The Newport River Estuarine System

William W. Kirby-Smith
John D. Costlow

Duke University Marine Laboratory
Beaufort, North Carolina 28516

UNC-SG-89-04

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$2.50

This work was sponsored by the Office of Sea Grant, NOAA, U.S. Department of Commerce, under Grant No. NA81AA-D-0026, Project No. R/MD-8, and the state of North Carolina through the University of North Carolina. The U.S. Government is authorized to produce and distribute reprints for governmental purposes notwithstanding any copyright that may appear hearon.

UNC Sea Grant College Publication UNC-SG-89-04
April 1989

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Preface

The Newport River Estuarine System (NRES) is a relatively small, shallow, coastal plains estuary located near the center of the North Carolina coast south of Cape Lookout. Its national and international reputation as a site for marine research is the result of the close proximity of four major research organizations. These are the National Marine Fisheries Service (NMFS) Laboratory, the North Carolina Division of Marine Fisheries, the Duke University Marine Laboratory (DUML), and the University of North Carolina Institute of Marine Sciences. Many scientists are engaged in research at these facilities, and most of them make some use of the NRES, if only to supply organisms or seawater for laboratory experiments.

This report is a summary of what is known about the Newport System, Carteret County, North Carolina, based upon publications covering 125 years of scientific inquiry. The report is a technical publication designed to provide background information to scientists, students and interested laymen and to provide the technical basis for understanding the impacts of human activities in and around this estuary. Much information used in this report comes from unpublished sources, such as doctoral and masters degree dissertations and technical reports to government agencies. Few scientific journals are interested in publishing detailed site specific observations because few scientists find such material useful in their research. Furthermore, most scientists working in the NRES or any other area are interested in generalizing their research findings in an effort to answer larger questions. Thus much of the data reported in journals tends to be condensed. However, unabridged data is often invaluable when site specific questions or problems arise. The effort is made here to preserve this information.

There are several problems with referencing unpublished sources, not the least of which is the availability of these as primary literature sources. This is especially a problem with one widely used source for information here, the annual reports of the National Marine Fisheries Service Laboratory, Beaufort, N.C. (1961-1982). These papers were written as progress reports of ongoing research and were not designed to be primary literature sources; they carry the caveat on their title page "For Administrative Use Only." Although many of the papers in these reports have been published elsewhere, there are cases where this is not so or where interesting details have been obscured by summarizing the original data. In an effort to avoid the loss of valuable information, these data have been included here where necessary, even though the original reference may be difficult to find. Readers will have to make their own judgment as to whether or not such data are useful.

The report presented here relies primarily upon work published up through 1980. Several more recent publications have been added where they have been brought to the attention of the author. As a result of this project, a detailed bibliography of over 1,400 references dating 1860 to 1980 has been assembled and is available from the Natural History Resource Center of the Duke University Marine Laboratory.

Thanks To

A large number of people have contributed directly and indirectly to this project. We acknowledge the hundreds of research projects and individuals whose work provided the raw material, much unpublished, for this synthesis. A number of staff from all the local marine research and educational facilities provided helpful comments and discussion of drafts at various stages in this preparation. J.S. Kazarian, P. Fowler, J. Ustach, K. Sandoy, andE. Barber spent untold hours developing the original bibliography and typing references. H. Nearing did the word processing.

The UNC Sea Grant College Program provided major funding for this project with additional support from Duke University.

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Summary & Recommendations

The Newport River Estuarine System (NRES), a small shallow coastal plain estuary, is located in central eastern North Carolina just south of Cape Lookout. The system is tripartite consisting of the Newport River estuary proper, Back Sound/North River estuary to the east and Bogue Sound (a lagoon) to the west. All share a common opening to the sea, Beaufort Inlet. Although physically small, the system has received considerable attention because of more than 100 years of scientific research. This research is primarily the product of work done at four marine science laboratories: The National Marine Fisheries Service, the N.C. Division of Marine Fisheries, Duke University Marine Laboratory and the University of North Carolina Institute of Marine Sciences. No single research project has attempted to describe either the physical/chemical environment or the biology of the entire system. But rather the numerous projects have been separated by subject matter, time and/or space within the system. Much of the research has used the NRES as a place to conduct research and has not addressed the specific character of the system.

This report synthesizes what is known of the physical and chemical nature of the NRES. In the process of preparing this paper an extensive bibliography of approximately 1,400 papers was assembled. From those selected, approximately 1,400 that dealt with the physical/chemical environment or the field biology of organisms or ecological systems of the NRES. A computerized bibliography of these references is available from the Natural History Resource Center of the Duke University Marine Laboratory. Of the approximately 800 references 116 have been used here to discuss the physical and chemical characterization of the NRES.

The NRES is a relatively small estuary with a total area of approximately 163 km^2 (63 mi^2) draining a land area of 595 km^2(230 mi^2). Geologically the system consists of an unconsolidated mixture of sand, silt and clay with oyster reefs providing the only natural hard substrate. The NRES is very shallow with an average depth of 1 m (3.3 ft), a maximum depth in natural channels of approximately 6 m (20 ft) and a depth in dredged channels up to 12 m (40 ft). The middle and upper portions of the estuarine system are relatively flat with depths of 1 to 2 m (3-6 ft) at low tide. In the upper reaches in the rivers and streams, water depths of up to 4 m (12 ft) are encountered. Numerous marshes and intertidal shoals are common in the lower estuary and along the edges of the upper estuary. Detailed and accurate mapping of the location and aerial extent of the marine habitats, especially the salt marshes, intertidal shoals and open water has not been done. Historical aerial photography (1940-present) should be used to provide detailed maps and quantify changes in the system that may be natural and man-made. Such mapping should include changes in land use in the past 100 years that might have an impact upon the natural system.

Hydrography of the NRES is controlled by semi-diurnal tides of approximately 1 m (3 ft) height. The time and height of the tides decrease as the tide wave moves upstream from the mouth to the headwater of the system. Currents are greatest in the channels near the inlet, decrease in the shallow central sections and increase again in the narrow riverine headwaters. It has been estimated that approximately 43 percent of the total high tide volume of the water moves in and out of the estuary with each tide. The system is nearly vertically homogenous and well mixed except in the riverine headwaters where fresh surface water frequently overlies more saline bottom water. Residence time of the water depends upon the rate of freshwater inflow coupled with wind- and tide-induced mixing. For water entering at the narrows, the average flushing time through the estuary to Beaufort Inlet has been estimated to be approximately 12 tidal cycles or six days. Discrepancies exist in estimates of total volume and intertidal volume of the NRES. An accurate description of water volume and mixing dynamics, under different wind and tidal regimes, is needed to adequately describe natural biological processes and human impacts. In addition, the history of dredging activities in the NRES has not been written and a detailed investigation of how dredging may have influenced the physical and chemical characteristics of the NRES has not been done. These remain primary research needs for our understanding of how the estuary functions.

Water temperatures in the NRES vary with air temperature on a seasonal basis reaching a mean minimum temperature of approximately 5 C (40 F) in late January and early February and a mean maximum of approximately 30 C(86 F) in late July and early August. During the spring and fall rapid shifts of 5 C to 10 C (8 F to 18 F) can occur. Patterns in daily, seasonal and annual water temperature in the NRES are well known and require no additional study.

Salinity is highly variable in the upper estuary where it is frequently 0 ppt following heavy rains or wet periods and more than 36 ppt during droughts. Rapid changes of 20 ppt in one hour are possible. In the lower estuary, salinities are higher and less variable, approaching seawater salinities (34 ppt). At any one place, tides commonly cause changes of 3 to 5 ppt. Salinities in Bogue Sound are higher and less variable than those in the Newport River Estuary. Salinities are influenced by local rainfall and rate of evaporation and transpiration in surrounding marshes. Annual rainfall is equally distributed throughout the year with no pronounced wet or dry season. However lower temperatures reduce evaporation and transpiration, so that salinities are generally lower in the winter/spring compared with the summer/fall. The importance of salinity in determining the biological nature of the various parts of the NRES is obvious. Any hydrographic study should include descriptions of salinity. Specifically needed is a description of how watershed development and the presence of the dredged channel through Beaufort Inlet influence temporal and spatial patterns of salinity throughout the NRES. In addition, a stream discharge monitoring station should be placed in the headwaters of the Newport River.

Dissolved oxygen is generally at or near saturation due to tidal and wind mixing. Some low oxygen values occur in bottom water or protected embayments during the summer. Dissolved oxygen should be a concern in assessing further watershed development, especially in areas of restricted circulation during summer. However, no additional studies of dissolved oxygen are needed except as may relate to specific questions.

The pH of NRES waters is generally 8 to 8.2 except in the low salinity sections where pH varies between 6 and 7. No additional studies of pH are needed to understand pH values in the NRES.

Light penetration in the NRES is low, generally between 1 to 2 m (3-6 ft). It is greatly influenced by wind-generated wave resuspensions of silts and by phytoplankton. Clearest periods are in late fall and early winter. Minimum values are common in the shallow upper estuarine areas with increasing transparency upstream into fresh water and in the lower estuary near the inlet. At any one place the water is usually much clearer at high tide than at low tide. Due to deepening channels or increasing suspended sediments, decreases in light penetration influence primary production and thus should be an important part of assessing environmental impacts of any new activities within the NRES and its adjacent drainage basin.

Bottom sediments in the NRES are generally sand and shell fragments in the lower estuary and varying mixtures of silt, clay and sand in the upper estuary. Organic content is inversely related to mean grain size. More protected areas generally have finer sediments. Sedimentation rates are similar to other East Coast estuaries with rates of 3 to 4 mm/year (0.12- 0.16 in/yr). Sedimentation rates are higher in eelgrass beds and marshes. Dredging dramatically increases rates of sedimentation in areas nearby. Additional studies of sediments of the Newport River and North River are not needed except as they are related to specific local questions. A detailed study of the sediments on Bogue Sound is needed.

Extensive investigations of trace metals have resulted in a wealth of data for distribution and cycling of the elements in water, sediments and organisms. These data are the results of studies by the National Marine Fisheries Laboratory that have been aimed at understanding the behavior of trace metals in all estuaries. These studies will continue to provide data on trace metal cycles in the NRES.

Inorganic plant nutrients (N and P) are generally low in abundanc. But the system has moderate productivity so that recycling is probably important and rapid. Major inputs of nutrients are river, rainfall and runoff from adjacent land. As with most estuaries, the NRES is slightly nitrogen limited in terms of primary productivity. An assessment of the impacts of additional nutrient loading of the NRES is needed. Such an assessment should describe how development may have changed nutrients in the past as well as looking toward the effects of increased development in the future. Recent publications from a National Science Foundation project at the Duke University Marine Laboratory promise to answer a number of questions concerning nutrient cycling in the NRES.

In summary the major gaps in our knowledge of the physical nature of the NRES are (1) the lack of detailed habitat mapping with a historical perspective and (2) an extremely limited understanding of the hydrography of the system, especially with regards to wind and tide effects on water movements. This knowledge is particularly needed to assess impacts of land development, population growth and industrial expansion in the watershed.

History of Scientific Research

The following brief account of the history of scientific research in the NRES is excerpted from an unpublished manuscript by Dr. and Mrs. I.E. Gray, both deceased. It was written with the help of their daughter Sally Gray.

The history of published research in the NRES began more than a century ago with a short publication by William Stimpson (1860) entitled "A Trip to Beaufort, N.C." He described collections of mollusks and decapods that he and Theodore Gill gathered during March of that year. These two scientists were interested in adding to the collections of the Smithsonian Institution from a region of the coast known to be strongly influenced by the Gulf Stream. In the 1870s, a series of five publications written by two medical doctors serving at Ft. Macon described the terrestrial and aquatic fauna of the NRES area (Coues 1871a,b; Yarrow 1877; Coues and Yarrow 1878a,b). Also during the 1870s, two famous ichthyologists, David Starr Jordan and Charles H. Gilbert, worked in the area and published two papers on the fishes of Beaufort Harbor (Jordan and Gilbert 1879; Jordan 1886).

Probably because of the geographical location and accessibility of marine habitats, the Marine Laboratory of Johns Hopkins University was established in Beaufort in the summer of 1880. The new laboratory led to a dramatic increase in the number of publications based upon research done in the NRES. Between 1880 and 1886, William Keith Brooks, his associates and students worked out of a large rented house located at what was then the extreme eastern end of Beaufort. The results of these investigations appeared in "Studies from the Biological Laboratory of the Johns Hopkins University" and in the Johns Hopkins University Circular. All the papers were published in 1887 under the title "Notes on the Fauna of Beaufort, N.C." Although the laboratory did not remain continuously at Beaufort after 1886, scientists from Johns Hopkins continued to work in this area until the mid-twentieth century.

In addition to the interest created by the basic research activities in the NRES, the importance of fisheries resources in Carteret County aided in the establishment of a laboratory by the U.S. Fish Commission. Based upon information from the N.C. Geological Survey (a state organization that directed scientific projects on the coast), in 1899 North Carolina fisheries were twice as important in number of people employed and value of products as all other South Atlantic states combined. Carteret County was the most important county in the state. Because of this commercial importance, state geologist Joseph Austin Holmes asked the U.S. Fish Commission, headed by George M. Bowers, to establish a research station. In 1899 a U.S. Fisheries Laboratory was authorized, the second such laboratory in the United States. Henry Van Peters Wilson was appointed as director. Wilson, a Johns Hopkins scientist who was teaching at the University of North Carolina, had worked in Beaufort in 1886 and was familiar with the area. In Wilson's own words:

> "Some nine miles from Beaufort Inlet the coastline makes a sharp right-angled bend, with Cape Lookout at the angle. From the end of the cape a narrow lineof shoals extends much farther out. The cape and its submerged continuation form a wall, as it were, reaching seaward for fifteen miles. Cape Lookout itself is so shaped as to embrace a bay, a quiet and beautiful sheet of water, Lookout Bight. The coast configuration thus forms a remarkable natural trap into which fish, migrating northwards, fall. It is doubtful whether a better place can be found anywhere on our coast for the carrying out of observations on oceanic species and on bay and river species during the oceanic period of their life."

The first scientists associated with the newly authorized laboratory worked from a rented building in the summer of 1899. From Johns Hopkins came such well-known scientists as William K. Brooks, William C. Coker, Gilman A. Drew, Caswell Grave and D.S. Johnson. In addition, Robert E. Coker from the Goldsboro public schools, John Irving Hamaker from Trinity College in Durham and E.B. Wilson from Columbia University joined the group. In 1901, Winterton C. Curtis from the University of Missouri and Thomas Hunt Morgan from Bryn Mawr College were also present.

In May of 1900, the U.S. Congress authorized construction of a building to house the Fisheries Laboratory. This was completed in 1902 on Pivers Island across the bay from Beaufort. Caswell Grave was then in charge of the facility. The U.S. Fisheries Laboratory was established to provide scientific data used in development of commercial fisheries. The most important lines of early research were concerned with oyster and diamondback terrapin culture. Robert E. Coker, who later founded the University of North Carolina Laboratory in Morehead City, served as custodian of the Fisheries Laboratory from 1902 through 1904. He received his Ph.D. degree from Johns Hopkins University in 1906 and worked with the U.S. Bureau of Fisheries until 1923 when he joined the faculty of the University of North Carolina in Chapel Hill as professor of zoology.

A second laboratory located in Morehead City houses the North Carolina Division of Marine Fisheries. Their programs began in 1915 with the establishment of the North Carolina Fisheries Commission Board. In 1927, the Division of Commercial Fisheries was established, and in 1964 the research and development section was started. James T. Brown and Edward G. McCoy were the first biologists in this section. Research at the Division of Marine Fisheries is centered around studies that support the development and regulation of commercial and sports fisheries specific to North Carolina.

The Duke University Marine Laboratory was founded in 1938 in Beaufort, N.C., by Arthur Sperry Pearse, a zoologist at Duke University. Pearse, a professor at Duke since 1926, had traveled extensively and worked on marine organisms in a number of locations worldwide. He began his research in North Carolina at the U.S. Fisheries Laboratory in Beaufort and was so impressed by the location that he decided to establish a laboratory for the training of students in marine biology. Pearse convinced the university to purchase the vacant land on Pivers Island to the south of the U.S. Fisheries Laboratory and to construct a laboratory for the training of students and for basic marine research. He felt that such training and basic research would complement the more practical fisheries investigations carried out at the fisheries laboratory.

In 1944, Robert E. Coker of the University of North Carolina in Chapel Hill began to work with the North Carolina Department of Conservation and Development (formerly the Geological Survey and now the Department of Natural Resources and Community Development) to develop the Institute of Fisheries Research. This laboratory began operations in 1947 in Morehead City at the site of a former Marine Corps section base. The aim of the original laboratory was to promote the development of North Carolina marine fisheries through the application of basic science and economics to fisheries questions. The laboratory, now named the Institute of Marine Sciences of the University of North Carolina, has become more broadly based in its research activities with programs of basic and applied research as well as teaching.

In addition to the four marine research laboratories in the area, there are two facilities devoted to public education in marine affairs. The N.C. Maritime Museum in Beaufort has extensive displays of local maritime history and the staff sponsor field trips for laymen and student groups to nearby estuarine habitats. The N.C. Aquarium at Pine Knoll Shores has extensive displays of live marine organisms and sponsors a number of public education activities throughout the year.

The Newport River Estuarine System

Geography

The Newport River Estuarine System (Figure 1) consists of three major parts: (1) the Newport River estuary that extends from the Beaufort Inlet inland to a point near the town of Newport; (2) a portion of Bogue Sound extending from Beaufort Inlet west to a point west of Broad Creek near Intracoastal Waterway Marker 33 (Brett 1963; F.J. Schwartz personal communication); (3) Back Sound and North River from Beaufort Inlet to a line between "Bottle Run Point" and Harkers Island and including the "Straits" as far east as Browns Island (personal observation). Because the geographical limits of these three parts are not hydrographically distinct from adjacent systems, the establishment of these boundaries is arbitrary. However, for the sake of discussion these are the limits used in this publication.

The tripartite nature of the NRES is typical of the estuarine systems in southern North Carolina where elongated barrier islands are broken by inlets in the vicinity of small coastal-plain rivers. Each tripartite system consists of one branch extending perpendicular to the coast and ending in a small river with the other two branches extending laterally as high salinity sounds behind the barrier islands. These two lateral branches separate hydrologically from adjacent systems at the time and place where tidal flows meet between two inlets.

Knowledge of the relative proportion of land to water (Table 1) found in each of the three subsystems of the NRES is important in understanding the variability in the physical and chemical characteristics of the estuary as influenced by freshwater inflows. All three major parts of the NRES fit Pritchard's (1967) definition of an estuary, a definition that emphasizes the importance of fresh water derived from land drainage to reduce salinities. The most estuarine in character of the three subsystems of the NRES is the Newport River Estuary. It has a land area 11 times as large as the open water area. The Newport River drains a large coastal plain swamp/forest, a part of the Croatan National Forest. Bogue Sound, with a land/water ratio of 0.97, is more of a lagoon than an estuary. Numerous small creeks empty into Bogue Sound all along its length. Each of these could be classified as miniature estuaries during periods of rainfall or when surface groundwater causes fresh water to seep into them. At other times they can be considered tidal embayments with salinities little different from the open waters of Bogue Sound. The third area, Back Sound and North River, shares characteristics of both of the other two parts of the NRES. Back Sound resembles Bogue Sound, and the North River is more similar to the Newport River Estuary. In overall area, the Newport River estuary is the smallest (31 km²; 12 mi²) of the three parts; Back Sound/North River (60 km²; 23 mi²) and Bogue Sound (77 km²; 30 mi²) are two to three times its size.

The physical features of the NRES are defined by unconsolidated sediments (sand and mud) and are thus subject to rapid short-term changes due to movements of these sediments. In the past and continuing to the present day, changes in sea level have resulted in alteration of the size, shape and position of the NRES. A summary of changes in the past 250 years in the lower estuary is given by Klavans (1983). Beaufort Inlet has been open since 1708 (El-Ashry et al. 1968). It migrated approximately 150 m (500 ft) to the northwest between 1866 and 1948 (U.S. Army Corps of Engineers, 1948). Further evidence of inlet migration can be found in the position of the islands and marshes in

Table 1. Approximate areas of land and water in the watershed of the three parts of the NRES (km²). For locations see Figure 1.

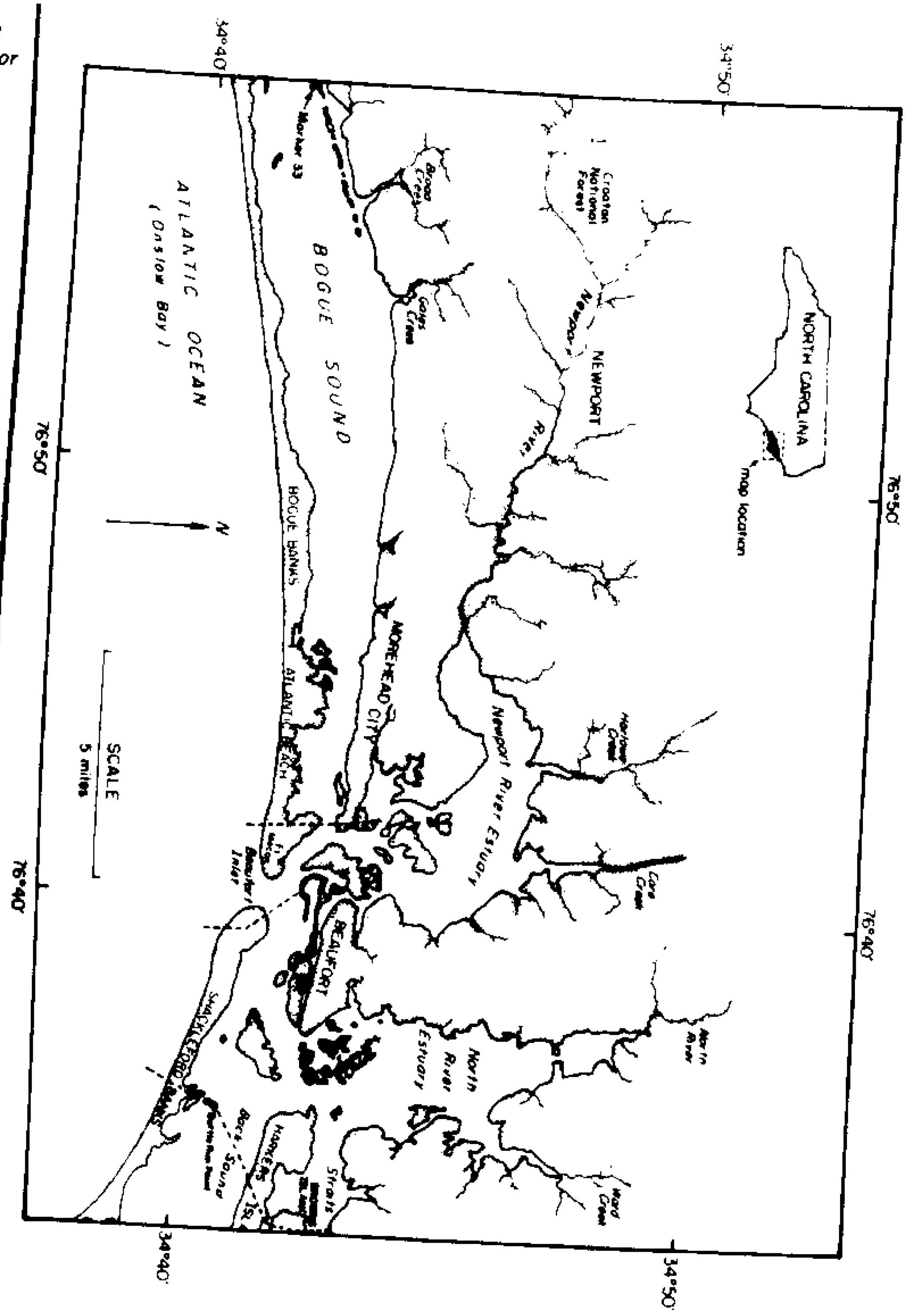
Location	Land	Water	Total	Land/Water
1. Newport River estuary	340	31	371	12.0
2. Bogue Sound	75	77	152	0.97
3. Back Sound/North River	180	60	240	3.0
Total	595	163	758	3.7

1. From the Beaufort Inlet to Newport (Wolfe (1975).

2. From Marker 33 between Broad Creek and Goose Creek to the Beaufort Inlet (estimated from topographic maps).

3. From Bottle Run Point on Shackleford Banks to Harkers Island, Browns Island across the Straits, including all of North River to the Beaufort Inlet (estimated from topographic maps).

