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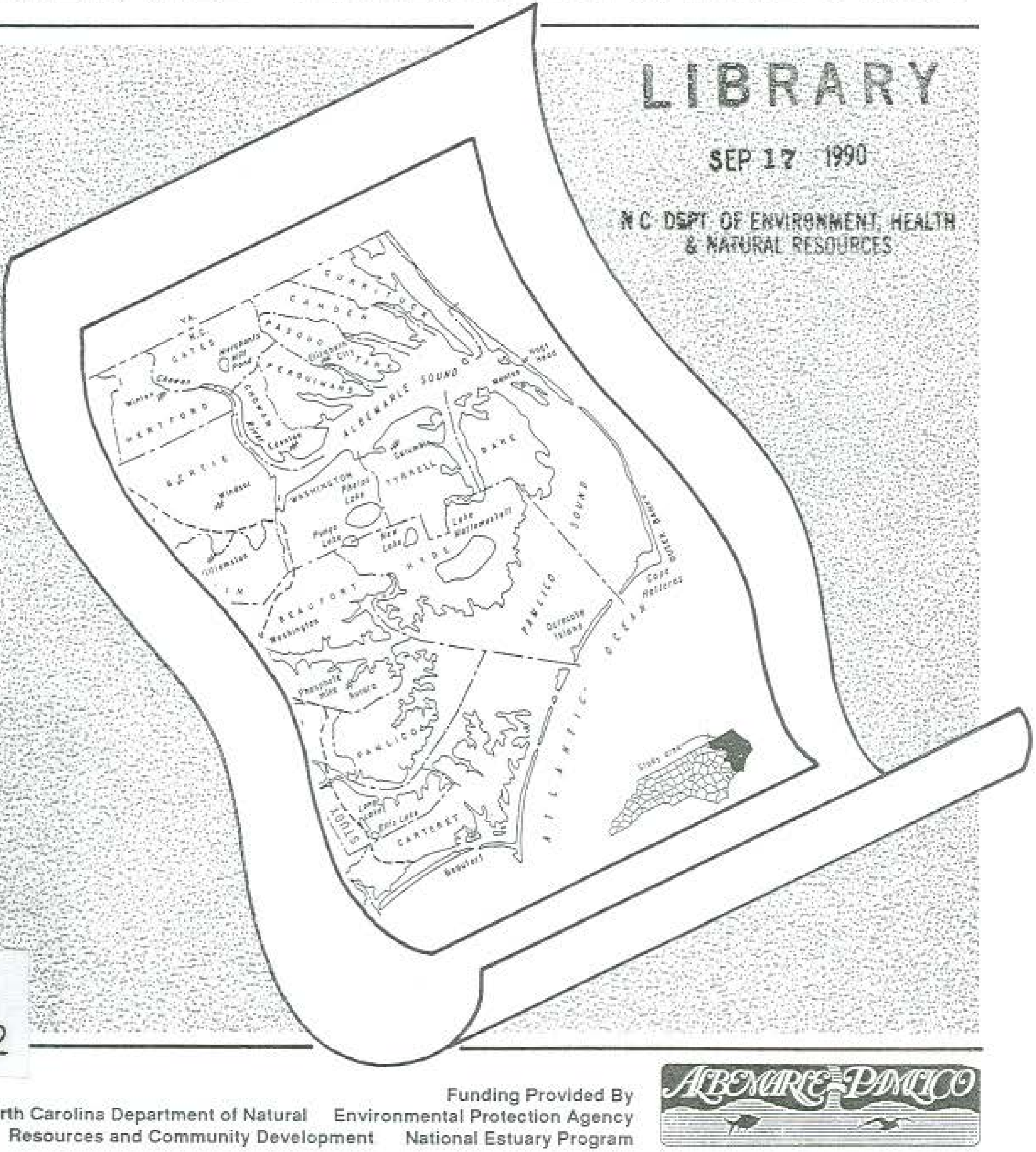
A SCOPING STUDY OF THE DISTRIBUTION, COMPOSITION, AND DYNAMICS OF WATER-COLUMN AND BOTTOM SEDIMENTS: ALBEMARLE-PAMLICO ESTUARINE SYSTEM

ALBEMARLE - PAMLICO ESTUARINE STUDY



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ALBEMARLE-PAMLICO

A SCOPING STUDY OF THE DISTRIBUTION, COMPOSITION, AND DYNAMICS OF WATER-COLUMN AND BOTTOM SEDIMENTS: ALBEMARLE-PAMLICO ESTUARINE SYSTEM

by

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ABSTRACT

Relative to its size and in terms of its sedimentary processes, the Albemarle-Pamlico estuarine system is one of the least studied coastal bodies of water in the United States. This paper provides a synthesis of what we know about sedimentation in the Albemarle-Pamlico system, based on archived data published over the last 30 years and new, unpublished data, collected over the past 18 months. The literature reflects considerable past research effort on sediment grain size and mineralogy, but very little on flux of particulate material, or the role of sediments as a sink for pollutants and a source for regenerated nutrients.

The physiographic complexity of the system, which includes barrier islands, a deep central basin, four river systems, and extensive fringing embayments, does not appear to be reflected in the form of sedimentologic complexity. In general, the surficial cover of sediments ranges from medium sands in the inlets and on the shoals of the Outer Banks to fine silts and organic-rich clays in the central basin and embayed river mouths and channels. The transition zones from sands to muds are typically sharp and are usually related to bathymetry.

