part of the POC examined above, but Dame and Stillwell (1984) sampled 72 tidal cycles over 18 months at Town Creek and determined that it accounted for less that 1% of net aboveground *Spartina* production. They suggested that this material was not a major source of organic carbon exported from North Inlet.

For carbon on the larger scales, Dame et al. (1986) documented large net exports of particulate carbon from North Inlet and changes in DOC fluxes suggested that this constituent was coupled with the forested uplands surrounding the inlet. However, the DOC measurements were so variable from tide to tide and season to season that the net DOC export calculated was probably not totally reliable. The Outwelling Study, by measuring whole-inlet fluxes and net annual exports/imports, set the stage for examination of nutrient fluxes at other sites within the inlet on much smaller spatial and much shorter temporal scales. These additional studies were designed to examine variabilities in constituent concentrations and/or to identify particular sources and sinks for individual constituents. One such study was conducted in the Bly Creek basin by Williams et al. (1992) to examine organic carbon transports, and it will be discussed below in keeping with the historical timeline approach to this section on Water Quality.

Dame et al. (1984) looked at how oyster reefs in North Inlet process organic matter using the tunnel previously described (Dame et al., 1985). In essence, although oysters removed considerable amounts of particulate organic matter by their filter-feeding mode of ingestion, they did not ingest all of it that moves across the reef. However, they did significantly reduce the amounts of POC and increase the amounts of ammonia in the overlying flow, i.e., they were a sink for POC and a source of ammonium. Concentrations of orthophosphate, a nutrient that is not utilized by oysters, did not change as water moved through the tunnel. Uptake rates of POC in the tunnel were between 1400 and 4400 mg m^{-2} h^{-1}. The physical effects of reduced water flow via friction as water travels over an oyster reef may be biased more towards sedimentation than towards biofiltration. This study raised many questions about the ecological role of oyster reefs, particularly their role in the biogeochemical cycling of nitrogen.

To quantify how oyster reefs process the primary nutrient elements (C,N,P), Dame et al. (1989) used the portable 10-m long tunnel again. POC was taken up by the oyster reef on 95% of the flooding tides measured and released on 63% of the ebbing tides. Some of this uptake and release was due to sedimentation and resuspension in addition to oyster feeding. Maximum POC uptake rates occurred in spring and summer through early fall when metabolic rates of the oysters are elevated. DOC was released on both flooding and ebbing tides, but some of this was from microbes and benthic algae associated with the reef inside the tunnel. Annual fluxes showed net uptakes of TOC and POC on flooding tides and net release of DOC and TOC on ebbing tides. On balance, there was a significant annual release of DOC and possibly uptake of POC. Uptake of TOC by the enclosed oyster reef was 1200 g C m^{-2} yr^{-1}, but this value was not statistically different from zero. Thus the most consistent fluxes were releases of DOC (and ammonia) from the oyster reef.

Using data from the LTER project's daily 10:00 am water samples (at Oyster Landing, OL, Clambank Landing, CB, and Town Creek, TC) from March 1981 to August 1982, Wolaver et al. (1986) examined variability in POC and DOC concentrations. Their goal was to determine and hypothesize reasons for the observed tidal, seasonal, and annual variability in carbon concentrations in North Inlet. Important findings were that DOC's variability, both spatially and temporally, was best explained by variations in salinity, suggesting that runoff from the forested watershed was a major contributor of DOC to the

marsh. DOC concentrations were also lower when streamflow was low. DOC was also associated with groundwater flow and seepage from the marsh surface, biological uptake or sorption onto particles, sampling station, and origin of the water mass. POC, on the other hand, was high in summer and low in winter. Rain events scoured POC from the marsh surface, particulate materials flushing off the marsh surface at low tide, and biological productivity in the water column all contributed to the variability found in POC concentrations. Water flow velocity was also important in the larger tidal creeks as a correlate with POC values.

As part of the Bly Creek Study, Wolaver et al. (1988b) examined the role of the marsh surface in carbon exchanges with a tidal creek during tidal inundation and during exposure at low tide via runoff, seepage and rainfall when it occurred. Is the marsh surface a source or a sink for carbon? DOC concentrations were related to freshwater runoff from the adjacent forest and were highest in late winter and early spring. As concentrations did not vary appreciably from ebbs to floods, the marsh surface was deemed to be neither a source nor a sink for DOC during tidal inundation. Rain events did move DOC off the marsh into the creek, however. POC values were higher in summer, and the vegetated marsh (both high and low) was a sink for POC during tidal inundation. Occasionally high POC values were associated with ebbing waters and rain/wind events. More DOC and POC were exported from the marsh when above normal amounts of water accumulated on the marsh in depressions as the tide ebbed. Rain events were important drivers of carbon export off the marsh surface. Basically none of the predictor variables related well to DOC concentrations because the DOC's main source was the forest via a blackwater stream that ran into Bly Creek. A more complicated scenario for POC involved fluxes associated with tidal height (time of inundation) and the removal of POC as tidal floodwaters encountered plant stems via sedimentation or deposition. On an annual basis, exchanges of carbon between the marsh and tidal creek, suggested that this system was a sink for POC and a source for DOC. The marsh may not be the source of carbon outwelling from North Inlet (Dame et al., 1986) after all.

Sea surface microlayers and foams contain numerous organic-rich components such as proteins, carbohydrates, lipids, fatty acids, etc. Harden and Williams (1989) collected sea foam and POC at two stations in Town Creek from January to December 1985. Their data suggested that neither *Spartina alterniflora* nor benthic microalgae were a major source for POC to sea foam. Rather their isotope values suggested that foam contained *in situ* organic carbon whose signature was not altered by the presence of heterotrophic bacteria in the samples. Isotope values for the foam varied seasonally, suggesting that different sources formed foams at different times of year. Using long-term data on productivity from other investigations, macroalgae were implicated as the source of POC in the foam in winter, while phytoplankton provided the POC to foam in summer. Differences in the signatures between DOC and POC also suggested that some DOC may be derived from terrestrial sources. Future work on DOC and POC should be done using at least dual stable isotope analyses to better identify the source materials. McMahon et al. (1990) also used stable carbon isotopic analysis to link bacterial CO_2 to the dissolved inorganic carbon found in Coastal Plain aquifers of South Carolina.

Williams et al. (1992) measured dissolved and particulate organic carbon (OC) fluxes in the Bly Creek basin for a year starting in June 1983. The 34 sampling efforts were designed to capture diurnal, lunar, and seasonal sources of variability and to identify sources and sinks of OC in the basin that is isolated on three sides and has only one opening into the inlet. Inputs to the Bly Creek basin were measured in a small blackwater stream emptying from the forest and included groundwater flux from piezometer stations, but DOC could not be measured in precipitation because birds used the gauges as perches. Mean DOC concentrations leaving the basin varied between 2.5 and 11.8 mg C L^{-1}, being lowest in summer and fall and highest in late winter and spring. This marsh basin exported 1.65×10^{5} kg DOC for the year, with most export during the period January to May. Maximum export was during mid-February to mid-March,

corresponding to times of freshwater runoff as had been seen earlier by Wolaver et al. (1986). Stream input only accounted for about 10% of the total DOC flux from the basin to the inlet, however. Another 10% of DOC flux from the basin could be accounted for by flux from the marsh surface as it drained during ebbing tides, and a smaller flux came from oyster reefs. These researchers could account for less than 25% of the DOC total flux from the Bly Creek basin. Seepage from the marsh and groundwater probably account for the rest, but they also felt that forest runoff, particularly after storms, was inadequately sampled. The estimate for annual import of POC was 2.04×10^4 kg, but the standard error around this mean was larger than the mean, i.e., POC import was probably zero. There was significant import and export of POC when measured over single tide cycles, however. Imports were significant during very high tides, as marsh vegetation promoted settling of POC. Bly Creek is in a younger part of the system, and compared to the whole-marsh exports of carbon, the export of POC relative to DOC becomes less important as the marsh increases in age (Dame and Gardner, 1993).

Wahl et al. (1996) studied organic carbon inputs from three first-order blackwater streams. Two were in suburbanized/residential Murrells Inlet (impounded Gasque Creek and un-impounded Dog Creek) and the third was at the natural forested edge of Oyster Creek in North Inlet, the control comparison stream. Runoff at Oyster Creek was 40% of precipitation and only 26% of rainfall at Gasque Creek. The dynamics of storm flow runoff at the three sites was quite different, primarily because Oyster Creek had a much less steep elevation gradient than the other two drainage basins. Mean DOC concentrations were about twice as high in the forested Oyster Creek where episodic pulsed releases of DOC occurred. The retention ponds of urbanized areas capture the first flush of suburban runoff, while releases from the forest were more gradual. Freshwater storm flow mixes with tidal waters near the outlet of Oyster Creek.

Wahl et al. (1997) measured DOC in drainage from the forested area that runs into Oyster Creek in North Inlet starting in October 1993 until September 1994. This was the pristine control site for a comparative study of drainage and runoff in Dog Creek in urbanized Murrells Inlet 32 km north of North Inlet. Both streams were blackwater. Although total drainage, sediment loads from erosion, septic tank proximity, and a steeper slope prevailed in Dog Creek, mean annual DOC concentration in the urbanized stream was only half as great as in the North Inlet creek. However, the annual load of DOC in the two areas was almost equal simply because of the greater runoff load in Dog Creek. Suspended sediment concentrations were also much higher in Dog Creek. Nutrient loads were also compared between the sites, and nitrate-nitrite nitrogen was 11 times higher in Dog Creek. Nutrient loading there was more or less continuous during the year, whereas the forested site in North Inlet had episodic loadings after rain events. An interesting look at the ionic chemistry of soil in the forest adjacent to North Inlet after it was flooded by storm surge during Hurricane Hugo is provided by Blood et al. (1991).

From April 1994 to July 1995, Aelion et al. (1997) monitored groundwater from wells in both Oyster Creek in North Inlet and in Dog Creek in Murrells Inlet (see Wahl et al., 1997 mentioned above). They also found significantly higher total organic carbon concentrations in the forested Oyster Creek site than in Dog Creek. Denitrification was the major focus of their study.

Bollinger and Moore (1993) measured residence times of water in the upper 10 cm of marsh sediments in North Inlet using radium isotope tracers. Their data suggested that this water has residence times in sediments ranging from less than one hour to as much as 26 hours. Seasonal changes in the storage of organic carbon in the sediments related to bioturbation probably caused a net reduction of radium carrier phases in the marsh sediments during summer.

Data from previous nutrient flux and transport studies served as input to a dynamic budget model of subsystem interactions in North Inlet, in which POC and DOC played significant roles (Childers et al.,1993b). One of the six subsystems, oyster reefs, once again was shown to have significant impacts

on organic carbon removal from the water column. The Stella model provided insights as to how each subsystem (subtidal benthos, oyster reefs, upland forest, marsh surface, nearshore coastal ocean) inter-related constituent-wise with the water column subsystem. Model manipulation of the area covered by oyster reefs and the amount of sea-level rise provided ideas for future research. Spatial variability in fluxes of nutrients emerged as a major concern about what has been missing in the Outwelling and Bly Creek Studies. A need for flux studies in older portions of the marsh (Bly Creek is in a young area of the marsh) would supplement what has been learned from whole marsh studies like the Outwelling Study summarized by Dame et al. (1986).

Goni and Thomas (2000) sampled forest litter, soil, sediments, and plants from three locations along transect D from the forest to the short *Spartina* zone in Crab Haul Creek. Living tissues from the forest samples had the lowest ash content, about 5% by weight. Aboveground *Juncus* and *Spartina* tissues ranged between 45 and 52% OC, while belowground tissues of these plants had between 29 and 43% OC. Forest pine litter samples had depleted C isotope composition, while *Juncus*, a C-3 plant, was enriched, and *Spartina*, a C-4 plant, was most enriched. Among their many findings, the humus fraction contained the largest percent OC in all horizons at all three stations, 60-90%. The macro-organic fraction contained 5-40% OC. The sand fraction always had the lowest, < 5% OC. Based on the isotope signatures and biochemical composition of the various fractions of OC, the authors speculate about the many possibilities regarding the origin of the OC measured at each site. For instance, because the *Spartina* site was probably populated by *Juncus* several hundreds of years ago, some of the isotope depletion found in the deeper belowground core section below *Spartina* now could be from old *Juncus* residue. Or some of the residue could have been mixed downward by storm activity and/or bioturbation. Some of the signal could have come from benthic microalgae or methanogenic bacterial biomass. Isotope studies for carbon must usually be interpreted in light of many possibilities as to the source material, and this study recognizes that there are many possible sources for the organic carbon found in saltmarsh sediments.

Goni and Gardner (2003) sampled groundwater from piezometers seasonally during 1997 and 1998 from the Crab Haul Creek transect D (forest to marsh) used by Goni and Thomas (2000) above. In addition they took surface water samples from the creek and from the mouth of North Inlet. They studied the spatial and seasonal changes in groundwater DOC as related to other geochemical and hydrological data existing for the site. Earlier piezometer data for the transect estimated that groundwater flows from the forest to the marsh at a rate of about 8 m (25 ft) per year (Thibodeau, 1997). DOC concentrations ranged from 6 to 120 mg L^{-1} in the study and were highest in the shallow parts of the aquifer in the forest and declined with depth there. Concentrations were always elevated beneath the *Juncus* vegetation zone. Forest groundwater showed the greatest seasonality in DOC concentrations at any location along the transect or in surface waters in the inlet. DOC levels in Crab Haul Creek (higher at low tide) ranged from 3.3 to 13 and ranged from 3.6 to 9.9 mg L^{-1} in the inlet mouth. Plots of DOC versus salinity illustrated the non-conservative behavior of DOC. The authors discussed the areas where aquifer geochemistry affected DOC levels and the carbon cycle: 1) contrast between surface and deep forest groundwater; 2) mid-marsh seasonal changes; and 3) trends in deeper groundwater along the whole transect. Much of the differences seen could be accounted for by heterotrophic decay that increased DIC levels, with the rest of the losses from sorption and chemical precipitation. DOC sorption processes cause formation of the Spodosol soils common beneath the forest. In the mid-marsh, DOC concentrations increased due to evapotranspiration and possibly tidal recharge. Groundwater upwelling was eliminated as a significant cause of increased DOC levels. They found a deep wedge of saltwater in the aquifer that moved landward in dry periods and seaward in times of high precipitation. Overall, despite uncertainties in their calculations, they estimated that groundwater delivery of DOC could account for about 20% of the annual discharge of DOC from North Inlet to the ocean.

Using the piezometer transect network across the upper reaches of Crab Haul Creek, Cai et al. (2003) sampled groundwater periodically from May 1996 to March 1998. The same transects were used by Gardner and Reeves (2002) and Goni and Gardner (2003). Measurements of various carbon dioxide-relevant parameters were used to dissect the diagenetic processes in this shallow groundwater aquifer. The groundwater ranged in salinity from fresh on the forested edge of the transects to 40 at the marsh-side terminus. Concentrations of the constituents were analyzed using graphical dilution lines that showed how the two end members (fresh, salty) of the mixing zone beneath the sediment interacted chemically. Aerobic decomposition, sulfate reduction, and methanogenesis occur along the transects, all having implications for the amount of dissolved inorganic carbon in the groundwater. Without going into details of these biogeochemical reactions here, their question was whether the highly elevated DIC levels in the groundwater were being delivered to the coastal ocean, either directly or via marsh exchange with the tides, in sufficient amounts that they should be considered in calculations of carbon mass balance for the global ocean. Cai et al. (2003) made several extrapolations (all with high levels of uncertainty) that were reasonable based on the available data and showed that discharges of DIC could be significant. They suggested the need for additional study of how and in what amounts this source of carbon reaches the sea.

Maroney (2005, unpublished) did thesis work on samples collected from the Crab Haul Creek Transect D as well. She cited previous thesis work there by Jones (1999, unpublished) who found that DOC concentrations decreased eastward along the transect and were of vascular plant origin. Maroney's study was done to determine the source and compositional changes of organic matter in groundwater along Transect D. She hypothesized that high molecular weight DOM would degrade as it transitioned into the marsh where it will mix with OM of marine origin. Surface and deep groundwater samples were collected in October, 2000, along with surface water from North Inlet. DOC concentrations decreased with both depth and distance from the forest. Percent OC values decreased from high values in the forest (39%) eastward also. Stable carbon isotope ratios of the OM were depleted in the forest and became progressively more enriched eastward where they were most enriched in the North Inlet water. The major source of high molecular weight DOC in the forest region was C-3 plants. This material was still present in the marsh but contained OM of marine origin from tidal mixing. In North Inlet both total DOC concentration and % OC of high molecular weight material were significantly higher than in Crab Haul Creek.

Bernot et al. (2008) measured stable carbon (*del-*^{13}C) isotopes in *Spartina alterniflora*, surface and deep sediment in experimental fertilized plots in North Inlet. They were enriched in the plant and in surface sediments relative to control, unfertilized plots. Thus the stable carbon isotope signature changed as the nutrient status of *Spartina* changed.

Chow et al. (2012) studied the biogeochemistry of the Crab Haul forested area landward and westward of Crab Haul Creek in North Inlet. Their analyses of DOC in the cypress-tupelo wetland found high concentrations in October before the litterfall began in December. The relatively dry period between August and September was when nutrients accumulated prior to the late September rains which release the DOM from detritus layers. DOC concentration increased after the precipitation, from 15 to 42 mg L^{-1}. Later in the year (October into March) precipitation served to dilute DOC concentrations in surface waters of the wetland. Their calculations suggested that fresh litter is a major source of DOC, while old decomposed duff litter is a source of nitrogen. Although runoff from the forest into North Inlet is not large compared to tidal flows, it is still important to understand how sources of dissolved carbon generate material that flows into the inlet.

Dissolved, particulate, and inorganic forms of carbon cycle within and through North Inlet. DOC concentrations are higher during low tides and seasonally during winter and spring. Overall, DOC is exported to the ocean along with a net export of POC. DOC concentrations are higher during El Niño (higher precipitation) years and lower during years

of drought. The surrounding forest is a significant source of both DOC and DIC. Long-term, DOC concentrations have declined in North Inlet since 2004. Oyster reefs and the marsh surface are both sinks for POC and sources for DOC. Older portions of the marsh process carbon differently than younger portions closer to the forest.

» Contaminants

An important part of water quality concerns anthropogenically-produced substances that are dissolved in it or associated with its suspended particulates or bottom deposits and porewater. Many different types of pollutants exist (inorganic and organic) and they are input to receiving waters in varying amounts from a variety of sources, some easily identified (runoff flowing through pipes onto the beach – point source), some indistinct and widespread (aerial deposition, nonpoint source runoff from forests, pasture land or agricultural fields). Some contaminants will simply be diluted by the receiving waters, while others may undergo chemical changes or may become incorporated to some extent in sediments. A body of water having contaminated sediments is more likely to have poor water quality.

This section summarizes studies that have measured contaminants in North Inlet, used North Inlet as a baseline to compare with anthropogenitically impacted estuaries, or used sediments and/or organisms from North Inlet in contaminant experiments. Laboratory bioassays are used to test various contaminants for their potential effects on marine and estuarine organisms. Although direct extrapolation of laboratory results to the field situation is usually fraught with uncertainties, having pristine sediments and organisms available from North Inlet makes such studies possible. These baseline studies will become even more relevant for decision makers charged with managing the course of future coastal development because they highlight some of the possible impacts of potentially harmful or unsustainable contaminant management practices in the coastal zone. Comparative studies using North Inlet's fauna, sediments or other assets in a control capacity also serve to remind us of the importance and value of the National Estuarine Research Reserve program in providing empirical, science-based data as guidance for these management practices.