Map showing the location and major features of the NRES.



Back Sound. They suggest a continuous westward migration of the inlet. Recent changes in the inlet (1949-1971) include an addition of 2.4 km (1.5 mi) of land to the western end of Shackleford Banks and a 0.16 km (0.1 mi) recession of the eastern tip of Bogue Banks. Annual dredging and construction of rock jetties has stabilized the position of Beaufort Inlet. Other major man-made changes in channels and shoals over the past hundred years have included: (1) increasing the size and depth of the main ships channel into the Morehead City state port and turning basin (Dredged materials were deposited on the natural channels and marshes at the northeastern end of Bogue Banks. This restricts the flow of water in and out of Bogue Sound); (2) dredging of Taylors Creek and Beaufort Harbor (This changes the elevation of the adjacent shoal with the addition of dredged materials); (3) dredging of the Intracoastal Waterway, thus creating a channel that connects the Newport River Estuary with the Neuse River Estuary to the north and Bogue Sound with the White Oak River Estuary to the west; (4) constructing of the Morehead City-Beaufort Causeway in 1927. (This restricts the flow of water in and out of the Newport River Estuary to two narrow channels.)

Bathymetry

The NRES is a shallow body of water averaging approximately 1 m (3 ft) in depth at mean low water with a few deeper channels (Figure 2). Klavans (1983) published cross-sectional diagrams of the lower part of the NRES that provide vertically exaggerated pictures of depth profiles along seven transects (Figure 3). Most of the navigational channels are maintained by dredging, and only a few are maintained by natural scouring of the tidal currents. Frequency of dredging is site-specific with some places requiring dredging every year. Others may only be dredged occasionally.

Close to the inlet the position and size of the unmaintained channels and the adjacent shoals varies dramatically from year to year as the strong tidal currents move the sand. Away from the inlet, the natural channels are more stable, but even here a strong gale or hurricane will often result in a rapid shift in position. As would be expected, the strongest tidal flows and the greatest mass movement of water follows the channels (for example, see Kazarian 1983).

The bathymetry of the Newport River estuary (Figure 2) is relatively simple. The lower estuary, identified as that area from Beaufort Inlet to a line drawn between the mouth of Core Creek and Crab Point, consists of a complex of natural and man-made channels running through a group of marshes and islands (Figure 3; Transects A-D). The main ship channel leads through the inlet to the N.C. State Port at Morehead City and has a project depth of 12.2 m (40 ft). Beginning just south of the Newport River bridge and running northward is a segment of the Intracoastal Waterway with a project depth of 3.7 m (12 ft). The waterway passes between the Newport marshes and Phillips Island, continuing north and west into Core Creek and connecting with the Neuse River via a canal. Occasional dredging is done at places in the waterway to maintain the project depth. A second navigational channel with a project depth of 4.6 m (15 ft) begins just south of Radio Island and continues into Beaufort Harbor where it splits into two branches. One branch passes up Taylors Creek and out into the North River. The other passes north through Gallants Channel under the Beaufort bridge, and rejoins the waterway just northeast of Phillips Island.

There are several natural channels in the lower estuary. One of these branches off the waterway just north of the Newport River bridge and passes between Crab Point and the Newport marshes. This Crab Point thoroughfare has a depth of up to 6 m (20 ft) but shoals to 1 m (3 ft) as it enters the main body of the open estuary. A second natural channel passes from the Newport River bridge to the east of Phillips Island and continues north across the Gallants Channel extension of the Intracoastal Waterway branch to Beaufort. This channel is over 6 m (20 ft) deep in places. A third natural channel begins as an extension of Gallants Channel and runs along the eastern side of the estuary, turns to the west and crosses the waterway and then shoals to 1.2 m (4 ft) as it enters the main body of the open estuary. This channel reaches depths of 3 to 5 m (10-15 ft).

The upper portion of the Newport River estuary consists of an open, smooth-bottom shallow area. Its deepest portion, approximately 2 m (6.6 ft), is in the middle. Progressing up the estuary to the west, the depths become shallower. At the western end of this portion there are several oyster reefs. The largest, Cross Rock, extends from the north shore of the estuary three quarters of the way across toward the south shore. Cross Rock is exposed at low tide but mostly covered at normal high tide. The water west of Cross Rock is extremely shallow, averaging less than 30 cm (1 ft) in depth at low tide. Then much of the area is exposed as a large uniform mudflat. The river-dominated portion of the estuary begins at the point where the estuary suddenly narrows (appropriately named the Nar-

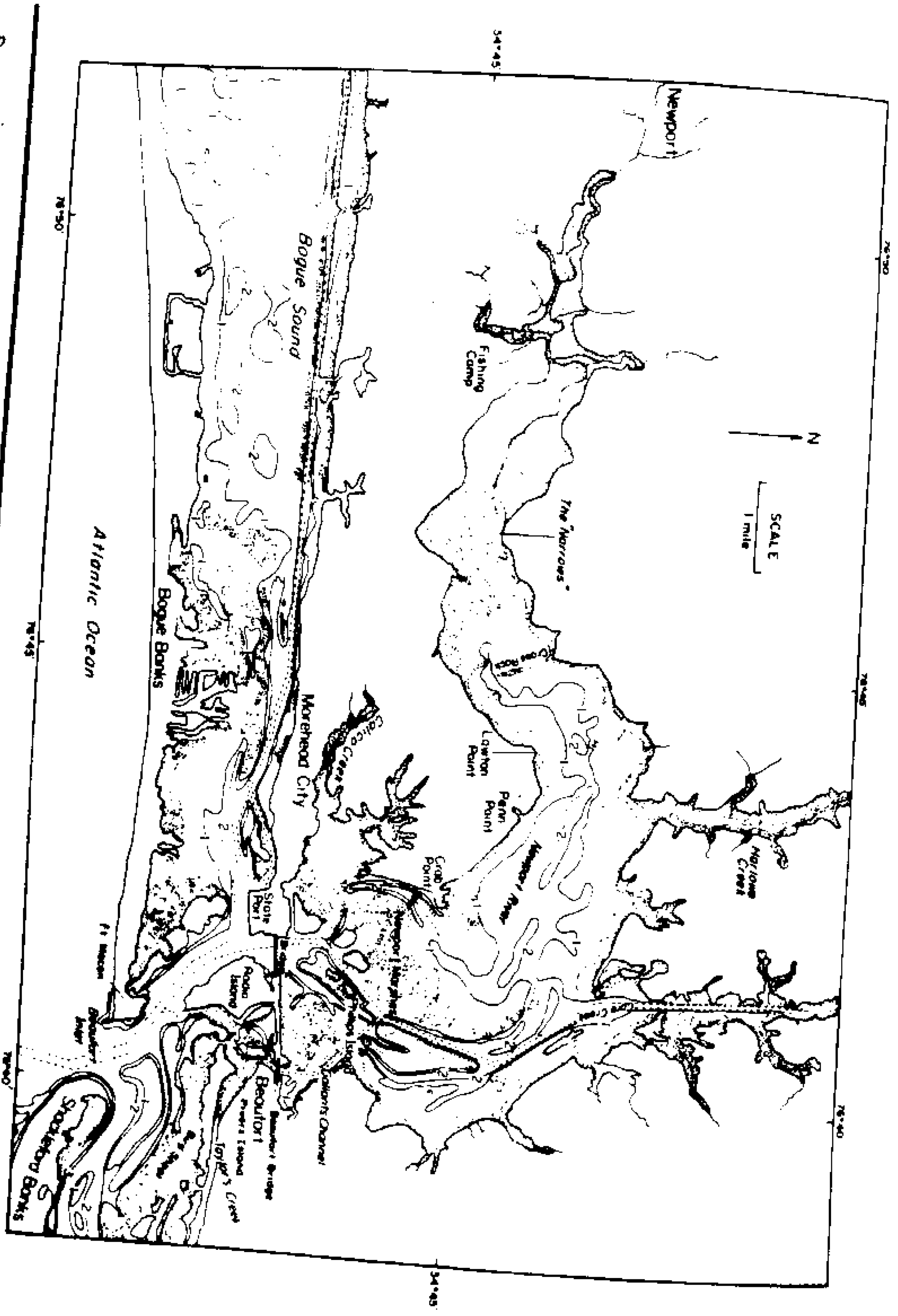
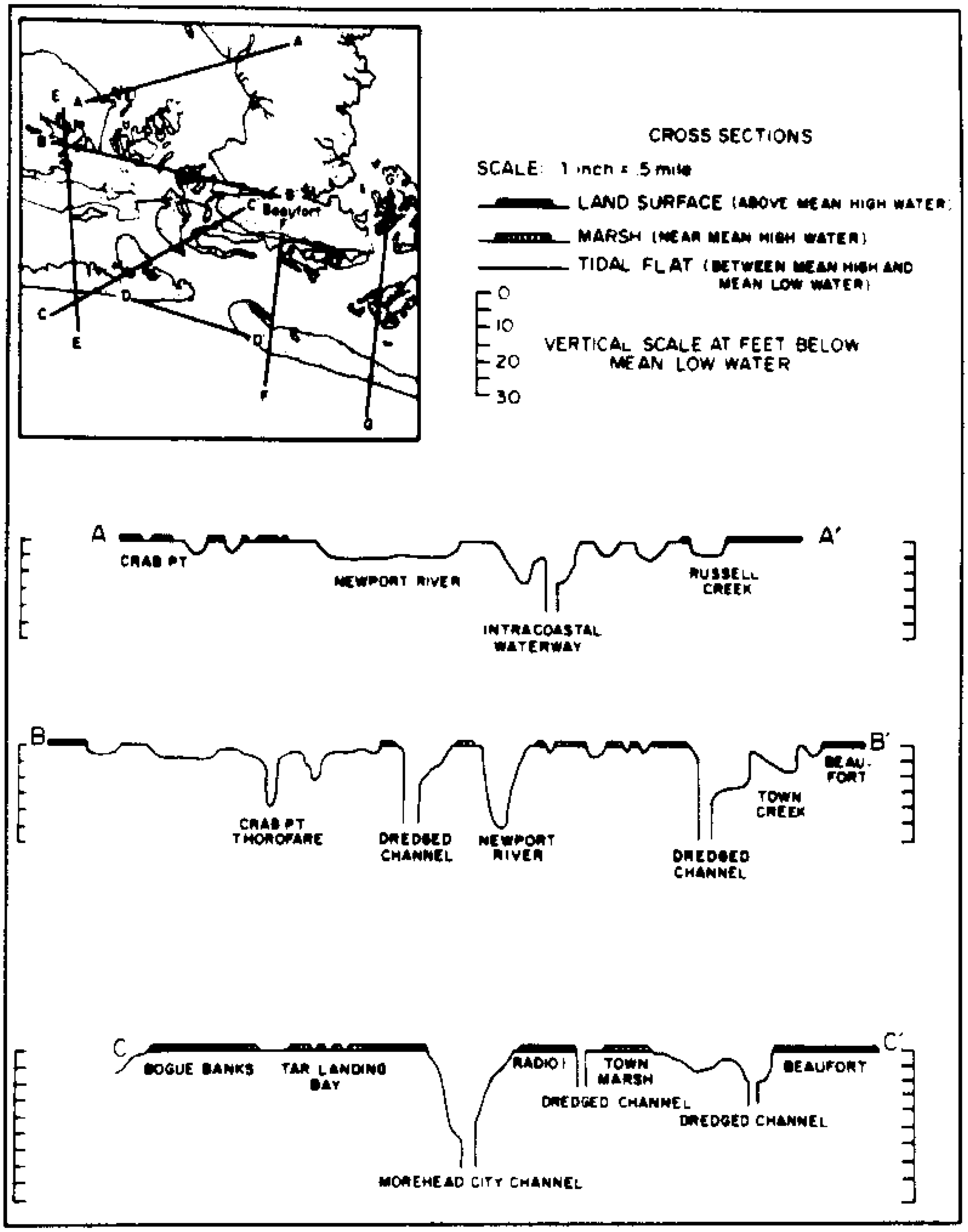


Figure 2. *Bathymetric map of the Newport River estuary (depth in meters).*

Figure 3A. Typical cross sections of the lower NRES (redrawn from Klavans, 1983)

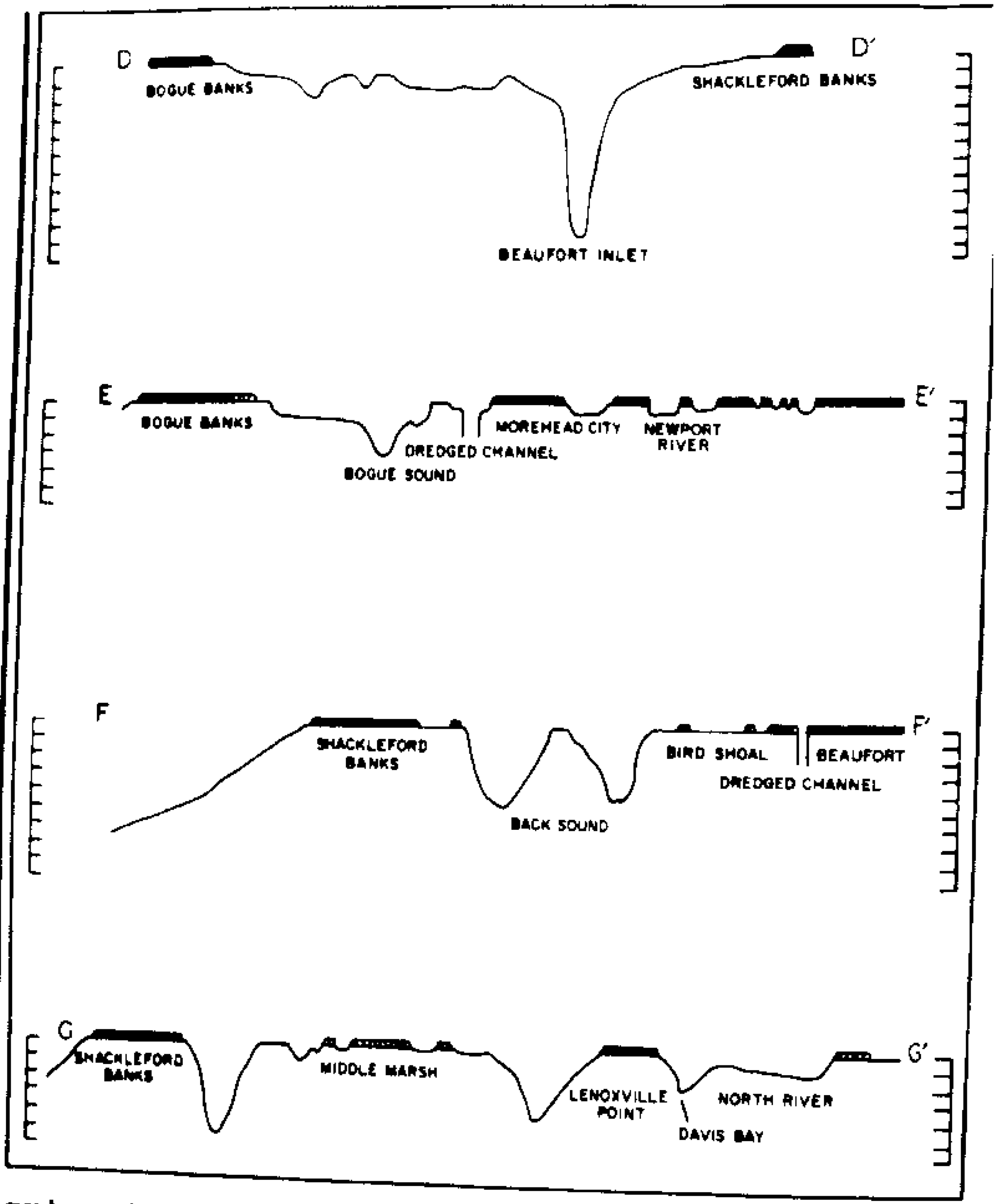


rows) to approximately 20 m (65 ft) width and deepens to 2 to 4 m (6.6-13.1 ft). This channel extends in a meandering fashion through marsh and forest becoming more and more riverine in nature until, near the town of Newport, it becomes a small coastal plains river.

The intertidal and subtidal portions of Bogue Sound are shown in Figure 4. At the eastern end of the sound is the state port with maintained depth of approximately 12 m (40 ft). The Intracoastal Waterway with a project depth of 3.7 m (12 ft) runs west from the port along the north shore of the sound (Figure 3; Transect E). The remainder of the area is shallow, averaging 1 m (3 ft) deep with some shallower sand shoals and a few deeper "holes" that may be 3 to 4 m (9-12 ft) deep. The sound is restricted at its eastern end by marshes and dredge- spoil islands.

The Back Sound and North River part of the NRES (Figure 5) consists in its lower section of a series of branching tidally scoured channels 5 to 7 m (15-20 ft) deep (Figure 3; Transects F-G). The position of many of these channels is constantly shifting, particularly in the area between Bird Shoal and Shackleford Banks. Two large marsh areas, Middle Marsh and the North River

Figure 3B. A continuance of Figure 3A. Note that depths are in increments of 5 ft (1.5 m).



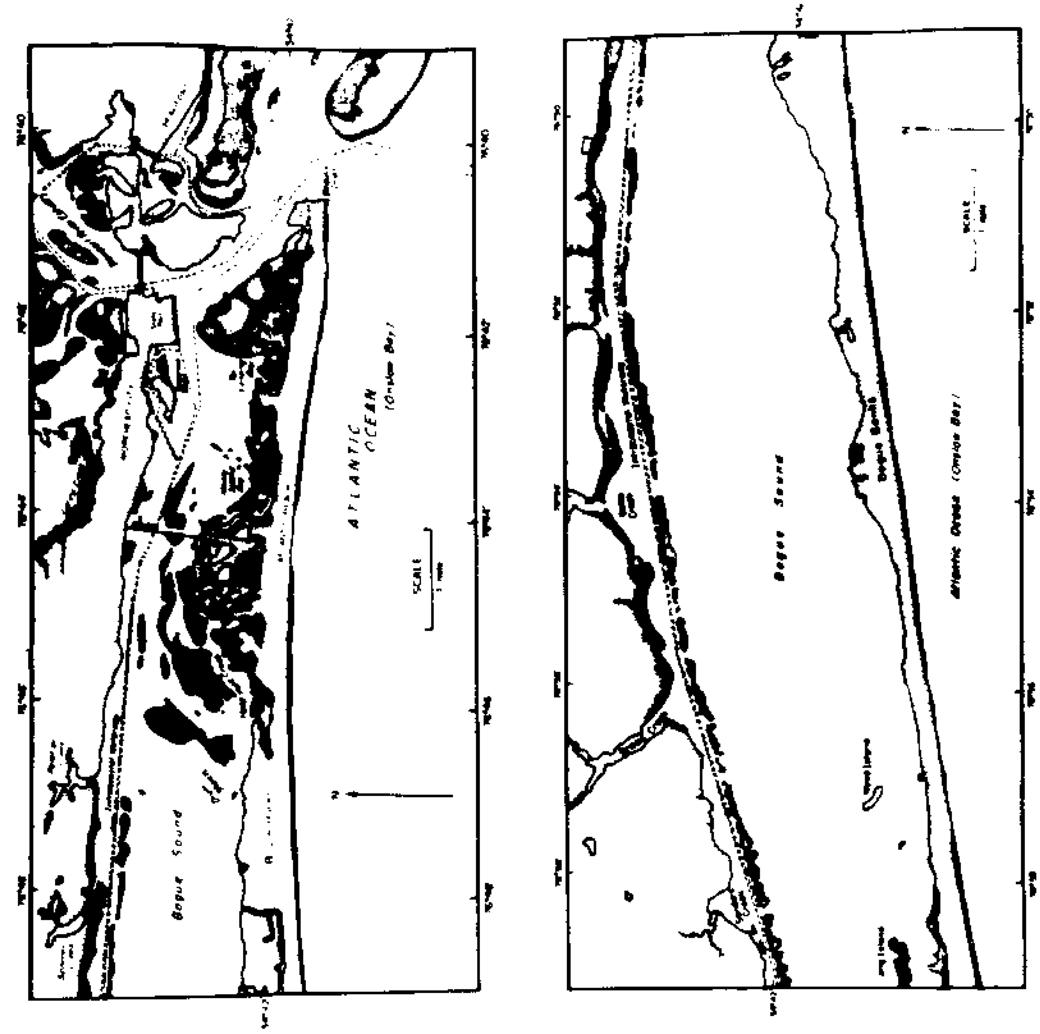
marshes, restrict the water surface area in the lower portion of this area. The eastern boundary of this part of the NRES cannot be fixed in space or time since waters of Back Sound and the Straits are freely connected with those of Core Sound. Although it has not been studied, the extent of water exchange across this boundary is probably dependent upon the tides acting together with variations in wind speed and direction.

The North River is a well-defined body of water. There are several small, undredged channels in its lower portion. In the upper part of the North River, there is no main channel and the water is very shallow, averaging 1 m (3 ft) deep south of the US 70 causeway and bridge and less than 30 cm (1 ft) deep north of the bridge. The estuary ends in a number of small tidal creeks that drain the surrounding swamp forest. Except for a short bridge, the upper most part of the North River is almost completely isolated by the US 70 causeway. The impact of this causeway has not been investigated.

Tides and Hydrography

The hydrography of the NRES is in large part determined by semidiurnal (twice daily) tides of approximately 1 m (3 ft) height. The recent study by Klavans (1983) of the lower NRES has provided a detailed picture of the tides and tidal currents of the system. In addition, volumes

Figure 4. Eastern and central part of the Bogue Sound part of the NRES.



of water movement, tidal exchange rates and tidal currents have been studied in the Newport River estuary (Brett 1963, Cronin 1979, Culliney 1969, Hettler 1974, Hyle 1976, Jennings et al. 1970, Mohammad 1961, Pinschmidt 1963) and to a lesser extent in Bogue Sound (Brett 1963).