Much of the terrigenous sediment is apparently trapped in the lower courses of the major rivers by processes of estuarine circulation, even though sediments may be deposited and resuspended many times before coming permanently to rest on the the bottom. The distribution of particle-reactive tracers in the lower Neuse River, the second largest contributor of sediment to the APES basins, suggests that deposition is related to focusing in a migrating turbidity maximum. Since the same mechanisms that concentrate fine-grained sediments may also concentrate heavy metals, pesticides, or other toxic substances that are adsorbed onto the surfaces of the sediment particles, preferential accumulation sites for organic-rich muds may thus be the accumulation sites for these toxic materials.

On the basis of sediment character it is reasonable to conclude that 1) parts of the Albemarle-Pamlico estuarine system may have high sedimentation rates relative to rates of sediment input and that rapid vertical flux by large aggregates offers an explanation for the fluid-mud deposits that would otherwise be absent, 2) fine-grained sediments that escape the estuarine sediment "trap" are confined to Pamlico Sound by the Outer Banks barrier islands and are simply recycled until finally coming to rest in the deep basin, 3) short-term advective processes are secondary to longer-term processes, such as sea level rise and barrier island migration, in the net advection of Albemarle-Pamlico sediments, and 4) at the present rate of terrigenous sediment input and relative sea level rise the Albemarle-Pamlico estuarine system will never reach a sediment-filled state.

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SUMMARY AND CONCLUSIONS

1. The Albemarle-Pamlico estuarine system is characterized by several features that influence and perhaps, in some cases, govern the distribution of sediments and the processes of sedimentation. The system comprises large, shallow bodies of water that have little or no free connection with the open sea; it has a complicated shoreline geometry with different freshwater sources and orientations relative to prevailing winds; and, it has a low tide range with circulation that is dominated by wind-driven currents.

2. Relative to its size and in terms of its sedimentary and geochemical processes, the Albemarle-Pamlico estuarine system is one of the least studied coastal/estuarine bodies of water in the United States. Although the literature reflects considerable past research effort on sediment grain size and mineralogy, very little is known about sediment dynamics, flux of particulate material, or the role of sediments as a sink for pollutants and a source for regenerated nutrients.

3. The same mechanisms that concentrate fine-grained sediments may also concentrate heavy metals, pesticides, or other toxic substances that are adsorbed onto the surfaces of the sediment particles. Preferential accumulation sites for organic-rich muds may thus be the accumulation sites for these toxic materials, at least until such time as they are released diagenetically or through resuspension.

4. An extensive review of the literature of the APES basins, including the tributary estuaries, has revealed that over 3300 bottom samples have been taken since the mid 1950s; 862 of these were subjected to a sieve, pipette, or hydrometer analysis and the remainder were examined microscopically, through x-ray diffraction analysis, or left unanalyzed. Of the 25 primary literature sources only 6 were journal articles or technical reports; the remaining 19 were M.S. or Ph.D. theses prepared from about the mid 1960s to the mid 1970s.

5. This review shows that sediments in the Albemarle-Pamlico estuarine system are derived from four major sources: river input, shoreline erosion, the continental shelf, and autochthonous biogenic production. A fifth, minor contribution is windblown silt and sand from the dunes of the Outer Banks and from large, periodically unvegetated agricultural fields. Not only is freshwater discharge so low that it would take more than a year for flow volume to equal the volume of the estuarine system, but the discharge of sediments is so low that the Albemarle-Pamlico system receives less sediment in a year than the Mississippi River delivers in 2 days.

6. The most striking features of sediment texture in Currituck, Albemarle, Croatan, Pamlico, and Core Sounds are the overall abundance of fine sand, the simplicity of distributional

patterns, and the sharpness of textural transitions. Textural differences between Albemarle and Pamlico Sounds can be explained by sediment sources. Whereas Albemarle Sound received large amounts of organic-rich muds from tributary rivers (before upstream impoundments), Pamlico Sound derived much of its sediment from barrier islands and from shore erosion.

7. The lower Pamlico and Neuse River estuaries have muddy bottoms from fine-grained sediments that have been derived from deeply weathered Piedmont soils. Transitions from channel-flank sands to channel-bottom muds are extremely sharp in the estuaries. Some data sets show adjacent samples that differ in sand content by 99%. As in Albemarle Sound, the fine-grained sediments are clearly confined to the deep axis of the estuary and sand on the channel margins are supplied from local shoreline erosion.

8. Examination of two Landsat Thematic Mapper (Band 2) images has revealed three features that may be important to suspended-sediment flux. First, the highest turbidities, irrespective of wind direction or river stage, are in Pamlico Sound. Second, within Pamlico Sound the suspended-sediment concentrations, at least in surface waters, appear to be over the muddy central basin. Third, the surface turbidity patterns are more complex than the bottom textural patterns and may reflect differential sediment resuspension, water column mixing processes, or eddies that have formed from wind-induced movement of surface waters.

9. In common with most estuaries and lagoons, the Albemarle-Pamlico system may be expected to retain within its boundaries a major fraction of the sediment supplied, regardless of source. The two accumulation sites for silt- and clay-sized sediments, the fresh-to-brackish estuarine waters associated with riverine sources and the deep central basin of Pamlico Sound, are not connected; rather, they have discrete boundaries and are separated by a region of fine sand. These two environments, which are lithologically very similar, represent two quite different processes of sedimentation. Whereas muds in Albemarle Sound, Pamlico River and the Neuse River are products of rapid sedimentation from deposition of flocculated particulates, muds in the central basin of Pamlico Sound are products of presumably slow sedimentation from many cycles of deposition and resuspension.