Because North Inlet has the designation of being a relatively pristine coastal salt marsh habitat, it is attractive to use as a control, or unpolluted, sampling site for comparison with other similar coastal habitats that are proximal to urban and industrial development. Sanger et al. (2008) sampled coastal sites from North Carolina to Georgia in a comprehensive assessment of all types of pollutants that can be found in this stretch of the southeastern (U.S.) coastline. They sampled both intertidal and subtidal systems for a wide variety of water quality and contaminants measures in sediments and biota. Amongst the 19 areas sampled, North Inlet was clearly an outlier in that very few contaminants were found to be present at Clambank and in Town Creeks, the only two sites that were sampled in 2005. Thus it is accurate to state that North Inlet, with its predominantly forested watershed, is relatively pristine. The area does, however, contain many contaminants, but most are in quite low concentrations, at or below detection limits. The challenge, then, is to ensure that the NI-WB NERR remains in this relatively pristine condition in the future, even as quantitative analytical detection methods become more sensitive.

North Inlet is unique in that few and/or low amounts of these potentially toxic substances have been introduced to its waters. Fecal coliform bacteria in North Inlet come almost entirely from animal wastes in runoff from the surrounding forest or possibly from birds, as septic tank discharges are minimal. Hydrocarbons from recreational boat traffic are present in low quantities. Winyah Bay, however, receives municipal, agricultural and industrial wastes and as such has been monitored for pollution loads more regularly than North Inlet. Much of the work on pollution in North Inlet has been performed using this relatively pristine site as the reference or control (unpolluted) site, for comparison with other urbanized, but otherwise similar, sites of interest. Vernberg et al. (1992)

report a concise overview of trends in some comparative studies of pollution (primarily PAHs and metals) between Murrells Inlet and North Inlet as a reference site. This was part of the Urbanization of Southeastern Estuaries Study, or USES. Porter et al. (1996) provide details about how such comparative pollution data (between North and Murrells Inlets in their example) can be input to a Geographic Information Processing program to model how urbanization impacts coastal estuaries. Their model used data on nonpoint source inputs, the area of wetlands alterations, vegetation, and oyster recruitment. Porter et al. (1997) also used GIS to provide a management-useful overlay of comparative grass shrimp abundances. This sentinel organism is much more abundant in North Inlet, presumably because of development's impacts on Murrells Inlet tidal creeks. The difference in census sampling of both inlets is startling, as 10% of the areas sampled in Murrells Inlet had no grass shrimp at all and 90% of the North Inlet areas sampled had higher abundances than the highest numbers found in Murrells Inlet.

Further emphasizing differences found between developed and pristine coastal marshes, Weinstein (1996) reviewed anthropogenic impacts on salt marshes, including dredging, contaminants (insecticides, herbicides, heavy metals, trace elements, dioxins, polycyclic aromatic hydrocarbons (PAHs), and polychlorinated biphenyls (PCBs)), oil, marina and boating impacts, eutrophication, pathogens, and marsh creation/restoration/mitigation. This is a good overview of the salt marsh pollution literature, most of which is directly relevant to the southeast coast of the U.S.

Blood and Vernberg (1992) provide an overview of pollutants that covers data collected from 1970 to 1985. Information on heavy metals (arsenic, cobalt, lead, zinc, mercury, cadmium, copper, nickel, chromium), dozens of different pesticides, and coliform bacteria are provided there. Most of their information is for Winyah Bay. As they reported, North Inlet's *E. coli* loads were mostly much lower than the acceptable upper limit allowed for shellfish harvest (> 200 colonies per 100 ml), and only a few water samples from North Inlet close to Winyah Bay exceeded that limit. An early study of bacterial contamination in North Inlet by Scott and Lawrence (1982) also found total coliforms and fecal coliform numbers were very low.

The South Carolina Estuarine and Coastal Assessment Program (SCECAP) from 1999-2004 found that coliform bacteria does not pose a problem in the middle sections of North Inlet based on its two sample sites in/near Old Man Creek. The SCDHEC Shellfish Sanitation Program (SSP) 2007 Annual Update Report for Area 05 (North Inlet and Winyah Bay areas) has affirmed this from their Jan 2004 – Dec 2006 data, by classifying the region as an *Approved Area* (Stations 05-12 & 05-14, Figure 40) (Warren, 2007). This means that fecal material, pathogenic microorganisms, and poisonous or deleterious substances are not present in concentrations which would render shellfish unsafe for human consumption. The whole of North Inlet supplies habitat for a large shellfish resource, and there are 15 long-term monitoring sites throughout the estuary to regulate it (Figure 40). The SSP 2007 Annual Update Report classified the upper and lower most sections of North Inlet as *Restricted Areas*; shellfish harvesting is not allowed, except by special permit (Warren, 2007). Waters of a *Restricted Area* contain deleterious or poisonous substances to a degree which may cause the water quality to fluctuate unpredictably, and therefore, pose a human health. The lower North Inlet estuarine stations: 05-01, -05, -06, -07, -09 and the upper station -13 have remained a *Restricted* shellfish classification since Jan 1998, with sites's -05, -06, and -07 shellfish and water quality classification consistently being rated *Restricted*. In the late 1990s, stations -02, -08, and -16 had consistent *Approved* water quality and shellfish ratings; however, starting in Jan 2001, they became "borderline" stations, where water quality ratings remained *Approved*, but the shellfish rating remained *Restricted*. This was due to the unpredictable fluctuation of the water quality in these areas.

No substantial changes in pollution sources had occurred in the North Inlet section of Area 05 since the SSP 2000 Annual Update Report (data review dates: Jan 98 – Dec 2000). However,

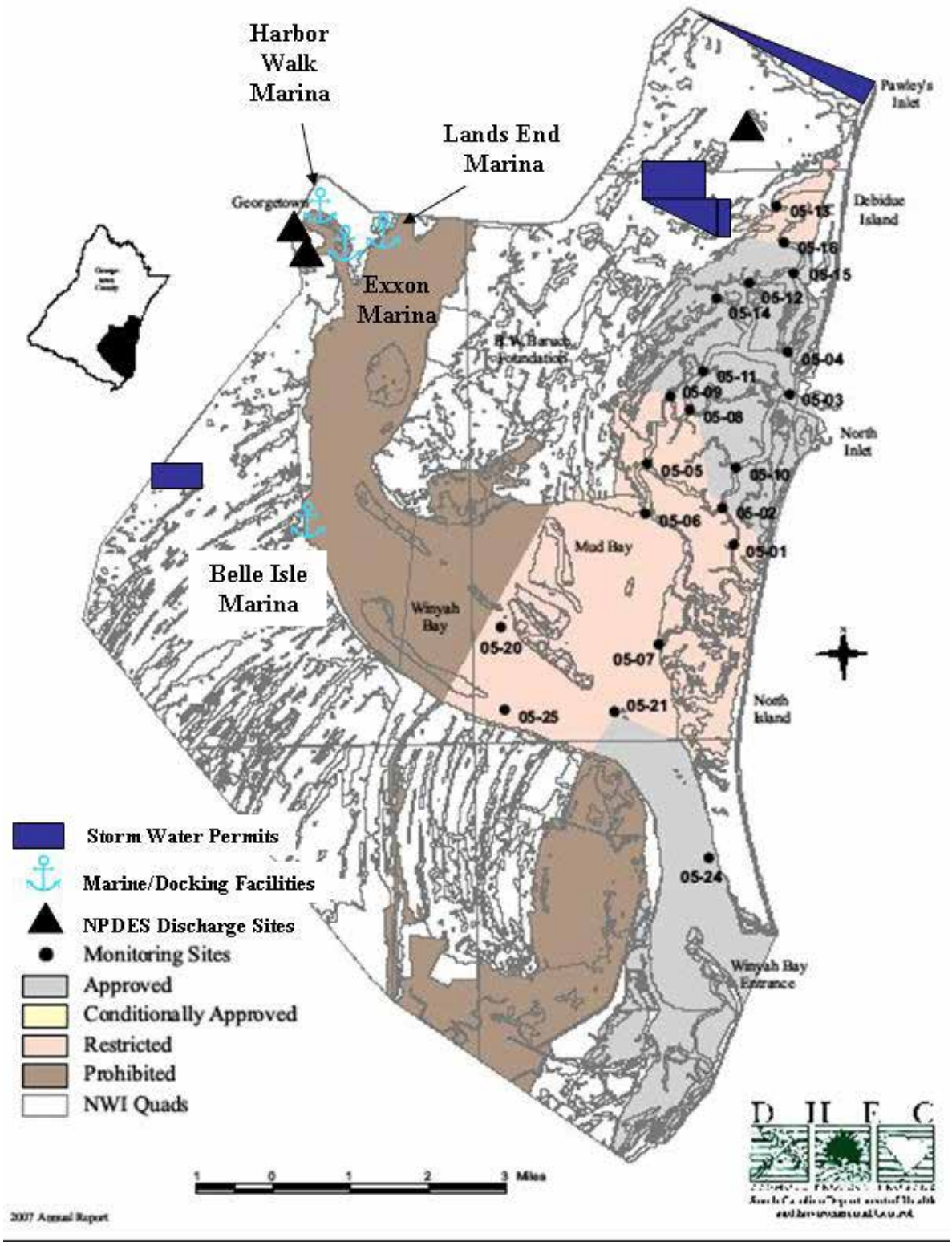

Figure 40. 2007 shellfish management classification for Area 05 (North Inlet and Winyah Bay). Monitoring stations and potential pollution sources impacting shellfish harvesting are also indicated. NPDES discharge sites = National Pollutant Discharge Elimination System sites. Map and assessments are from SCDHEC Shellfish Sanitation Program (SSP) 2007 Annual Update Report for Area 05 (Warren, 2007). Figure is a modified version of the original SSP 2007 base map.

from Jan. 1998 through Dec. 2006, violations of shellfish water quality criteria within North Inlet were and continue to be primarily attributable to nonpoint pollution sources from river flooding into Winyah Bay, as well as, rainfall-induced runoff from natural and engineered systems that drain the surrounding highlands that support substantial wildlife populations, golf courses, and residential developments (Warren, 2007). River flow into Winyah Bay and subsequently into Mud and Oyster Bays adversely impact the water quality in the southern portions of North Inlet. Hydrographic and meteorological conditions, such as strong southerly-southwesterly winds combined with high river flows, complicate water quality predictions and increase the area of intermixing between North Inlet and Winyah Bay/Mud Bay.

DeBordieu Colony, adjacent to the upper (northern) portion of North Inlet, has its own domestic wastewater treatment facility (NPDES #ND00656668) maintained by Georgetown County Water and Sewer District (GCWSD). This facility is in close proximity to waters suitable for the direct harvest of shellfish (Figure 41). Even though this facility utilizes a high degree of treatment, it sprays its effluent onto its forest floor and golf courses. The Colony also has a fairly high degree of residential development and golf course maintenance, and its stormwater, containing various chemical compounds, is "stored" onsite in upland ponds and brackish water impoundments near Debidue Creek. This creek's water quality is highly variable and appears to be impacted by freshwater discharges from these upland ponds. To address this water quality issue, an additional NPDES Permit (SC0048984) was approved in 2010 that enables GCWSD to divert excess treated effluent from DeBordieu Colony in the North Inlet watershed to the Waccamaw River. To the west of North Inlet, ditches from the Belle W. Baruch Foundation property drain uplands and lowlands that contain substantial wildlife populations, such as deer, hogs, raccoons, and squirrels, that potentially could add to the fecal coliform counts; however, the flow rates appear to be substantially less at these sites than at the main culverts along the northern portion of the estuary (Warren, 2007).

Hurricanes and large rainfall events are other causes for shellfish area closures. Whenever a National Weather Service Hurricane Warning is issued, all open areas within the warning area are immediately closed to harvest. These precautionary closures remain in effect pending an evaluation of storm-related pollution impacts. Areas will be reopened when the Department determines that conditions are acceptable for the sanitary harvest of shellfish. Open shellfish areas are also closed upon actual receipt of a 24-hour rainfall total of 4.0 inches or more. Shellfish water quality monitoring stations within the area are sampled for fecal coliform bacteria levels prior to re-opening.

A review of SC Shellfish Program classification data for the 1986 through 2005 annual shellfish reports (data through 2004) indicates relative stability in terms of acreage within individual classification types (Newell, 2006). However, for the 2005 report year (2002 through 2004 data), a moderate decrease from 2004 *Approved* classification acreage was observed; approximately 1300 acres in Georgetown County were reclassified from *Approved* to *Restricted* (Newell, 2006). In general, these reclassifications were due to the influences from rainfall runoff and/or river flow.

NORTH INLET WATER CLASSIFICATIONS

The classification and standard regulation of specific water bodies in North Inlet is found in South Carolina Regulation 61-69 (Bureau of Water, 2006); the Regulation describes waters' desired uses and specific standards for protection. Water quality standards are used to classify and regulate pollution decisions of SC waters; these standards are found in Regulation 61-68 and are based on 1) the character of the body of water and surrounding land, 2) current or future use of the waters and its water quality, and 3) the levels of seven types of pollution (including but not limited to refuse, toxic wastes, fecal coliform, pH, and temperature). The classifications are based on desired uses and not on natural or existing water quality. They are the legal means used to obtain the necessary treatment of discharged wastewaters to protect designated uses. No degradation of existing uses is permitted regardless of classification and no degradation

of natural conditions is allowed in *Outstanding Resource Waters* (*ORW*). The upper most and middle water bodies of North Inlet are classified as *ORW* and/or *Shellfish Harvesting Waters* (*SFH*) (Figure 41). *ORW* are waters that receive the highest level of protection because they have an exceptional recreational or ecological importance or value. These types of waters include waters in parks or wildlife refuges, waters supporting endangered or threatened species, waters known to be significant nursery areas for commercially important species or waters which are used for scientific value or study. *SFH* is tidal saltwater protected for shellfish harvesting (oysters, clams, and mussels). This class has the strictest bacteria standard because people often eat shellfish raw. These waters are also suitable for uses listed in Classes *SA* and *SB*. The lower reaches of North Inlet influenced by Mud Bay are listed as Class *SB* waters (Figure 41). Class *SA* water is tidal saltwater suitable for primary and secondary contact recreation, crabbing, and fishing, except harvesting of clams, mussels, or oysters for market purposes or human consumption. These waters are also suitable for the survival and propagation of balanced indigenous communities of marine fauna. Class *SB* water has the same criteria as *SA* waters, except for the levels of dissolved oxygen (DO). Daily DO average for *SA* waters must not be less than 5.0 mg/L, with a minimum or 4.0 mg/L, and for Class *SB* waters, DO daily average must not be less than 4.0 mg/L.

Figure 41. Classification of water bodies in North Inlet based on Regulation 61-69 (Bureau of Water, 2006). Classes: Outstanding Resource Waters = ORW, Shellfish Harvesting Waters = SFH, and Class SB = see text above for definition

POLYCHLORINATED BIPHENYLS

The earliest study of polychlorinated biphenyls (PCB) toxicity using North Inlet fauna was conducted by Vernberg et al. (1977a) on newly-hatched swimming larvae of the common marsh fiddler crab, *Uca pugilator*. These investigators were among the first to test PCBs on non-adult marine life forms. LC_{50} (96-hr) concentrations were between 5 and 50 ppb for the larvae, and Aroclor 1254 was generally more toxic than Aroclor 1016. Adults were much less susceptible to Aroclor than larvae. The experiments with interacting temperature and salinities were difficult to interpret because of high variability in survivorship. Vernberg et al. (1978a) measured respiration with a Gilson respirometer on adult fiddler crabs (males and females from Clambank Landing) exposed to sublethal concentrations of the PCBs Aroclor 1016 and 1254. Over a range of temperatures from 10 - 35 °C, *Uca pugilator's* metabolic responses were basically unaffected by exposure to these PCBs.

Harpacticoid copepods are ubiquitous small crustaceans near the base of the food chain eaten by many estuarine-dependent larval or juvenile fishes, shrimps, and crabs. An abundant harpacticoid species from intertidal creeks in North Inlet, *Microarthridion littorale*, was tested with various concentrations of a sediment-associated PCB called Aroclor 1254 by DiPinto et al. (1993). Ninety-six hour exposures found 50% of the animals dead at concentrations of 251 mg kg^{-1} for females, but only at 117 mg kg^{-1} for males. Reproduction in this copepod was impaired at a very low concentration, 4 mg kg^{-1}, of Aroclor 1254. Chandler (1986) had earlier proposed a standard procedure for collecting sediments in North Inlet used to culture harpacticoid copepods in studies of various

contaminants in their sediment-associated phase to which these crustaceans are susceptible.

A trophic transfer study of polychlorinated biphenyls (Aroclor 1254) from sediments to benthic copepods to bottom-feeding juvenile estuarine fish was conducted by DiPinto and Coull (1997). Fish fed clean copepods in contaminated sediments accumulated about 5X more PCB than fish fed contaminated copepods in clean sediments from North Inlet. The fish (spot, *Leiostomus xanthurus*) eats these meiobenthic copepods naturally, but the time course of these experiments, just one feeding bout, was too short for PCB elimination to equilibrate their body burdens over longer periods of time as would occur in nature. The octanol-water partitioning coefficients of the different PCB congeners played a significant role in the short-term results obtained.

TRACE METALS

Sauer and Watabe (1984) collected juvenile mummichog (*Fundulus heteroclitus*) from North Inlet and took them to Columbia, SC, for a study of zinc uptake into the fish's scales. Animals were kept in aquaria dosed with 0.1, 1.0 and 10.0 mg $ZnCl_2$ for up to 10 weeks and then sacrificed. They found Zn in the calcified region of the scale and suggested that this metabolic uptake was a detoxification mechanism. Sauer and Watabe (1988) demonstrated the inhibitory effects of Cd and Zn on calcium uptake by mummichog gills. Sauer and Watabe (1989) then examined the effects of Zn on scale formation in this fish.

Cadmium toxicity to the fiddler crab, *Uca pugilator*, was lethal when concentrations of 110 micrograms per gram in gill tissue were reached (O'Hara 1973a). Accumulation of cadmium by the crab was greatest at high temperatures and low salinities (O'Hara 1973b).

Hutcheson (1974) exposed adult blue crabs, *Callinectes sapidus*, to aqueous solutions of cadmium chloride at several different temperatures and salinities. Uptake and concentrations were highest at low salinities and higher temperatures, with hepatopancreas, gill, and carapace tissues having the highest concentrations. Claw muscle did not accumulate cadmium to an appreciable extent.

Vernberg et al. (1977b) set out to establish a uniform bioassay procedure for sublethal concentrations of cadmium with male adult grass shrimp, *Palaemonetes pugio*, from North Inlet. Uptake of Cd was proportional to salinity at 25 °C and more was taken up under flow-through conditions. Molting frequency was stimulated at low concentrations and inhibited at higher levels. Respiration rates were variably higher in the flow-through system as well. It was concluded that *P. pugio* was too hardy an organism to use in bioassays.

Mirkes et al (1978) found deleterious effects of cadmium and mercury on the development rate, survival, and swimming speeds of larval mud crabs, *Eurypanopeus depressus*. However, there were differential effects depending on which larval stage was tested with which element. For instance, swimming rate was stimulated by cadmium but depressed by mercury, and cadmium was more toxic to some stages than others.

The North Inlet standard sediment from Bread and Butter Creek was used to measure the effects of cadmium on a meiobenthic copepod in laboratory cultures by Green et al. (1993). Three phases of Cd were prepared: aqueous, sediment, and porewater. Each was presented to copepods over a range of concentrations with appropriate sham treatments as controls. The copepod, *Amphiascus tenuiremus*, was most sensitive to the aqueous phase as measured by LC_{50} values. The sediment-associated phase was least toxic. Reasons for such

The copepod, *Amphiascus tenuiremus.*

reduced acute toxicity may have had to do with the digestive tract chemistry of the copepod.