Hyle (1976) showed that sea bed drifters released in the Beaufort Inlet can be carried into Bogue and Back Sounds as well as the main body of the Newport River estuary, thus confirming the observed tidal flow of water into and out of these areas apparent to everyone who has had experience on these waters. In addition, it is common knowledge that the patterns and volumes of water flow within the shallow sounds is profoundly influenced by wind speed and direction. For instance, during prolonged strong northeasterly winds, water will move from the Pamlico Sound through Core Sound to Back Sound and then out the Beaufort Inlet (Thayer 1969, Gutsell 1930). No doubt strong southwesterly winds will reverse this flow. Similar flow patterns probably occur in Bogue Sound also, especially with winds from the east (unusual) or the west. There have been no quantitative studies of these wind-induced flows.

Physically and hydrographically, the Newport River estuary, considered here as a part of the NRES, can itself be subdivided into two distinct parts. The main body of the estuary extends from the Beaufort Inlet to the Narrows (Figure 2) and is roughly 15 km (9.3 mi) in length and 4 to 5 km (2.5-3.1 mi) in width in its broadest segment (Mohammad 1961). This main section has an area of 26 km^2 (10 mi^2) (Hyle 1976). Jennings et al. (1970) said that this portion of the estuary had an average low tide depth of about 1 m (3 ft) and a tidal range of 0.8 m (2.6 ft). Hyle (1976) calculated a mean high water depth of 1.2 m (3.9 ft) and a high tide volume between the Beaufort and Morehead City causeway and the Narrows of 31 x $10^6 m^3$ (40.5 x 10^6 yd^3). Low water volume was calculated to be 17 x $10^6 m^3$ (22.2 x 10^6 yd^3), giving a tidal volume of 14 x

Figure 5.
Back Sound and North River part of the NRES.

10^6m^3 (18.3 x 10^6 yd^3) which is 45 percent of the total high tide volume. Based upon these calculations, nearly one half of the volume of the main part of the estuary moves in and out with each tide.

The second part of the estuary, that which continues above the Narrows, differs significantly from the main body of the estuary. This section consists of a narrow rectangular channel which meanders through a combination of low salinity saltmarsh (Spartina cynosuroides) and pine forest for approximately 27 km (16.8 mi). The exact point at which the estuary ends and the river begins varies, depending upon how far upstream the tidal flow of sea water extends. The tidal flow of water up and down the lower portion of this section of the estuary is very strong. Cronin (1979) estimated that 1 x 10^6m^3 (1.3 x 10^6 yd^3) of water moves through this narrow channel with each half tidal cycle.

Mohammad (1961) calculated that the entire Newport River estuary from Beaufort inlet to the town of Newport contained 73 x 10^6m^3 (95.4 x 10^6 yd^3) of water at low tide and had an intertidal volume of 29 x 10^6m^3 (37.9 x 10^6 yd^3). This would equal a high tide volume of 102 x 10^6m^3 (133 x 10^6 yd^3). Subtracting Hyle's (1976) estimate of the high tide volume of that segment of the estuary from the causeway to the Narrows (31 x 10^6m^3; 40.5 x 10^6 yd^3) from Mohammad's (1961) volume of the total Newport estuary (102 x 10^6m^3; 133 x 10^6 yd^3) results in an estimate that the portion of the Newport River estuary lying between the Beaufort Inlet and the causeway combined with that above the Narrows has a high tide volume of approximately 71 x 10^6m^3 (92.5 x 10^6 yd^3). This volume is not possible given the sizes and depths of these two segments. Since neither Hyle (1976) nor Mohammad (1961) show the steps in their calculations, it is not clear which is the more appropriate set of figures to use.

Estimates of the total volume of the NRES can be made using the areas from Table 1. Assuming an average depth of 1 m (3.28 ft) at low tide then the estimated volume of the Newport River estuary, Bogue Sound and Back Sound/North River estuary portions of the area would be 31 x 10^6m^3 (40.5 x 10^6 yd^3), 77 x 10^6m^3 (101 x 10^6 yd^3), and 60 x 10^6m^3 (78.4 x 10^6 yd^3), respectively. Thus the total volume of the NRES would be 168 x 10^6m^3 (220 x 10^6 yd^3).

Hettler (1974) measured the volume of water entering the Newport River estuary north of the Beaufort/Morehead City causeway on a flood tide on August 21, 1973. He measured the flow using synoptic current meter transects across four channels: the channel under the Newport River bridge, the channel under the Beaufort bridge, the channel under the Pivers Island bridge and the channel between Beaufort and Pivers Island. Adding the flow under the Newport River bridge and the Beaufort bridge gave the total flood tide volume of 42 x 10^6m^3 (54.9 x 10^6 yd^3). This volume is three times that of Hyle (1976), who calculated a volume of 14 x 10^6m^3 (18.3 x 10^6 yd^3) between the causeway and the Narrows, and 1.4 times that of Mohammad (1961), who estimated a tidal volume of 29 x 10^6m^3 (37.9 x 10^6 yd^3) for the entire estuary from the inlet to Newport. Hettler's (1974) data allowed him to calculate the percentage of the total flow passing through each of the four channels: 87 percent under the Newport River bridge and 13 percent under the Beaufort bridge. The 13 percent was made up of 6 percent flowing between Pivers Island and Beaufort, with 7 percent flowing under the Pivers Island bridge.

According to Klavans (1983), the tides in the NRES begin as a semidiurnal (twice a day) tide arriving at Beaufort Inlet. Because the tides are mainly lunar, each successive wave occurs approximately 25 minutes later. The tidal wave travels as a progressive damped wave at an average speed of approximately 2 knots (1.02 m/sec) as it progresses up the estuary. Away from the inlet the tide becomes mixed, mainly semidiurnal, meaning that there is a slight difference between the height of successive high or low stands of water. Moving inland away from the inlet the height of the tide wave decreases. In the Newport River estuary, this attenuation is low, averaging 0.1 ft/mi (1.9 cm/km), because the wave is partially reflected off the northern shore. Attenuation in Bogue and Back sounds is much greater, averaging 0.4 ft/mi (7.6 cm/km), because there is no reflection. Due to frictional drag, the maximum flood and ebb tide currents precede the times of high and low water. At the inlet, maximum flood currents occur 1.4 hours before high water, and maximum ebb currents occur 1.8 hours before low water. Three miles upstream in the middle of the Newport River estuary maximum flood currents precede high water by 3.1 hours, and maximum ebb currents precede low water by 2.8 hours.

In addition to the very detailed studies published by Klavans (1983), more simplified information on the tides in several parts of the system is available from two annual publications of the National Ocean Survey, National Oceanic and Atmospheric Administration, U.S. Department of Commerce: *Tide Tables for the East Coast of North and South America* and *Tidal Current Tables for the Atlantic Coast of North America*. For the most part, the data in these volumes are restricted to locations near the inlets. According to these tables, the mean tide range at Pivers Island is 0.91 m (3.0 ft), and the spring tide is 1.1 m (3.6 ft). Maximum current velocities in the channels near Beaufort Inlet range from 50 to 100 cm/sec (1-2 knots). According to Mohammad (1961), the tide tables for 1960 indicated a mean and spring tide range of 0.76 m (2.5 ft) and 0.91 m (3.0 ft), respectively. This suggests that the tidal ranges have increased over the past two decades, perhaps as a result of increases in the depth and width of the channel through the inlet.

As discussed by Klavans (1983), the times for high and low tides are delayed in proportion to the distance away from the inlet with he wave moving at an average speed of approximately 2 knots (1.02 m/sec). In the most extreme case, Mohammad (1961) found that near Newport the time of low tide was delayed 3 hours and the time of high tide 2.5 hours from the tides near the inlet. At a station located 1 km (0.62 mi) upstream from the Narrows, Culliney (1969) reported that the tides were one to two hours later than those predicted for Pivers Island. Brett (1963) reported that the tides in the center of Bogue Sound occurred approximately three hours later than the tides at the Beaufort Inlet. Continuous records of tides are made by the National Ocean Survey tide station at the Duke University Marine Laboratory, and the records are available from the NOS office in Rockville, Maryland. In addition, for the past 22 years the U.S. Army Corps of Engineers has kept a record every eight hours of tide height and current direction at the Core Creek bridge.

Freshwater flow can be an important contributor to current velocities above the mouth of the Narrows. However, where the estuary widens below the Narrows, tidal and wind drive currents are responsible for most of the mass water movements. In addition to the tidal current velocities reported in the U.S. Department of Commerce Tidal Current Tables, there have been several research reports that include measurements of tidal currents. Near Beaufort Inlet, Klavans (1983) reported mean maximum flood speeds of 1.0 m/sec (3.28 ft/sec) and mean maximum ebb speeds of 0.91 m/sec (2.98 ft/sec). Speeds then decreased at stations located up the estuary from the inlet, and the flood or ebb speed depended upon station location.

Mohammad (1961) measured surface current speed and direction on the ebb and flood tide at 13 locations between Beaufort Inlet and Newport (Figure 6). Strongest currents were found in the middle of the main ship channel near Beaufort Inlet and in the Intracoastal Waterway between Beaufort Inlet and Core Creek (1.1-0.35 m/sec; 3.6-1.14 ft/sec). Currents within the Narrows were somewhat weaker (0.38-0.21 m/sec; 1.25-0.69 ft/sec) and the currents in the shallow open estuary were the weakest measured (0.37-0.06 m/sec; 1.21-0.20 ft/sec). Surface current velocities were slightly higher on the ebb as compared to the flood tide. Due to the interference of wind-generated currents, Mohammad (1961) did not measure tidal currents when wind velocities exceeded 16 km/hr (10 mi/hr).

Culliney (1969) in an appendix to his thesis lists current velocity data from four locations between Pivers Island and the Narrows. He measured velocities hourly for one complete tidal cycle during four seasons. Maximum current velocities ranged from 0.84 to 1.65 km/hr (0.23-0.45 m/sec; 0.75-1.48 ft/sec), considerably less than those observed by Mohammad (1961). However, Culliney's stations were located out of the main axis of the channels and would be expected to have lower current velocities. Culliney (1969) also noted that at his station located in the middle of the estuary the winds strongly influenced the velocity (direction and speed) of the surface currents.

Tidal currents have been discussed in great detail by Cronin (1979) for the Narrows (Table 2). He reported currents that might be considered "typical" for estuarine waters: stronger flows downstream and longer ebb flow times near the surface. Flood tidal currents were stronger and longer lasting near the bottom. He averaged the currents at 0.5 m (1.64 ft) depths over a number of tidal cycles in an effort to calculate the residual nontidal current (the net speed and distance traveled) and the depth of no net motion (depth at which all the water flowing downstream past a point on the ebb would flow upstream on the flood). After the second day of his first study (Table 2), there was massive freshwater runoff following heavy rains. This runoff resulted in a large downstream residual current (net flow) and a large average displacement per tidal cycle. Differences between surface and bottom illustrate the still present, but mostly overpowered, bottom flood tide water movement. The last study (#4, Table 2) shows conditions that are probably more typical for the estuary. At this time the average residual current downstream was on the surface and upstream was on the bottom with a "depth of no net motion" in between. Maximum tidal currents averaged approximately 0.50 m/sec (1.64 ft/sec) except during the period of heavy runoff when current velocities measured greater than 0.50 m/sec on the ebb tide and less than 0.50 m/sec on the flood tide.

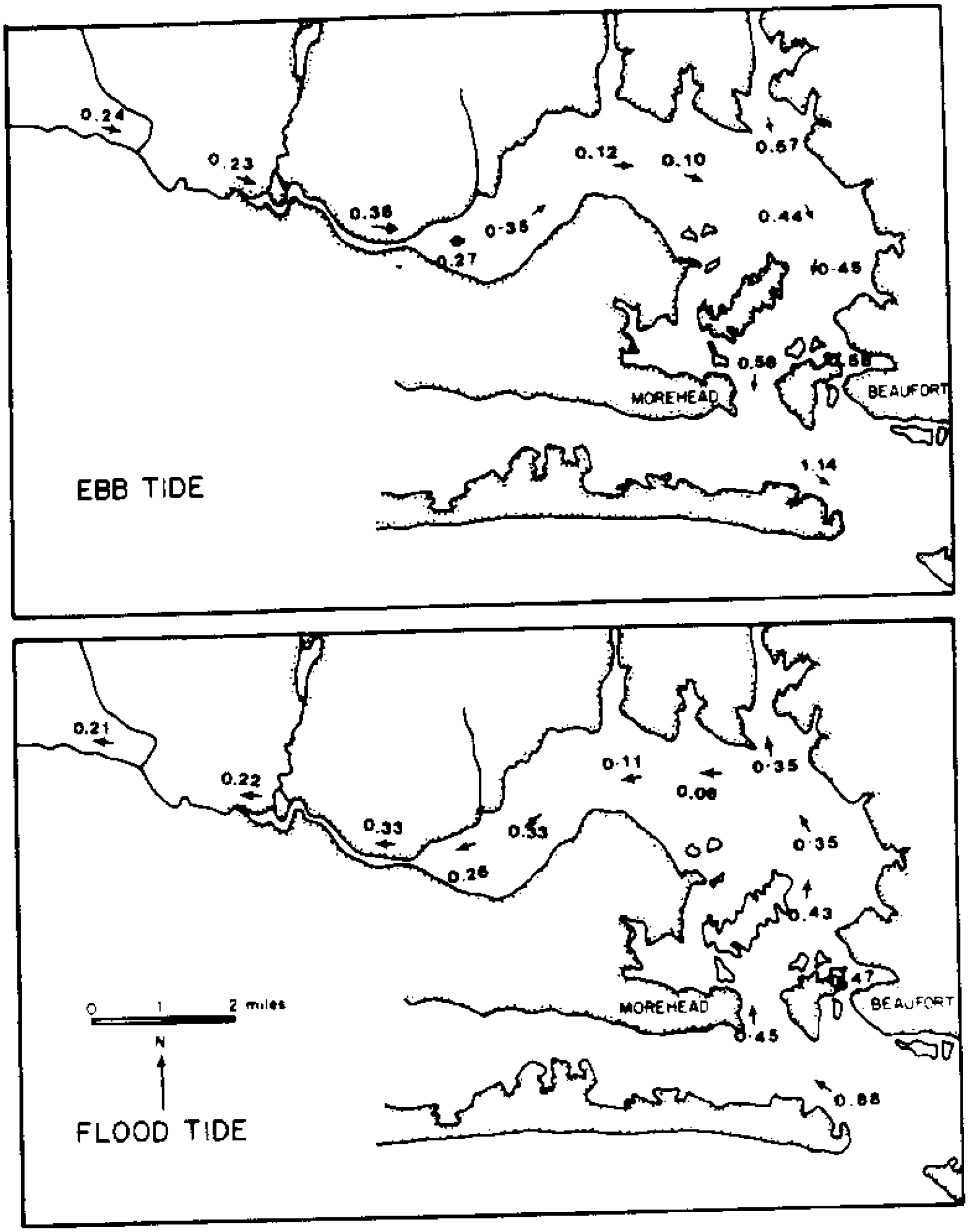


Figure 6. *Surface tidal currents (m/sec) on ebb and flood tides in the Newport River estuary (from Mohammad, 1961).*

The data on currents in Bogue Sound are fewer than for the Newport River estuary. Klavans (1983) had two stations in the Intracoastal Waterway in Bogue Sound. At the Atlantic Beach bridge, maximum flood speed was 0.73 m/sec (2.39 ft/sec) and maximum ebb speed was 0.74 m/sec (2.43 ft/sec). South of Sugarloaf Island maximum speeds were 0.58 m/sec (1.90 ft/sec) and 0.83 m/sec (2.72 ft/sec), respectively. Brett (1963) reported maximum tidal current velocities in the eastern end of Bogue Sound of 1.1 mph (0.50 m/sec; 1.64 ft/sec) and maximum velocities of 0.46 mph (0.20 m/sec; 0.66 ft/sec) in the middle section of the sound.

In the Back Sound and North River portion of the NRES, Klavans (1983) had two stations. In the channel between Middle Marsh and Carrot Island, he reported a maximum flood speed of 0.44 m/sec (1.44 ft/sec) and a maximum ebb speed of 0.66 m/sec (2.16 ft/sec). In a channel between Shackleford and Middle Marsh, the speeds were 0.71 m/sec (2.33 ft/sec) flood and 0.54 m/sec (1.77 ft/sec) ebb. Fonseca et al. (1983) reported an average maximum tidal velocity of 0.45 m/sec (1.48 ft/sec) at a site near Middle Marsh.

Table 2. Characteristics of the nontidal (residual) currents in the Narrows of the Newport River estuary averaged over several tidal cycles for four distinct time periods. Upstream values are positive; downstream are negative (Cronin 1979). A=average residual nontidal current in cm/sec; B=average displacement per tidal cycle in meters; C=number of tidal cycles averaged; D=depth of no net motion in meters; E=tidal depth range in meters.

Study	Depth(m)	A	B	C	D	E
#1 July 1-5 1977	0.0	-21.1	-9440			
	0.5	-19.4	-8660			
	1.0	-17.7	-7880			
	1.5	-15.5	-6940			
	2.0	-13.6	-6090	8	0	2.4—3.7
#2 Aug. 27-29 1977	0.0	-7.6	-3400			
	0.5	-5.8	-2590			
	1.0	-3.8	-1710			
	1.5	-1.8	-780			
	2.0	0.0	0			
	2.5	+1.1	+470	4	2.00	3.0—3.8
#3 July 7-11 1978	0.0	-5.5	-2480			
	0.5	-4.2	-1870			
	1.0	-2.8	-1260			
	1.5	-1.6	-700			
	2.0	-0.4	-160			
	2.5	+1.1	+470	7	2.13	3.0—4.1
#4 Aug. 29-Sept. 1 1978	0.0	-2.5	-1110			
	0.5	-2.0	-870			
	1.0	-1.4	-620			
	1.5	+0.2	+80			
	2.0	+1.5	+670			
	2.5	+3.9	+1750	5	1.45	3.0—3.8

Mixing and Exchange Rates

The NRES is usually well-mixed vertically by the winds and tidal currents. Occasionally, slight density gradients exist in the shallow open waters during periods of calm winds and/or heavy rainfall. More frequently, slight density stratification can be found in the deeper channels due to small differences in temperature and/or salinity between surface and bottom waters. Only in the protected and deep headwaters, such as the estuary above the Narrows, does strong density stratification occur very often. The NRES can thus be classified as a typical vertically homogeneous estuary.

Several estimates of exchange rates and horizontal mixing have been made for the Newport River estuary. Mohammad (1961) estimated an exchange ratio of 28 percent, with this ratio defined as the proportion of water moving seaward during each tidal cycle that does not return on the following flood tide. He assumed complete mixing of waters within the estuary and no return into the inlet of water that exited on the ebb tide. These two assumptions are undoubtedly false. Mohammad's exchange ratios should be considered as a theoretical maximum. Jennings et al. (1970) estimated flushing times, i.e. the time necessary for material entering the system via the Newport River to pass through the estuary. These flushing rate calculations were based upon estimates of river flow rates, tidal volume and bathymetry of the estuary. The report used a modified tidal prism method but showed no calculations and gave no references for the method. Their flushing times varied from 4.5 days (8.7 tidal cycles) during a period of estimated high river flow (11.2 m^3/sec, 17.8x10^6 ft^3/tidal cycle) to 9.6 days (18.4 tidal cycles) during estimated periods of low flow (0.4 m^3/sec, 0.6x10^6 ft^3/tidal cycle) with a mean of 6.4 days (12.3 tidal cycles). Jennings et al. (1970) also suggested that there was some exchange of water with the Neuse River estuary via the Core Creek Canal, but they did not quantify it.

The most complete estimates of flushing rates have been made by Hyle (1976). He used the tidal prism method of Ketchum (1951), plotting high tide, low tide and tidal prism volumes as a function of distance down the estuary from the Narrows to the Beaufort/Morehead City causeway (Figure 2). He then divided the estuary into seven segments using the tidal prism method. Exchange ratios for each segment were

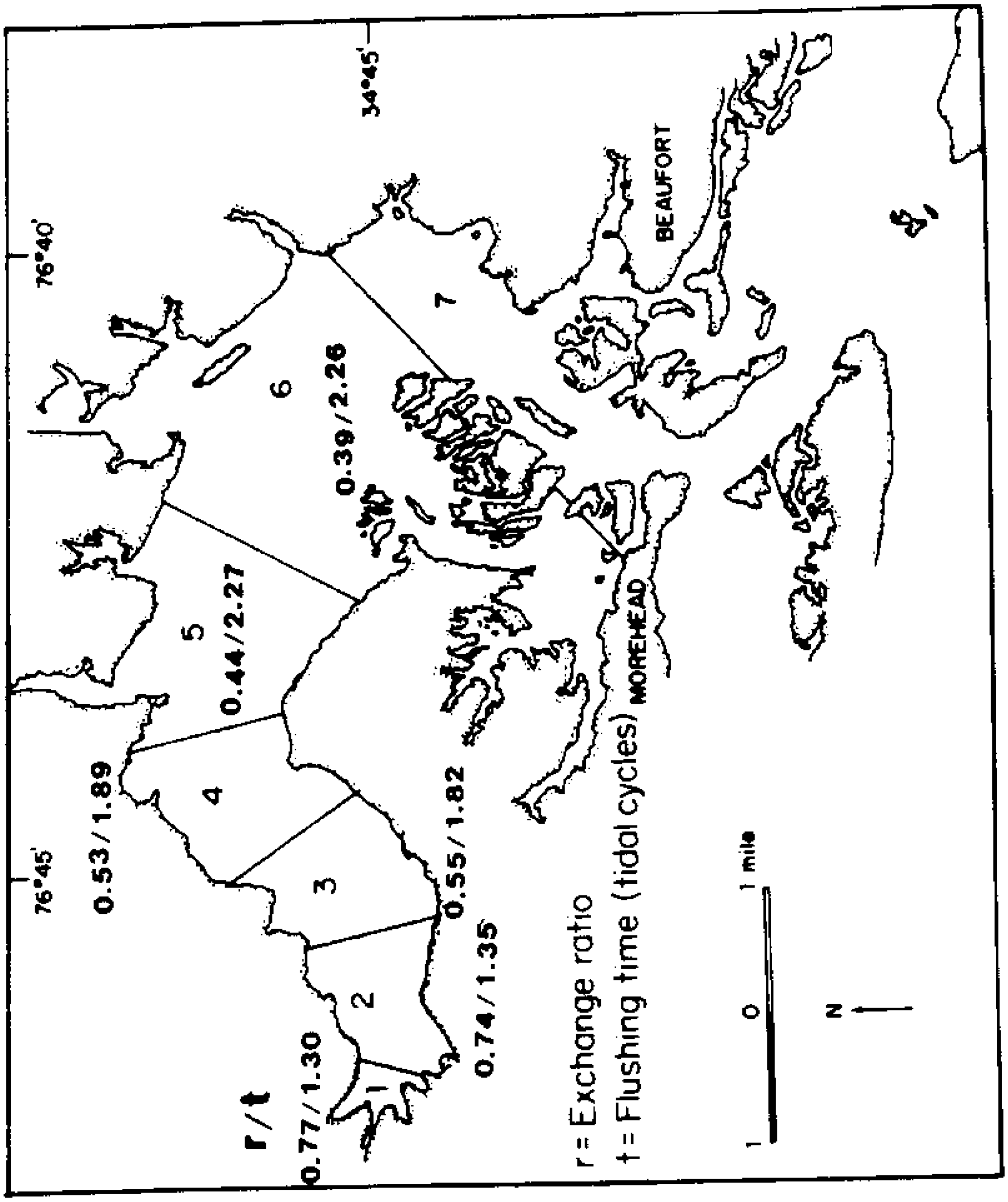


Figure 7. *Exchange ratios and flushing times (r/t) for segments of the Newport River estuary (from Ayle, 1976).*

calculated by $r_n=P_n/(P_n+V_n)$, where r_n is the exchange ratio, P_n is the intertidal volume, and V_n is the low tide volume of the "n"th segment. Hyle apparently used the same technique as Mohammad (1961), except that Hyle divided the estuary into seven segments. Mohammad considered the whole estuary as one segment.