10. Muds that bypass the rivers are confined by, and recycled in, the sound until they ultimately end up residing in the deep central basin. Any accumulation is from particles that have escaped the estuarine "trap." Thin laminae of mud deposited over the broad sand blanket during periods of high sediment discharge are probably winnowed from shoal areas by storm waves. Sedimentation rates in the deep basin of Pamlico Sound are unknown and sufficient data are not available to quantify the presumably small amount of sediment that may escape through the three inlet systems.

11. The sharpness of textural transition zones suggests that well-defined dispersal pathways do not exist. A reasonable hypothesis is that net advection of sediment is limited to the very fine particles which are transported to the deep basin and the very coarse particles (medium sands) which are transported through the inlets and accumulate as flood tidal deltas. In terms of sediment volume, most material undergoes little net transport and is responding to slow basin- to global-scale processes such as sea level rise and barrier island migration.

12. Locally, short-term deposition rates of fine-grained sediments may be quite high. Soft, gel-like fluid muds which are often an indication of rapid sedimentation, are present in the estuarine reaches of the Pamlico and Neuse Rivers and in Albemarle Sound. However, except for these localized regions of fluid mud accumulation, sedimentation processes in the APES area are occurring too slowly to ever fill the basins. Order-of-magnitude calculations indicate that, even when assuming a very modest sea level rise of only of 1 mm/yr, the APES basins will never reach a sediment-filled state, unless river input changes drastically or the input from other sources exceeds river input by 6 times.

RECOMMENDATIONS

The main objective of this project was to provide a comprehensive summary of our state-of-knowledge of the origin of sediments, their composition and size, and their inferred dispersal and flux within the Albemarle-Pamlico system. The following recommendations are thus made on the basis of this literature review and reflect scientific information needs in the three areas below. Specific recommendations are to focus future research efforts on answering the priority questions outlined in the following paragraphs.

1) Suspended sediments in the water column. The literature review clearly points out that we have considerable knowledge about the distribution of grain sizes on the bottom and their mineralogy and sedimentary structures. The basic information we lack concerns the particles in the water column and the processes that have led to the observed bottom deposits. The most pressing questions concerning suspended sediments are: What is the spatial distribution of suspended sediment (lateral and vertical), and how does it change through time? What is the dispersal pathway of sediments once they reach the estuarine portions of the rivers? Does an estuarine turbidity maximum always exist, and, if so, is it tied to recirculation of suspended sediments upstream? What are the settling rates of suspended sediments, and do they settle as individual particles, electro-chemically bound floccules, or as organically-bound marine-snow agglomerates?

2) Seabed accumulation. Although the bottom sediments throughout nearly all of the Albemarle-Pamlico system have been described, the descriptions are based mostly on surficial grab samples. A wealth of information is also contained in the underlying deposits since this is where past conditions have been recorded. Furthermore, if pollutants are adsorbed onto sediment particles, then the accumulation sites for sediments are also the accumulation sites for pollutants, at least until such time as they are released diagenetically or through resuspension. The most pressing questions are: What is the ultimate fate of sediments that enter the system from the rivers? What are the average rates of sediment accumulation? Where do sediments accumulate most rapidly? Have the accumulation rates changed over historic times and over the past, say, 100 years as a result of land-use practices?

3) Seabed - water column exchange processes. An important consideration in the release of nutrients or toxic substances that are adsorbed onto sediment particles concerns what exactly happens when sediments reach the bottom. The fundamental question is: Are the accumulation sites temporary or permanent? A careful distinction must always be made between deposition and accumulation. Whereas deposition refers to temporary emplacement of particles on the seabed, accumulation is the net sum of many episodes of deposition and removal. Thus the seabed and water

column are linked by the possibility (or probability) that sediments can be resuspended. A number of other important related questions are: What is the resuspension potential of the various sedimentary environments of deposition? What is the frequency of resuspension? Does the shape of fine-grained sediments play a major role in resuspension potential? What are the effects of storms? With this information in hand we should be better able to predict resuspension-related impacts on water quality.

INTRODUCTION

This project completion report contains results of a one-year scoping study of sediments in the APES (Albemarle Pamlico Estuarine Study) region of eastern North Carolina. The overall goal of the project was to provide a comprehensive summary of our state-of-knowledge of the origin of sediments, their composition and size, and their inferred dispersal and flux within the Albemarle-Pamlico system. The basis for the study was archived data published over the last 30 years and new, unpublished data, collected over the last 18 months. The project was initiated in direct response to Tasks E.6 (Sediment Distribution and Motion) and E.15 (Chronic Effects of Suspended Sediments) of the Water Quality and Estuarine Relationships section of the original APES Call for Proposals (May 1987).

Specific objectives of the project were to 1) collate, for the first time, approximately 25 data sets from maps of various small scales onto a series of base maps from which the diagnostic characteristics of the bottom sediments could be described, 2) provide a regional survey of suspended sediments under several different environmental conditions using Landsat Thematic Mapper (TM) imagery, and 3) determine inferred pathways of sediment dispersal, vertical flux rates, and probable short-term deposition and long-term accumulation sites for the most mobile sediments, the mud fraction. As the first basin-wide description of bottom and suspended-sediment character, this study was designed to: serve as a reference for benthic habitat studies in which substrate could be a critical factor; provide a first-order map showing potential storage sites for sediments of different sizes and composition; provide an index for sediment resuspension, where resuspension threshold is governed largely by grain size; and, characterize bottom type in such a way that it could be used as input to future modeling studies of water motion and sediment dispersal.