Cadmium's sublethal effects on an abundant burrowing brittlestar, *Microphiopholis gracillima*, in North Inlet were studied by D'Andrea et al. (1996). Echinoderms are infrequently used in marine toxicology studies. Because this animal lives in sediments and normally regenerates tips of its arms that are lost to predators, regeneration measures were used as a physiological assay for effects of cadmium exposure administered to animals in small aquaria. Newly regenerated arm tips were thinner in Cd treatments than those of controls and uptake of cadmium by the animal's calcium carbonate exoskeleton was proportional to the Cd exposure levels tested. Cd adversely affected arm regeneration which would have negative consequences for recovery from tissue loss and survival in the field.

Vernberg and O'Hara (1972) measured the uptake of mercuric chloride in the fiddler crab, *Uca pugilator*, under six temperature-salinity regimes. Mercury toxicity was greater at lower temperatures, and gills transferred Hg to the hepatopancreas more effectively at higher temperatures.

In a comparative study between Murrells Inlet and North Inlet in 1997, oysters were collected and analyzed for methylmercury and total mercury, Hg (Kawaguchi et al. 1999). All but one of the 31 oyster samples from throughout Murrells Inlet were below detection limits for total Hg (<0.1 microgram per gram wet weight). They found 109 micrograms/g in a composite tissue sample in the heavily urbanized north end of Murrells Inlet. All 9 North Inlet samples were below detection limits. However, the more sensitive method used to detect methylmercury was able to detect similar nanogram levels of total mercury in both estuaries. Methylmercury levels were the same in both inlets as well, at about 10 nanograms/g. About half the Hg present in oysters was in the form of methylmercury, and concentrations were about 50% above the national average found in the Mussel Watch Program at the time.

Guentzel and Tsukamoto (2001) measured total and methylmercury in Winyah Bay and North Inlet using "clean protocols" in October 1999. In North Inlet they were interested in the degree to which microbial processes transform inorganic divalent mercury to organic or methylmercury and how much is evaded from the water column to the atmosphere. They used several antibiotic treatments to stop microbial activity and a photosynthesis inhibitor (DCMU) in creek water samples. Abiotic formation of gaseous Hg accounted for about 25-33% of the total evasion rates measured. In Winyah Bay, colored water (essentially DOC) was found to scavenge mercury and is the carrier phase for this element in the estuary. Total Hg declined along the axis of Winyah Bay with increasing salinity. Using data from Kawaguchi et al. (1999), they computed log bioconcentration factors (from water to tissues) in oysters in North Inlet that ranged between 5.0 and 5.1 for total Hg and between 5.7 and 6.0 for methylmercury. Formation of elemental Hg in North Inlet was due either to microbial activity and/or is linked to the light/dark cycles of photosynthesis, probably by blue green algae. Because microbial formation of elemental mercury in the water column reduces the total amount of substrate available for conversion to methylmercury, future studies should examine the role of the microbial food web in mercury cycling dynamics.

Most of South Carolina's lakes, streams, and estuaries have a mercury advisory warning about the danger of eating mercury-contaminated fish (Figure 42). In 2007 all rivers in Georgetown County were under "a fish consumption advisory" (Bureau of Water, 2007). The recommended type of fish and serving size depended upon where the fish was caught. Details are available online at http://www.scdhec.gov/FoodSafety/FishConsumptionAdvisories/. Certain sizes for some species and other species, no matter their size, should not be eaten from any SC bay, estuary, or coastal waters.

Results of the 2002-2006 annual North Inlet National Atmospheric Deposition Program (NADP) chemistry analysis includes mercury and other ions related to water quality (Figure 43a). K, Mg, Ca ranged in deposition amounts less than 3 kg/ha/

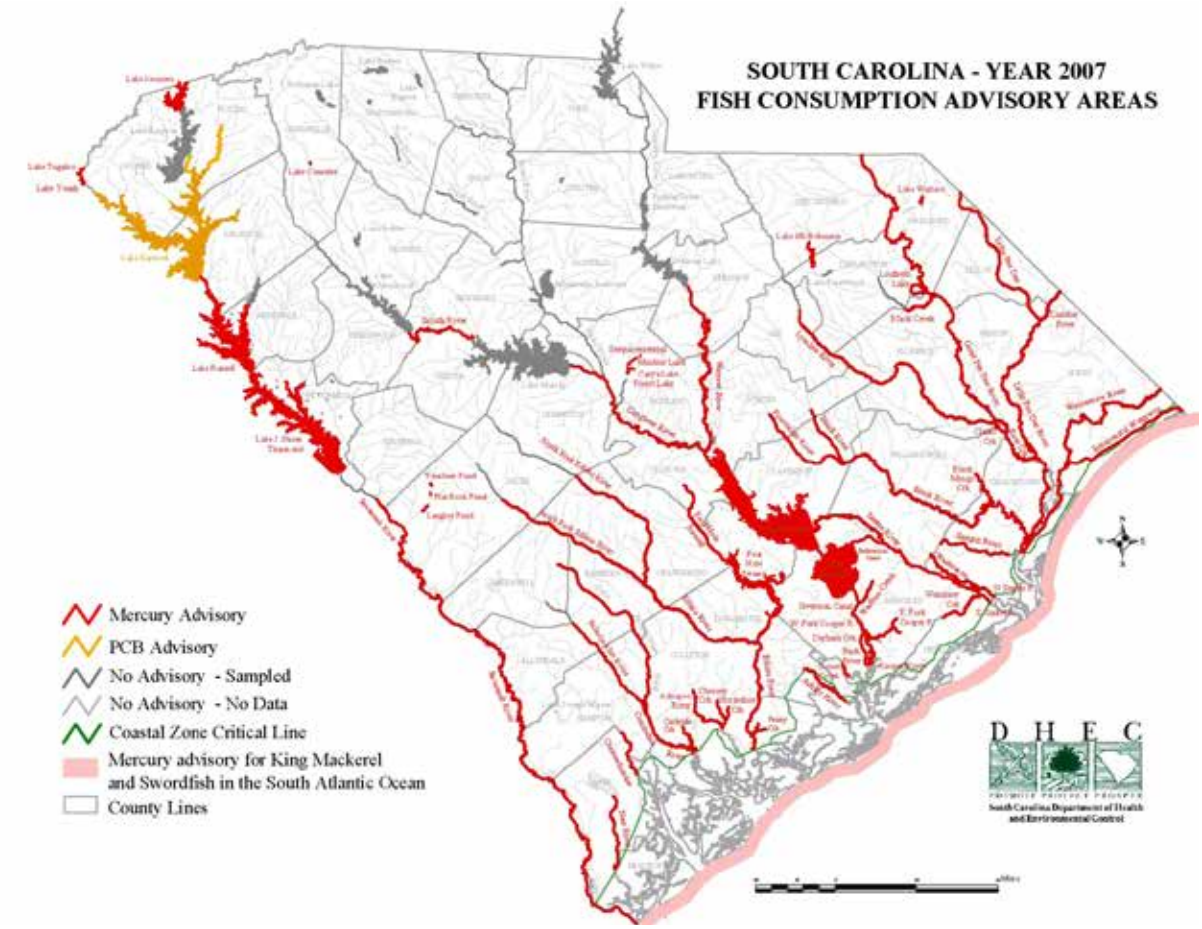

Figure 42. South Carolina 2007 Fish Consumption Advisory Areas. Map derived from SCDHEC online website: http://www.scdhec.gov/environment/water/fish/map.htm.

yr, while Na, and Cl values ranged from 10-45 kg/ha/yr. Ozone and acid rain causing chemicals (NH_4^+, NO_3^-, and SO_4^-) increased in levels in 2003 (Figure 43b). Deposition levels are related to the amount of rainfall (concentration x rainfall), and 2003 & 2005 were unusually rainy years. 2006 had the lowest total rainfall of the span of years. Mercury, as measured in the nearby Cape Romain National Wildlife Refuge, rarely had weekly deposition levels over one µg/m^2 from March 2004 through April 2007 (Figure 44). Atmospheric mercury levels can vary greatly depending on the location. And according to 2006 values, it appears that North Inlet and Winyah Bay are exposed to low to moderate levels of mercury in comparison to the rest of the east and gulf coast (Figure 45).

HYDROCARBONS AND PAHs

Sanders (1995) compared the concentrations of PAHs in sediments and oysters in a comparative study between urbanized Murrells Inlet and North Inlet as a control. Thirty sites were sampled in each estuary. In Murrells Inlet the highest PAH concentrations in composite samples of oyster tissue were found in animals collected near marinas, high density residential areas, commercial enterprises, or storm-drain runoff. A similar concentration gradient from the more urbanized northern end of Murrells Inlet to its mouth was found in the top 3-5 cm of the sediment samples collected – highest in the tidal creeks and lowest near the mouth of the estuary. Sediment PAHs were not the same as the lower molecular weight, more soluble fractions accumulated by the oysters. Similar gradients in sediments or oysters did not exist in North Inlet.

A more comprehensive comparison of PAHs and trace metals between Murrells and North Inlets was reported by Fortner et al. (1996). Over 30 stations were sampled in the two inlets where

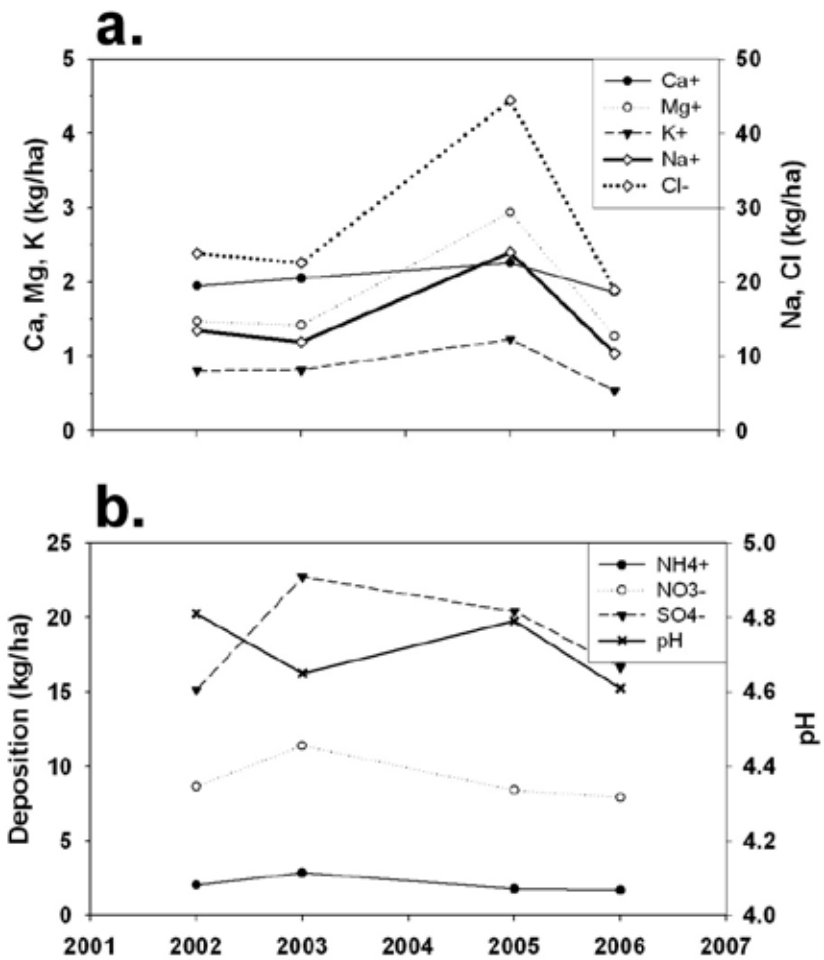

Figure 43. Annual deposition rates for NADP chemistries in North Inlet.
Note: missing data for 2004. Rates are measured in kg/ha.

oysters and sediment were both collected at each station in November 1990. Ten different PAHs and 7 trace metals were analyzed in the samples. Between 30 and 60 oysters were homogenized for the chemical assays. Mean PAH levels were in the 100 nanogram per gram dry weight of sediment level in North Inlet and were significantly higher in Murrells Inlet sediments at just over 500 ng/g. There was wide variation in oyster tissue PAH levels in both inlets. Fluoranthene and pyrene comprised more than 50% of the PAHs found in Murrells Inlet, and the number of PAH compounds found per sample ranged from 4 to 10, depending on station. North Inlet oyster PAH levels were also variable but averaged significantly lower (71 ng/g dry tissue weight) than in Murrells Inlet (452 ng/g). Trace metal sediment concentrations were likewise highly variable (about 10-fold) in both inlets but averaged higher in North Inlet than in Murrells Inlet. This difference suggested there was little anthropogenic input of trace metals in Murrells Inlet. Oyster trace metal levels were variable

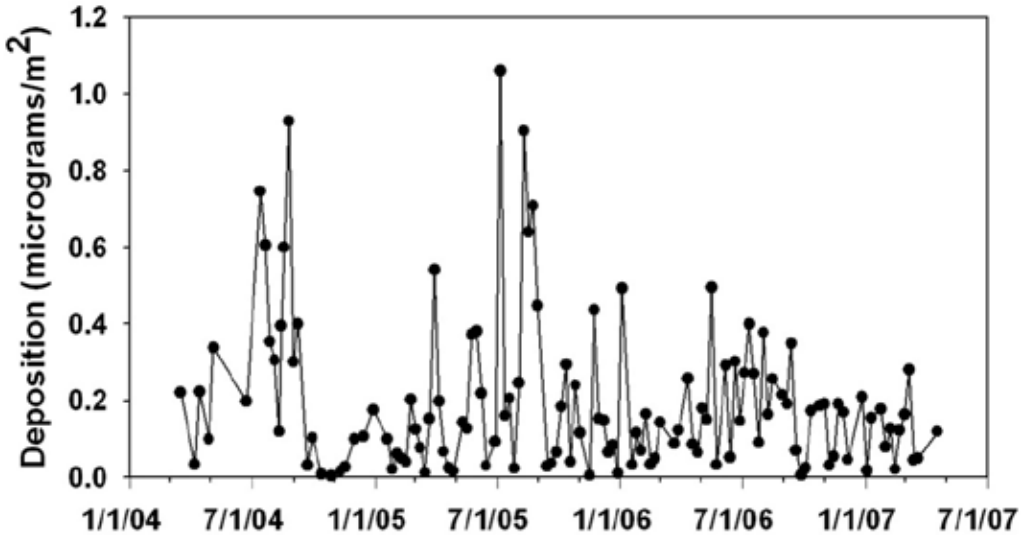

Figure 44. Total weekly deposition rates for mercury (Hg) from the Mercury Deposition Network (part of NADP) in the nearby Cape Romain National Wildlife Refuge. Rates are measured in µg/m^2.

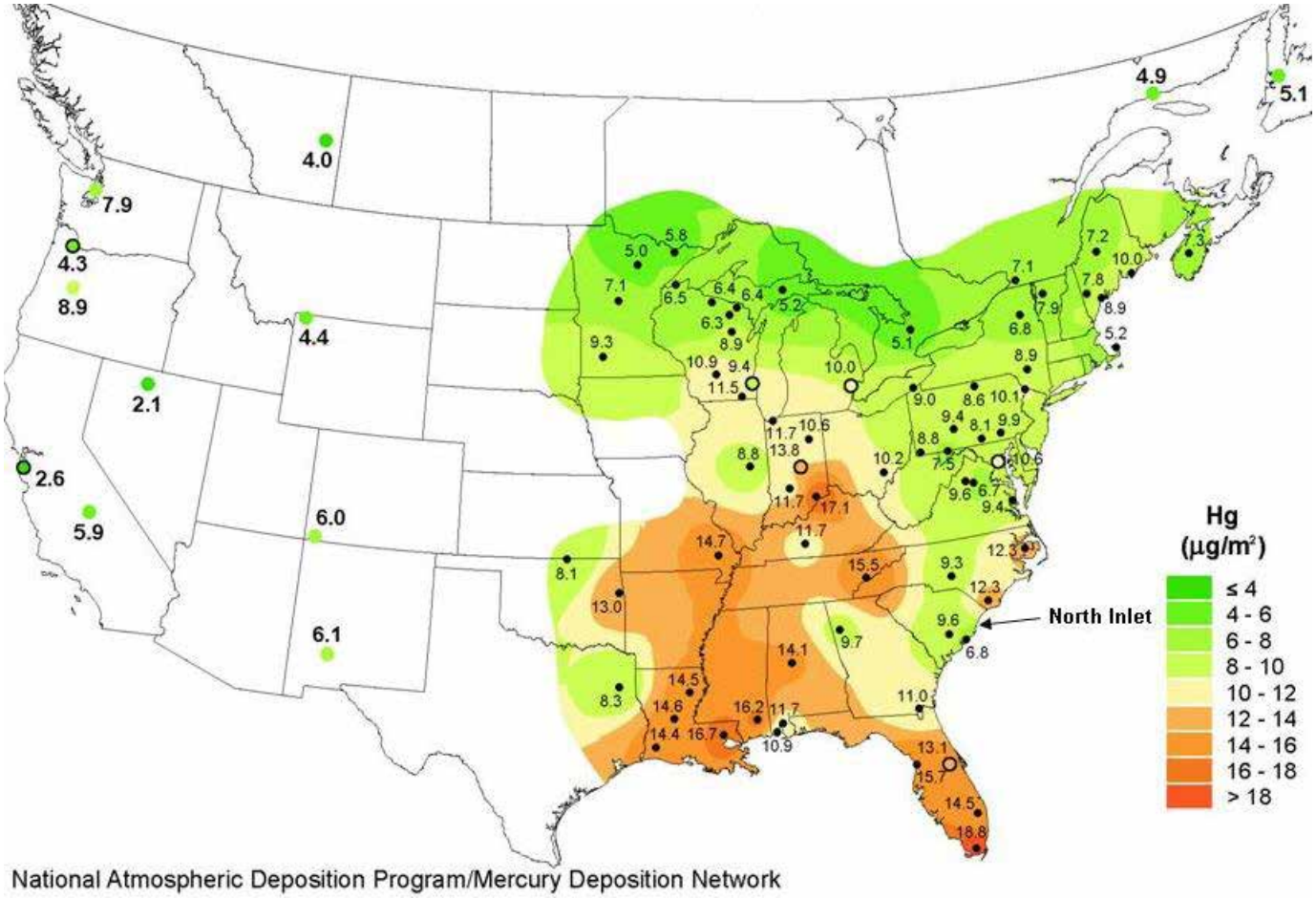

Figure 45. Total mercury wet deposition for 2006.

and significantly higher in Murrells Inlet, ranging from 560-3100 micrograms per gram dry tissue in Murrells Inlet and from 450 to 2600 in North Inlet. No lead or tin was found in North Inlet oysters. Zinc was most commonly found in North Inlet oysters. Some additional comparisons with other coastal estuaries were made, including Charleston Harbor.

Additional comparative studies between Murrells and North Inlets that focused on the effects of PAHs on oysters were done by Weinstein (1995). He examined changes in PAH body burdens and in the mixed-function oxygenase (MFO) system (cytochrome P_{450} and others) as indicators of pollution stress. These were monitored quarterly for a year at Clambank Creek in North Inlet, and at two sites in Murrells Inlet. MFO components were lowest in North Inlet in October 1993. PAH tissue levels were always higher in Murrells Inlet oysters, often as much as 40 X higher. Seasonal changes in the MFO system were suggestive enough that they may have potential as biological indicators of hydrocarbon impact. Histological differences between the oysters in Murrells Inlet and North Inlet were reported by Weinstein (1997) who found that thinning of the oyster's digestive epithelium is an indicator of fluoranthene exposure in this mollusk.

Chandler et al. (1997a) cultured a common member of the North Inlet macrobenthic community, a polychaete worm (*Streblospio benedicti*), and measured its reproduction under spiked concentrations of six PAHs most often found in Murrells Inlet sediments. This worm is well-known to be pollution tolerant and in these studies suffered no ill effects on mortality or weight gain

after as much as 18 days of exposure. However, their vitality declined dramatically from days 18-27 in the fluoranthrene treatments as this PAH accumulated in the worm's tissues.