The results of Hyle's (1976) calculations (Figure 7) show flushing times increasing downstream as the volume of the segments becomes greater. Total flushing time was estimated to be 12.06 tidal cycles of 6.26 days, using 1.925 tidal cycles/day as a conversion factor. This flushing time is very close to the mean of 12.3 tidal cycles estimated by Jennings et al. (1970).

These estimates assume that none of the tidal water ebbing out of the lower segment returns on the next flood tide and that complete mixing occurs within a segment. Thus within each segment these exchange rates should be considered theoretical maximum rates.

Mixing and exchange rates for Bogue Sound and for the Back Sound/North River area have not been estimated. Hyle's (1976) sea bed drifter data and Kazarian's (1983) dye movement data show that water from the Newport River estuary is probably mixed into the two other parts of the system with every tidal cycle. The rate of this mixing and how it is influenced by winds remains to be investigated.

Temperature

The water temperature data available for the NRES is voluminous. The National Marine Fisheries Service (NMFS) and the Duke University Marine Laboratory (DUML) maintain records of water temperature in the Beaufort Channel. The University of North Carolina Institute of Marine Sciences (IMS) keeps records of water temperature in Bogue Sound. And most of the field studies that have been done in the area report temperatures. The earliest complete annual record of water temperatures (Coker 1923) could serve as a predictor of the annual cycle of temperatures today.

The most extensive set of temperature data is that of the NMFS laboratory. This data set consists of a computerized summary of continuous recordings from five stations in the Newport River estuary in the late 1960s and 1970s (J. Willis, in preparation).

Water temperature in the NRES varies seasonally with changes in air temperature. Since the estuarine system is very shallow, it has a relatively large surface to volume ratio. This ratio coupled with the rapid tidal and wind mixing means that water temperatures can change very rapidly in response to changes in air temperature. Figure 8 (Kirby-Smith 1982) is a plot of maximum and minimum daily water temperatures for a three-year period taken at Pivers Island. The data illustrate three types of temporal variability in water temperatures. On a daily basis there is usually a 1 C to 3 C difference between maximum and minimum temperature associated with the tides. In the winter (January-February), maximum temperatures usually coincide with high tide (oceanic water); minimum, with low tides (estuarine water). The reverse is true during the summer (July-August). A second temporal cycle is evident in Figure 7 as a one to two week "saw tooth" pattern. These weekly variations are the result of passing weather fronts that during the spring and fall can result in a 10 C change in water temperature over a few days. In the spring and fall, the passing fronts cause an approximate 5 C change over periods of one week. If the data shown in Figure 8 were plotted as biweekly or monthly mean water temperatures, then the curves would be smoothed and would show a very regular pattern of seasonal changes with minimum biweekly mean temperatures near 5 C in January and February and maximum biweekly mean temperatures near 29 C in July and August.

The seasonal pattern in mean weekly water temperatures was analyzed in detail by Hettler and Chester (1982) from 1962 to 1981. Based upon the results of their analyses, weekly mean water temperatures can best be predicted by the following equation:

$$T_w = 17.88 - 5.20 \, Sin(2PiW/52) - 7.94 \, Cos(2PiW/52)$$

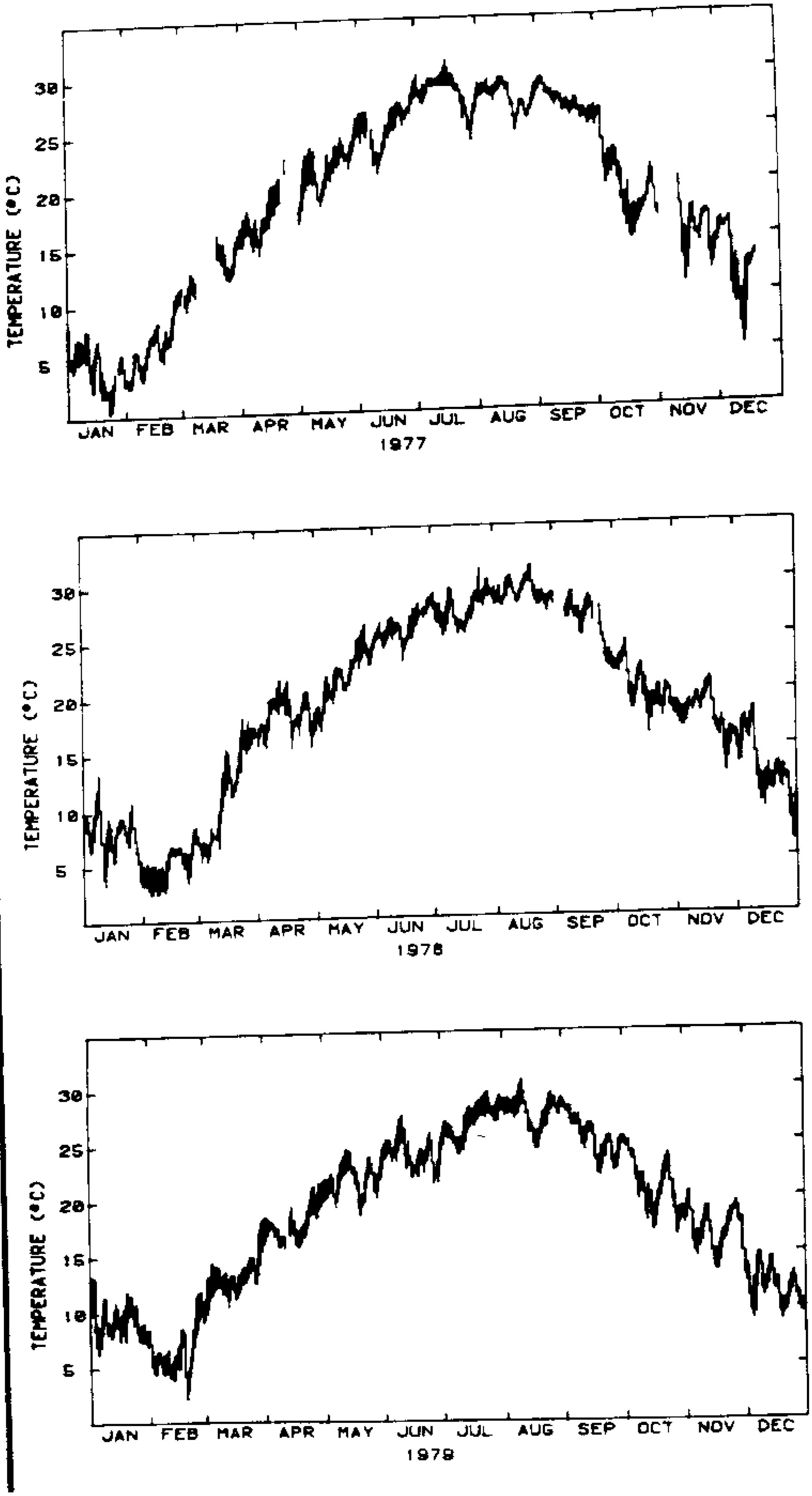
where W is the week of the year (1-52). They also found a strong correlation ($r^2 = 0.97$) between mean weekly air and water temperatures on an annual cycle. However, examination of the relationship when mean weekly water temperatures were below 12 C showed a much poorer relationship between air and water temperatures ($r^2 = 0.67$).

In addition to the regular seasonal differences in temperature, there are significant but unpredictable differences from year to year (Figure 8). For instance, the winter of 1976-1977 was extremely cold but short. A minimum temperature of near 0 C occurred on January 25, 1977. However the temperature had warmed to 12 C by March 1. In 1978, the winter temperatures were not as cold, but the winter lasted longer. In contrast, 1979 would be considered a mild winter with only a few days when the water temperature remained below 5 C with a very rapid warming in the last week of February. Summer differences also occur from year to year, although the maximum temperature recorded is usually around 30 C. In 1983, a record-breaking heat wave during the late summer resulted in maximum daily water temperatures at Pivers Island remaining at or above 30 C from about mid-July to mid-September (Duke Marine Laboratory records). The highest water temperature recorded was 32.8 C on August 22 which, using he DUML data, was a record for the Beaufort Channel for the period 1970 to 1984. Furgeson (personal communication) reports similar highs (32.5 C) during late August and early September 1970.

In addition to its variability in time, temperature also varies significantly in space in the Newport River estuary. Furgeson (personal communication) has observed a 10 C change over a 1 km distance between the Narrows and Cross Rock. Other spacial variability occurs in the shallow water covering the intertidal flats. In the summer with a low tide in the middle of the day the shallow waters over the flats may be 5 C warmer than the nearby channels, and temperatures in isolated tide pools may be 10 C warmer (personal observation). In the winter, the reverse is true.

Temperatures in the open waters of the estuary vary much less from place to place. Pinschmidt (1963) found slightly cooler temperatures summer and winter in the fresh headwaters of the estuary near Newport, but he also noted very little differences in temperatures among locations in the main body of the estuary. Rice and Furgeson (1975) compared a continuous record of temperature from a location near Phillips Island in Gallants Channel (Station 1) with that at

Figure 8. *Maximum and minimum daily water temperatures in the Beaufort Channel at the Duke University Marine Laboratory dock for 1977 to 1979 (from Kirby-Smith, 1982).*



a location above the Narrows at Fishing Camp (Station 5). At Station 1, the mean annual temperature was 19.0 C with a range of 31.0 C to 2.1 C and a maximum hourly gradient of 4.0 C. At Station 5, the mean was 18.0 C, the range was 32.5 C to 0.0 C, and the maximum hourly gradient was 6.2 C. Mohammad (1961) and Hyle (1976) remarked that there was little difference in temperature among their stations in the estuary. The very significant differences in temperature between locations as shown in Hyle (1976) are probably due to sampling on two separate dates. Brett (1963) reported relatively high temperatures (32 C to 33 C) for Bogue Sound in September 1959. This data suggests that Bogue Sound may have slightly higher summer maximum temperatures as compared with waters off Pivers Island.

The only long-term recorded water temperature for the North River is a computerized set of data from 1971 to the present. These data are taken once a month (March-November) at two stations, one at the U.S. 70/Bridge and a second upstream where the system narrows.

Salinity

Salinity, the total amount of dissolved solids in one kilogram of seawater, is expressed here as ppt (parts per thousand). Estuaries are defined, in part, as places where seawater is measurably diluted by fresh water. Since the time, place and amount of fresh water entering the NRES from precipitation and runoff from rivers and creeks is predictable only within wide limits, it is not surprising that salinity is highly variable in time and space. It might be expected that the ultimate limits on salinities in an estuary would be from fresh water (0 ppt) to open ocean seawater (34.5 ppt). However, in the NRES evaporation in the summer can frequently raise salinity in the protected waters of the estuary and sounds to 36 to 38 ppt.

Next to temperature, salinity has been the most commonly recorded environmental variable in the published literature relevant to the NRES. These records vary from detailed tidal cycle studies at one time and place (for example, Cronin 1979) to 17-year monthly averages (Williams and Deubler 1968). The most extensive salinity record collected in the NRES was at the NMFS laboratory, which collected continuous records of salinity at five stations over a several years during the late 1960s and 1970s (J. Willis, in preparation). The stations in this study were located as follows: (1) Gallants Channel across from Phillips Island, (2) in the middle of the estuary opposite the mouth of Core Creek, (3) in the middle of the estuary opposite Harlowe Creek, (4) in the small channel of the southern tip of Cross Rock, and (5) at Fishing Camp approximately 4 km upstream from the Narrows.

Historically, the Winslow (1886) published the earliest report that dealt with salinity. He measured specific gravities at different tidal stages and seasons. Wheeler (1910) quantitatively analyzed the chemical composition and reported specific gravities for four samples of seawater from the Newport River estuary. Hoyt (1920) reported maximum, minimum and mean monthly seawater density for 1913 to 1914 at Pivers Island (Table 3). The most extensive (temporally) early report of salinity published for

Table 3.
Mean monthly seawater density readings based upon daily (5 p.m.) readings taken at Pivers Island from 1913 to 1914 by Hoyt (1920). Salinities are estimates using Hoyt's (1920) mean monthly temperatures (Hoyt's Table 9 for 1913-1914) as the temperature at the time of density measurement combined with Zerbe and Taylor (1953) seawater temperature and density reduction tables.

Date		Average Temperature	Maximum		Minimum		Average	
			Hydro.	Sal.	Hydro.	Sal.	Hydro.	Sal.
1913	June	21.0	1.0228	32.2	1.0184	26.7	1.0209	30.1
	July	27.8	1.0238	36.4	1.0216	33.5	1.0228	35.1
	Aug	27.8	1.0226	34.9	1.0200	31.4	1.0210	32.7
	Sept	24.6	1.0204	30.7	1.0132	21.2	1.0168	25.9
	Oct	19.9	1.0236	33.3	1.0170	24.6	1.0199	28.4
	Nov	13.6	1.0240	32.0	1.0102	14.1	1.0209	28.1
	Dec	10.5	1.0256	33.6	1.0192	25.4	1.0226	29.7
1914	Jan	9.4	1.0248	32.1	1.0186	24.3	1.0212	27.7
	Feb	9.4	1.0220	28.6	1.0100	13.2	1.0179	23.4
	March	9.8	1.0204	26.7	1.0100	14.9	1.0173	22.7
	April	16.8	1.0218	30.1	1.0150	21.2	1.0183	25.5
	May	22.0	1.0234	33.7	1.0190	27.8	1.0212	30.7
	June	26.1	1.0258	38.2	1.0210	31.9	1.0234	35.0
	July	28.0	1.0246	37.5	1.0220	34.0	1.0230	35.4

Table 4. Maximum and minimum salinities recorded at Pivers Island from 1924 to 1928 and based on daily hydrometer readings (Gutsell 1930).

Month	Year									
	1924		1925		1926		1927		1928	
	max	min	max	min	max	min	max	min	max	min
Jan.	32	31	27	14	32	22	33	26	35	26
Feb.	30	16	24	18	29	20	35	28	35	26
Mar.	29	20	27	18	31	20	31	22	34	25
Apr.	31	18	30	15	33	21	34	25	35	27
May	33	27	32	30	35	27	35	31	35	23
June	32	23	35	31	36	22	37	34	37	32
July	30	21	36	28	35	33	38	35	38	35
Aug.	32	21	35	24	38	34	38	30	38	35
Sept.	32	6	35	28	37	32	35	28	35	24
Oct.	25	14	35	28	34	30	34	28	32	19
Nov.	28	16	35	27	35	28	34	27	34	21
Dec.	32	23	33	27	34	27	34	20	37	23

the NRES was that of Gutsell (1930). He presented a summary of four years (1924-1928) of data from daily hydrometer (specific gravity converted to salinity) readings at Pivers Island (Table 4). Williams and Deubler (1968) provided long-term salinity data, particularly for Bogue Sound. Unpublished records of salinity are currently kept for Bogue Sound at the Institute of Marine Sciences and, on occasion, at the Duke University Marine Laboratory for the Beaufort Channel. Numerous records of salinity (discrete samples taken periodically) exist in the published record (Allwein 1966, Culliney 1969, Brett 1963, Chestnut 1952, Commito 1976, Hyle 1976, Kruczynski 1971, 1973, Maturo 1956, Mohammad 1961, Pinschmidt 1963, Schwartz and Chestnut 1973, Williams et al. 1973).

The temporal and spacial variability of salinity in the NRES are well illustrated in Figure 9 (Pinschmidt 1963). Monthly means of weekly collections, obtained alternately at low and high tides, are presented for five stations located in a transect from Beaufort Inlet to Newport. Surface and bottom salinities are presented for a one-year period, August 1960 to July 1961. Although the extremes may not have been measured by Pinschmidt (1963), his data (Figure 9) are representative of the patterns that have been observed in the estuary. Salinity near the Beaufort Inlet is high with relatively little variation, averaging between 30 and 35 ppt. Moving up the estuary the salinity drops and becomes more variable. Beyond the Narrows, salinities fall to near zero at Newport. In general, bottom salinities are slightly higher than surface salinities, suggesting some stratification. However, because wind-mixing is so strong in these shallow waters (at least below the Narrows), this slight stratification probably has little biological significance. Seasonally, salinities are usually lower in the winter and spring due to lower evaporation and transpiration in he marshes. However, temporal pattern of rainfall does not have a strong seasonal component, and occasional decreases in salinity can be expected during any month of the year.

Rice and Ferguson (1975) published a one-year summary (Table 5) of the salinity data collected from the five stations in the Newport River estuary. Cross Rock and the estuary opposite Core Creek had the greatest range in salinities (30 ppt), but Fishing Camp had the greatest maximum hourly gradient, 20.0 ppt, a value not much different from the annual range, 26.3 ppt. Data from the estuary opposite Core Creek are more variable than those from stations upstream or downstream. This suggests a possible influence of Neuse River estuary water moving into the Newport via the Intracoastal Waterway. Ignoring this station, it is apparent that salinity variability increases upstream on an annual range and in maximum hourly gradients. In the future, more detailed analysis of these data will probably address the question of temporal and spatial variability in greater detail (J. Willis, in preparation).

The greatest documented short-term reductions in salinities occurred following very heavy rainfall in the autumn (possibly associated with a tropical storm). A measurement of 6 ppt was taken at Pivers Island in September 1924 (Gutsell 1930) and 10.2 ppt at Pivers Island following a hurricane in September 1955 (Wells 1958). Higher than oceanic salinities are occasionally recorded during summer months associated with drought and high evaporation (Gutsell 1930,

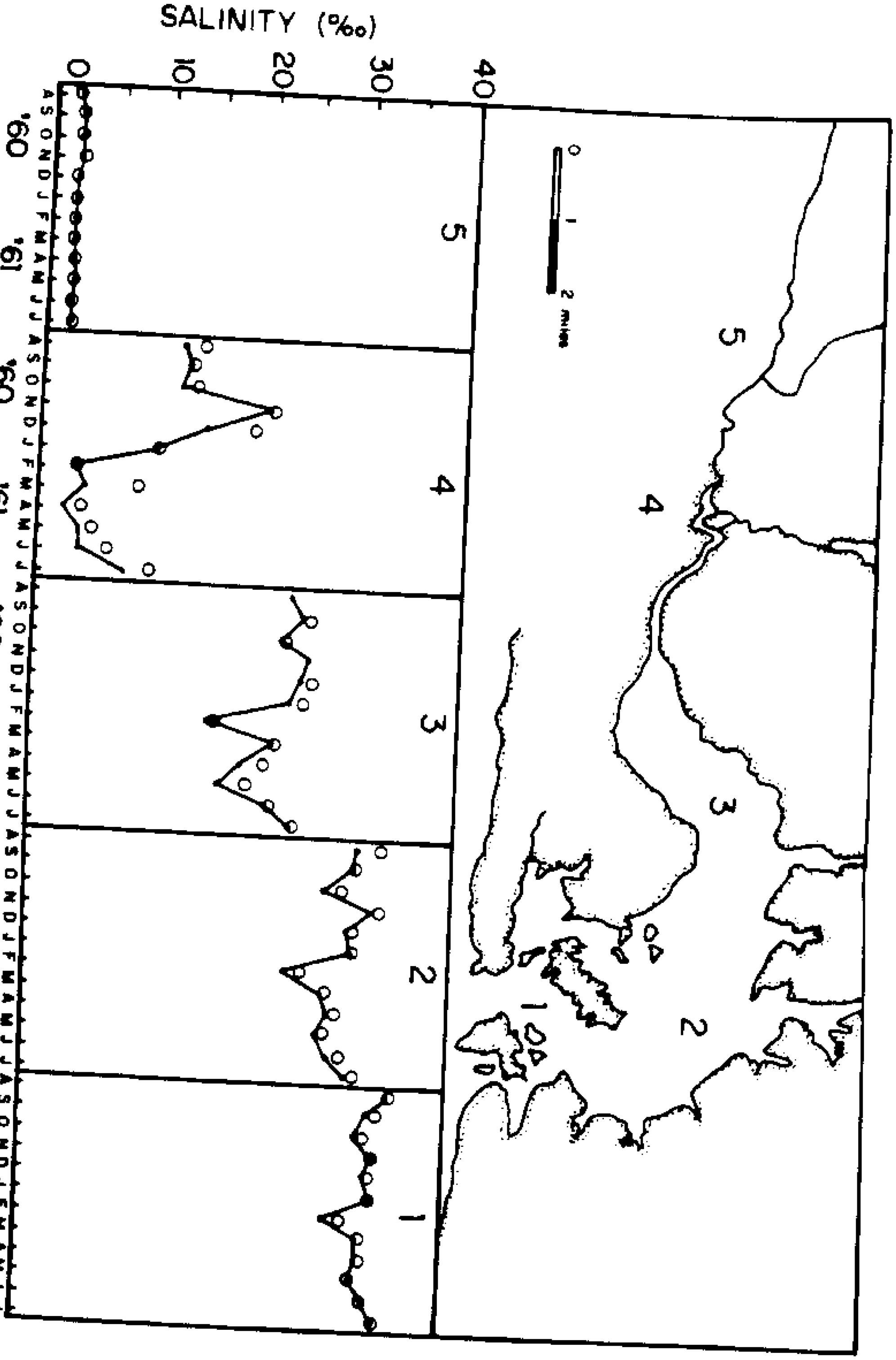


Figure 9. Patterns in time and space of salinity (ppt) at five locations in the Newport River estuary. Data are monthly means of weekly collections obtained alternately at low and high tides at five stations located in the Newport River estuary (from Pinschmidt, 1963).

Table 5. Fluctuations in salinity (ppt) at five stations in the Newport River estuary from Oct. 1969 to Oct. 1970 (Rice and Ferguson 1975)

Station	Mean	Range	Max. Hourly Gradient
(1) Gallant Channel	27.8	35.5 — 15.4	7.6
(2)Core Creek Range Light	23.2	36.5 — 6.0	12.8
(3) South of Harlowe Creek	21.0	32.0 — 7.0	6.7
(4) Cross Rock	17.2	30.0 — 0.0	12.0
(5) Fishing Camp	3.8	26.3 — 0.0	20.0

Culliney 1969, Krucsynski 1971, Thayer et al. 1980). The highest published salinity of open waters in the NRES is 49.7 ppt at Cross Rock in November 1974 (Committo 1976). However it is unlikely that any appreciable volume of water had such a salinity for more than a few hours due to the rapid mixing of estuarine waters.