Rationale for Study

Sediments will surely play an increasing role in future management of the Albemarle-Pamlico estuarine system. In shallow-water regions, such as the APES area (Fig. 1), the water column and surficial sediments interact continually, exchanging and redistributing particles and solutes so as to impact the operation of the entire system. Consideration of sedimentary processes and their dynamics in the estuaries is therefore essential in addressing water quality issues, and research into these processes is a vital part of any system-wide management effort. However, in contrast to the water, the sediments are often an unseen and apparently passive component in an estuary. Sediment distribution and properties are slow to change, and their role in water-column events is not always apparent. Yet, sediments may play a critical role in transporting pollutants, modulating productivity, and releasing nutrients.

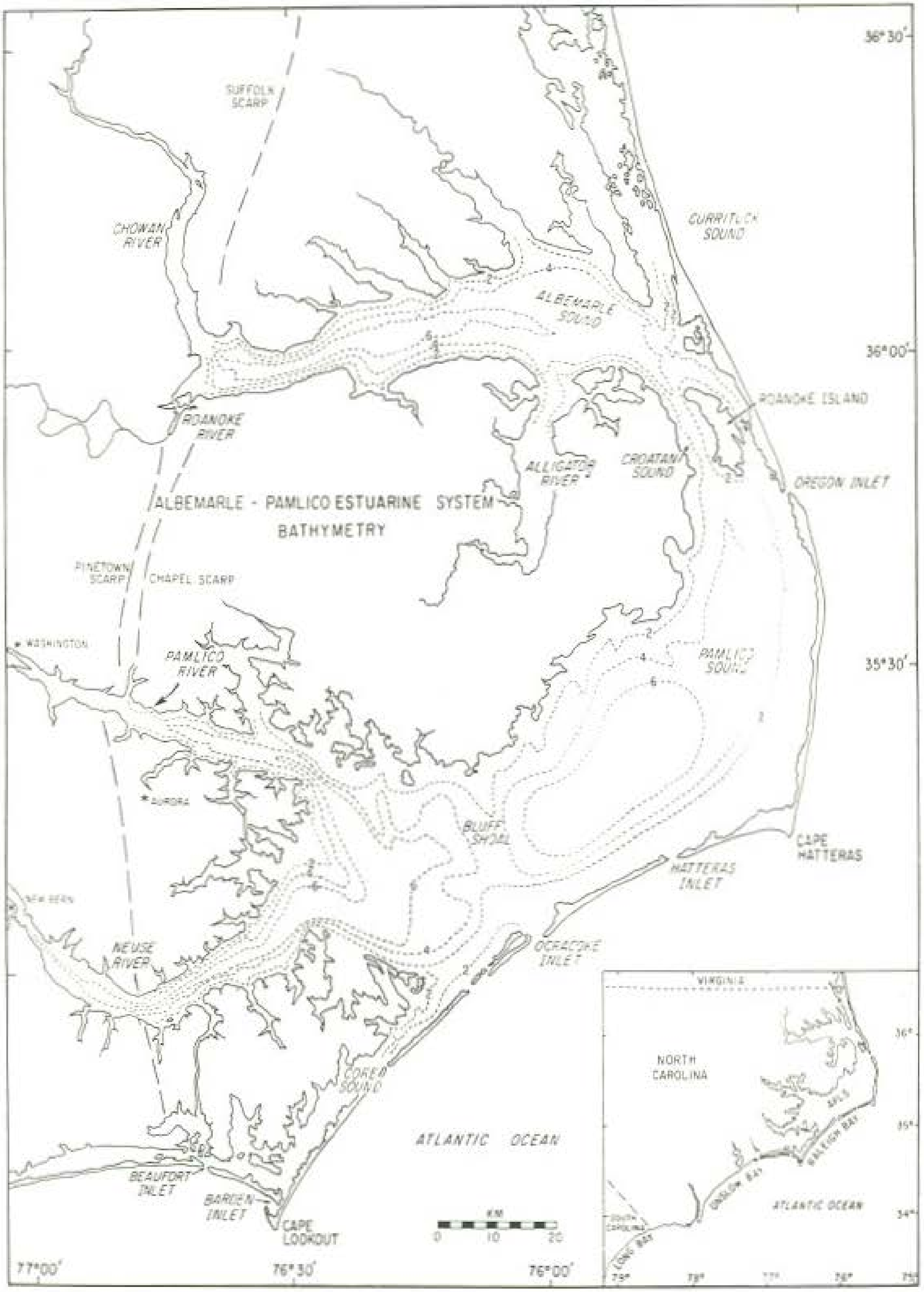

Figure 1. Index map of the Albemarle-Pamlico estuarine system showing bathymetry (meters) and complex shoreline configuration.

For example, the same mechanisms that concentrate fine-grained sediments may also concentrate heavy metals, pesticides, and other toxic substances that are adsorbed onto the surfaces of the sediment particles. Preferential accumulation sites for organic-rich muds may thus be the accumulation sites for these toxic materials, at least until such time as they are released diagenetically or through resuspension. The shallow waters of Albemarle and Pamlico Sounds are of considerable interest in this regard since they generally have very limited exchange with the adjacent waters of the Atlantic, yet receive muddy sediments from deeply weathered piedmont soils of a large and rapidly expanding urban area to the west (Raleigh/Durham/Research Triangle Park).