Fulton et al. (1996) performed yet another comparative study between Murrells Inlet and North Inlet, the reference site. They used *in situ* bioassays, bioaccumulation in oysters, and field population studies to assess the impacts of nonpoint source pollution. Trace metals and PAHs were the focus of their studies. It should be noted that in these types of studies, results are correlative, as no direct cause and effect manipulative field experiments were performed except for the mesocosm lab studies that used contaminated sediments from Murrells Inlet. However, measuring performance of the same organisms in control and test sites certainly can point to differences in the habitat in each and can help identify additional types of studies needed to isolate causative factors. Highlights of their comparison-site findings included no differences in survival of grass shrimp or mummichogs in the *in situ* bioassays, greater accumulations of PAHs in the Murrells Inlet oysters that were translocated to the test site from a distant estuary, reduced growth in sheepshead minnows in Murrells Inlet, reduced numbers of grass shrimp in Murrells Inlet, and reduced molting of meiobenthic copepods exposed to sediments from Murrells Inlet. Murrells Inlet, the urbanized site, clearly had higher levels of contaminants than North Inlet. Variations on this study were also published by Fulton et al. (1993).

Another study of PAHs in municipal runoff by Ngabe et al. (2000) also used North Inlet tidal creeks as their relatively uncontaminated control area that receives these pollutants only from atmospheric deposition and boat traffic. Wirth et al. (1998) used sediments from North Inlet to test PAH toxicity on laboratory cultures of grass shrimp (acute LC_{50} tests) and on a benthic copepod (sublethal reproduction tests). These tests used PAHs commonly found in Murrells Inlet. Sanger et al. (1999) made extensive comparisons of organic contaminants in sediments (e.g., PAHs, PCBs, DDT) of South Carolina tidal creeks, including Crabhaul Creek in North Inlet.

Kovatch et al. (2000) measured the toxicity of PAH- and metal-contaminated sediments to a meiobenthic harpacticoid copepod, *Microarthridion littorale*. They compared the effects of sediments from three locations, with North Inlet being the least contaminated site compared to an Environmental Protection Agency Superfund site (Diesel Creek) and an abandoned shipyard site (Shipyard Creek) in Charleston Harbor, SC. Although contaminated sediments reduced adult survival and reproductive success of the copepod, none of the effects could be related to genetic differentiatons at the population level.

Vo et al. (2004) compared the effects of PAH toxicity on a harpacticoid copepod in culture using sediments from both North Inlet (control) and Murrells Inlet (PAH contaminated). PAHs undergo photolysis when exposed to sunlight, and the degradation products of PAHs may have different toxicities than the intact molecules. Most bioassays using PAH-contaminated sediments are done indoors, so these investigators exposed their test organisms to sediments with and without ultraviolet light exposure to simulate natural outdoor exposure conditions. The contaminated sediments under UV exposure were more toxic to the copepod than those not undergoing photoinduced PAH toxicity. Survival was always higher using North Inlet sediments, whether exposed to UV or not. The authors then developed a model to calculate that 8-16% of the area suitable for meiobenthic copepods in the northern portion of Murrells Inlet was in jeopardy due to increased PAH toxicity from UV exposure.

Another study of light-induced toxicity with the PAH fluoranthene was done by Southerland and Lewitus (2004). Natural phytoplankton communities from North Inlet and Murrells Inlet were exposed to this compound, as were cultures of a benthic green microalga, *Ankistrodesmus sp*. Xanthophyll pigment responses suggested that phytoplankton from Murrells Inlet that were already exposed to higher PAH levels were more susceptible to UV-enhanced fluoranthene toxicity than those from North Inlet.

Li et al. (1990) dosed tall *Spartina alterniflora* taken from North Inlet using PVC cores with a 1x and a 10x chronic (daily) exposure to a modified crude oil mixture for two years in a greenhouse. The cores

were fertilized monthly. Both microbial activity and plant growth were monitored. After acclimation for 9 months, the dosing began. The 1x treatment stimulated plant growth and microbial activity for up to 7 months after the oil additions ended, but the 10x treatment significantly reduced growth. They suggested that the microbial community in the cores may have been carbon-limited and that the extra nitrogen fixation that occurred stimulated plant growth. This study attempted to mimic what would happen under the much more likely scenario of chronic exposure to oil-contaminated surface water rather than the well-known destructive effects of acute oil spill exposures on salt marsh flora.

PESTICIDES AND HERBICIDES

Gulka et al. (1980) collected ivory barnacles (*Balanus eburneus*) attached to oyster shells in North Inlet and exposed them to a range in concentrations (1-1000 ppb) of the insecticide diflubenzuron that interferes with chitin formation in arthropods. Mortality and molting frequency over 28 days was measured. Large barnacle mortalities occurred in the second week in both fed and unfed conditions over essentially the whole range of concentrations tested. Molting frequencies increased by about 30% as well, and mortalities occurred mostly when animals were in the process of molting.

Harder et al. (1980) measured the insecticide toxaphene in samples of rainwater collected at various sites in North Inlet from July 1977 to December 1978. Samplers were set out and emptied at intervals that included mostly times of no rainfall, but other samplers were used exclusively during rain events. Concentrations in each type of sampler were similar indicating that washout, not aerial deposition, was the most important transport mechanism from the atmosphere. Concentrations ranged from 13-497 nanograms per kg rainwater, and were highest in summer when toxaphene use is high on crops of cotton, soybeans, peanuts, and grain. Concentrations were below detection limits in winter and early spring. Air samples were also collected and ranged between 0.33 and 7.2 nanograms per kg of air, about the same as seen in air over the western Atlantic ocean. PCBs, DDT and DDE were also found in rainwater samples in North Inlet. They estimated aerial input of 1.2 kg toxaphene to North Inlet from June to September 1977. Ancillary measurements of toxaphene found it present in samples of oysters, blue crab, and mummichog fishes in concentrations between 30 and 60 micrograms per kg wet weight. They also found evidence that toxaphene is degraded, possibly by a reductive chlorination process, in anoxic sediments, but toxicological measurements have not been made for these alteration products. Unfortunately, no toxaphene measurements have been made in North Inlet since this 1977 study.

Bidleman et al. (1981) reported aerial deposition of organochlorine pesticides in North Inlet and Columbia, SC. They used the same rain stations as above to collect several compounds (DDT, toxaphene, PCBs, Chlordane, Aroclor 1254). Based on measures of the washout ratio, they found that most deposition, even during rain events, occurred as particulate fallout rather than from vapor dissolution into raindrops. Other results were similar to those in Harder et al. (1980).

Another pollution survey was funded internally by the Baruch Foundation in 1987-1989. Six sites were tested once per year to obtain baseline levels of contaminants in the upper, middle, and lower portions of the estuary (Crosby, 1989). In 1987, water, sediment, and oyster tissue were tested for heavy metals, chlorinated pesticides/PCBs, and chlorinated herbicides. All compounds, except lead and cadmium, were below detectable limits; these two compounds were found in very low levels in oyster tissue and sediments (Table 3). PAHs and additional heavy metals were analyzed in 1988. No detectable levels of chlorinated pesticides/PCBs, chlorinated herbicides, or PAHs were found in oyster tissue or sediments; however, very low levels of metals were detected in oyster tissue (arsenic, copper, cadmium, chromium) and in sediments (arsenic, copper, chromium) (Table 3). In 1989 the annual survey tested other compounds in oyster and sediment samples where bioaccumulation and concentration are likely to occur. Because golf courses adjacent to the northern section of North Inlet were being managed with organophosphorus

Table 3. Contaminants tested at six sites within North Inlet from 1987 – 1989 (Crosby, 1989). Compounds at or above detectable levels are in ***bold italic***.

Year	Water	Sediment	Oyster Tissue
1987	Cadmium	***Cadmium***	***Cadmium***
	Lead	***Lead***	***Lead***
	Mercury	Mercury	Mercury
	Chlorinated Pesticides/PCB	Chlorinated Pesticides/PCB	Chlorinated Pesticides/PCB
	Chlorinated Herbicides	Chlorinated Herbicides	Chlorinated Herbicides
1988	Arsenic	***Arsenic***	***Arsenic***
	Copper	***Copper***	***Copper***
	Chromium	***Chromium***	***Chromium***
		Cadmium	***Cadmium***
		Chlorinated Pesticides/PCB	Chlorinated Pesticides/PCB
		Chlorinated Herbicides	Chlorinated Herbicides
		PAHs	PAHs
1989	Not Tested	***Arsenic***	***Arsenic***
		Copper	***Copper***
		Chromium	***Chromium***
		Cadmium	***Cadmium***
		Lead	Lead
		Mercury	Mercury
		PAHs	***PAHs***
		Organophosphorus Pesticides	Organophosphorus Pesticides
		Dioxins (2 sites)	Dioxins (2 sites)

pesticides in the late 1980s, this type of compound was also added for analysis in the 1989 study. There was also concern regarding dioxin levels in the environment from nearby metallurgical processes, coal-fired power plants, automobile exhausts, pulp and paper bleaching processes, and various incineration processes. Two sites within North Inlet were sampled for dioxin. No detectable levels of organophosphorus pesticides or dioxin were found in either sediments or oyster tissues in the estuary (Table 3), but 5 of 12 PAH compounds were detected in oysters above levels previously reported for SC oysters. Various metals, including lead and mercury, were also detected in the sediment, with highest concentrations occurring in the southern-most section of North Inlet near Winyah and Mud Bays.

Chandler et al. (1994) tested the effects of a highly lipophilic synthetic pyrethroid pesticide called fenvalerate on meiobenthic organisms from North Inlet (nematodes and two harpacticoid copepod species). This pesticide has both an aqueous and sediment-associated phase. In 96-hr LC_{50} tests, nematodes were most sensitive, the copepods less so. One of the copepods was much less sensitive to the aqueous phase than to the sediment phase. The pesticide was highly toxic to these animals.

Green et al. (1996) tested early larval (naupliar), juvenile (copepodite) and adult life stages of a meiobenthic copepod in acute toxicity tests with concentrations of Chlorpyrifos, an organophosphate insecticide, in its sediment-associated phase. The naupliar stages were much more sensitive in LC_{50} bioassays than the other life stages of the copepod. The sediments used in these tests were from North Inlet tidal creeks and were treated in a standardized manner such that they could be used in quantitatively comparable tests with sediment-associated phases of other organic toxins. Interestingly, the supposedly protective standard criterion for toxicity calculated with equilibrium partitioning theory for

this pesticide was at a concentration higher than that which was found to be lethal to this copepod, i.e., supposedly safe levels in sediments were not safe for this species.

Strawbridge et al. (1992) and Chandler and Green (1996) also used North Inlet sediments in their harpacticoid copepod toxicity culture experiments. However, a novel approach to the use of spiked-sediment treatments was published by Chandler et al. (1997b). They took multiple intact sediment cores from a mudflat in North Inlet at low tide, transported them back to the laboratory where they were placed into "culture", and a spiked sediment treatment layer was later placed on top of the original sediment surface. As the deeper sediments became less and less oxygenated over time, the meiofauna migrated up into the spiked layer where they came into contact with the insecticide chlorpyrifos. At the taxon level, exposure had no effects on harpacticoids or nematodes. Three of 4 species of copepods increased in abundance relative to controls. That these experiments gave different results than single-species bioassays was surprising and suggests that survivorship/mortality can be quite different when whole communities are exposed to contaminants.

DiPinto (1996) used a similar experimental set-up as used before (DiPinto et al., 1993) for trophic transfer studies with PCBs. In these experiments, the hydrophobic organophosphorus pesticide azinphosmethyl (APM) was used to label meiobenthic harpacticoid copepods and sediment. Bottom-feeding juvenile fish (spot, *Leiostomus xanthurus*) were fed APM-contaminated copepods in clean sediment or clean copepods in APM-contaminated sediment, and were then sacrificed to measure their body burden of the pesticide as well as levels of acetylcholinesterase (AChE) in fish brain tissue. APM binds with and blocks this enzyme, so it would be utilized rapidly and decline in fish exposed to APM. When feeding on clean copepods in APM-contaminated sediments, the fish accumulated more APM in their bodies than when feeding on APM-contaminated copepods in clean sediments. Relative to controls, fish brains had 23% less AChE activity after feeding on contaminated copepods in 1993, but activity levels were not depressed in the 1994 experiments. AChE levels were also depressed by 21% in fish feeding on clean copepods in contaminated sediments. Surprisingly, APM did not accumulate in the bodies of fish fed contaminated copepods, but did accumulate when they fed on clean copepods in contaminated sediment. Sediments are normally taken into the mouth when spot feed on benthic meiofauna. Thus sediments were a source of APM accumulation in both copepods and fish in these experiments.

PATHOGENS

Perkinsus marinus is a pathogenic protozoan that causes dermo disease in oysters in North Inlet and elsewhere. White et al. (1998) examined the spatial distribution of diseased oysters using a GIS interpolation method called kriging. They sampled oyster reefs twice (September and December 1996) in Murrells Inlet and North Inlet at over 30 stations in each estuary, scored the prevalence of dermo, and mapped the distribution of the disease's prevalence. There were no spatial patterns in the oyster disease in North Inlet, as distribution of the pathogen was random and differences among sites were small. Bushek et al. (2007) studied the effects of nutrient additions and one common herbicide on growth of the parasitic pathogen, *P. marinus*. Concentrations tested were above those found in North Inlet, but only the herbicide negatively affected growth of the dermo-causing organism.

In summary, North Inlet contains only minimal amounts of contaminants or pollutants. Aerial and precipitation deposition appear to be the main routes of entry into the North Inlet system. However, some pathogenic bacteria and other pollutants enter the southernmost portions of North Inlet from Winyah Bay. Many researchers have used organisms and/or sediments from pristine North Inlet in bioassay and toxicity studies, and several comparative studies using North Inlet as the control site have been made of the impacts of anthropogenic contaminants in Murrells Inlet, a nearby developed estuary, that clearly illustrate the value of having the North Inlet - Winyah Bay NERR remain pristine into the future.

Winyah Bay

Brown Pelicans rest on an island in Winyah Bay.

» Geology and Geomorphology

Although the recent geological history of the area is shared by Winyah Bay and North Inlet estuaries, they have undergone some independent transformations, largely because of the riverine influence in Winyah Bay. About 15,000 years ago when the coast was more than 100 km seaward of its current location, the Pee Dee River most likely occupied its present valley. Evidence of the penetration of the ocean and salinization of the river at what we now recognize as Winyah Bay probably occurred about 5000 years ago. As a result of the prevailing southward long-shore drift over the past several thousand years, the mouths of both Winyah Bay and North Inlet estuaries migrated southward. The area that we now recognize as Mud Bay probably occupied much of what is now the North Inlet salt marsh, and the expansion of the North Inlet salt marsh into Mud Bay appears to be continuing today (Vogel, et al. 1996).

Increases in upstream penetration of salt water into the Pee Dee River and its tributaries resulted in a succession of botanical zones. Accounts of human uses of the rivers in the last several centuries suggest an ongoing conversion of cypress swamps to tidal wetlands as sea level continues to rise and river inflow decreases.

» Tidal Regime/Hydrology

Winyah Bay is a Class B, partially-mixed coastal plain estuary with major sources of river water input and a much greater range of salinity than North Inlet. It drains a 47,000 km^2 watershed originating in North Carolina with six rivers (Lynches, Pee Dee, Little Pee Dee, Black, Waccamaw, Sampit) having a combined mean annual discharge of 450 m^3 s^{-1}. Seasonal and year-to-year variations in discharges vary greatly, but during short-term, severe flood conditions, discharge can be as high as 7,800 m^3 s^{-1} (Blood and Vernberg, 1992). About 90% of the freshwater inflow to Winyah Bay comes from the Pee Dee River. The origin of the Pee Dee River is in the Piedmont and high sediment loads are typical, whereas the Black, Waccamaw, and Sampit Rivers originate on the coastal plain and drain forest and swamps; their waters tend to be dark and clear.

Lower Winyah Bay connects to the Atlantic Ocean through a pair of long jetties that originate from the barrier islands. The north jetty is on North Island, about 14 km south of North Inlet. The inlet separates North Island and the South/Cat Island complex. The tidal range in lower Winyah Bay is about 1.4 m. In Georgetown Harbor (Sampit River), about 18 km up the bay, the range is about 1.2 m. Winyah Bay may be best characterized as a turbulent and turbid system. Surface current velocities in Winyah Bay often exceed 2 m/sec and are especially high in the ship channel and lower Bay where the jetties force water through the narrowest part of the Bay. The irregular and ever-changing profile of the bottom causes large boils and eddies when the tide is flowing strongly in the lower Bay. Vertical and horizontal mixing can be complete during some stages of the tide, but often, during flooding tides, conspicuous lines are formed in the lower Bay where clear, greenish ocean water meets turbid, brown water that ebbed from the upper Bay.

Circulation patterns in Winyah Bay are heavily influenced by tides and wind. Flooding tides direct currents landward, while ebb tides reverse this flow direction. Bottom flow is usually up river (landward) and can carry salty water several kilometers

upriver of the Highway 17 bridges, even farther during periods of drought when river discharge is low. Tidal effects can be observed 100 or more kilometers upriver as the flooding tide slows river discharge and results in temporary increases in the depth of freshwater in the rivers. This is followed by decreases in depth as the tide ebbs in the lower Bay. It is not uncommon to see blue crabs, flounders, red drum, striped mullet, and dolphins tens of miles upriver during prolonged droughts, as happened in the year 2002.

The main axis and channel of Winyah Bay orients NW-SE for almost 30 km and has a surface area of about 155 km^2. Because of the high amounts of sediment suspended in the riverine discharge, Winyah Bay's main shipping channel must be dredged one or more times each year to maintain the federally authorized navigation channel depth of 8.3 m, while mean depth is 4 m. Ocean-going freighters regularly use the Port of Georgetown, and sustained dredging is critical for the economy of the area. Due to a shortage of funds, major dredging of the ship channel did not occur between 2006 and 2013, and the accumulation of sediments created channel depths in some reaches that prohibited the passage of large ships.

There are many, mostly marsh, islands in Winyah Bay. A series of islands that lie along the eastern edge of the ship channel in the mid bay were mostly created from dredged materials in the 1800's. In recent decades, dredged materials from the mid and upper bay channel were deposited in upland impounded areas on Hobcaw Barony, Hobcaw Point, or adjacent to the Sampit River. Materials from the lower bay have been loaded into a hopper ship and dumped in the ocean outside of the jetties.

One major feature of Winyah Bay is a particularly shallow area in the middle bay called Mud Bay (called Muddy Bay by many locals). This shallow lagoon lies east of the ship channel, southwest of the North Inlet estuary. Being off of the main stem of tidal flow, current velocities in Mud Bay are lower which favors the accumulation of fine sediments. Most of this area is not navigable even with small boats near low tide, but it is an important area for fishes, shrimps, and crabs. No Man's Friend, Haulover, and South Jones Creeks connect Mud Bay to North Inlet. The dynamics of the tidal exchanges that occur there are described in the North Inlet section.

» Water Quality in Winyah Bay

SALINITY

Winyah Bay's surface salinities are considerably lower than North Inlet's most of the time and range from essentially zero at the surface up-estuary towards the river mouths to oceanic salinities at its juncture with the Atlantic Ocean. There is a salt wedge on the bottom that can extend many miles landward away from the ocean, especially during periods of low runoff, low river discharge, or drought. Allen et al. (1984) documented strong salinity stratifications in Winyah Bay, with haloclines present throughout the year especially at stations nearer the mouth of the estuary. Water circulation in Winyah Bay is complex and salinities at a single location in the middle of the bay can vary by 20 or more in one tidal cycle. High spatial and temporal variability in salinity creates conditions that are physiologically challenging for animals that need to regulate their internal levels of salt. Accordingly, only organisms with wide tolerances and abilities to respond quickly to changes live in the middle and upper bay.