Salinities of Bogue Sound water are generally higher and less variable than those at Pivers Island in the lower Newport River estuary (Williams and Deubler 1968). A monthly mean salinity comparison between Pivers Island (1947-1949) and Bogue Sound at the Institute of Marine Science (1949-1966) indicates that seawater had mean low values in March of 25.5 ppt at Pivers Island and 29.7 ppt at Bogue Sound and mean high values of 33.0 ppt in July at Pivers Island and 33.7 ppt in June at Bogue Sound. Kruczynski (1973) measured salinities along a transect through Bogue Sound from Bogue to Beaufort Inlets on three dates. The data show decreasing salinities from the two inlets with a minimum value closer to Beaufort than Bogue Inlet. Brett (1963) observed a 1 to 2 ppt increase in salinity from the north to the south shore of Bogue Sound and attributed this to freshwater runoff from the creeks along the mainland (north) shore. Campbell (1973) measured salinity in Gales Creek, located off Bogue Sound, for one year. His data have a typical estuarine pattern: high values at the mouth of the creek, fresh water on the surface of the headwaters, frequent stratification in the upper reaches and much lower salinities throughout the system following heavy rainfall.

The N.C. Division of Marine Fisheries has collected the most extensive set of salinity data for the North River. It has data from two stations, #46-U.S. 70 Bridge and CC5 upstream where the estuary narrows. The data, taken from 1971 to 1986, consists of data taken once a month from March through November. Those data indicate that salinity in the North River is very similar to that in the Newport River with upstream values from 0 ppt to over 30 ppt depending upon local rainfall. Some salinity data for the Back Sound/North River area are given in Williams et al. (1973). Data from Thayer et al. (1980) suggest that salinities are relatively high (average 34-35 ppt) in the area between Beaufort Inlet and Harkers Island. A horizontal salinity gradient must occur in the North River estuary. Except for the headwaters (Kirby-Smith and Barber 1979), no detailed studies of salinity or other water quality parameters are available for this area.

Short-term (tidal) variations in salinity can be very significant depending upon the location. Culliney's (1969) data from his 12-hour tidal cycle studies (Figure 10) illustrate the tidal variability in salinity as a function of location in the estuary. In the Newport River estuary, the least salinity variability associated with the tides was found near the inlet (Station 1) and again in the middle of the estuary between Harlow Creek and Lawton Point (Station 3). Greater salinity variations existed at Station 2, and the greatest variability observed was at the Narrows (Station 4). The low variability in tidal salinity changes in the middle of the estuary was also noted by Hyle (1976). Jennings et al. (1970) suggested that drainage from the Neuse River via Core Creek canal may be responsible for the high variability in the area between Phillips Island and the entrance to Core Creek. Such increased variability near Core Creek was also present in the data of Rice and Ferguson (1975). It had a maximum hourly gradient of 12.8 ppt. Palumbo (1978) recorded means and standard deviations for salinity over a 24-hour period at three locations and three dates in 1978 in the Newport River estuary. His data showed very low salinities and low variability at a station half way up the Narrows, intermediate but highly variable salinity at a point between the Narrows and Cross Rock, and high salinities with low variability at Pivers Island. Cronin (1979) occupied stations 2 to 4 km (1.2 - 2.5 mi) upstream from the mouth of the Narrows on four occasions. He sampled every hour at 0.5 m (1.6 ft) depth intervals over four-day periods. At the beginning of his study 1, salinities were oscillating between 2 ppt to 3 ppt at low tide and up to 28 ppt at high tide. Following heavy rainfall, the salinities dropped to near zero on low and high tides. More typical for this area are Cronin's (1979) studies 2 to 4 that show sa-

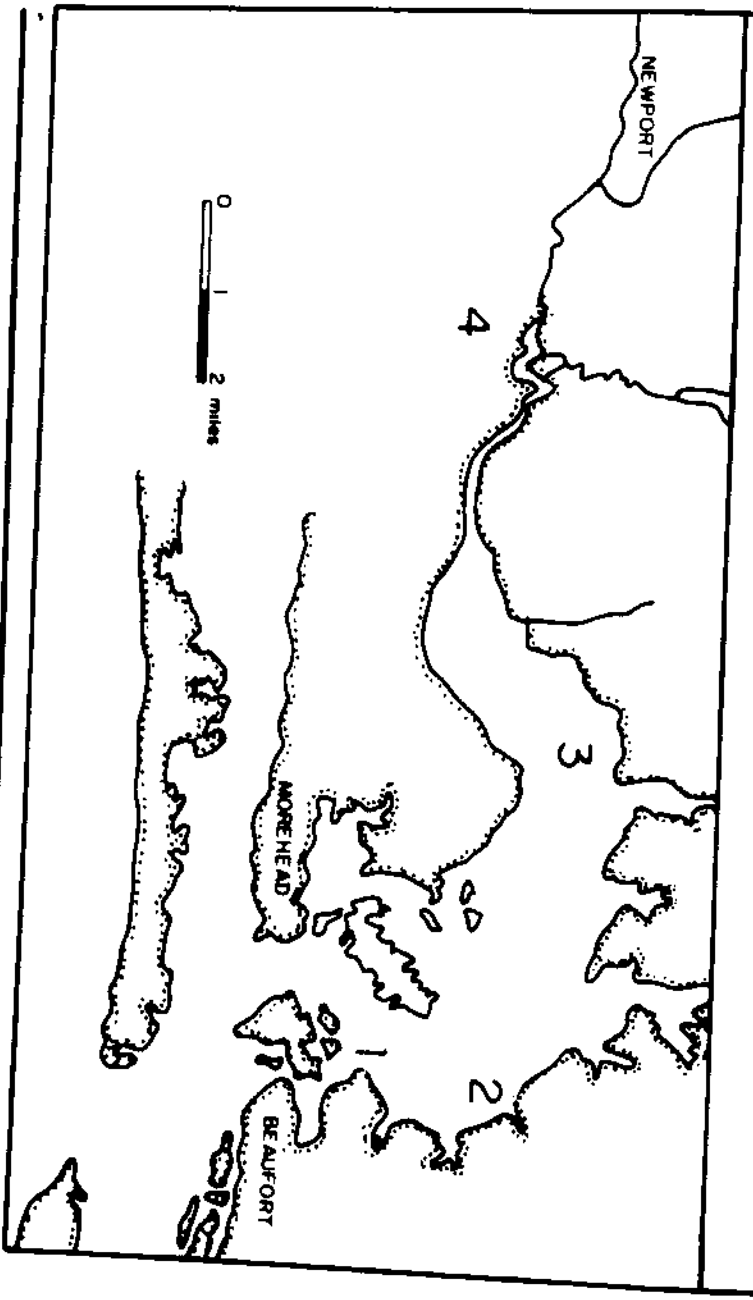


Figure 10. Short-term variations in salinity (ppt) in the Newport River estuary. Data (maximun, minimum, range) are from 12-hour tidal cycles during the four seasons (from Culliney, 1969).

SEASON	STA. 4			STA. 3			STA. 2			STA. 1		
	MAX	MIN	RG	MAX	MIN	RG	MAX	MIN	RG	MAX	MIN	RG
AUT	13.7	1.2	12.5	27.4	26.3	1.1	35.0	27.1	7.9	34.6	31.8	2.8
WIN	6.9	3.8	3.1	31.4	30.1	1.3	35.6	29.0	6.6	37.0	36.1	0.9
SP	15.2	0.7	14.5	23.1	18.4	4.7	30.0	22.0	8.0	30.0	26.9	3.1
SU	-	-	-	23.9	20.2	3.7	-	-	-	31.7	30.4	1.3

linity varying over 15 ppt to 20 ppt during a tidal cycle. As discussed above, this location in the Narrows has the most variable salinities that have been reported (Rice and Ferguson 1975) for the Newport River estuary and a maximum hourly gradient of 20.0 ppt.

Possible long-term shifts in average salinities in the Newport River estuary were discussed by Culliney (1969). To explain a shift in shipworm species present at Pivers Island over a 70-year period, Culliney (1969) compared his salinity data with that of Atwood and Johnson (1924). He indicated that salinities had increased significantly at Pivers Island. He attributed this shift to the enlargement of the main ships channel through Beaufort Inlet and thus an increased tidal flow. Other sets of salinity data support the idea that salinities in the Newport River are higher on the average today than they were prior to the 1930s. Table 3 presents data from 1913 to 1914 (Hoyt 1920) collected at Pivers Island. It suggests that the maximum, minimum and mean salinities are lower than the recent values collected at the Duke Marine Laboratory dock on Pivers Island by the author. A more extensive set of early data (Table 4) comes from Gutsell (1930). These data are based upon summaries of daily hydrometer readings taken at Pivers Island for several years. Comparing these data with the recent data, the maximum salinity values for the summer months 1925 to 1928 are similar to those recorded recently. But the minimum values are almost always lower, particularly during the winter months. These data thus support Culliney's (1969) suggestion. One set of data that does not support this idea is that of Allwein (1966). She measured high tide salinity values in the main channel between Radio Island and Beaufort Inlet once a week from 1964 to 1965. Her values ranged from a high near 32 ppt in August 1964 and 1965 to a low of approximately 22 ppt in July 1964. Because her samples were all taken just inside the inlet at high tide, it is probable that there was a systematic error 3 ppt to 4 ppt lower than actually existed. But despite this error, her data suggest a considerably lower salinity regime than exists at present.

It is possible that what appears to be long-term shifts in salinity are in fact alternating wet and dry periods that may span several years. By comparing salinity records with rainfall and/or river runoff data, perhaps we could answer the question of whether or not long-term salinity changes have occurred in the Newport River estuary. Furthermore, a detailed study of the effects of channel enlargement via dredging might suggest whether the changes in physical circulation could have resulted in salinity changes. However, one potential problem with the salinity record lies in the possibility of systematic errors in the original measurements due to differences in the techniques used over the years.

Rainfall

Rainfall data for the NRES (Table 6) suggest that there is little seasonality to the pattern of precipitation in eastern North Carolina. There is no pronounced wet or dry season. The greatest average monthly rainfall occurs in the late summer and is associated with afternoon and evening thunderstorms. The least rainfall is in the spring. However, because of the low evaporation and transpiration rates in the winter (December- February), this time is considered the wettest. Also runoff into the estuary is probably greater because the soil is frequently saturated. The U.S. Department of Commerce's National Oceanic and Atmospheric Administration is the primary source for rainfall data. Local sources vary. Although currently the Atlantic Beach Police Department, the University of North Carolina Institute of Marine Sciences, and Open Grounds Farm, Inc. maintain daily records. Data are also available from the Cherry Point Marine Air Base in Havelock, N.C. They log meterological data every hour.

Stream Discharge

Discharge data are not kept for any streams entering the NRES and the nearest station is located on the Neuse River at Kinston. These data, available from the U.S. Geological Survey, would be of no value in the NRES except that water can flow from the Neuse River estuary into the Newport River via the Core Creek Canal. As mentioned previously, tide height and current direction data are recorded every eight hours by the U.S. Army Corps of Engineers at the Core Creek bridge. The Kinston/ Neuse River data are indicative of regional (Southeastern U.S.) rainfall patterns and thus might be useful interpreting long-term trends in salinity.

Table 6.
Rainfall (in inches) for the NRES. Data for 1966 to 1968 (from Culliney, 1969) represent an average of Morehead City and Cherry Point Marine Base data. The data for 1975 to 1976 are from Kirby-Smith and Barber (1979) taken at Open Grounds Farm about 8 miles from the Newport River estuary. The 10-year average is from Cape Hatteras (NOAA 1977).

Month	1966	1967	1968	1975	1976	1977	10-year average
Jan.	5.9	3.9	5.3	5.0	3.5	3.0	4.3
Feb.	4.3	4.7	1.4	4.8	1.8	1.5	4.2
Mar.	3.3	0.6	1.6	3.0	2.8	5.5	3.8
Apr.	0.8	2.4	2.8	6.1	0.4	0.9	3.1
May	9.7	4.1	3.0	3.2	5.5	4.7	3.3
June	7.7	2.8	3.2	5.3	8.2	4.3	4.4
July	11.6	11.8	9.7	14.9	3.4	4.8	5.9
Aug.	6.1	8.3	3.0	1.8	17.0	4.0	6.8
Sept.	5.7	3.5	5.5	11.0	5.7	9.4	5.8
Oct.	1.6	1.8	7.5	2.6	3.3	6.1	4.8
Nov.	1.4	1.6	4.5	2.0	3.1	6.4	4.6
Dec.	4.1	4.7	2.2	5.3	4.1	4.3	4.5
Total	62.2	50.2	49.7	65.0	58.8	54.9	55.5

Jennings et al. (1970) estimated stream flow in the Newport River for 1968 based upon rainfall, temperatureand the area of the watershed. Monthly values ranged from a low of 0.4 m^3/sec (0.52 yd^3/sec) in August to a high of 11.2 m^3/sec (14.6 yd^3/sec) in January. The annual (January-December 1968) average was 4.2 m3/sec (5.5 yd^3/sec). Evans (1977) states that the average flow of the Newport River is 3.6 m^3/sec (4.7 yd^3/sec). This estimate was based upon the data of Jennings et al. (1970) and used November 1967 to October 1968 for averaging.

Dissolved Oxygen

The amount of dissolved oxygen is an important indicator of the biological activity in the water and the ability of the water to support life. Oxygen enters the water through diffusion across the air/water interface and is subsequently mixed through the water column. Oxygen also enters the water via the photosynthetic activities of green plants during the daylight hours. Almost all organisms, plant and animal, require oxygen for metabolism. However, some organisms are more tolerant of low oxygen concentrations than others. At saturation,the amount of oxygen in the water increases with decreasing temperature and decreasing salinity. In addition to the actual amount of oxygen in the water, the percent oxygen saturation of the water is often reported. This is a normalizing technique that allows comparisons of oxygen from samples which differ in temperature and salinity.

Oxygen has rarely been reported in field studies of the NRES. Four systematic studies report oxygen concentrations over time at several places. Mohammad (1961), Pinschmidt (1963) and Hyle (1976) provided data for the Newport River estuary. Campbell (1973) presented detailed oxygen data for Gales Creek estuary off Bogue Sound. The oxygen concentrations reported in the first three studies are very similar so only those of Pinschmidt (1963) will be discussed (Figure 11). In the main body of the Newport River estuary (stations 1 to 3) the oxygen concentrations in surface water were all high, ranging from 6 mg/l to 10 mg/l (ppm) depending upon seasonal temperatures. At station 3, in the middle of the estuary, the bottom waters were 1 mg/l to 2 mg/l lower in oxygen than surface waters during the summer. This was the same location that had the least salinity variability with tidal changes and the weakest tidal currents. Thus low bottom oxygen concentrations in the summer at station 3 were probably a result of reduced mixing. Upstream of the mouth of the Narrows (stations 4 and 5), oxygen values decreased dramatically, especially during the summer when they ranged between 1 mg/l and 4 mg/l in surface and bottom waters. These low oxygen values may be the result of high bacterial metabolism due to the high concentrations of dissolved and particulate organic material found entering the system in the fresh water of the river. Campbell (1973) observed the same general pattern of oxygen concentrations in Gales Creek off Bogue Sound. Kirby-Smith and Barber (1979) reported consistently low oxygen values in fresh waters entering the headwaters of North River.

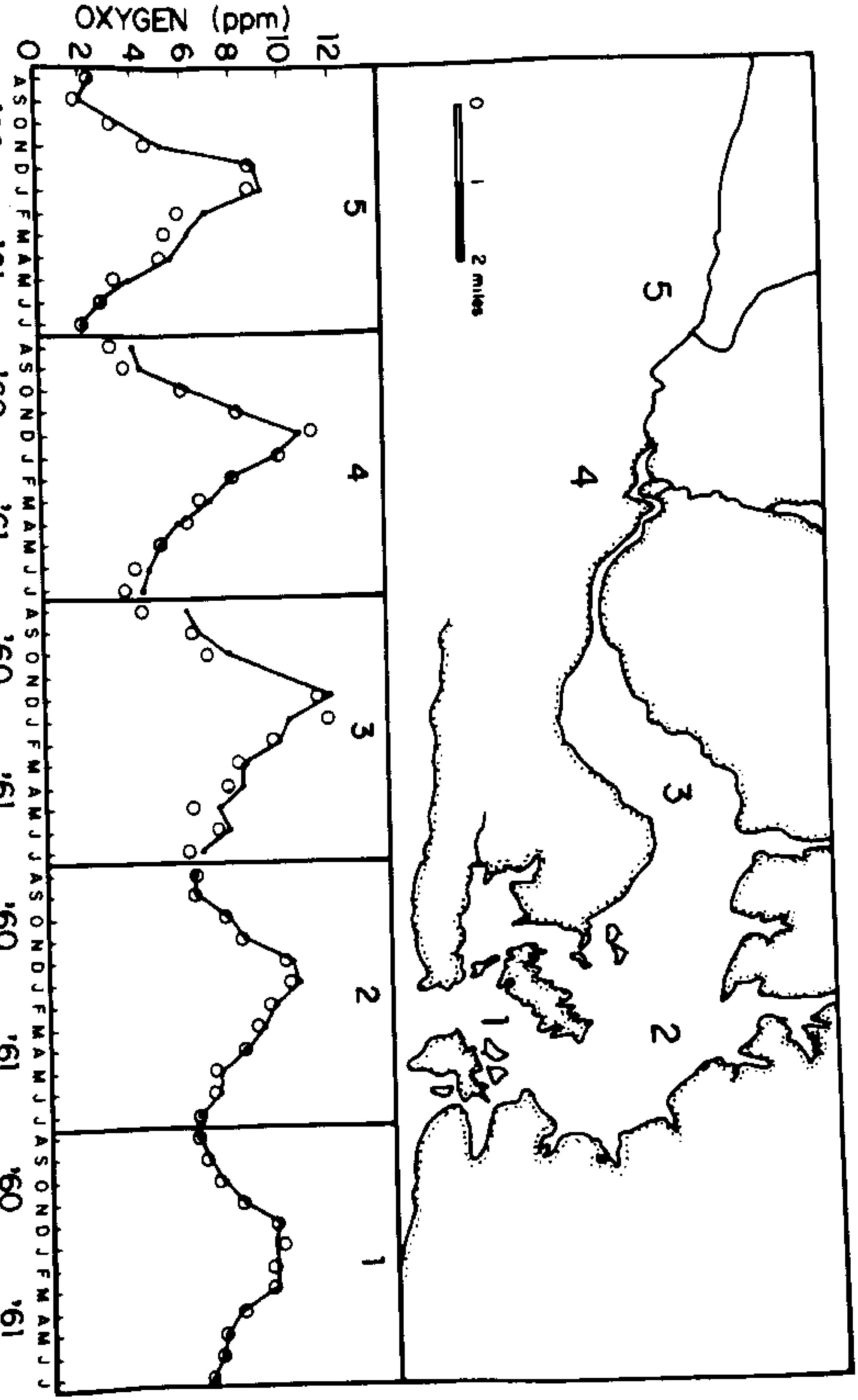
A more ecologically meaningful way to examine oxygen concentrations is in terms of per-

Table 7.
Percent saturation with oxygen of surface (S) and bottom (B) waters (1960-1961) for five stations in the NRES (Fig. 9). Data were calculated using the oxygen concentration, temperature and salinity from Pinschmidt (1963) combined with oxygen saturation values of seawater (temperature and salinity) from a table by W. Van Winkle, College of William and Mary, based upon formulae in Green and Carritt (1967).

Month	N	Station 1		Station 2		Station 3		Station 4		Station 5	
		S	B	S	B	S	B	S	B	S	B
Aug.	3	96	96	92	92	92	—	66	47	29	27
Sept.	5	98	95	92	88	*85	—	58	49	24	20
Oct.	4	96	95	94	97	96	84	72	69	35	*32
Nov.	1	96	95	98	98	33	—	89	88	49	42
Dec.	3	101	100	101	98	112	107	97	102	72	70
Jan.	2	99	98	104	98	96	106	83	82	71	67
Feb.	2	99	98	89	87	92	90	70	55	57	47
Mar.	3	106	104	100	96	94	90	69	67	*59	#58
Apr.	3	93	92	91	92	90	82	56	59	51	48
May	3	91	92	90	87	87	76	55	55	40	34
June	4	98	99	97	95	102	97	53	47	30	23
July	4	97	97	91	91	95	87	59	48	22	22

Averages of N (number) samples are presented except those * were N=1 and # were N=2.

Figure 11. Patterns in time and space in dissolved oxygen (ppm) at five locations in the Newport River estuary. Data are monthly means of weekly collections obtained alternately at low and high tides (from Pinschmidt, 1963).



cent saturation of the water. Table 7 contains data recalculated from Pinschmidt (1963) to give mean monthly percent saturation of oxygen in the surface and bottom at each station. Several generalizations can be made from this data. (1) The open waters of the Newport River estuary have average oxygen saturation values of 90 to 100 percent year-round with values greater than 100 percent frequently occurring, probably as a result of either rapid changes in temperature or high phytoplankton productivity. (2) The average bottom water percent saturation values are almost always lower than the surface values, suggesting a relatively high biological oxygen demand (BOD) in the water column and sediments. (3) Up the smaller protected rivers and creeks from the main body of the estuary, the percent saturation values drop and are especially low in surface and bottom waters during the summer months.

Low oxygen concentrations or percent saturations occur naturally in several situations in the NRES: (1) in the bottom water of vertically stratified areas in the summer, where mixing and diffusion of oxygen from the surface cannot keep up with the BOD of the sediments and bottom water; (2) in eutrophic (nutrient-enriched) areas where supersaturation with oxygen may occur during the day when the plants are actively photosynthesizing, followed by near total depletion of oxygen during the night as the plants and animals use the oxygen faster than it can diffuse through the air/water interface; (3) in organic rich sediments where the bacterial use of oxygen exceeds diffusion or transport of oxygen into the sediments.

It is probable that many summer or early fall fish kills frequently reported in North Carolina estuaries are associated with morning (7 to 9 a.m.) oxygen minima and with the mixing of oxygen-depleted bottom waters with surface waters such that for a short time the water column may have too little oxygen for some species of fish. This would be particularly evident if there had been an accumulation of hydrogen sulfide in the bottom waters. It would cause a chemical oxygen demand as the deoxygenated water mixed with the oxygenated water. The oxygen-depletion would be quickly eliminated by diffusion of oxygen from the atmosphere into the water and photosynthesis during the day, leaving no clue to the dead fish.

pH

The inverse log of the hydrogen ion concentration (pH) is used as a measure of the acidity (pH less than 7) and alkalinity (pH greater than 7) of natural waters. Seawater normally has a pH of 8.2, which is slightly alkaline. It resists changes in pH primarily through a carbonate/bicarbonate and ion buffering system. The fresh waters of coastal plain streams have a pH averaging 5 to 6 (Kuenzler et al. 1977). Small "black water" streams draining the pocosin swamp forests in Carteret County are naturally extremely acidic with an average pH of 4.2 (range of 3.4 to 5.4), and fresh water draining from developed land has a pH of near 7 (Kirby-Smith and Barber 1979). In addition to the effects of fresh water runoff, pH can also be influenced by the productivity of the water. Uptake of CO_2 by plants can raise the pH while respiration of organisms produces CO_2, lowering the pH. Changes in CO_2 due to productivity and respiration and the associated shifts in pH are most noticeable in small protected bodies of water with slow mixing (Odum and Hoskin 1958).