Furthermore, sediments are important from a management standpoint because:

1) shoaling is more than just a hazard to navigation. It reduces the volume of the estuary, thereby increasing the impact of storm tides on coastal property; it alters the size and distribution of habitats available to important fish and shellfish; it can change over time the distribution of water-column turbidity, affecting, through light penetration, primary productivity.

2) decomposition of organic matter in the sediments represents an oxygen demand which, when combined with physical stratification, can lead to bottom-water anoxia and fish kills. Nutrient elements which are re-mineralized in the decomposition process make the sediments a nutrient bank for the water column; withdrawals may be gradual and continuous, due to diffusion, or abrupt, due to major sediment-resuspension events. Primary productivity in the water column responds to these nutrient inputs.

3) many sparingly soluble or particulate pollutants, both chemical and biological, are stored in the most mobile sediments, the mud fraction. Passage of these materials through the food web causes waters to be closed to shellfishing, and the primitive nature of our understanding of the effects of this pervasive contamination is a serious concern for the future.

Relative to its size and in terms of its sedimentary and geochemical processes, the Albemarle-Pamlico estuarine system is one of the least studied coastal/estuarine bodies of water in the United States. Although the literature, as shown in the following paragraphs, reflects considerable past research effort on sediment grain size and mineralogy, very little is known about sediment dynamics, flux of particulate material, or the role of sediments as a sink for pollutants and a source for regenerated nutrients. The clear connection between transport of sediments and transport of toxic and non-toxic substances on their surfaces is an important reason to begin integrating studies of particulates into estuarine studies of eutrophication, habitat loss, agricultural impact, and fisheries.

HYDROLOGY AND ENVIRONMENTAL SETTING

The Albemarle-Pamlico estuarine system is characterized by several features that influence and perhaps, in some cases, govern the distribution of sediments and the processes of sedimentation. First, the system comprises large, shallow, fresh-to-brackish bodies of water that have little or no free exchange with the ocean. The Outer Banks island chain, which forms the seaward margin, has only four "permanent" inlets along its 270 km length (Fig. 1). Second, the geometry of the shoreline is complicated, and the major estuaries have different freshwater sources and different orientations relative to prevailing winds. Because the APES area is a system of drowned river valleys, the tributary estuaries are oversized for the amount of water they now carry, resulting in low velocities from freshwater inflow. Third, the tide range is low, and circulation appears to be dominated by wind-driven currents. Maximum tide range (~1 m) is in the vicinity of the inlets but tides are rapidly damped to 10 cm or less throughout most of the APES region.

The few published reports on hydrology and flow dynamics in Albemarle and Pamlico Sounds show that wind, at least in the short term, is the controlling factor in circulation (Roelofs and Bumpus, 1953; Knowles, 1975; Singer and Knowles, 1975; Giese, et al., 1979; Pietrafesa et al., 1986). Average wind speeds are 15 km/hr, but can reach 48 km/hr every month of the year when examined from the standpoint of long-term statistics (Fig. 2). The most important feature of winds is that they blow from the south to southwest between April and August and from the north to northwest between September and February. Although winds in March have a nearly uniform directional distribution, nearly 10% of all winds during the month of March exceed 30 km/hr.

Sea level has had a profound effect on shoreline configuration and depth of the estuarine waters. Albemarle Sound and the Neuse and Pamlico Rivers leading into Pamlico Sound are shallow, drowned river valleys that formed during the last post-glacial rise in sea level which began approximately 18,000 years ago (Curray, 1965). The relatively slow rate of sea level rise during the last 3000-5000 years (1-2 mm/yr) has allowed shoaling and redistribution of sediments in much of the system.

Depths in Albemarle Sound increase gradually with distance from shore to the relatively flat central axis of the sound (Fig. 1). Although the maximum depth is 9.1 m, the average depth is only 5.3 m, and in Croatan Sound, the limb which connects Albemarle Sound to Pamlico Sound, depths are less than 3.6 m (Folger, 1972a). Pamlico Sound is divided into two broad basins by Bluff Shoal, a north-south oriented cross-lagoon shoal adjacent to Ocracoke Inlet (Fig. 1). Bottom topography in the northern area dips smoothly toward the center to a maximum depth of 7.3 m. There are few topographic irregularities other than the shoals of a tidal delta that extends from Hatteras Inlet. In the southern part, where average depths are 5.4 m, two large finger shoals project to the middle of the basin from the western margin and a large tidal delta from Ocracoke Inlet merges with Bluff Shoal from the east.

Four river systems, the Chowan, Roanoke, Tar/Pamlico, and Trent/Neuse, provide 78.9% of the freshwater input to the APES region (Table 1). The remainder is supplied directly by precipitation and local runoff. The most important hydrologic feature of the rivers is the small volume of freshwater that they deliver and, as a result, the long residence time of water in the basins (45 days in Albemarle Sound, Copeland et al., 1983; 32 days in the Neuse River estuary, Knowles, 1975). According to data from Giese et al. (1979), approximately 14 months would be required to fill the APES basins at the average annual rate of volume inflow of 28.3 km^3/yr.