The NI-WB NERR SWMP effort to characterize water quality in Winyah Bay is limited to the operation of a single station in the mid-bay. The Thousand Acre SWMP site is located inside a shallow subtidal channel at the western side of the brackish Thousand Acre Marsh. Tidal exchange is with Mud Bay, the large lagoonal extension of central Winyah Bay. Some typical examples of the temporal variability seen in salinity at the Thousand Acre Marsh monitoring station are presented below.

The data in Figure 46 were collected during a period of low river and watershed runoff. A slight tidal salinity signature is evident as water flooding from the lower bay elevates salinities by 4 or 5 around high tide. However, salinity varies considerably over the course of a year (Figure 47). The intermediate

salinities measured on July 3-4, 2010 were preceded by a period of lower salinities in June due to a major inflow of freshwater to the estuary starting around June 1st. Decreasing freshwater inflow through July resulted in much higher salinities by mid-July when another freshet began. The 12-month record showed salinities in the 0-5 range during winter and 10-15 range in the fall.

The seasonal means for 2010 and other years between 1994 and 2010 are shown in Figure 48. The lowest salinity values in the time series occurred during winters, but winter was not the lowest season during every year. The lower overall salinities observed in the 1990s reflect the frequent occurrence of El Niño events in winter and spring during that decade. The major droughts of 2000-2002 and 2007-2010 are also evident with high salinities during those periods. Although not shown in the plot, there was a significant long-term

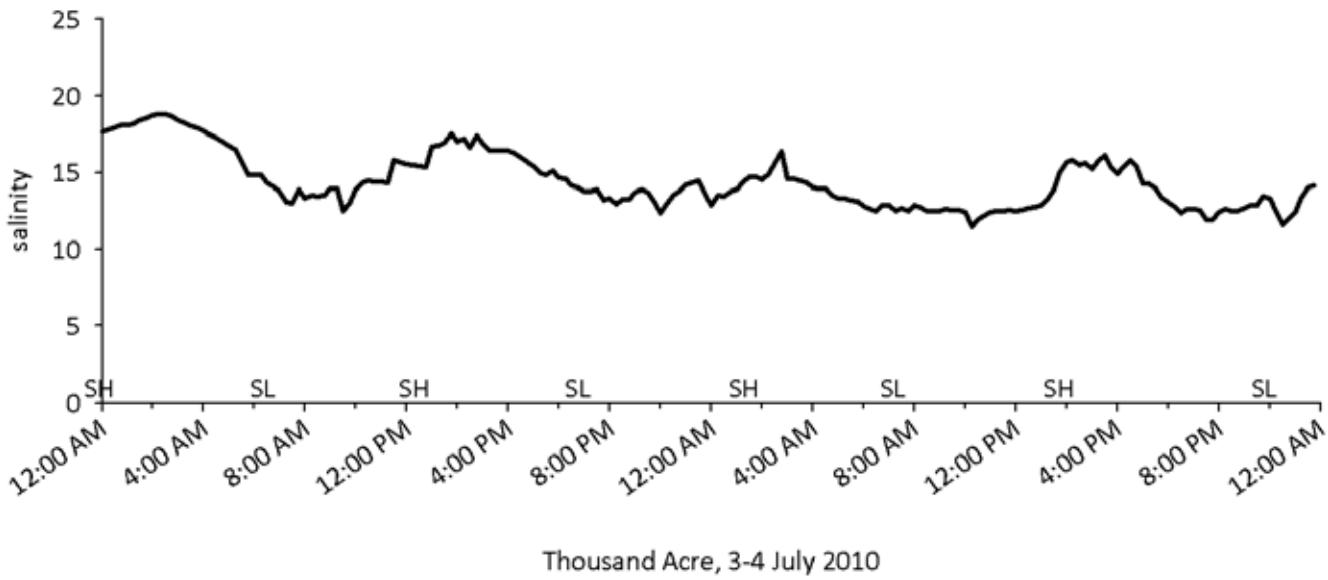

Figure 46. Salinity data collected at Thousand Acre Marsh at the NI-WB NERR SWMP station every 15 minutes during July 3-4, 2010. SL= slack low tide; SH=slack high tide.

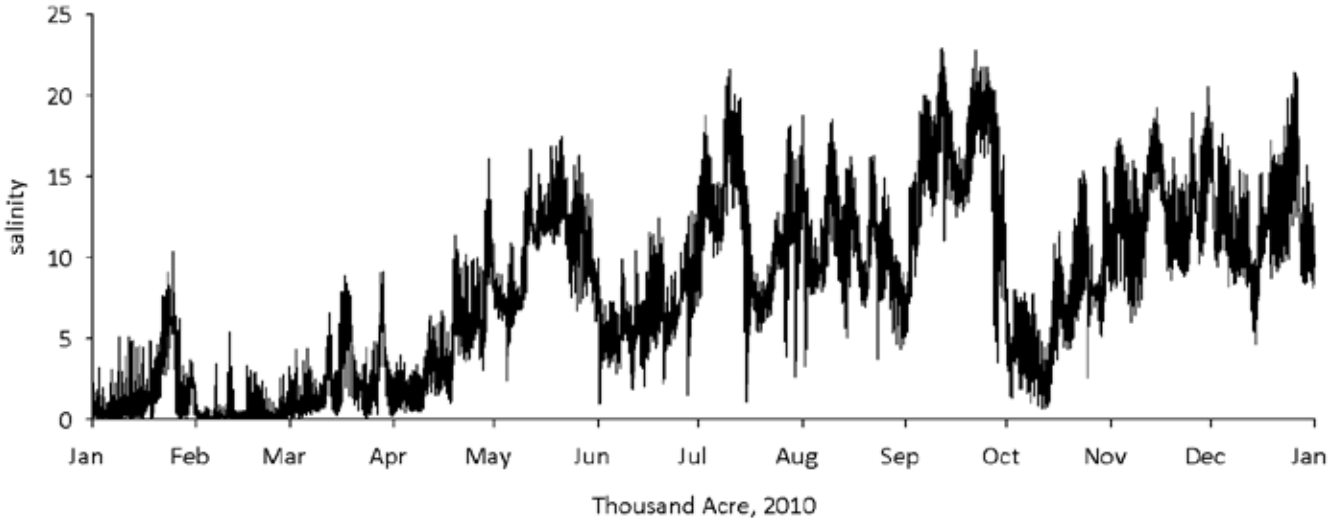

Figure 47. Salinity at the NI-WB NERR SWMP site at Thousand Acre Marsh in 2010 based on 15 minute data.

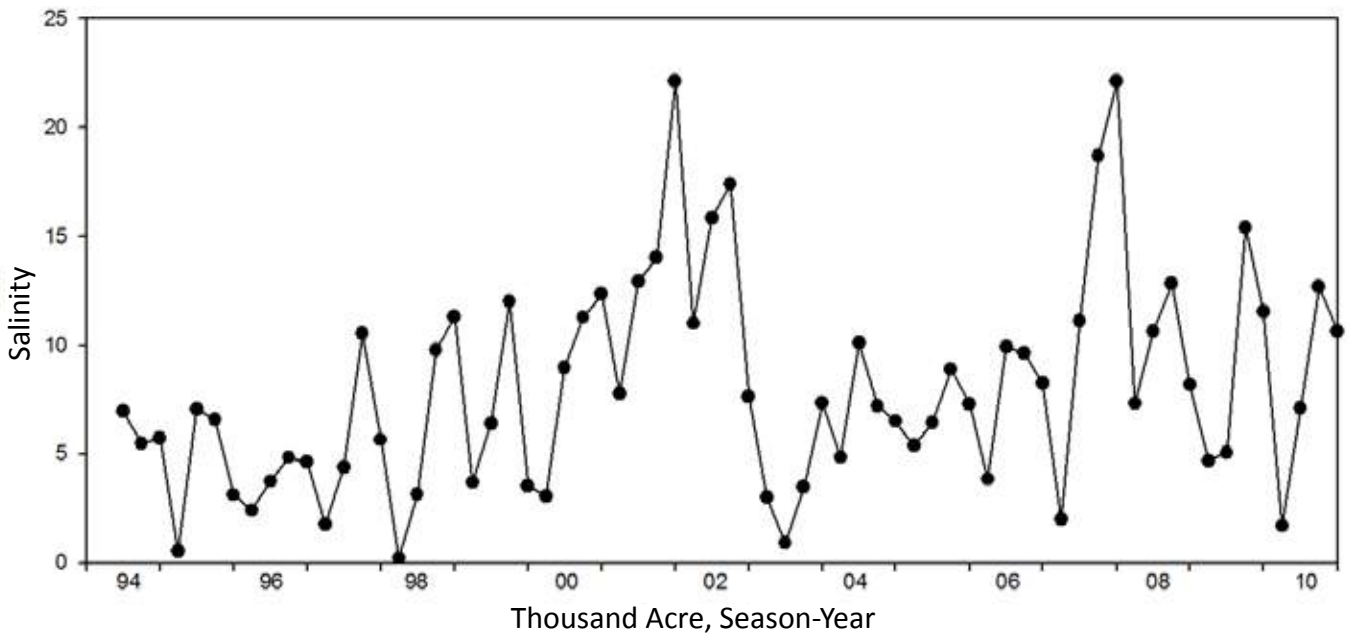

Figure 48. Mean seasonal values for salinity from Spring 1994 through Fall 2010 at the NI-WB NERR SWMP station at Thousand Acre Marsh.

increase in mean seasonal salinity over the 15 year period. This was related to the long-term significant decrease in discharge from the Pee Dee River which accounts for about 90% of the freshwater entering the estuary from all five rivers.

Many other studies in Winyah Bay address salinity, but almost all of these studies were primarily focused on the dynamics of nutrients, suspended sediment, phytoplankton, or animal populations. Goni et al. (2009) measured salinity while examining river discharge effects on particulate organic matter in Winyah Bay. Robinson et al. (2000) is an unpublished undergraduate study on recruitment of benthos as affected by runoff and subsequent changes in salinity in Mud Bay in Winyah Bay.

WATER TEMPERATURE

Winyah Bay's water temperature follows the same seasonal pattern as in North Inlet but is lower (to about 4° C) in winter and often higher (to 32° C) in summer. The average low is 6° C and average high 28° C, and there is a regular decrease in water temperature with depth where there is little to no vertical stratification or thermocline formation most of the time (Allen et al., 1984). Bottom temperatures hover around 4-5° C in winter and around 27-28° C in summer (Allen et al., 1984). The shallowest expanses of Winyah Bay, including Mud Bay and Thousand Acre Marsh, can warm more quickly during warm spring days than the deeper portions of the Bay. Conversely, water in shallow sections of the bay can chill by several degrees during a cold early fall night. The effect of cooler overnight temperatures can even be detected in the summer, as different water masses move past fixed locations with the tides. Figure 49 shows that on July 3 and 4, 2010 water temperature decreased overnight as waters in the shallow Thousand Acre Marsh ebbed down the creek toward the NI-WB NERR SWMP site at the confluence with Mud Bay. The plot also shows a rapid increase each morning during mid-flooding tide, a result of warmer water from Mud Bay entering the creek and displacing the cooler water that had drained past the monitoring station with the previous ebbing tide.

Diel, tidal, and diurnal changes in water temperature are evident in the plot of 15 minute data over the 12 months of 2010 (Figure 50). Water temperature was highest and most stable from

Figure 49. Water Temperature measured at Thousand Acre Marsh at the NI-WB NERR SWMP station every 15 minutes during July 3-4, 2010. SL= slack low tide; SH=slack high tide.

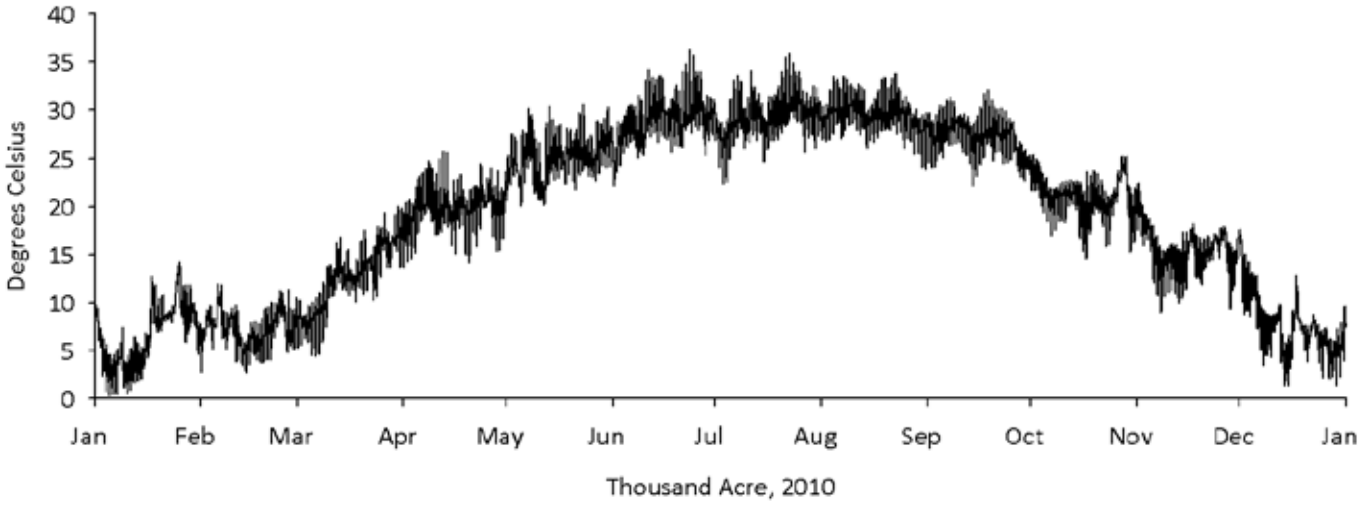

Figure 50. Water temperature at the NI-WB NERR SWMP site at Thousand Acre Marsh in 2010 based on 15 minute data.

May through September. Except for some short intervals of especially warm (~35° C) and cool (~23° C), water temperature was usually between 25-30° C during this five month period. In 2010, the lowest temperatures occurred in January and December, when the shallow waters cooled to 1 or 2° C for days to weeks at a time.

A plot of the mean seasonal water temperatures from 1994-2010 (Figure 51) indicated that winter 2010 was the coldest in the time series. Summer 2010 was the warmest of all of the years. Observed changes in extremes and thus variability in temperature records have become widely recognized in the last decade or two and these are often referred to as evidence for a changing climate.

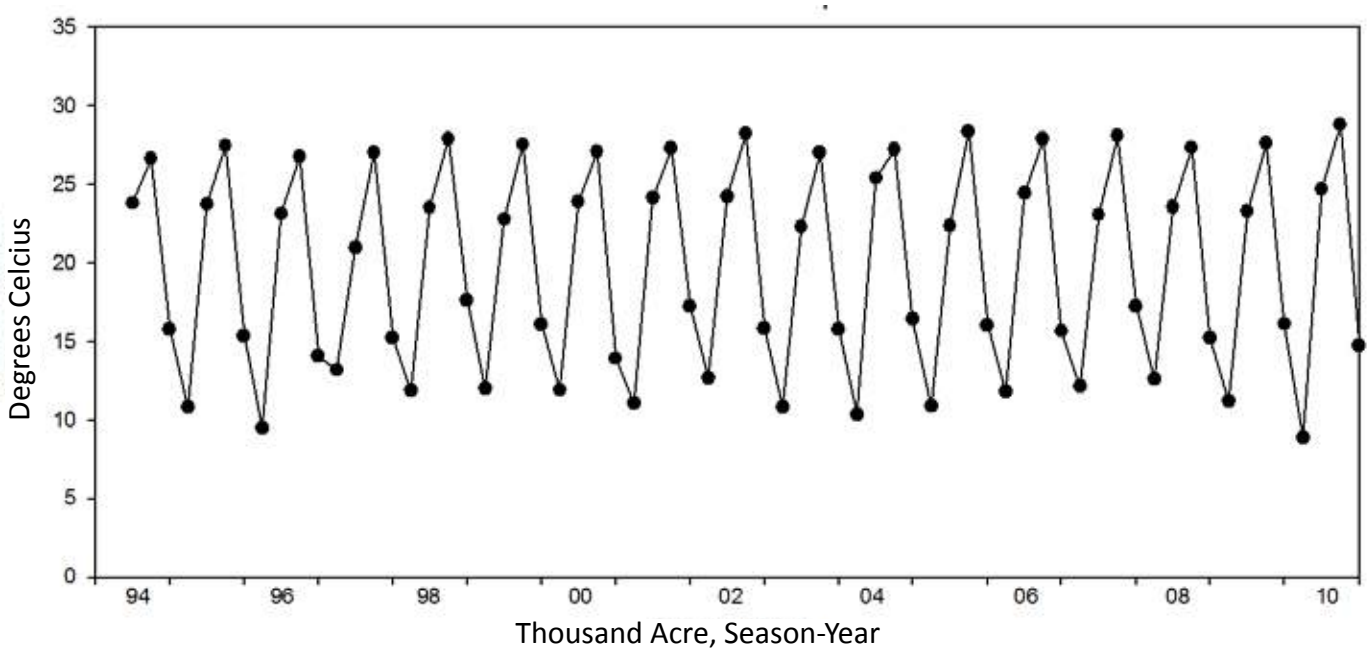

Figure 51. Mean seasonal values for water temperature from Spring 1994 through Fall 2010 at the NI-WB NERR SWMP station at Thousand Acre Marsh.

PH AND REDOX POTENTIAL

The SCDHEC STORET database for Winyah Bay showed no regular pattern of pH change at the MD080 station by the Georgetown bridge (Highway 17) over a ten-year period (1977-1986) when it ranged between 4.9 and 8.2 (Blood and Vernberg, 1992). Surface waters at that station are usually brackish, not salty.

SEDIMENTS AND TURBIDITY

The rivers emptying into Winyah Bay carry runoff and frequent heavy suspended sediment loads that either settle in the estuary or get transported seaward. Non-riverine, direct watershed runoff also enters the system along with aerial inputs of dust particles. The flow of fresh, brackish, and saline waters in Winyah Bay is complex (Kim and Voulgaris, 2005) and responds to the semi-diurnal tidal cycle for miles upstream. Some of the rivers have dams that sequester much of the sediment load that would otherwise move seaward or be deposited in the lower reaches of the estuary. Based on the sediment budget for the drainage basin for North Inlet and Winyah Bay reported by Phillips (1991), only about 4% of the gross eroded sediment reaches Winyah Bay on a yearly average. This is because the system is "transport limited", i.e., there isn't always enough flow to move all the sediment in the system seaward. Thus dredging is required to maintain channel depths for ocean going ships to reach the Port of Georgetown, which is about 17miles (29 km) from the ocean.

Secchi disc depths in Winyah Bay are typically less than one meter and can be even less than 0.5 m in Mud Bay (Allen et al., 1984). Turbidity is highly variable in estuaries on times scales of minutes to hours. The data in Figure 52 show that even in a two day period, turbidity can vary by a factor of up to 25. High short-term spikes in turbidity can result from the introduction of a large sediment load following a rain event that eroded sediments off the marsh or from a major disturbance such as a boat wake or resuspension due to a school of bottom-feeding fishes close to the sensor. Typically turbidity is higher around mid-tide when currents are at peak velocity and fine bottom material is most easily resuspended. Figure 52 also shows the tendency for the lowest values to occur around slack tide when the water is clearer.

Short-term spikes in turbidity occur throughout the year but are most frequent and highest during summer when thunderstorm frequencies and the

activities of major bioturbators are greatest (Figure 53). Turbidity is lowest from January through March.

Year-to-year differences in turbidity were recorded from 1994 – 2010 at Thousand Acre Marsh (Figure 54). The seasonal pattern for tubidity is less regular than for the other physical properties measured at this site. The highest turbidity values occurred from 1998 – 2002 with the highest value in the time series occurring in winter 1998. During most years, winter is the season with the lowest turbidity of the year. Lower values from 2003 – 2010 could be related to lower rainfall and river discharge following El Niño years in the 1990s.