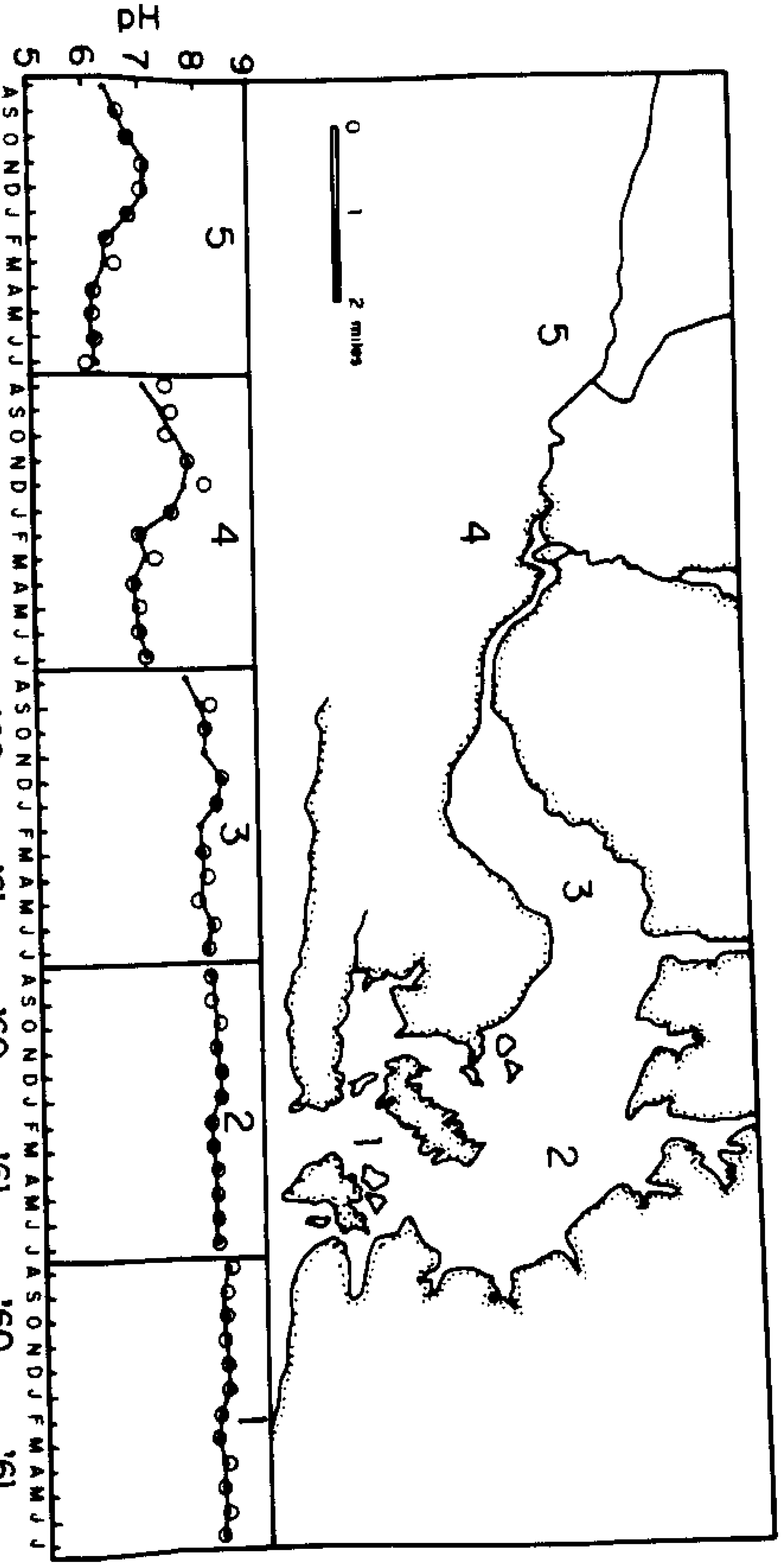
Figure 12 presents monthly mean pH values for five stations in the Newport River estuary (Pinschmidt 1963). The pH of the high salinity open waters of the estuary is fairly constant with values of 8 to 8.2. In areas where salinities are lowered, the pH begins to drop, reflecting the additions of more acidic fresh water. In the freshwater section of the Newport River near Newport, the pH varies between 6 and 7. Other investigations have reported very similar results (Wells 1958, Mohammad 1961, Campbell 1973, Culliney 1979, Palumbo and Ferguson 1979), and there is no reason to doubt that pH follows the same trends throughout the NRES. Diurnal changes in pH can be expected, especially during warmer months. Cycles of primary production and respiration cause increases in CO_2 at night and decreases during the day. Thus minimum pH values would be found in the early morning and maximum values in the early evening.

Light

The transparency of estuarine waters is important because of the influence of light on rates of primary productivity and the effects of light on the behavior of organisms. Transparency is most frequently measured by secchi disc, although electronic instruments are sometimes used to measure the quantity and quality of light as a function of water depth. Secchi depth is defined as the water depth at which a 30 cm white disc disappears from view as it is lowered through the water.

In addition to the water molecules, there are dissolved and particulate materials that result in decreased light penetration in estuarine waters. The high concentrations of dissolved humic ac-

Figure 12. Patterns in time and space of pH at five locations in the NRES. Data are monthly means of weekly collections obtained alternately at low and high tides (from Pinschmidt, 1963).



ids in the freshwater streams entering the NRES result in water that is clear but has a very dark yellow color. These streams are often referred to as "black water" because from a distance the streams appear black. For several days following very heavy rainfall and runoff, it is possible to see this discolored water throughout the entire estuary.

The particulate matter that causes decreased light penetration consists of a wide size range of nonliving (silts, clays, organic detritus) and living (bacteria, phytoplankton, zooplankton) materials. By far the greatest weight of suspended materials is silts and clays (Fisher 1975). However, during high productivity, increased standing stocks of phytoplankton can substantially decrease light penetration. Often during the fall and winter, rapid decreases in water temperature result in very clear waters, probably as a result of phytoplankton settling out of the water column.

Rice and Ferguson (1975) point out that the light entering the NRES varies seasonally with average local noon (meridian) intensities of 87 Klux in the winter (December - January) and 170 Klux in the summer (May - July). More importantly for plant production, daylight is longer in the summer (14 hours 30 minutes) than in the winter (approximately 10 hours). However, Rice and Ferguson (1975) go on to state that, within the water column, turbidity extremes due to silt and plankton have a greater impact on light availability than does seasonal change.

Near the Beaufort Inlet in the main ships channel, Sutcliffe (1950) measured secchi depths every two weeks for a two-year period and reported these as extinction coefficients (Extinction Coefficient = 1.7/Secchi depth in m). At high tide, he found (recalculated here from extinction coefficients) a maximum secchi depth of 3.7 m (12.1 ft), a minimum depth of 0.55 m (1.8 ft) and an average depth of 2.0 m (6.6 ft). At low tide these values were as follows; a maximum of 3.6 m (11.8 ft), a minimum of 0.76 m (2.5 ft) and an average of 1.4 m (4.6 ft).

Pinschmidt (1963) recorded decreasing light penetration from Beaufort Inlet to the headwaters of the estuary near Newport (Figure 13). He remarked that the greatest turbidity was associated with the shallow, open water just downstream from the Narrows, where the wind, waves and tides kept the silt in suspension. Pinschmidt (1963) also remarked that the low light penetration in the river near Newport was due to dissolved reddish-brown humic materials, not to suspended particulates. From Figure 13, it is clear that transparency is greatest during the winter and least during the spring and summer, probably as a result of decreased phytoplankton abundance during the winter. At Station 1 in the Beaufort Inlet, a second peak in transparency occurred during the early summer of 1961 but was not observed at the other stations. This may have been the result of a predominance of continental shelf water in the inlet at that time. It has been observed that extremely clear Gulf Stream-like water with associated *Sargassum* weed sometimes appears in the lower Newport River in the late spring and early summer. At such times, light penetration can be at least as great as 4 m (13 ft) (personal observation).

Williams (1966) reported average extinction coefficients for two time periods (May to September and September to May, 1964-1965) at a number of stations in the NRES Core Sound (Table 8). These data, which are based upon 11 samples during the one- year period, have been recalculated as secchi depths. These values are similar to those of Pinschmidt (1963), which show decreasing light penetration from the inlet to the headwaters of the estuaries. Williams noted little difference between summer and winter values, probably because of the relatively few samples taken. North River is seen to be very similar to the Newport River in transparency.

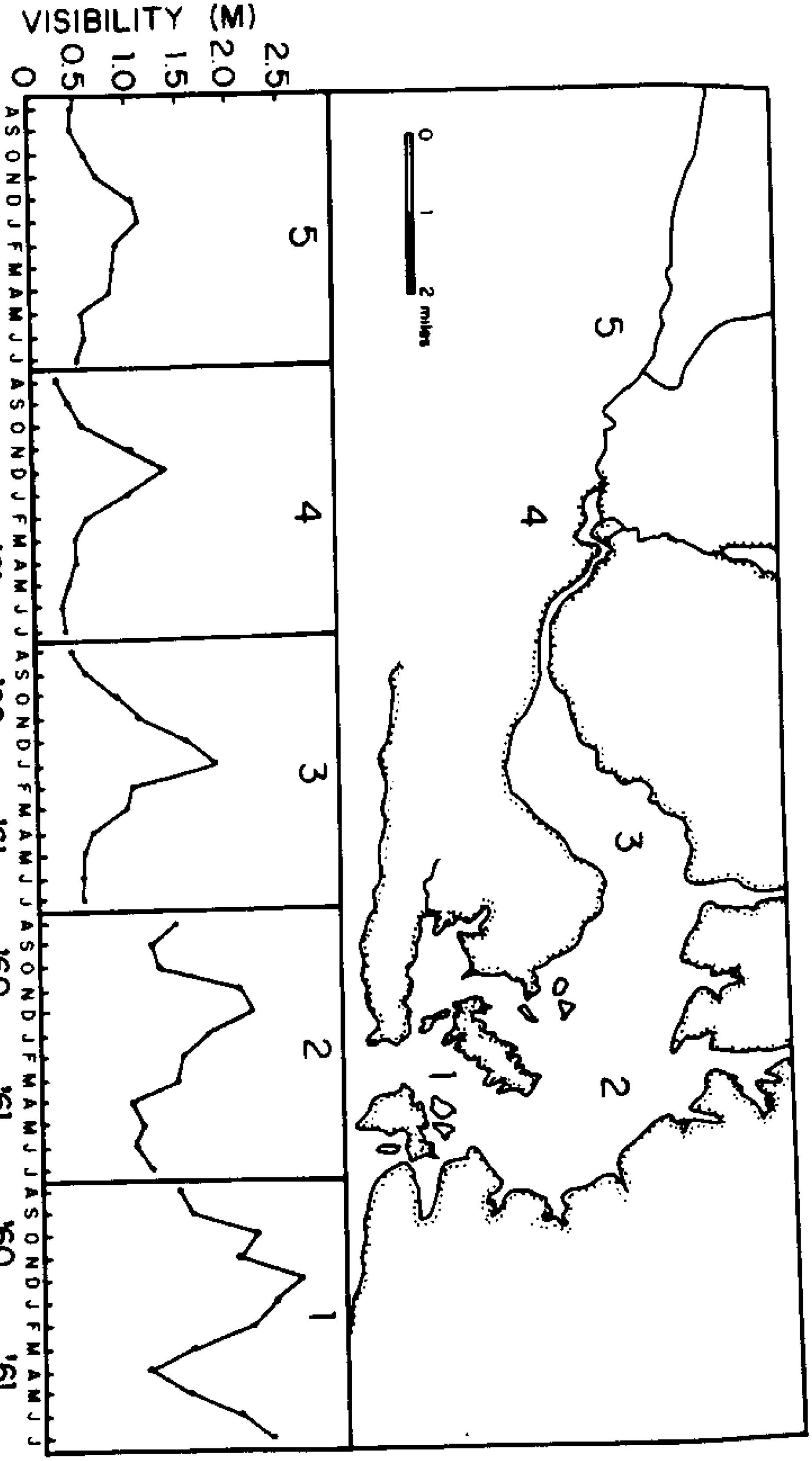
Brett (1963) periodically measured secchi depth along several transects across Bogue Sound during a one-year period. He reported that the disc was almost always visible on the bottom, thus it provided little useful quantitative information on water transparency. However, Brett (1963) qualitatively described the turbidity, stating that the water was usually murky or cloudy, especially during the warmer months. During the winter, beginning with the onset of cold weather, the water became clear enough to see shells on the bottom in 8 ft (2.4 m) of water.

Fonseca et al. (1985) measured light attenuation coefficients over a 12-month period at two locations in Back Sound. At Shackleford Shoal, the average coefficient was 3.99, equivalent to a secchi depth of 0.42 m (1.4 ft). In a Middle Marsh embayment the average coefficient was 5.26, equivalent to a secchi depth of 0.32 m (1.0 ft). Except for a consistent increase in water clarity in the winter, there was no obvious seasonal pattern to the light extinction.

Sediments

The characteristics of the sediments of an estuary are extremely important in determining the type of biological community that will be found in any particular place. The bottom of the NRES consists primarily of unconsolidated sediments with varying mixtures of pebble- and granule-sized shell fragments (64 mm - 2 mm;

Figure 13. *Patterns in time and space of visibility (Secchi depth in meters) at five stations in the NRES. Data are monthly means of weekly collections obtained alternately at low and high tides (from Pinschmidt, 1963).*



2.52 - 0.79 in), sand (2 mm - .063 mm; 0.79 - 0.025 in), silt (.063 mm - .004 mm; 0.025 - 0.0016 in) and clay (less than 0.004 mm; 0.0016 in). There are man-made hard substrates (jetties, sea walls, pilings), but except for oyster reefs there are no natural hard substrates or rock outcrops.

Sediments are most frequently described by measurement of size distribution of particles and mineral content (mineralogy). In addition, such characteristics as roundness, percent calcium carbonate (shell fragment) and percent organic matter are occasionally determined. The particle size distribution and the percent organic matter are the most important variables that relate to the biological activity on and within the sediments.

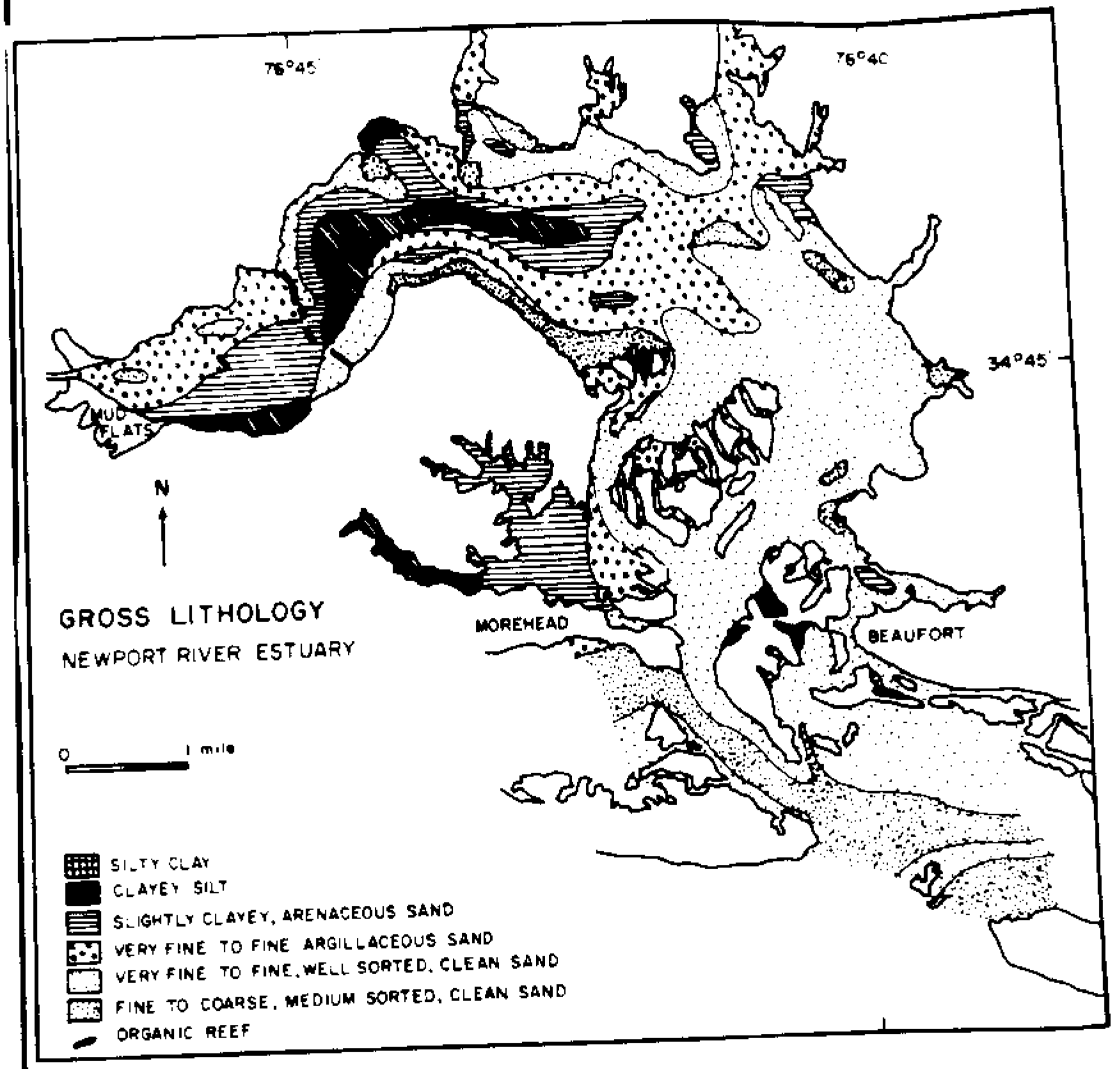
There are a number of published reports dealing with the sediments of the NRES. Grave (1901) discussed sedimentation relative to oyster reefs in the area. Batten (1959, 1962) described the patterns of sediment distribution in the vicinity of the Beaufort Inlet. Johnson (1959) published an extensive account of the sediments of the Newport River estuary. This was followed by a very similar report (Edwards 1961) for sediments of the North River estuary. Brett (1963) characterized the sediments along a series of transects in Bogue Sound. Park (1971) described the mineralogy of sediments throughout the NRES. Price et al. (1972) described sediment size distribution at 10 stations in the NRES. Folger (1972) provided some information on sediments in the area. Price et al. (1976) graphically presented a picture of the size distribution and organic content of sediments collected along six transects across the NRES. Chester et al. (1983) published the same data in tabular form. Thayer et al. (1980) report sediment size and organic content for seven stations in the NRES. Sediment accumulation rates have been measured in salt marshes (Williams and Murdock 1972) and eelgrass beds (Thayer and LaCroix 1974). Changes in sediment composition in areas adjacent to maintenance dredging activities were examined by Thayer et al. (1974). Klavans (1983) summarized what is known about sediment transport in and around Beaufort Inlet. He discussed in detail sediment movement in response to tidal currents in that area. Fonseca et al. (1985) measured sediment flux rates over a 50-day period at eight sites in and near Middle Marsh at the mouth of North River.

The most complete description of the surficial sediments in the NRES is that of Johnson (1959). He used qualitative microscopic examination to (gross lithology) describe 184 samples from throughout the Newport River estuary. The results of this investigation (Figure 14) show that, in general, the farther away from the inlet and the more protected the habitat, the finer the sediments. Silt and clay sediments dominate only in the middle or deeper portion of the upper estuary and in the protected salt marsh creeks. In addition, there is a very extensive intertidal and subtidal mud bottom at the mouth of the Narrows that is predominately silt/clay. Johnson (1959), Price et al. (1976) and Chester et al. (1983) have reported somewhat sandy sediments in the shallower areas bordering the north and south shores of the upper part of the estuary. This is probably due to erosion of the land and wave resuspension and removal of silts and clays. Sediments under the open waters in the middle and lower part of the estuary are all sand. Johnson (1959) performed a quantitative size analysis on 63 of his samples; calculated the per-

Table 8. Mean Secchi depth as a function of location in the NRES (recalculated from Williams 1966; numbers in parentheses are his station numbers). Mean depths are for a section of the estuary, not the depth at the point sampled.

Location		MeanSecchi May-Sept.	Depth(M) Sept.-May	MeanWater Depth (M)
Newport River				
Upper	(2)	0.20	0.29	0.7
Middle	(3)	0.65	0.77	1.0
Middle	(4)	1.21	1.42	0.9
Lower	(6+8)	1.70	1.55	4.1
Bogue Sound				
East End	(7)	1.70	1.42	1.5
North River				
Upper	(11)	0.53	0.65	0.6
Middle	(13)	0.94	1.00	0.7
Middle	(14)	1.21	1.42	0.9
Lower	(15)	1.42	1.42	1.6

Figure 14. Gross lithology of the sediments of the Newport River estuary (from Johnson, 1959).