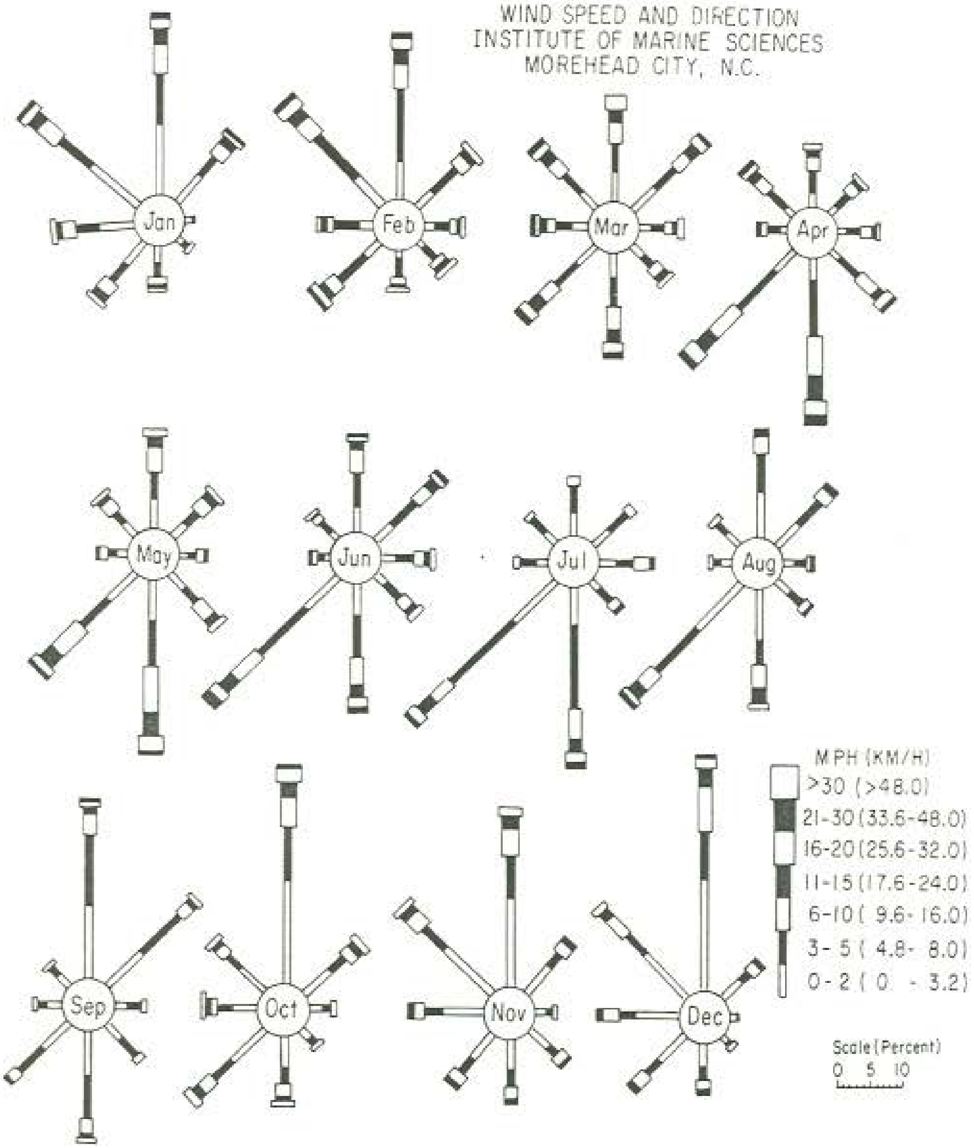

Figure 2. Distribution of wind speed and direction summarized by month from archived data (1979-1981) taken near Beaufort Inlet.

Table 1. Hydrologic characteristics of the Albemarle-Pamlico estuarine system (Data from Giese et al., 1979)

Variable	Pamlico Sound	Albemarle Sound
Drainage Basin (km^2)	27,091	46,309
Surface Area (Km^2)	5,335	1,243
Total (Km^2)	32,426	47,552
Volume (m^3)	2.60×10^{10}	6.58×10^9
Depth (m)		
Average	4.8	5.3
Maximum	7.3	9.1
Net Inflow (m^3/s)		
Precip - Evap	70.8	22.6
Neuse River	172.6	
Pamlico River	152.8	
Roanoke River		251.8
Chowan River		130.2
Other land areas	14.2	82.1
From Albemarle Sound	486.7	
Total (m^3/s)	897.1	486.7

The maximum total inflow occurs during February when precipitation is relatively high, evaporation is low, and inflow from the Albemarle Sound, which lacks an outlet to the ocean, is at a maximum. Minimum inflow occurs in June when evaporation is very high but inflow from Albemarle Sound is near its annual minimum (data from Giese et al., 1979).

The three-fold change in the volume of freshwater input between February (1542 m^3/s) and June (521 m^3/s) has an enormous, but not instantaneous, effect on salinity. Highest and lowest average salinities have been noted to occur in April and December, respectively (Epperly and Ross, 1986). Figure 3 shows typical patterns of surface isohalines in April and October when freshwater input varies by a factor of two. Albemarle Sound, except near its juncture with Croatan Sound, is nearly always fresh. However, salinities in Pamlico Sound usually range from 15-20 ppt with the highest values close to the inlets (Schwartz and Chesnut, 1973; Williams et al., 1973). The relative locations of inlets and freshwater sources contribute to general north-to-south and west-to-east salinity gradients. The vertical salinity gradient in Pamlico Sound is on the order of 1 ppt, but may reach 5-10 ppt in the estuarine sections of the Pamlico and Neuse Rivers (Giese et al., 1979; Hobbie and Smith, 1975) Both rivers have long estuarine stretches that vary substantially in their seasonal density structure.