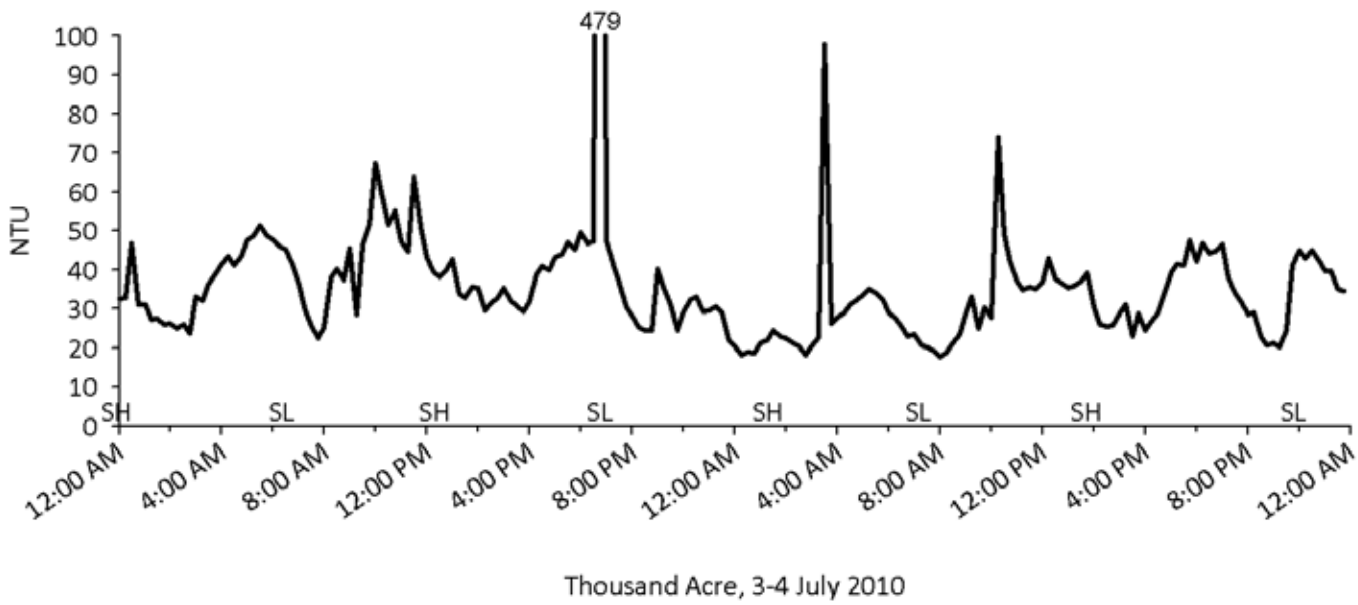

Figure 52. Turbidity (Nephelometric turbidity units) at Thousand Acre Marsh at the NI-WB NERR SWMP station every 15 minutes during July 3-4, 2010. SL= slack low tide; SH=slack high tide.

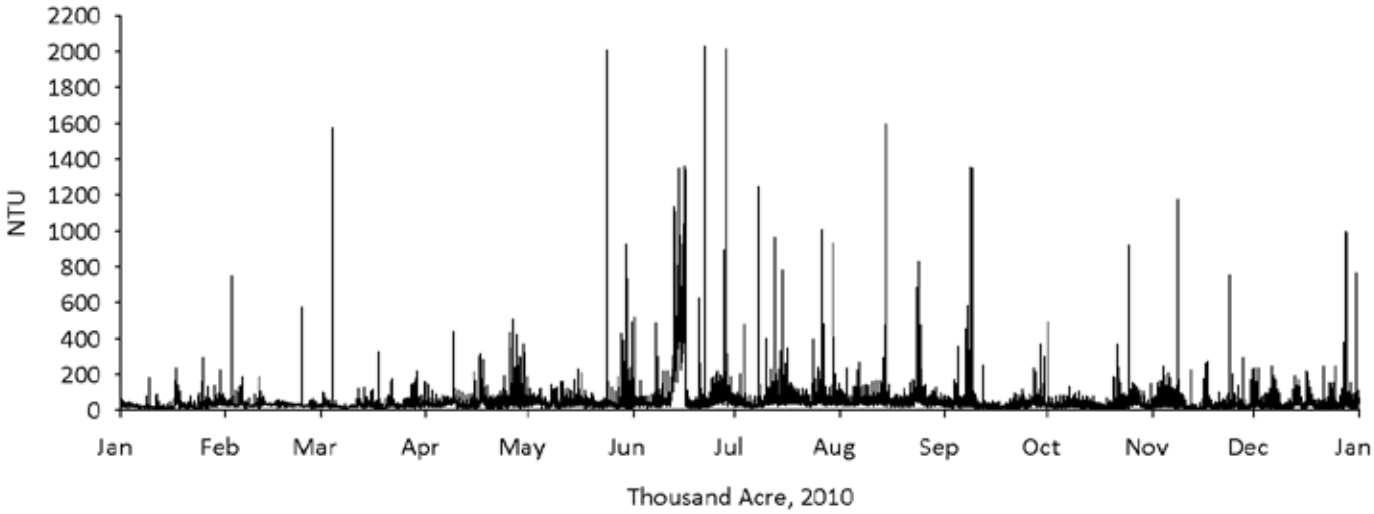

Figure 53. Turbidity (Nephelometric turbidity units) at the NI-WB NERR SWMP site at Thousand Acre Marsh in 2010 based on 15 minute data.

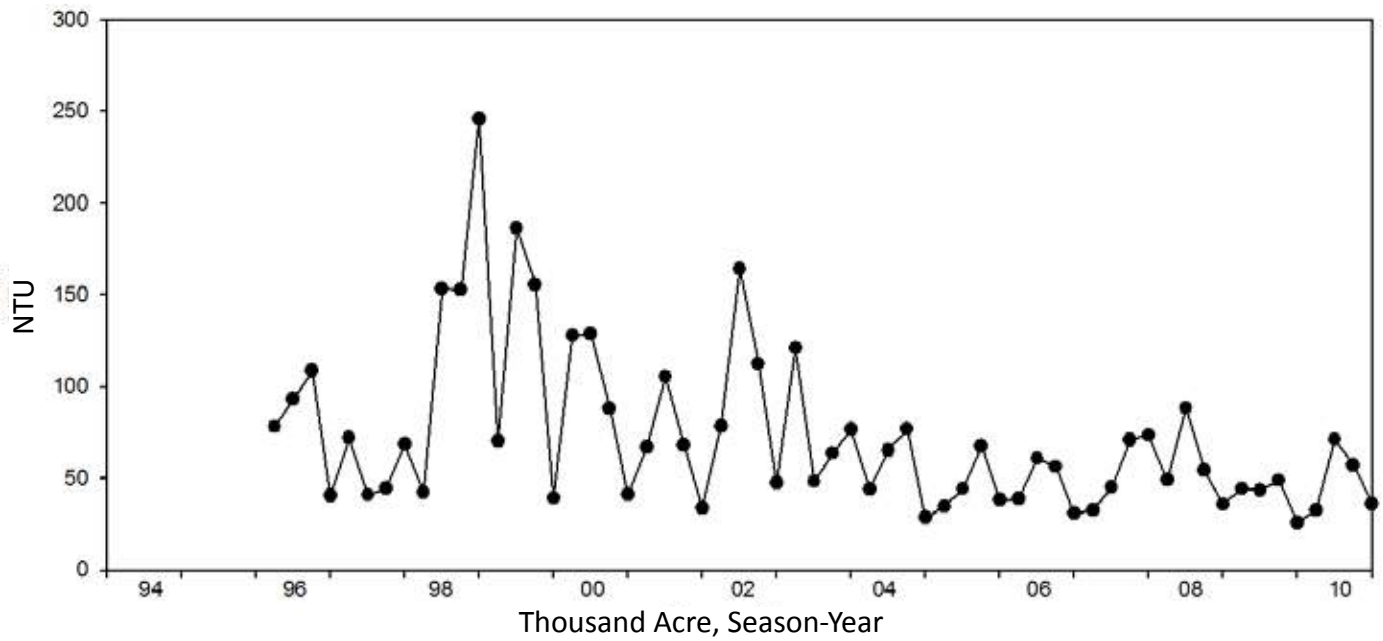

Figure 54. Mean seasonal values for turbidity (Nephelometric turbidity units) from Spring 1994- through Fall 2010 at the NI-WB NERR SWMP station at Thousand Acre Marsh.

SUMMARY OF OTHER STUDIES ON TURBIDITY IN WINYAH BAY

Coen (1995) provided a review of the potential impacts of mechanized shellfish harvesting methods. Harvesters typically produce lots of turbidity while bringing clams or oysters up from the bottom. As mechanical harvesters have been permitted and used in Winyah Bay just to the south of Mud Bay, there may be elevated levels of suspended sediments in the water during harvest times.

Patchineelam et al. (1999) constructed a preliminary sediment budget for the Winyah Bay estuary. They determined that only about 50% of the watershed's sediments reach the coast. In Mud Bay, the part of the Winyah Bay estuary that lies within the NI-WB NERR boundary, sedimentation is high, averaging about 5.5 mm per year. They estimated that 80% of the fine-grained sediments (by mass) accumulates in adjacent marshes and mud flats or gets removed by dredging activities and is deposited offshore. Despite the amounts of sediment entering the Winyah Bay system, only a small amount of fine-grained material actually reaches the coastal ocean.

Patchineelam and Kjerfve (2004) continued their work in Winyah Bay by measuring suspended sediment concentrations in the water column in 1996 during a transient estuarine turbidity maximum event. The salt-freshwater interface was pushed 8 km seaward by the exceptionally high river discharges. In the turbidity maximum layer at the pycnocline, sediment concentrations changed between ebb and flood tides. Bottom layers accumulated as much as 30 g/m^3 during slack tides, and sediment was re-suspended by tidal currents. The turbidity maximum layer was enhanced by flood tides and diminished in concentration by ebb tide as turbulence was inhibited.

Goni et al. (2003) measured particulate organic matter in the water column of Winyah Bay at stations along a down-bay transect and in Mud Bay. They were interested in the seasonal changes of these allochthonous (arriving from elsewhere) inputs to the estuary. Suspended sediments and their associated organics were partitioned into their carbon and nitrogen constituents. Using stable isotope analyses, they determined that sediments and their organics landward up-bay from the mouth were terrestrial in origin, while those at the lower end of the bay were from tidal inputs. As organic

carbon was the focus of the study, other results will be discussed in the "Carbon" section below.

Goni et al. (2005) sampled the turbidity maximum zone in the water column of the upper reaches of Winyah Bay to study how suspended sediments influence their associated organic matter. Total suspended sediment (TSS) concentrations ranged over two orders of magnitude (50 – 400 mg per liter) depending on depth sampled and stage of the tide and were not correlated with salinity. As this study was conducted outside the boundaries of the NI-WB NERR, their geochemical analyses will not be discussed until later. TSS exhibited non-conservative mixing behavior in the estuary and had higher concentrations in the lower portion of the bay nearer the ocean and with depth at all stations sampled.

DISSOLVED OXYGEN

The NI-WB NERR SWMP water quality monitoring station at Thousand Acre Marsh records dissolved oxygen. Repeatable patterns were evident in a plot of the 15 minute data from July 3 and 4, 2010 (Figure 55) where levels were highest around high tide and decreased through the ebbing tide each day and night. The rapid large increase in dissolved oxygen concentration during the beginning of each flooding tide is interpreted as the arrival of more oxygenated water from Mud Bay. Lower ebb tide values at the monitoring station could be due to the persistence of organic-rich water with high biological oxygen demand (BOD) in the creek.

Short-term variability in DO was also evident in the 12 month record for the site (Figure 56). Due to tidal and diel fluctuations, 8- 12 mg/L changes were not unusual within a day or between consecutive days during the summer. Despite that 'noise' in the data record, DO was generally lower from May through October than during the coolest months of the year.

The plot of seasonal mean values for DO showed more regularity from 2002-2010 than for the 1990s (Figure 57). The lower incidence of El Niño-related rain events and reduced river discharge into Winyah

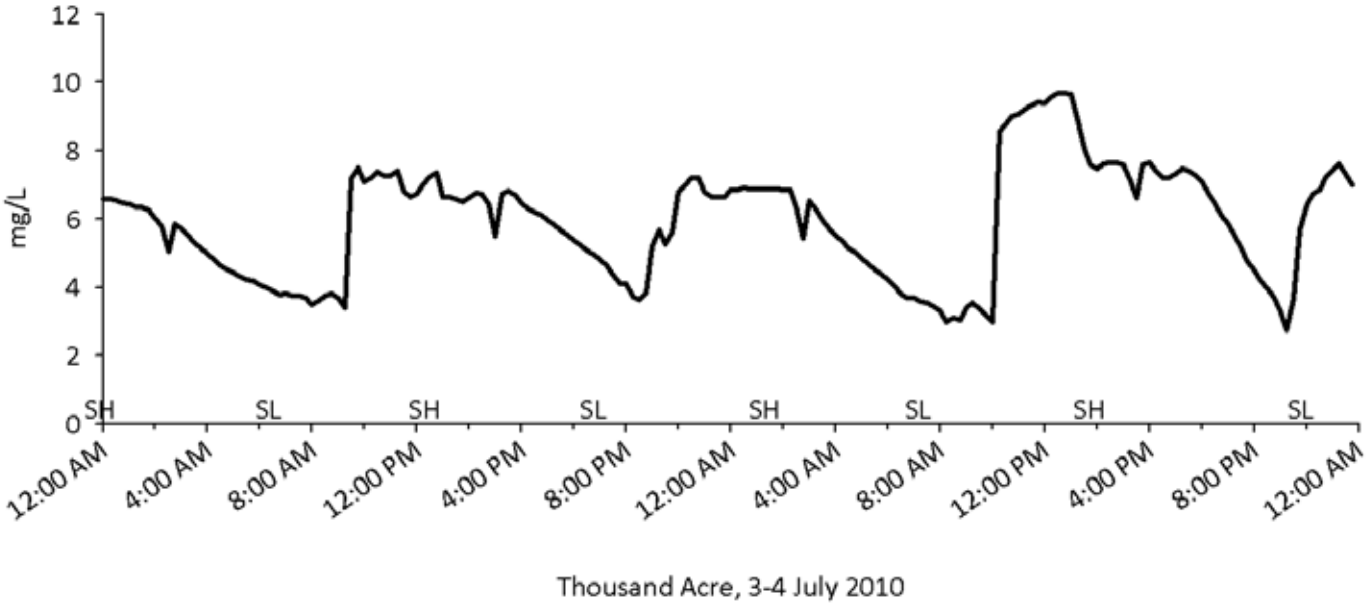

Figure 55. Dissolved oxygen data collected at Thousand Acre Marsh at the NI-WB NERR SWMP station every 15 minutes during July 3-4, 2010. SL= slack low tide; SH=slack high tide.

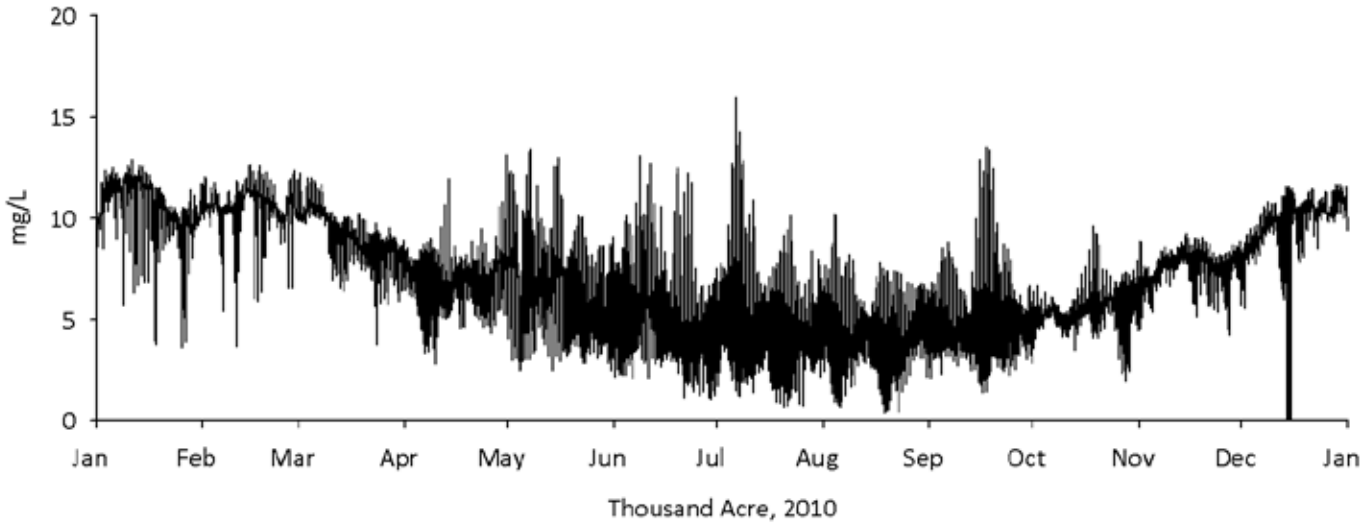

Figure 56. Dissolved oxygen at the NI-WB NERR SWMP site at Thousand Acre Marsh in 2010 based on 15 minute data.

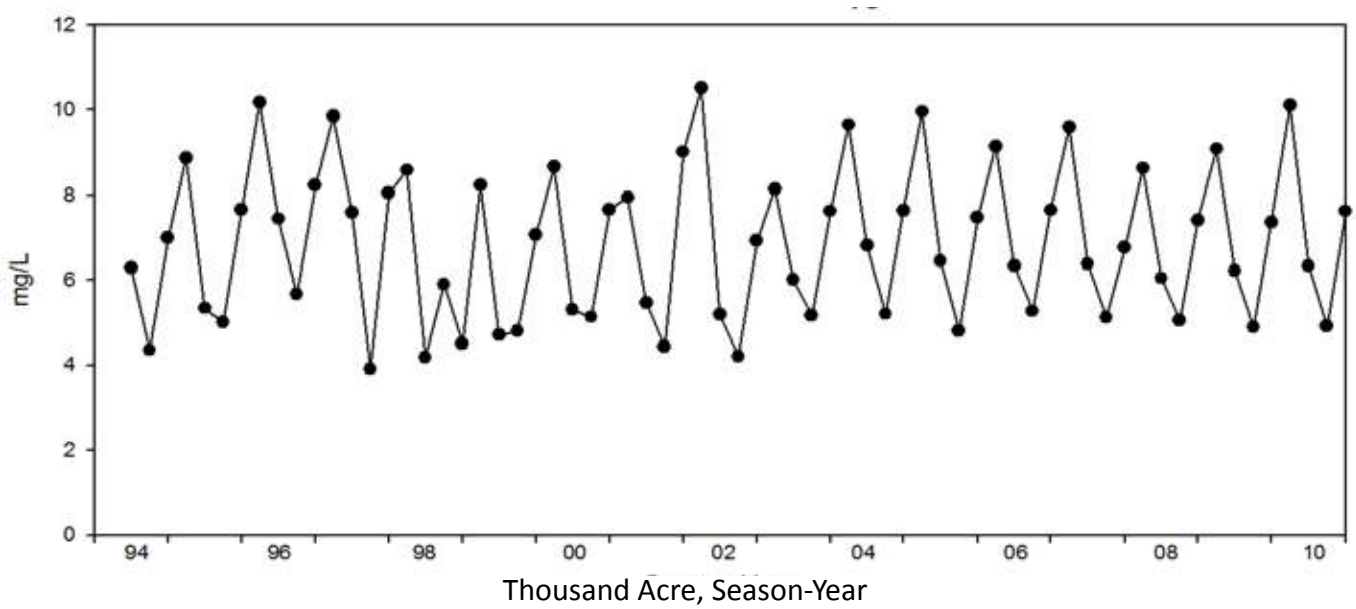

Figure 57. Mean seasonal values for dissolved oxygen from Spring 1994 through Fall 2010 at the NI-WB NERR SWMP station at Thousand Acre Marsh..