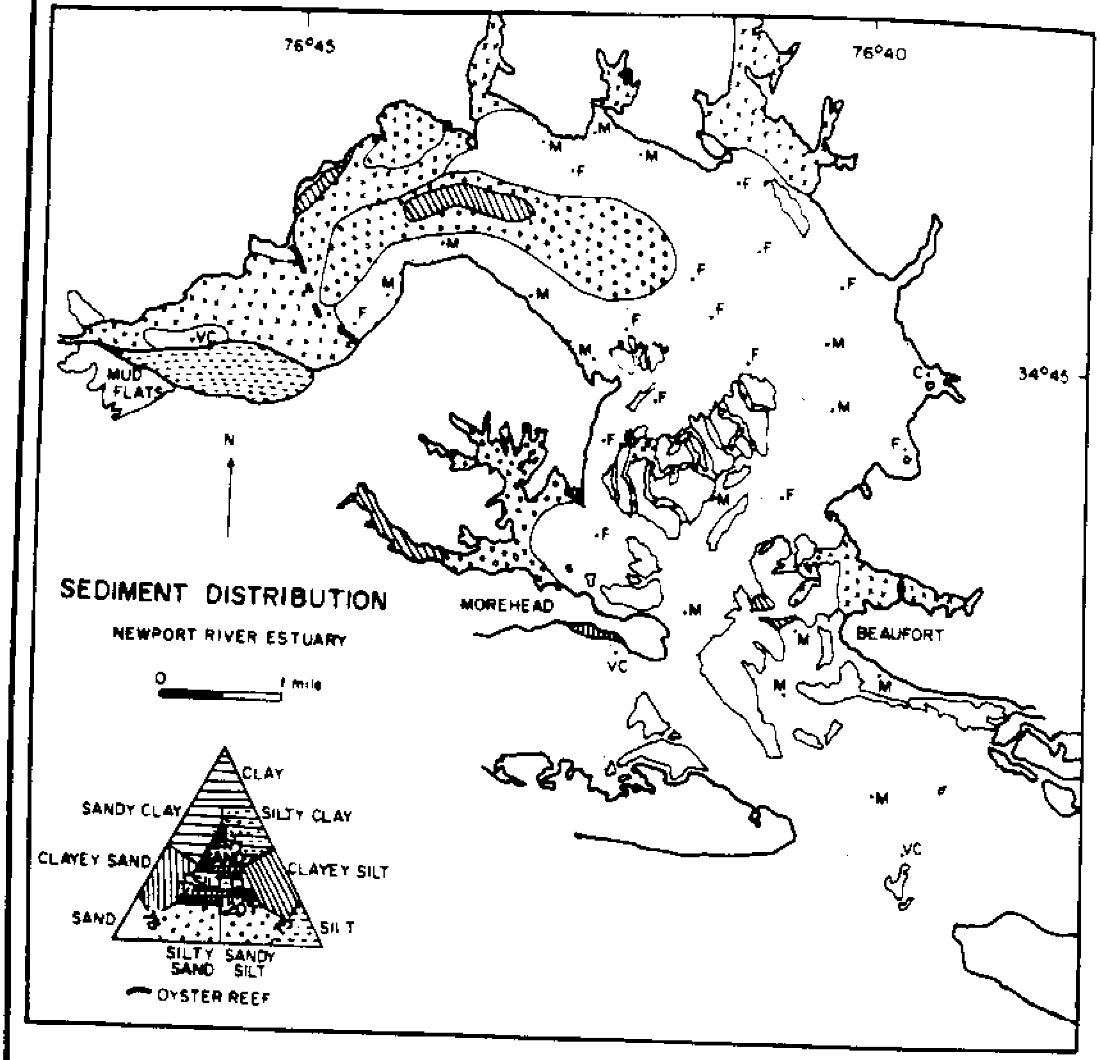


cent sand, silt and clay; and produced a map showing the distribution of these sediments (Figure 15). These data provide a quantitative confirmation of the qualitative observation of gross lithology.

On their six transects of the NRES, Price et al. (1976) and Chester et al. (1983) found a similar pattern in size distribution of sediments as did Johnson (1959). They reported that the sediments of the estuary were characterized by well sorted, fine grained particles with a maximum diameter of 0.25 to 0.50 mm (0.099-0.197 in; fine to medium sand). The upper estuary and Calico Creek have areas with high silt/clay content in some of the samples. In these muddy sediments, sand averaged 51 percent (range: 16 percent to 92 percent), silt averaged 38 percent (range: 3 percent to 68 percent) and clay averaged 11 percent (range: 5 percent to 14 percent). Organic matter and organic carbon content of the sediments had a strong positive correlation with silt/clay content and an equally strong negative correlation with percent sand. Organic carbon is usually about 50 percent of organic matter. In the upper part of the estuary, organic matter ranged from 1 percent near the shore to 10 percent in the deeper waters in the center of this section. Organic carbon values range from less than 1 percent to greater than 4 percent in the same area. In the middle and lower part of the estuary (except Calico Creek), sand content of the sediment averaged 90.6 percent (range: 81%-93%), silt averaged 3.5percent and clay averaged 5.9 percent. Organic matter and organic carbon content were low, averaging 0.7 percent and 0.4 percent respectively.

According to Johnson (1959), the calcium carbonate content of the sediments in the NRES ranged from 0.10 percent to 100 percent (in an oyster reef). Half of his samples had less than 1

Figure 15.
Mean grain size of sediments of the Newport River estuary (from Johnson, 1959).



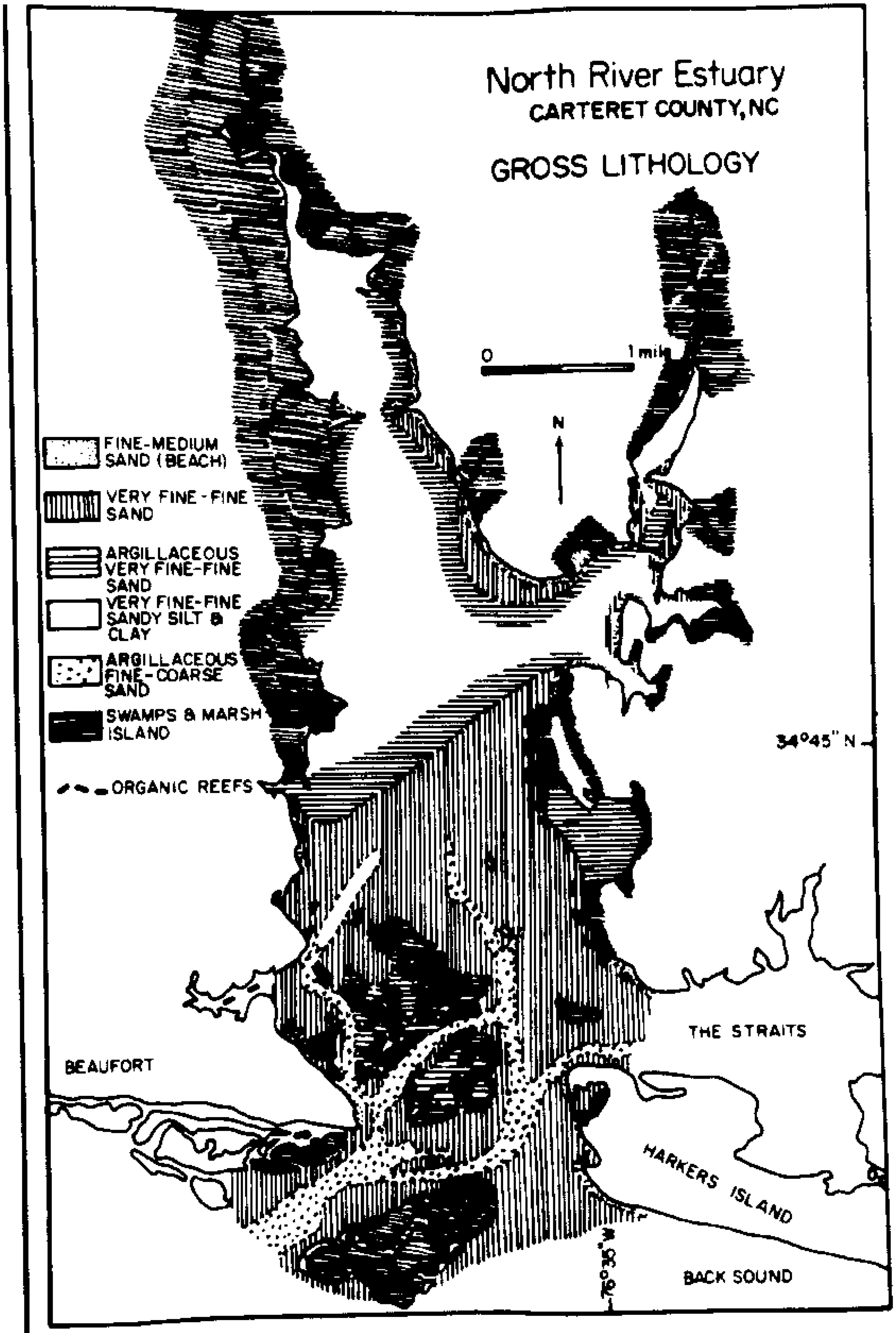
percent calcium carbonate and over 90 percent had less than 5 percent calcium carbonate. Although not sampled by Johnson (1959) or others, there are a number of areas in the bottoms of the deeper channels in the lower part of the estuary where large accumulations of very coarse shell occur (personal observation). The size distribution in these areas has not been determined, but many of the shell and shell fragments are several centimeters across. These subtidal shell reefs are formed by tidal transport of gastropod and pelecypod shells that accumulate in the channels and are kept free of finer sediments by the strong tidal currents. The shells are continuously destroyed by the boring activities of algae, sponges and bivalves so that there must be a continuous resupply of fresh shell to maintain these reefs.

Edwards (1961) collected 265 sediment samples from the North River estuary. His detailed analyses yielded results that were very similar to those of Johnson (1959), suggesting that the North River and Newport River estuaries are very similar sedimentary environments. A map (Figure 16) of sediment size distributions supports this conclusion.

The sediments of Bogue Sound have not been as extensively studied as those of the NRES. Brett's (1963) data suggest that most of the central and eastern end of the sound is covered with fine to medium sand with less than 1 percent organic matter.

Johnson (1959), Edwards (1961), Brett (1963) and Park (1971) examined the mineralogy of the clay size sediment particles from the NRES. Johnson (1959) reported finding only illite and chlorite. Edwards (1961) reported illite, chlorite and quartz, but Brett (1963) reported quartz, kaolinite and illite as the most important

Figure 16. *Gross lithology of sediments of the North River estuary (from Edwards, 1961).*



minerals (in that order). Park (1971) said that illite was the most abundant mineral. The mineralogy of the sands differs considerably from that of clays. In analyzing the mineralogy of 12 sand samples from the NRES, Johnson (1959) found that quartz (93.6 percent), plagioclase (3.5 percent), and feldspar (2.9 percent) made up the light mineral portion of the samples. The heavy minerals were less than 1 percent of the total sand fraction. Ilmenite, rutile and zircon were the chief heavy minerals. Traces of monazite, apatite, serpentine and horn blende were also present. Johnson (1959) reported a decrease in illite seaward. He attributed this to the increased transportation time due to the greater specific gravity for this mineral compared to rutile and zircon. Similar results for sands and heavy minerals were reported by Edwards (1961).

Johnson (1959) discussed the source and transport of sediments within the NRES. He says that most of the material contributed by the small rivers and creeks is in the silt/clay size range because of the low gradient of the coastal plain. The sediment accumulated at the mouth of the Newport River (Narrows) is silt, clayey silt, sandy silt and silty sand. There have been no studies of sediment input from the river that might be due to the "salting" out or flocculation of clay-sized particles. However, Hanson and Crumley (1980) discuss the formation of iron-rich organic particles that are created as fresh and salt water mix and are incorporated into sediments. Johnson (1959) suggests that most of the sand originated in the sea with some coming from erosion of adjacent sand "cliffs" and by wind transport. Sediments are distributed by the waves and tide- generated currents, and the size distribution is directly correlated with the local hydrodynamic regime: the stronger the currents the coarser the sediments. Edwards (1961) states that most of the sediments of the NRES consist of reworked Pliestocene deposits with some material brought into the estuary from streams, tidal currents and winds. Shells, Foraminifera and plant debris make up the component of these sediments which were formed within the estuary.

Wolfe et al. (1973) estimated the rate of sedimentation in the NRES as varying between 1 and 4 mm/yr (0.039 - 0.173 in/yr), with the greater rate occurring in the upper estuary near the Narrows. According to Evans (1977), this rate is close to the rate of sea level rise of 2.5 to 3.5 mm/yr (0.99 - 1.38 in/yr) along this coast during the last 30 years. Evans further states that this would explain the lack of significant change in depth profiles in the upper estuary over the past 100 years seen when comparing charts of the area from 1870 and 1968. Williams and Murdock (1972) examined sedimentation rates in salt marshes on 45 transects (260 stations) in the NRES and adjacent Core Sound. They placed sediment collectors on the surface of the marsh and collected these one year later. Two hundred six samples were recovered and the mean rate of sedimentation calculated to be 1.36 kg dry matter per meter squared per year (2.52 lb/yd^{2}yr). The range in values was 0.01 kg/m^{2}yr - 30.4 kg/m^{2}yr (0.019 - 56.4 lb/yd^{2}yr) with two-thirds of the stations having rates less than 1.00 kg/m^{2}yr (1.86 lb/yd^{2}yr). The rates fit a lognormal distribution. Rates were greatest in the low marsh and decreased towards the high marsh. Sedimentation rates greater than 5.0 kg/m^{2}yr (9.28 lb/yd^{2}yr) were said to be atypical for the estuary as a whole, with the highest rates only observed at the mouth of the Newport River (Narrows) and near areas that were dredged during the study. The sediment deposited in the lower marsh was mainly mineral (inorganic silt and clay). The organic content increased in the higher parts of the marsh. Using a graduated steel rod, Williams and Murdock (1972) also estimated the depth of marsh sediments over the non-marsh base. These results (Table 9) suggest that the rate of sedimentation is greatest at the headwaters of the estuary and decreases as you approach the sea, even in protected environments.

Fonseca et al. (1985) examined sediment flux rates at eight sites in and near Middle Marsh during an experimental seagrass planting project. Values ranged from no flux at a protected site to a maximum of 0.661 cm/day (0.260 in/day) on the deeper portion of the eastern half of a shoal between Middle Marsh and Shackleford Banks.

Table 9.
The depth of sediment accumulated in salt marshes over the nonmarsh base as a function of location within the estuary (Williams and Murdock, 1972).

Type Area	Number of Stations	Depth of Sediment (cm)		
		Avg.	Min.	Max.
Outer Banks	100	62	10	95
Intermediate	69	99	20	+200
Stream Mouth	58	148	20	+200
Total	227	95	10	+200

Thayer and LaCroix (1974) studied the influence of eelgrass (Zostera marina) on sediment deposition, using a technique similar to Williams and Murdock (1972). They placed their traps in front of, within and behind an eelgrass bed located on the south side of Phillips Island. Sediment accumulation rates were highly variable and ranged from 1 to 57 mm/yr (0.039 - 2.25 in/yr) during the winter and spring and from negative to 78 mm/yr (3.07 in/yr) during the summer and fall. Rates averaged 5 mm/yr (1.97 in/yr) in front of the grass bed, 23 mm/yr (0.91 in/yr) within the bed and 33 mm/yr (1.30 in/yr) behind the bed in an area between the bed and the island. The average for the whole embayment was 20 mm/yr (0.79 in/yr). They said that their values were much higher than those reported for open estuaries (1 mm/yr - 4 mm/yr; 0.039 - 0.158 in/yr). Fonseca et al. (1985) found increases in sediment height of 32 mm (1.26 in) in 234 days and 34 mm (1.34 in) in 424 days following the transplantation of eelgrass onto a shoal in Back Sound near Shackleford Banks.

Thayer et al. (1974) studied the changes in sediment characteristics due to maintenance dredging along a transect that crossed a channel in the Intracoastal Waterway in the lower NRES. They found a decrease in percent silt, clay, organic matter and organic carbon and an increase in percent sand. They attributed these changes to the winnowing of silts and clays from the disturbed material, thus leaving only the fine sands to settle on the adjacent undredged bottom.

Trace Metals

The distribution, abundance and cycling of some trace metals have been investigated in the NRES because of the importance of metals as micronutrients (iron, zinc, copper, manganese) and because of their potential or actual toxicity (copper, mercury, chromium, cadmium, zinc, lead). Most of our knowledge is the result of research done at the NMFS laboratory over the past 25 years. This work began as an effort to understand the fate of radioisotopes of metals in the estuarine ecosystem and continued as a study of the flux, bioavailability and toxicity of trace metals in estuarine and coastal waters. This research has provided a wealth of information on the reservoirs of metals (particularly iron, manganese, copper and zinc) throughout the estuarine water, sediments and organisms. In addition, there have been several processes-oriented projects and efforts to model fluxes of metals in the natural environment.

The concentration of trace metals in the water of the NRES has been discussed in detail. Willis (1962) reported a zinc concentration of approximately 10 µg/l (parts per billion) and Williams et al. (1964) measured zinc concentrations of 2000 µg/l to 14 µg/l. Cross et al. (1969, 1970) measured the concentration of iron, manganese and zinc in unfiltered sea water and found that iron and manganese decreased in concentration from the headwaters of the estuary to the sea. In their samples, manganese had mean values which decreased from 20 to 3.3 µg/l, with iron decreasing from 300 to 39 µg/l. The concentration of zinc remained relatively constant, 0.6 to 0.8 µg/l. They found significant temporal fluctuations, but they were not related to temperature or season. Evans (1977) presented data on concentrations of iron, manganese, copper and zinc in filtered seawater on three dates (October, February, April) along a transect that extended from the headwaters of the estuary to Pivers Island. He observed an increase in manganese from an average of 8 µg/l in the river to 15 to 20 µg/l in the upper estuary followed by a decrease to 2 µgl at Pivers Island. He observed a dramatic decrease in dissolved iron in the river water (approximately 250 µg/l) as it mixed with seawater in the estuary, probably due to flocculation (particle formation). Hanson and Crumley (1980) reported the same behavior of dissolved iron in the NRES. According to Evans (1977), this behavior of dissolved iron when it reaches seawater had been almost universally reported and therefore was not surprising. Copper had a low concentration in the river (1 µg/l) followed in the upper estuary either by an increase to approximately 5 µg/l or by a gradual decrease. Copper concentrations in the lower estuary were less than 1 µg/l. Dissolved zinc behaved similarly to copper with river concentrations of 1 to 2 µg/l and a lower estuary value of less than 1 µg/l Evans (1977) also examined the suspended particulate fraction for trace metals. Particulate manganese increased from less than 1 to 4 µg/g (parts per million) dry matter in the river to approximately 8 to 16 µg/g in the mid-estuary, decreasing again to less than 4 µg/l in the lower estuary. He found the concentration of particulate iron to be about 40 mg/g throughout the estuary. Particulate copper was approximately 17 µg/g and particulate zinc approximately 100 µg/g. Hanson and Crumley (1980) reported the ratio of particulate to dissolved iron increased from 0.47 in the river to 97 in the lower estuary.

The concentration of trace metals in sediments of the NRES has been the subject of several reports. Williams et al. (1964) reported zinc concentrations of 1.4 to 7.0 µg/g dry sediment. He said that this sediment zinc represented 93 percent of the exchangeable zinc and that this sediment zinc buffered changes in zinc in the water. Cross et al. (1969, 1970) measured iron, manganese and zinc in sediment at three locations: fresh water, upper estuary and lower estuary. They found concentrations of iron from near 4000 µg/g to less than 100 µg/g. Iron in sediments increased from sand to mud and increased with a decrease in salinity and an increase in particle size. Manganese concentrations ranged from less than 10 µg/g to 200 µg/g with the same pattern of distribution as iron. Zinc values ranged from less than 1 µg/g to 30 µg/g. The highest values were associated with mud and fresh water. Upper and lower estuarine sediments had lower concentrations and these were similar to each other. The concentrations of all trace metals fluctuated through time but with no seasonal (temperature) pattern. Whaling et al. (1977) analyzed sediment samples collected on several occasions over a five-year period in transects up two tidal creeks in the NRES. Calico Creek, located just north of Morehead City, receives the effluent from secondary treated sewage, but Turner Creek, located on the west side of the North River just north of Beaufort, does not receive effluent from a treatment plant. They give several sets of results that differ from each other depending upon the date of collection. As an example of their data, the mean values for the concentration of metals in 20 sediment samples taken in May 1974 along a transect up the creeks were as follows: for Calico Creek—(µg/g dry weight) mercury 0.46, cadmium 1.1, chromium 26, copper 36, iron 14300, lead 42, manganese 69 and zinc 155; for Turner Creek—mercury 0.09, cadmium 0.5, chromium 9, copper 11, iron 7800, lead 16, manganese 18 and zinc 105. Wolfe et al. (1975, 1976) studied the distribution of trace metals in sediments from an eelgrass bed at Phillips Island. They found an average of 17 gg manganese, 2125 µg/g iron, 2.5 µg/g copper and 9.75 µg/g zinc. They also separated the sediment into size fractions with sieves and found that the concentration of metals greatly increased with decreasing sediment size. All these data emphasize the importance of location and sediment characteristics in trace metal content.

Trace metal concentrations have been reported for a number of organisms inhabiting the Newport River estuary. These include algae (Wolfe et al. 1975, 1976; Gutknecht 1964), eelgrass (Drifmeyer 1980; Drifmeyer et al. 1977, 1978, 1980; Wolfe et al. 1975, 1976), marsh grasses (Williams and Murdoch 1969; Ustach 1969; Whaling et al. 1977; Drifmeyer 1980; Drifmeyer et al. 1980; Drifmeyer and Redd 1981; Drifmeyer and Rublee 1981), nemertina (Wolfe et al. 1975, 1976), polychaeta (Cross et al. 1970), gastropoda (Wolfe et al. 1975, 1976; Whaling et al. 1977), bivalves (Willis 1962; Wolfe et al. 1969, 1975, 1976; Wolfe 1970; Cross et al. 1972; Whaling et al. 1977; Willis and Jones 1977; Willis and Bargh 1978), amphipoda (Wolfe et al. 1975, 1976), decapoda (Willis 1962; Wolfe et al. 1975, 1976), echinodermata (Wolfe et al. 1975, 1976; Drifmeyer 1980), tunicata (Wolfe et al. 1975, 1976), fish (Cross and Brooks 1970, 1973; Cross et al. 1971, 1973, 1974; Willis 1962; Wolfe et al. 1975, 1976) and birds (Hardy et al. 1975).

The concentrations of essential trace metals (Mn, Fe, Cu, and Zn) in the major organisms of the eelgrass community (Wolfe et al. 1975, 1976) provide an example of what is known of the abundance of these metals in the biota of the NRES. In general, the sequence in concentration from higher to lower was iron, manganese, zinc and copper. Copper and zinc had the least variability within and among different groups of organisms while iron and manganese concentrations were much more variable. Sediments had concentrations of these metals somewhat similar to those in the organisms. In general, the finer the sediment the greater the metals concentration.

Some of the trace metal studies in the Newport River estuary have involved studies or estimates of fluxes and transport processes in the field. Williams et al. (1964) found that there was a rapid exchange of zinc between the sediment and water that involved sediment and microorganisms. The rate of exchange was higher at higher temperatures. Evans (1977) and Evans et al. (1977) found that the concentration of dissolved manganese in the estuary where the salinity was 4 to 14 ppt was in excess of what would be predicted based upon a conservative mixing of freshwater and seawater. They suggested that dissolved manganese becomes fixed to particles in the lower estuary and that these particles are returned up the estuary on the bottom where some of the manganese is reduced and dissolved from particles and put back into solution. Sanders (1975, 1978) found a similar phenomenon in Calico Creek where dissolved manganese was higher than could be predicted based upon conservative mixing. His data indicated that disturbance of the sediment probably accounted for most of the flux into the water column.

The potential biological availability of copper and cadmium in the Newport River was investigated by Sunda and Lewis (1976). They found that 98 to 99 percent of the copper in the river is bound to complexing ligands, probably to the humic and/or fulvic acids dissolved in the water. Because this binding increases with increasing pH but decreases with increasing salinity and decreasing dissolved organic matter, the availability of unbound copper (biologically active) is complex (Sunda and Lewis 1977). Cadmium is bound to a much lesser extent than copper. Sunda et al. (1978) and Sunda and Lewis (1979) confirmed that copper was bound to organic ligands in the Newport River. They discuss the two most chemically different sources of fresh water entering the river. One source of water is runoff from the land through surface soils. This produces water with low pH, a high concentration of dissolved organic matter and a low concentration of calcium and magnesium. The other source of water is groundwater seepage from deeper in the soils. It has near neutral pH, low concentration of dissolved organics and high concentration of calcium and magnesium. They developed the hypothesis that copper in the surface waters is kept from being complexed with the organic matter by the low pH. As this water is buffered in the river, the pH rises and the copper complexes with the dissolved organic matter. As the groundwater seepage dilutes the surface runoff, the concentration of dissolved organic matter is diluted and the complexation of the copper levels off. Evans (1977) noted some increase in dissolved copper (at times) in the lower salinity part of the estuary. He suggested that resuspension of sediments might cause a release of copper in pore waters in the upper estuary. Hanson and Crumley (1980) found that dissolved iron in the fresh water of the Newport River had a very strong non-conservative decrease upon reaching the lower river and the upper estuary, even though the salinity was still 0 ppt. The ratio of particulate to dissolved iron increased from 0.45 to 97 in a seaward direction. The dissolved iron in the river is probably mostly colloidal ferric oxide associated with the dissolved organic matter. In the lower river and upper estuary, this material flocculates (forms aggregated particulate matter), producing an iron-rich particle that can sediment out. This flocculation could be due to changing chemistry in the lower river and/or to microbial particle building.