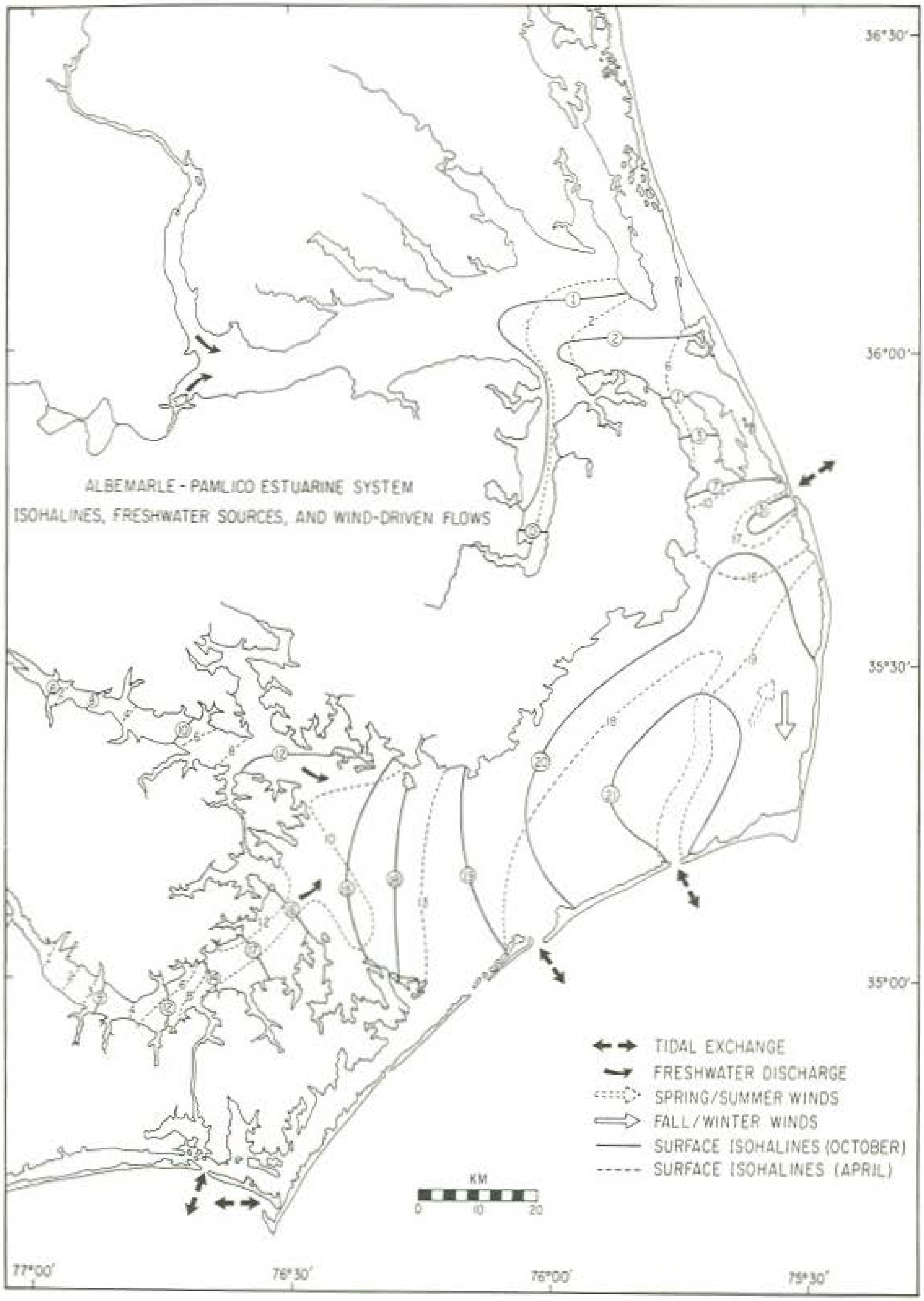

Figure 3. Sources of freshwater discharge, locations of tidal exchange, and typical isohalines in April and October. Predominant winds are aligned with the long axis of Pamlico Sound.

METHODS

This synthesis of the origin of sediments and their composition and size has been based on approximately 25 reports and journal articles published since the mid 1950s. Unfortunately, many of the reports were difficult to obtain and some were out of print. Further, the sample coverage in these studies was highly uneven and sometimes fragmentary. Data did not exist in some areas, such Currituck Sound, yet in other areas such as Pamlico Sound, there was considerable overlap. Methods of analysis varied as did the manner in which data were presented. Moreover, with few exceptions, water column data on suspended sediments had never been collected, published reports on turbidity were virtually nonexistent, and the field of sediment dynamics had been generally overlooked in favor of detailed lithologic descriptions. Despite these limitations, sufficient data were available to construct a first-order map of sediment grain size and to speculate on routes of sediment dispersal, vertical flux rates, and short- and long-term storage sites for the sediments most likely to concentrate pollutants, the fine silts and clays.

Bottom Sediments

The first step in summarizing bottom sediment character was to acquire every available published document that contained data on sediment grain size or mineralogy. Of the 25 primary literature sources only 6 were journal articles or technical reports; the remaining 19 were M.S. or Ph.D. theses prepared from about the mid 1960s to the mid 1970s. Data from a number of studies, originally published in thesis form and later printed as technical reports or in abridged form as journal articles, were traced back to their original sources. In each case, the most complete data set by a given author was taken as the primary reference and included in the summary tabulation. Unpublished data sets were not included in this summary.