Bay could have had some influence on this pattern, as major influxes of sediment rich in BOD were less common during winters and springs after 2001.

It is important to remember that the discussion of dissolved oxygen data from the Thousand Acre Marsh SWMP site is not necessarily applicable to Winyah Bay as a whole. This site is clearly influenced by the surrounding marsh, the tidal creek, and source water from the shallow Mud Bay area. Dissolved oxygen is expected to be higher in open waters, especially near the channels where tidal currents are strong. Based on the SCDHEC STORET database for the upper station near Highway 17, Winyah Bay's DO concentration is high and nearly saturated in winter and lowest in summer (Blood and Vernberg, 1992).

» Water Chemistry in Winyah Bay

NUTRIENTS

The NI-WB NERR 20-day water chemistry monitoring database, described in the North Inlet nutrient section, began sampling all tidal stages (day and night) in June 1993. Thirteen 1000-mL samples are collected every 20 days at 2 hour and 4 minute intervals, for 2 complete tidal cycles (24:48 hours).

The Thousand Acre Marsh monitoring site can be used to characterize both short- and long-term patterns in Winyah Bay. A 20-day sampling event in July 2010 showed that nitrate+nitrite (NN), ammonium (NH_4^+), and orthophosphate (PO_4^-) concentrations are influenced primarily by tide and not time of day (Figure 58). For this particular sampling period, NN levels were lower during slack low tide, whereas NH_4^+ and PO_4^- were at higher concentrations at slack low tide. Both NN and NH_4^+ levels were about an order of magnitude higher than PO_4^-.

A 2010 yearly plot of these nutrients at the TA site puts the July 3-4 values in context with the rest of the 20-day data for that year (Figure 59). July 2010 NN concentrations ranged from 6 to about 15 micromoles per liter, intermediate between the year's high and low values. Winter and spring had higher and more variable levels of NN, ranging from about 3 to 30 micromoles per liter. Figure 59 demonstrates that NH_4^+ and PO_4^- had the highest values (NH_4^+ with 28 and PO_4^- with 4 micromoles per liter) and the greatest amount of variability from about April/May through December. Winter NH_4^+ and PO_4^- levels were much less variable and had lower concentrations.

A plot of seasonal mean nutrient values shows differences within and among years, as well as long-term trends. Figure 60 indicates that fall NN values are the lowest (between 3 to 7 micromoles per liter), and winter and spring concentrations are typically the largest. NN values were highest from 2003-2007. Concentrations of NN were lower and less variable during drought years (latter part of 1999 through 2002). The long-term trend of NN in Winyah Bay appears to be increasing, with 2008 through 2010 having the highest average seasonal concentrations on record so far.

Thousand Acre Marsh NH_4^+ seasonal averages show an increasing trend from 1994 through 2010 (Figure 60); the latter 3 seasons in 2010 are some of the highest levels in the entire time series. The highest ammonium seasonal average (about 8 micromoles per liter) was observed in 1998, the year of one of the strongest El Niños in 100 years. For PO_4^-, there was a slight increase in values over the seasons/years (Figure 60). Unlike NH_4^+, orthophosphate levels did not increase during the 1998 El Niño; however, the 2003 El Niño had the highest concentrations (≥ 1.4 micromoles per liter) in the entire seasonal series (spring and summer).

SUMMARY OF OTHER NUTRIENT STUDIES IN WINYAH BAY

Between August 1980 and September 1982, Allen et al. (1982, 1984) conducted extensive and intensive sampling in Winyah Bay, including stations in Mud Bay (their PS and MB), and one adjacent to Thousand Acre marsh (their TA station). They measured physical, chemical, and biological components at 14 total sampling sites mostly along the main channel axis. These data still serve as a baseline for future studies conducted in the bay. Orthophosphate was present in low concentrations throughout the year, and it increased when river runoff was high. When primary productivity increased, orthophosphate and total phosphorus decreased greatly. Nitrogen concentrations were closely related to riverine inputs. Short-term variability was as great as long-term, seasonal variability. Total nitrogen, total dissolved nitrogen and nitrate-nitrite followed a general pattern of conservative mixing in the bay. In their earlier study at No Man's Friend and South Jones Creeks, total nitrogen tracked phytoplankton abundance (Allen et al., 1982). That is, it was low when chlorophyll-*a* concentrations were high.

Mackin and Aller (1984) measured the amounts of ammonium, NH_4^+, adsorbed onto sediment particles in Mud Bay and in Cooks Creek in North Inlet. Adsorption was insensitive to temperature changes. Aller and Yingst (1985) examined adsorption kinetics of sediment porewater as affected by the presence/

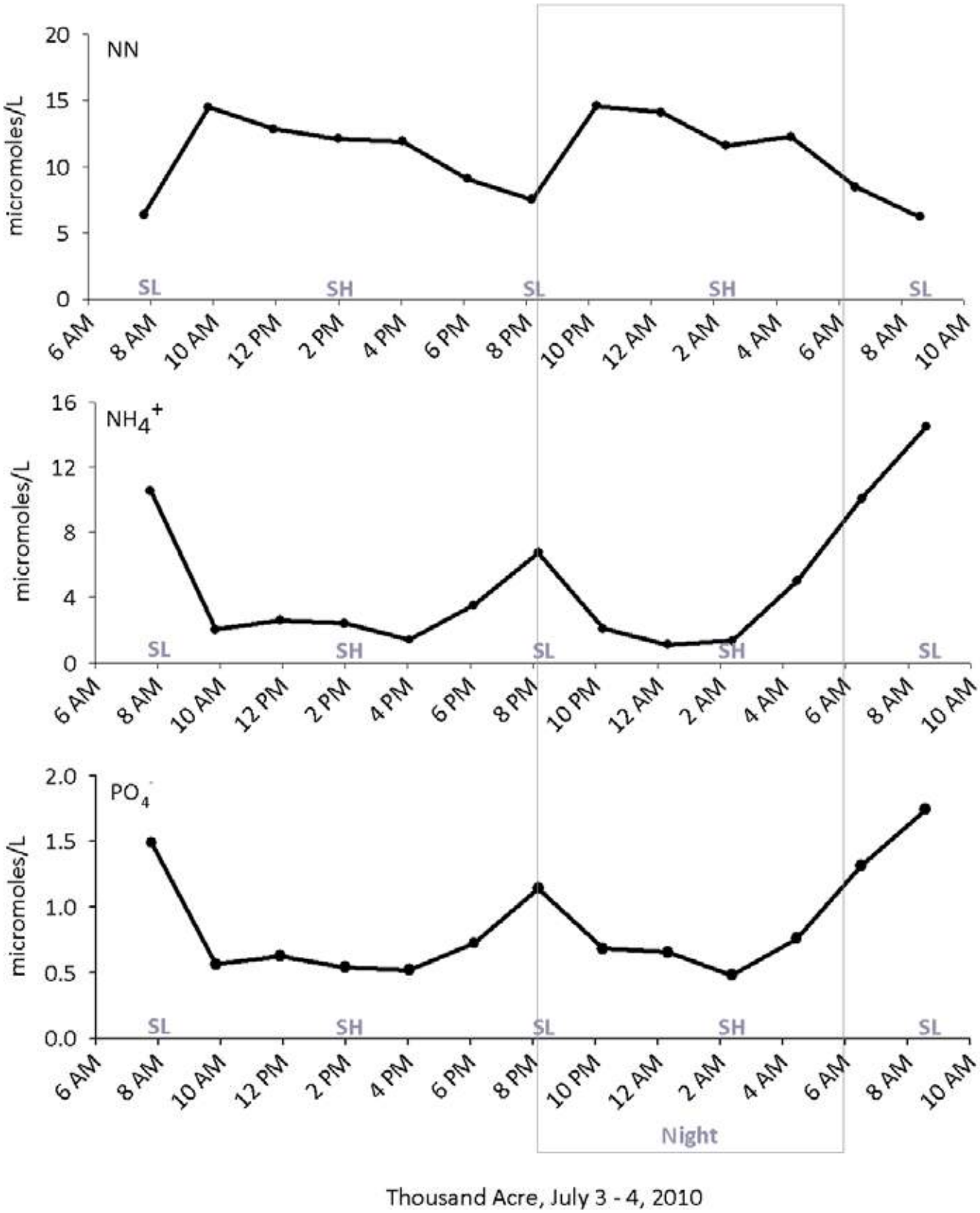

Figure 58. Thousand Acre Marsh nitrate+nitrite (top graph), ammonium (middle graph) and orthophosphate (bottom graph) concentrations during July 3-4, 2010 (a 20-day sampling event which last about 25 hrs). Water samples are collected every 2 hours and 4 minutes. SL= slack low tide; SH=slack high tide.

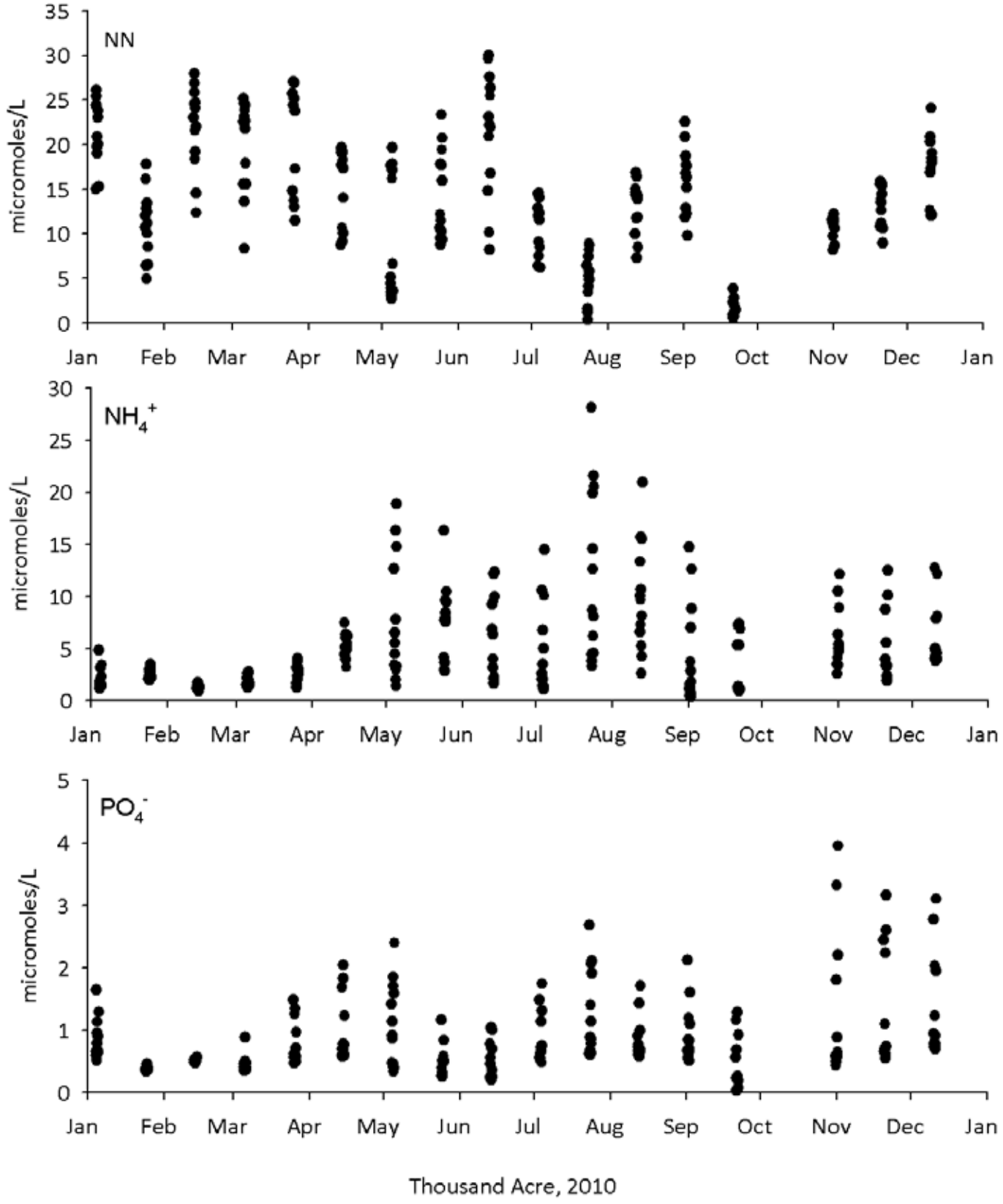

Figure 59. Thousand Acre Marsh nitrate+nitrite (top graph), ammonium (middle graph) and orthophosphate (bottom graph) concentrations for all 20-day sampling events during 2010. Water samples are collected every 2 hours and 4 minutes during each 25 hour sampling event.

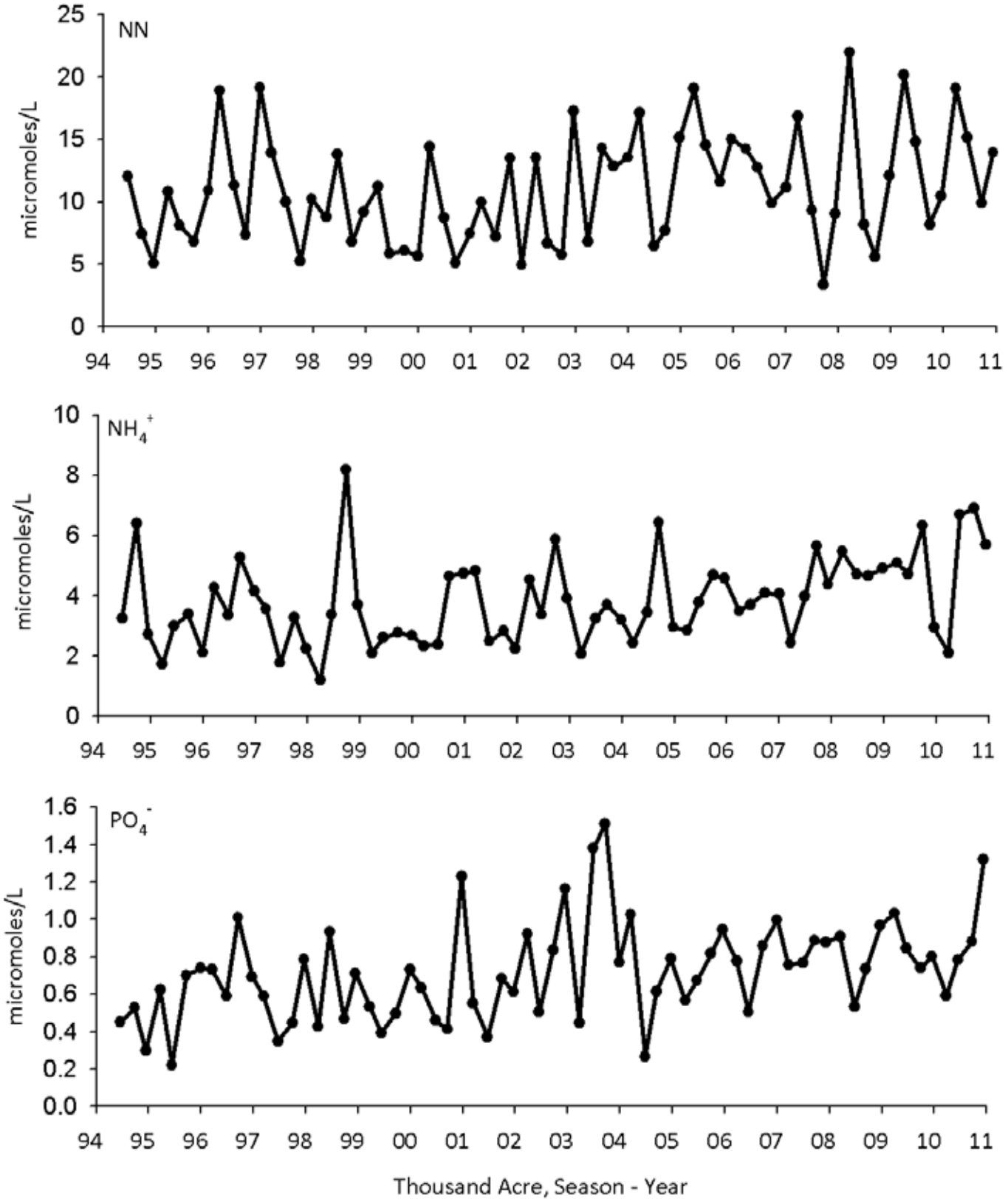

Figure 60. Thousand Acre Marsh nitrate+nitrite (top graph), ammonium (middle graph) and orthophosphate (bottom graph) concentrations for all 20-day sampling events from Winter 1994 through Fall 2010. Seasonal averages include all 2 hour and 4 minute data from each sampling event. January through March = Winter, April through June = Spring, July through September = Summer, and October through December = Fall.

absence of macrobenthic fauna. They collected sediment from Mud Bay for their aquarium-based experiments and found that organisms greatly alter the reaction rates for adsorption processes. Models of the process were constructed and validated with their empirical data. Ullman and Aller (1982, 1983) had earlier measured pore water diffusion rates and iodine remineralization rates, respectively, using Mud Bay sediments. Aller and Aller (1998), based on earlier experiments with Mud Bay sediments, concluded that remineralization rates for a variety of pore water chemical and elemental species are greatly altered by the presence of burrowing macrobenthos that irrigate their burrows. That is, decomposition of organic matter is accelerated by the enhanced solute transport activities of these organisms.

Winyah Bay waters enter North Inlet at high tide and under wind stress at other times. This intrusion carries significant amounts of nutrients that are partially utilized within North Inlet and may be exported out the mouth of North Inlet under certain conditions. The connections between these two bodies of water require more study, because continued coastal development's effects on the Winyah Bay drainage basin will ultimately affect the waters of North Inlet.

CARBON

The NI-WB NERR 20-day water chemistry monitoring program also collects and measures dissolved organic carbon (DOC). These collections and results are not formally part of the NERR System-Wide Monitoring Program (SWMP), but they are a part of the USC Baruch Institute's long-term monitoring programs. The NI-WB water chemistry collection protocols require sampling at all tidal stages (day and night). Thirteen 1000-mL samples are collected every 20 days at 2 hour and 4 minute intervals, for 2 complete tidal cycles (24:48 hours).

The Thousand Acre Marsh monitoring site is used to characterize DOC levels on both short- and long-term time frames in Winyah Bay. A 20-day sampling event in July 2010 shows that DOC concentrations were influenced primarily by tide (Figure 61) rather than time of day. Slack low tide DOC values were higher by about 3 to 6 milligrams per liter than during slack high tide. Figure 62 illustrates that this July 2010 sample was typical of DOC concentrations throughout the year; the exception was May when levels were over 25 milligrams per liter.