Changes in trace metal concentration through time and space have been examined in marsh grasses, eelgrass and several organisms. William and Murdoch (1969) found that the concentrations of zinc, manganese and iron increased in dead *Spartina alterniflora* compared to living plants. Drifmeyer (1980) and Drifmeyer et al. (1981) noted increases in concentration and total amounts of trace metals (manganese, iron, copper and zinc) as the decomposition of *Spartina alterniflora* progressed. They found that bacteria were not responsible for the increase in metals, but they were not able to rule out the influence of other microorganisms (yeasts, fungi and algae). Drifmeyer et al. (1977, 1978, 1980a,b) investigated the cycling of trace metals (manganese, iron, copper and zinc) in eelgrass, *Zostera marina*. Based upon their results and those of Drifmeyer (1980) on metals in the sea urchin, *Lytechinus variegatus*, it was concluded that direct herbivory was not a significant route of metal transfer within the community and that metal flux out of the community via the export of particulate dead and live eelgrass was extremely important to cycling in the estuarine system. Eelgrass growth, senescence and decomposition represent the most significant part of the biological cycling of these metals in the eelgrass ecosystem. Cross et al. (1971) examined changes in trace metals (manganese, iron, and zinc) in young estuarine fish during their period of most rapid growth. They examined juvenile croaker (*Micropogon undulatus*), spot (*Leiostomus xanthurus*), pinfish (*Lagodon rhomboides*), bay anchovy (*Anchoa mitchilli*) and Atlantic menhaden (*Brevoortia tyrannus*), five fish which constitute over 90 percent of the juvenile fish in the NRES (Turner et al. 1971; Turner and Johnson 1973). They found that the concentration of all three metals decreased with increasing size (age), except manganese in the anchovy (no change) and manganese in the menhaden (increased). Cross et al. (1974) examined the flux of manganese, iron, copper and zinc in total populations of menhaden, spot and pinfish in the estuary for the summer months (Table 10). These data indicate that, except for copper in pinfish, there is very low assimilation of iron, manganese and copper by the fish, but a large flux of these metals through ingestion and egestion. This flux is probably important in that fish feces are incorporated into surface sediments where they may be ingested by deposit feeding animals. Thus, these fish are an effective means of keeping these metals cycling within the estuary, but are not significant in the export of metals out of the estuary. There is a substantial assimilation of ingested zinc by menhaden and pinfish and of ingested copper by pinfish. Significant quantities of these metals can thus be transported through the estuary and the coastal waters as these fish migrate.

There have been two attempts to model the flux of trace metals in the Newport River ecosystems. Jennings et al. (1970) estimated the mass balance of manganese, iron and zinc in the entire estuary (Table 11). They used a simplified box model representing the estuary with imports from river water and exports from sedimentation,

Table 10. *The flux of trace metals through populations of juvenile fish in the Newport River estuary during summer months (Cross et al., 1974). I=ingestion, A=assimilation and E=egestion.*

Est. Pop.		Menhaden 1.8×10^7	Spot 2.8×10^7	Pinfish 0.9×10^7
Zinc	I	83	950	32
(g/day)	A	30	20	6
	E	53	930	26
Iron	I	17,000	39,000	2,200
(g/day)	A	170	120	13
	E	16,830	38,880	2,187
Manganese	I	200	810	21
(g/day)	A	6	6	1.5
	E	194	804	19.5
Copper	I	18	140	1.3
(g/day)	A	1.6	1.4	0.4
	E	16.4	139.6	0.9

tidal flushing, biological export and commercial fishing. Covering a one-year period (November 1967 - October 1968), tables of data are presented that include total import and export of metals in water, export in commercially harvested species and export by emigration of species. Their mass balance (Table 11) suggests that biological exports are insignificant compared to those due to physical processes. They did not include imports in seawater and organisms or from sediments that might be entering via the river. In a series of publications, Wolfe (1974a,b, 1975) and Wolfe et al. (1973) examined reservoirs and fluxes of manganese, iron and zinc in the biological and physical components of the estuary. Figure 17 (redrawn from Wolfe et al. 1973, Wolfe 1975) shows that the largest reservoirs and fluxes of metals involve the sediments, water and *Spartina*, with small reservoirs and fluxes in the other biota. Wolfe et al. (1973) and Wolfe (1975) describe the cycle of zinc more detail than that of the other metals, particularly with reference to various biotic components. They suggest that the biological cycling of zinc in the estuary is not closely tied to the sediment/water reservoirs and fluxes. They further discuss the problems with using the model to predict the fates and effects of an acute release of zinc into the natural environment. This discussion is especially useful in predicting the behavior, upon acute release, of many materials in the estuary.

Nutrients

As defined here nutrients are materials dissolved in seawater that are necessary for the primary productivity of plants. Nutrients include inorganic and organic compounds that (e.g. carbon dioxide) occur in such abundance that their availability seldom limits primary productivity. The materials most frequently studied as potentially limiting to productivity in estuaries are ions and compounds of nitrogen (nitrate, nitrite, ammonia, urea, primary amines), phosphorus (orthphosphate, organic phosphate) and silicon (silicate ion). Dissolved nitrogen and phosphorus are needed by all plants and silicon is also needed by diatoms, the most dominant phytoplankton group in the lower NRES. In general, the elements are rapidly cycled within the ecosystem due to excretion by animals and decomposition.

The concentration of nutrients in the NRES

Table 11. *Mass balance (Kg/yr) of trace metals in the Newport River estuary (Jennings et al., 1970).*

	Iron		Manganese		Zinc	
	Import	Export	Import	Export	Import	Export
Water	53,200	15,800	3,480	1,410	112	106
Biota	—	14	—	4	—	10
Sediment	—	134,000	—	1,750	—	440
Total	53,200	149,800	3,480	3,160	112	556

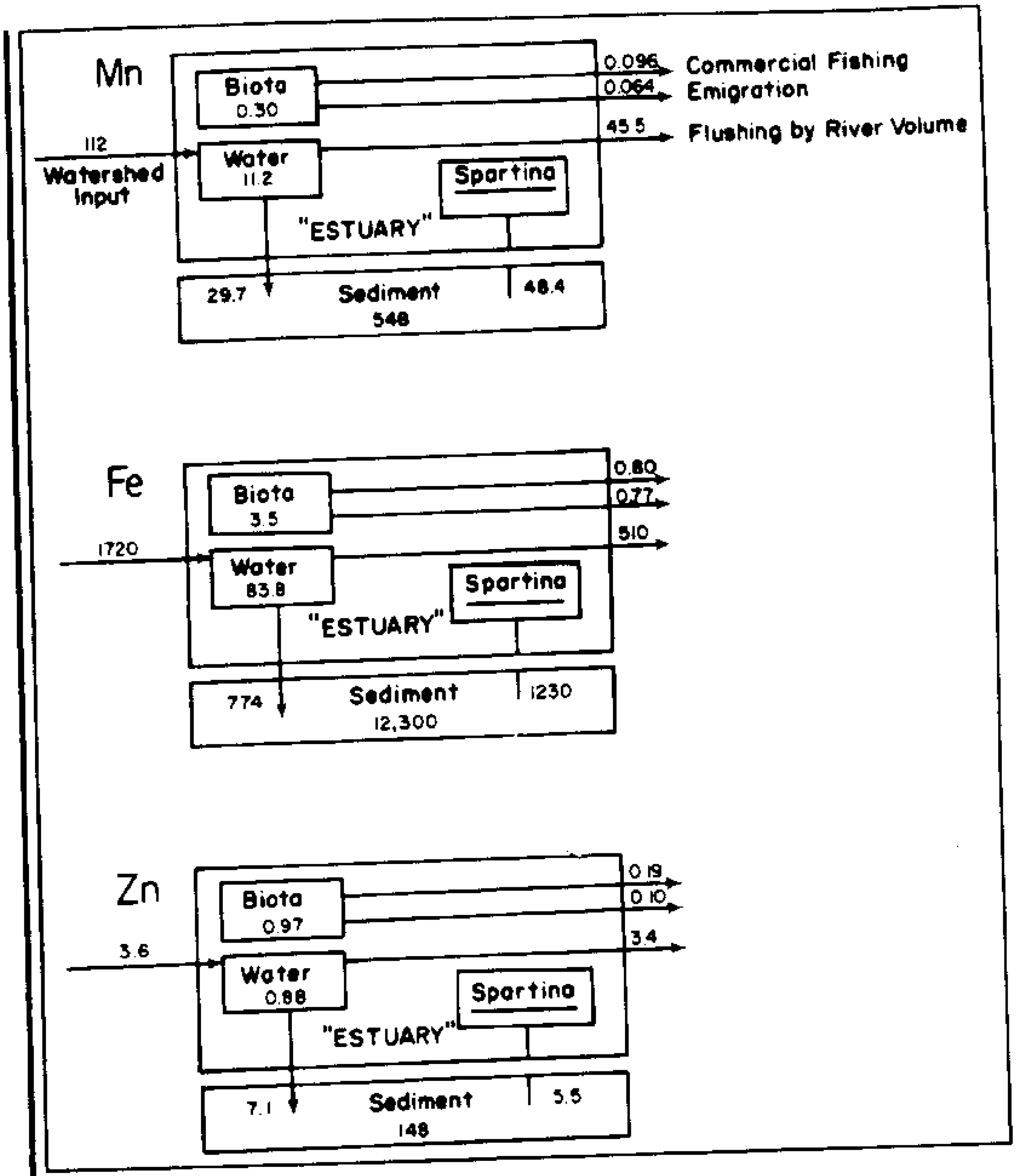


Figure 17. Model of fluxes of manganese (Mn), iron (Fe) and zinc (Zn) in the Newport River estuary. Units in boxes are mg/m² and on arrows are mg/m²/yr. Sediment is limited to top two centimeters. Total area is 31 km², and depth is 1.3 m (from Wolfe, 1975).

is variable in time and space. In a discussion of the studies of Calico Creek, Sanders and Kuenzler (1979) summarized nutrient data available from Thayer (1969) for the Newport River estuary and from Campbell (1973) for Gales Creek. These data (Table 12) show that Calico Creek, which receives effluent from the Morehead City Sewage Treatment Plant, has relatively high (non-limiting) concentrations of phosphorus and nitrogen. Gales Creek is a small estuary off Bogue Sound that has its freshwater origins in drainage from the Croatan Forest. Nitrogen concentrations in Gales Creek (Campbell 1973) were moderate, and phosphate values were low. However, the atomic ratios of nitrogen to phosphorus would still suggest a nitrogen-limited system. Average nutrient concentrations for the NRES (Thayer 1969) were low, suggesting that phytoplankton productivity is always nutrient-limited in this system.

Smith (1976) measured ammonia and urea (a form of organic nitrogen) concentrations at high and low tides from 1973 to 1974 at Pivers Island. Average ammonia concentration was approximately 1 µg.at N/l (range: near 0.0 to 3.28 µg.at N/l) and average urea concentration was approximately 2 µg.at N/l (range: near 0 to 3.25 µg.at N/l). She suggested that urea may be a significant form of nitrogen available to phytoplankton in the estuary.

Thayer (1971) compared average nutrient concentrations in three areas of the NRES: the freshwater of the Newport River, the Newport River estuary and North River (Table 13). Nutri-

Table 12. *Nutrient concentration (µg.at/l) during warm (May—Oct.) and cool (Nov.—Apr.) periods for three areas in the NRES. Walues are means and ranges with "nd"=not detectable (from Sanders and Kuenzler, 1979).*

	Nitrate	Ammonia	Phosphate
Calico Creek (Sanders and Kuenzler 1979)			
Warm	8 (3—15)	17 (10—25)	15 (5—46)
Gales Creek (Campbell 1973)			
Warm	1.5 (nd—7)	2.1 (nd—8)	0.4 (.05—.9)
Cool	0.6 (nd—4)	3.6 (nd—19)	0.3 (.05—.9)
Newport River estuary (Thayer 1969)			
Warm	0.3 (nd—.7)	0.4 (nd—1.3)	0.3 (0—.7)
Cool	0.4 (nd—2.1)	0.5 (nd—3.7)	0.3 (.2—1.5)

Table 13. *Average nutrient concentrations (µm/l) in three areas of the NRES. Warm=May to Sept., cool=Sept. to May. DIP=dissolved inorganic phosphate. DOP=dissolved organic phosphorus. PP=particulate phosphorus. Phosphorus is the annual average. (From Thayer, 1971.)*

	Newport River				North River	
	Fresh water		Estuary		Estuary	
	Warm	Cool	Warm	Cool	Warm	Cool
Nitrate	0.4	0.4	0.2	0.3	0.5	0.3
Nitrite	0.08	0.03	0.06	0.01	0.01	0.01
Ammonia	0.7	0.8	0.5	0.6	0.5	0.3
Total Aval. N	1.2	1.2	0.7	0.9	1.0	0.6
DIP	0.9		0.3		0.2	
DOP	0.4		0.4		0.3	
PP	0.2		0.3		0.2	

ent concentration in all three areas was low to moderate with slightly higher values in the freshwater area. Nitrogen to phosphorus ratios were generally less than 8, indicating a nitrogen limitation on productivity.

Kirby-Smith and Barber (1979) found relatively high nutrient concentrations in freshwater runoff from developed land into the headwaters of the North River, but natural swamp forest drainage had very low concentrations of phosphorus and nitrogen (Table 14). These data on nitrogen and phosphorus suggest that as population and development has increased around the NRES, the nutrient inputs have increased substantially, even though concentrations in the open estuarine waters remain low enough that phytoplankton productivity would be almost always nutrient-limited.

There are few data available on the concentration of silicon, probably because concentrations are so high that there is no indication that they would ever limit diatom production. Rosenberg (1981) reported concentrations of silicon of 10 to 20 µg.at Si/l in a diel study at Pivers Island. Kirby-Smith and Barber (1979) measured silicate on two occasions in natural swamp stream waters and the headwaters of the North River and reported values greater than 90 µg.at Si/l.

Table. 14 *Nutrient concentrations (µm/m) in a natural swamp stream and the headwaters of the North River recorded between Feb.1975 and Sept. 1976. "nd"=not detected. (Kirby-Smith and Barber, 1979).*

	Natural Stream			North River (Headwaters)		
	Mean	Range	N	Mean	Range	N
Phosphate	0.38	nd— 0.83	30	0.52	nd— 3.18	35
Nitrate	0.33	nd— 1.23	25	5.73	nd— 38.3	33
Ammonia	1.95	nd— 10.9	31	4.65	nd— 18.5	30

Data available on seasonal patterns of nutrient concentrations suggest that, in general, there is not a great difference in levels of phosphorus and nitrogen during the warmer months than during the colder months (Table 14). Thayer (1971) found that phosphorus and nitrate concentrations did have peaks in the late spring and early summer and that ammonia peaked in the late spring/early summer and again in the late fall. Rosenberg (1981) examined both diel and seasonal changes in nutrient concentrations in water pumped from the Beaufort channel at Pivers Island. Seasonal patterns and concentrations were similar to those of Thayer (1971) except that ammonia was four times as concentrated. Simultaneous measurements at the pump intake and in the outflow of the seawater system showed that this ammonia was generated in the seawater system, possibly as a result of excretion by fouling organisms within the pipes. In his diel studies, Rosenberg (1981) found that nitrate, nitrite and silicate showed little variability over a 48-hour period, but the concentration of ammonia, primary amines (an organic form of dissolved nitrogen) and phosphate increased during the night and decreased during the day (Figure 18). He attributed the increase at night to an increased rate of zooplankton excretion as they grazed on phytoplankton, coupled with a decrease in primary productivity (no light). The decrease in the day was attributed to rapid primary productivity, resulting in rapid uptake of those nutrients regenerated during the night. Chlorophyll *a* estimates of phytoplankton biomass supported this interpretation.

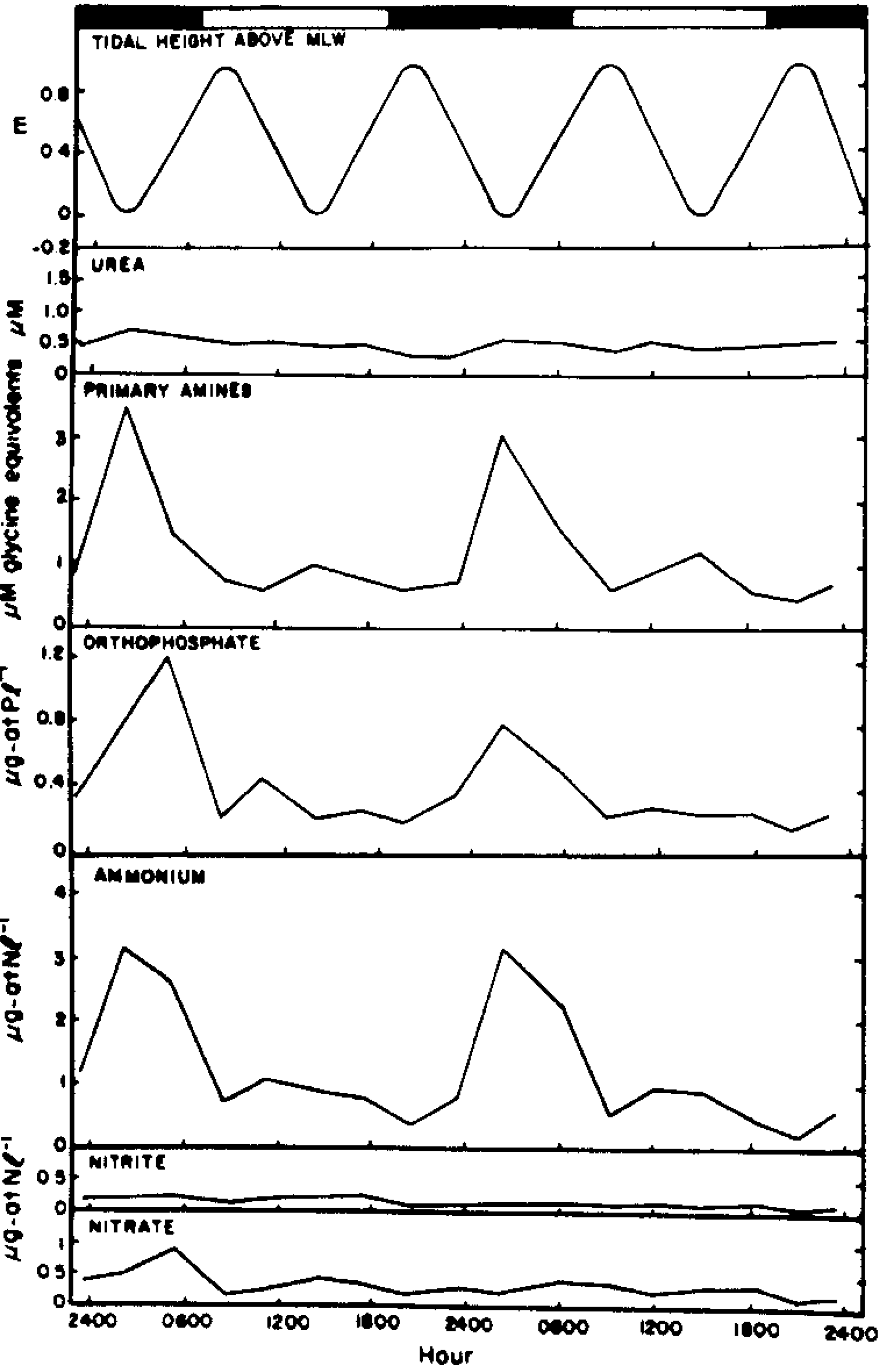
From 1982 to 1983, J. Ramus and his students at the Duke University Marine Laboratory investigated the nutrient and phytoplankton dynamics of the Newport River estuary by sampling a station in the middle of the estuary (north of Crab Point) every hour for two weeks on a seasonal basis. Litaker and Ramus (1983) report a strong tidal component in nutrient concentrations and phytoplankton abundance, with high values associated with low salinities and low values with high salinities. In addition, Litaker et al. (in press) observed the strong diel variability previously noted by Rosenberg (1981). Ammonium concentrations reached a maximum greater than 2 μg-at/l several hours after dawn and a minimum of less than 0.5 μg-at/l in the early afternoon. Chlorophyll *a* concentrations were greatest in the afternoon with a mean of 22 μg/l and lowest around dawn with a mean of 12 μg/l. The changes were due to zooplankton grazing and phytoplankton growth, data which suggest that biological factors are extremely important in controlling primary productivity through the process of rapid nutrient regeneration.

Nutrient concentrations in pore waters of sediments in the Newport River estuary have been investigated, particularly in relation to eelgrass beds. Kenworthy (1981), Kenworthy et al. (1980, 1982) and Kenworthy and Thayer (1978, 1979, 1980) found that the pore water in sediments outside eelgrass beds had an ammonia concentration of 50 μg.at N/l. But inside the beds this value increased to an average of 250 μg.at N/l. Ammonia concentration increased from the surface of the sediments to a depth of 6 to 9 cm after which it remained relatively constant. Bosso (1978) reported that the nitrate values in pore waters were approximately the same as those in the overlying water column.

There are only a few studies that deal with nutrient fluxes in the NRES. Thayer (1970) investigated the flux rates of phosphorus among the different forms in which it is found in the water column. His results indicated that there is a rapid exchange among dissolved inorganic phosphorus, dissolved organic phosphorus and particulate phosphorus. He suggested that dissolved inorganic phosphorus is not likely to become limiting to phytoplankton since it is readily replaced from the other forms of phosphorus as it is used. Smith (1976) studied the regeneration of nitrogen (ammonia and urea) by zooplankton and found that it accounts for only 16 percent of the nitrogen necessary for phytoplankton. She concluded that zooplankton probably play only a minor role in nutrient cycling in the estuary. However, the data of Sterns (1983) suggest that Smith's (1976) zooplankton biomass were greatly underestimated (by as much as a factor of 10) which would mean that nitrogen regeneration by zooplankton is probably the most significant source of this element in the Newport River estuary.

In the only study to date on the effects of benthic organisms in the NRES on nutrient regeneration, Bosso (1979) found that the common mud snail, *Illinassa obsoleta* probably plays only a small role in nitrogen regeneration from sediments to the water column, primarily by its burrowing activities.

Figure 18. Diel variations in nutrients in water collected off the Duke University Marine Laboratory dock (from Rosenberg, 1981).



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