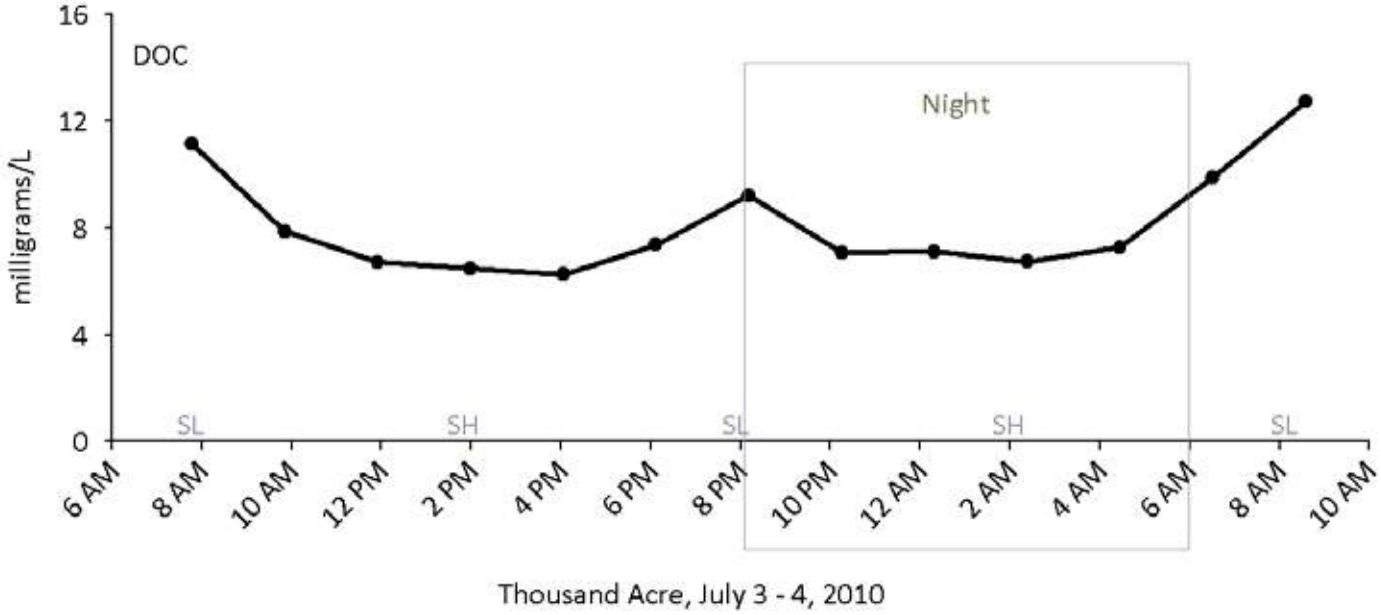

Figure 61. Thousand Acre Marsh dissolved organic carbon (DOC) concentrations during July 3-4, 2010 (a 20-day sampling event which last about 25 hrs). Water samples are collected every 2 hours and 4 minutes. SL= slack low tide; SH=slack high tide.

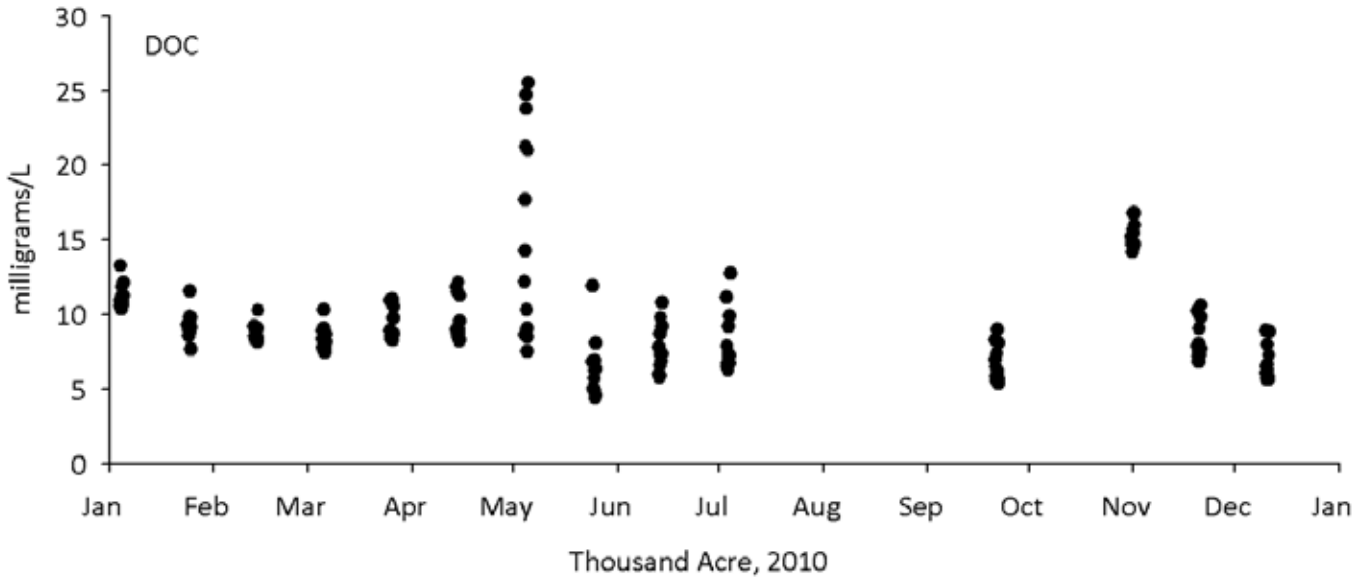

Figure 62. Thousand Acre Marsh dissolved organic carbon (DOC) concentrations for all 20-day sampling events during 2010. Water samples are collected every 2 hours and 4 minutes during each 25 hour sampling event.

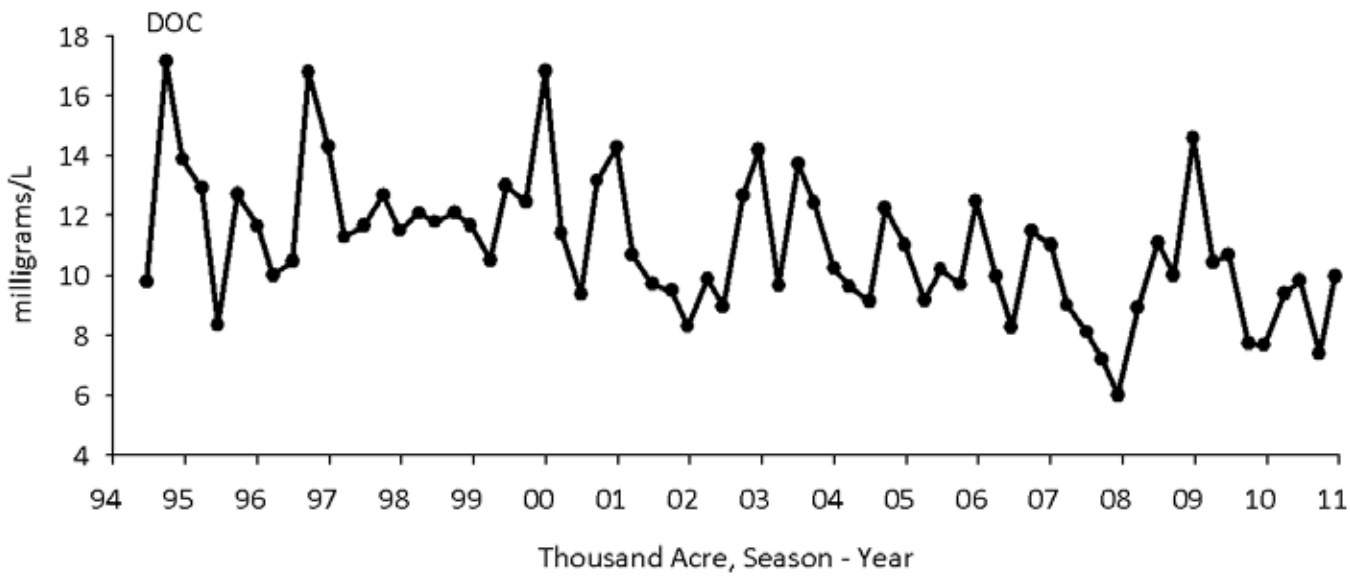

Figure 63. Thousand Acre Marsh dissolved organic carbon seasonal average concentrations for all 20-day sampling events from Winter 1994 through Fall 2010. Seasonal averages include all 2 hour and 4 minute data from each sampling event. January through March = Winter, April through June = Spring, July through September = Summer, and October through December = Fall.

Figure 63 demonstrates seasonal differences within and among years, with the greatest concentrations of DOC occurring from 1994 through 2000. The strong El Niño years 1998 and 2003, which had larger amounts of rain, did not have high seasonal DOC values. Even though high concentrations were recorded in 2002, 2003, and 2008, a decreasing trend for DOC was evident in Winyah Bay.

SUMMARY OF OTHER STUDIES ON CARBON IN WINYAH BAY

Eddins et al. (1999) collected oxic bottom sediments with a grab sampler from Winyah Bay during five months that spanned the seasons in 1996. Their sampling transect from the mouth of the bay up to the Pee Dee River was entirely along the main channel axis. No samples were taken

within the NERR boundary. They measured bulk organic carbon content (as weight %) and the stable carbon isotope ratio, *del*-^{13}C / *del*-^{12}C, on fine and coarse fractions of the sediment. The % OC for the fine fraction ranged between 2 and 10%, while the coarse fraction ranged between 1 and 12%, but only 12 % of the data exceeded 2% for coarse material. The fine fraction exceeded 2% bulk OC at all stations. The upstream stations had more negative carbon isotope ratios than stations lower in the bay. Both size fractions followed this trend. This trend reflects the greater distance of the lower stations from terrestrial sources of carbon in C-3 plants that use the Calvin cycle photosynthetic pathway. Seasonal changes were not observed in either bulk carbon content or stable isotope ratios. Most of the variability in the isotope signatures was likely due to mixing of source material (C-3 and C-4 plants, phytoplankton) in the bottom sediments.

Eddins (1999) collected water samples (top 1 m, bottom 1 m) at the same times and stations mentioned above to measure bulk POC concentration and its *del*-^{13}C stable carbon isotope values. She wanted to estimate what fraction of the POC was derived from terrestrial sources. Both surface and bottom *del*-^{13}C varied linearly with salinity, and bulk POC concentration varied between about 1 and 15 mg L^{-1} with no significant differences between top and bottom water concentrations. The estuary is well-mixed. Seasonal changes in the isotopic values were slight. During the fall sampling period, the salt wedge extended upstream to the farthest station where salinity was 5 compared to 36 at the estuary mouth. A turbidity maximum layer also caused minor variations in POC and stable isotope values. Using end member values from the literature for marine carbon and empirically measured values from the samples collected, a mixing model was used to estimate the contribution of terrestrial carbon to the bulk POC. The percentage contribution increased along the transect with distance from the estuary mouth and ranged between 50 and 90%. Both of these studies have implications for evaluating the inputs, fate, and effects of particle-associated pollutants in Winyah Bay.

Goni et al. (2003) analyzed samples from a Winyah Bay transect that included six stations in Mud Bay inside the NERR boundary. They were interested in determining the sources and distribution of organic matter in the bay and used elemental and stable isotope and organic biomarker analyses to do so. Surface water samples and bottom sediments were collected seasonally in 1998. DOC was measured for all water samples as well as weight % organic carbon (% OC). River and upper bay samples had the highest DOC concentrations, while Mud Bay's and the lower bay's were significantly lower. Mud Bay's DOC levels were highest in March. The % OC in sediment samples ranged between 1 and 5 % but had no discernable trends spatially with stations or seasonally. DOC concentrations in Winyah Bay were typically higher than POC concentrations by almost an order of magnitude. Biochemical markers and other evidence suggested that most of the % OC in Winyah Bay sediments was from terrestrial carbon sources and little from the C-4 source (*Spartina*) that surrounds the bay.

Goni et al. (2005) measured the stable isotopes for carbon in POC samples from Winyah Bay that were associated with the turbidity maximum zone. They found that vascular plants (C-3) and estuarine algae were the source materials for most of the particulate organic matter sampled, with little contribution from *Spartina* (a C-4 plant) or marine phytoplankton. Their study transect was outside the NERR boundary, however.

Goni et al. (2009) revisited Winyah Bay and sampled along its main channel axis, with all stations outside the NERR boundary. The % OC in water samples ranged between 1 and 6% and was positively correlated with river discharge volume. This paper focused more on the physical factors (discharge, wind, sediment transport) that affect materials important in biogeochemical cycles. Winyah Bay is apparently an efficient trap for suspended particulate materials under both low and high discharge conditions. Particle export to the ocean at depth occurs only under very high discharge conditions. This tendency to retain particulates makes the bay more susceptible to pollutants, eutrophication, and salt intrusion.

» Contaminants

POLLUTANTS, TOXICOLOGICAL STUDIES

Allen et al. (1984) provided an overview of the potential impacts of petroleum on fauna in Winyah Bay, particularly fishes, zooplankton, and the larval stages of crustaceans found there. They divided the bay into three zones based on the salinity gradient from 0 to 35: upper (freshwater river inputs, very low salinity), middle (the mixing zone, brackish water), and lower bay (primarily marine waters). Each of these regions has different susceptibilities to hydrocarbon inputs in its fauna, flora and aquatic denizens. Chronic discharges of oil and related products would have long-term negative impacts, particularly in the middle and lower parts of the bay.

Kucklick and Bidleman (1994a) looked at PAHs and pesticides in Winyah Bay and North Inlet in the microsurface and subsurface waters. Atrazine was found in the highest concentrations in May 1990 and was present throughout the year. Fluoranthene and pyrene were found most commonly in both surface microlayer samples and in subsurface waters. Pesticides were not enriched in the microlayer samples, but PAHs were on average 18 X more than in subsurface samples. Kucklick and Bidleman (1994b) measured salinity and fluorescence in water samples in Winyah Bay during 1990 to trace dispersal and distribution of the triazine herbicide, atrazine, entering the bay from rivers and low-atrazine seawater. Atrazine is a pre-emergent herbicide used on corn crops. They deduced that the herbicide behaved conservatively within the flushing time of the bay (< 18 hr). Atrazine and several other herbicides were also detected in much higher concentrations in Winyah Bay than in North Inlet, but most were found there as well but in quite low concentrations. Malathion, used in mosquito control programs, was also found in North Inlet. Organic pollutants are delivered to Winyah Bay and North Inlet throughout the year, some possibly via atmospheric transport, but in highest amounts after times of application to crops in the Winyah Bay drainage basin. Kucklick et al. (1997) also sampled PAHs in surface sediments in Winyah Bay and elsewhere in SC and found them in highest concentrations in the harbor and in areas near urban runoff entering from small intertidal creeks, the largest source of pyrogenic PAHs, whereas petroleum based PAHs had a more rural source.

Dorsch & Bidleman (1982) found hydrocarbon concentrations of 0.7 to 1.8 micrograms/liter in Winyah Bay water using fluorescence to measure dissolved organic matter. This low concentration contributed negligibly to the fluorescence signal given off by DOM. Bidleman et al. (1990) used fluorescence spectrometry to measure hydrocarbons in Winyah Bay and again found microgram levels (0.23 – 9.6 per liter). They also found nanogram quantities of PAHs in water samples, one of which, perylene, was most abundant, possibly having originated from sediment dredging.

Long et al. (1996) reported results of sediment toxicity bioassays performed as part of the U.S. Environmental Protection Agency's EMAP-E (Environmental Monitoring and Assessment Program – Estuaries). Winyah Bay was one of 22 estuaries included in the survey that had been identified earlier as having toxic sediments. Only 9 bottom grab samples from there were tested in June 1993. Three tests, each designed for a different chemical phase of the contaminants, were conducted: amphipod survival on bulk sediments, sea urchin development using sediment porewaters, and a microbial bioluminescence test using organic solvent extracts from the sediments. Winyah Bay's sediments were among the least toxic in the amphipod test. About a third of the porewater tests from each sample were toxic to sea urchin larvae, and about 75% of the samples were toxic in the bioluminescence test. What emerges from these assays is that porewater is more toxic than bulk sediment itself, whereas the microbial assays indicate more of a potential for toxicity than actual toxicity. A similar assessment was made by Long (2000).

Long et al. (1998) should be examined for details of the tests and sediment assays reported above. This report provides comparative data for estuaries

in SC and GA as part of NOAA's National Status and Trends Program (within the EMAP program) that monitors sediment toxins as well as body burdens of toxins periodically in fish and shellfish. Sampling in Winyah Bay took place in June 1993, and amphipod bioassays and sea urchin fertilization and microbial luminescence tests were conducted. Cytochrome P-450 assays were run as well. Sediment analyses included PAHs, organic pesticides and trace metals with appropriate quality control standards. This report details the findings for the 9 Winyah Bay samples mentioned in Long et al. (1996). Note, however, that none of the sampling stations was inside the NI-WB NERR boundary. These efforts, though, are relevant because of the connections between this larger body of water and North Inlet. Coller-Socha (1994) outlines toxicity tests done on sediments from the Winyah Bay navigation channel that contained dioxin compounds. Sanudo-Wilhelmy et al. (2004) provide an overview of the relative successes and failures of EMAP and NS&TP, showing that there were two peer-reviewed papers published on dissolved trace metals for the NI-WB NERR up to that time.

Foraminifera assemblages were examined for a comparison between the organic-rich sediments of the Intracoastal Waterway down into Winyah Bay and the less-rich intertidal sediments of Crab Haul and Clambank Creeks in North Inlet. Collins et al. (1995) found an impoverished transported benthic microfossil assemblage consisting of mostly non-living forams in the waterway, the bay, and at offshore stations, whereas the assemblages were rich and abundant in North Inlet. The authors attributed the differences to the high organic loads received by Winyah Bay.

Serum antibody responses were measured on a popular sport fish, the red drum (*Sciaenops ocellatus*) from several locations on the SC coast by Evans et al. (1996). They used an assay for anti-bacterial antibodies in blood serum and found that fish collected in Winyah Bay had the lowest percentage of non-responsive red drum. This low level of anti-bacterial response may have been correlated with the higher level of anthropogenic stress (contaminated sediments) in Winyah Bay relative to other locations.

More recently, assessment of South Carolina's coastal zone's health, known as SCECAP (SC Estuarine and Coastal Assessment Program) was begun in 1999. Every year through 2006, it has been measuring similar contaminants along the entire SC coast, with just two long-term, intermittently sampled sites in/near Old Man Creek in North Inlet and several in Winyah Bay. In 1999 & 2000 SCECAP found that North Inlet sediment samples contained contaminants, but were not in concentrations "that exceeded values considered to be high" (Van Dolah, et al., 2002). Tissue samples from whole body silver perch had detectable levels of contaminants, but did not exceed the FDA criteria for safe consumption. In 2001, however, a spot (Pisces) contained PAH and PCB levels which exceeded the 90th percentile of values for all SCECAP stations from 2000-2002 (n = 180; 60 per year). Every year from 1999-2004, SCECAP rated the mid-section of North Inlet estuary "Good" (the highest rating) based on fecal coliform, toxicity, contaminant concentrations, benthic index of biotic integrity, and water quality (Van Dolah, et al., 2008) (Figure 64). The middle and upper sections of Winyah Bay, however, did not fare as well, with designations in the fair and poor categories. This has remained the same in SCECAP's most recent report covering samples taken in 2005-2006 (Van Dolah et al. (2008).

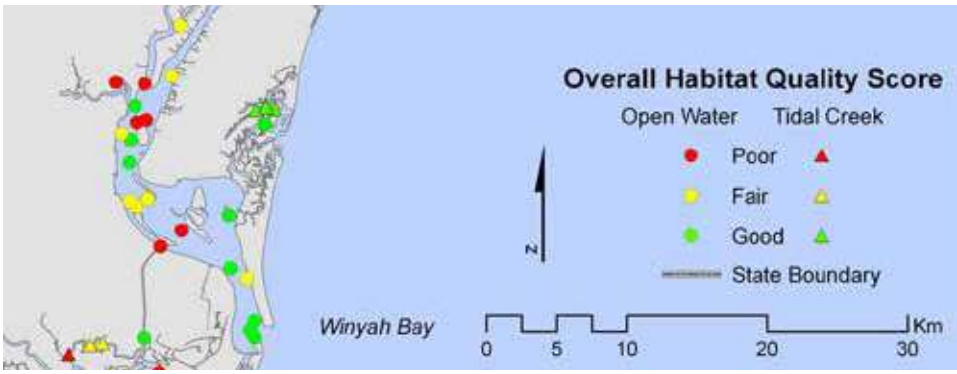

Figure 64. North Inlet and Winyah Bay overall habitat condition from 1999 through 2006. Map and assessment from SCECAP.