The next step was to produce a file for each literature source that contained sample locations, the type of sampling device, and the type of analyses undertaken. Data points showing sample locations on each map, as produced by the author of the report, were digitized using a Numonics Corporation digitizing tablet with Jandel Sigma Scan software. A horizontal line and two independent data points were established for each map in order to define the digitizer grid and establish the scale. For the purpose of digitizing, latitude and longitude of each sample location were converted to x and y coordinates. Sample locations are listed both as x-y coordinates and as latitude and longitude in a data file archived with the Land Resources Information Service, North Carolina Department of Natural resources and Community Development.

Since the chief task was to compile existing data, the main sources of error were beyond the control of this study and could not be quantified. These primary sources of error were those inherent in the original mapping process. For example, in many cases the type of navigation employed during sample collection was not specified, but presumably was dead-reckoning or visual sighting. In open water areas such as Pamlico Sound, these methods could lead to errors in sample location of hundreds or even thousands of meters. On the other hand, in small bodies of water such as the Newport River, where navigational aids and land reference points are abundant, accuracy of sample locations could be within a few meters. However, even in these areas, physical change in shoreline position over the 20-30 year period since the original work was performed could lead to large errors when locations are digitized and replotted on present-day base maps. Finally, the maps containing original sample locations had been traced with varying degrees of care and accuracy from nautical charts available at the time. The fact that some authors neglected to include latitude and longitude on their sample location maps necessitated that this step be performed as carefully as possible, using whatever reference points were available, before starting the digitizing process.

Errors introduced through digitizing were considered to be negligible. Resolution relative to the established x-y coordinates was substantially better than the ability to accurately plot the sample locations, as noted above. Moreover, one operator performed all the analyses, and unsteady hand movements were insignificant since digitizing involved points rather than areas. Small digitizing errors became even less important when taken in the overall context of producing a map of bottom sediment character. This is because the ability to produce accurate sample locations for the base map did not necessarily mean producing an accurate map of grain size parameters, since most authors provided summaries rather than listings of grain size data for each sample.

After compilation of existing bottom sample data, several areas were identified as being deficient: the entire Currituck Sound; and, North River, North Landing River, and Pasquotank River in Albemarle Sound. These areas were sampled from a small boat during a 3-day period in May, 1988. Using an Ekman grab sampler to obtain a scoop of the upper few cm of bottom sediment, 59 samples were taken along the channels of these tributary streams. All sampling locations were at fixed channel markers and spacing was on the order of 1 km. In the laboratory, each sample was analyzed for grain size following the standard procedures of Carver (1971). These procedures involved wet sieving to separate the sand and mud fractions, followed by a sieve analysis of the sand and pipette analysis of the mud fraction. A listing of grain size statistics for samples collected as part of this project is given in Appendix I.

Suspended Sediments

Khorram and Cheshire (1983) have shown that Landsat multispectral scanner (MSS) digital data can be used successfully to map water quality parameters in the APES region. Their study used regression models to correlate ground truth with digital data from a single Landsat scene. This current scoping project took the next logical step by examining additional scenes under different seasons and flow conditions to develop more generalized conceptual models. The Landsat Thematic Mapper (TM), which has better resolution (30 m versus 80 m in MSS) and narrower spectral windows was chosen for these examinations. Unfortunately, purchasing digital data in the form of computer compatible tapes, which would have allowed quantification rather than just qualification of suspended sediment concentration, was prohibitive because of cost.

The first step in acquiring imagery was to obtain a listing from EOSAT (Earth Observation Satellite Company) of available TM scenes, the percent cloud cover, and the quality of the images. TM Band 2 (green) was selected on the basis of past experience as having the best spectral window for sensing patterns of turbidity. Although penetration into the water column is dependent on turbidity level and may be quite limited, the observed surface patterns can be the same as those at greater depths when the basin is shallow and the waters are well mixed. Thus it is not an unreasonable assumption that turbidity patterns in surface waters of the APES region reflect similar turbidity patterns in the bottom waters.

Six scenes from four contrasting environmental conditions (based on wind speed, wind direction, and river discharge) were purchased as 1:1,000,000 film negatives. These were: spring flood (4/1/85); strong northeast winds (10/16/87, 10/7/84)); strong southwest winds (8/10/86, 4/7/87); and calm conditions under low river discharge (11/27/85). Two of the problems in opportunistic use of Landsat imagery are the uneven quality of the negatives and the frequency of cloud cover over coastal bodies of water. Because of these problems, only the periods of northeast and southwest winds showed discernible variations in surface radiance that could clearly be established as indicative of turbidity patterns. Even with a repetition rate of once every 16 days, TM imagery of superb quality over large areas, such as the entire APES region, is quite limited.

RESULTS: SEDIMENT DISTRIBUTION AND DISPERSAL

Sources of Sediments

Sediments in the Albemarle-Pamlico estuarine system are derived from four major sources: river input, shoreline erosion, the continental shelf, and autochthonous biogenic production. A fifth, minor contribution is windblown silt and sand from the dunes of the Outer Banks and from large, periodically unvegetated agricultural fields. Table 2 shows water and sediment discharge from the four rivers that enter the APES region. Not only is freshwater discharge so low that it would take more than a year for flow volume to equal the volume of the estuarine system, but the discharge of sediments is so low that the Albemarle-Pamlico system receives less sediment in a year than the Mississippi River delivers in 2 days (9.6×10^5 versus 210×10^6 metric tons/yr).

Table 2. Water and sediment input to the Albemarle-Pamlico estuarine system (data from Giese et al., 1979).

River	Area Drained (km^2)	Freshwater Discharge (m^3)	Sediment Discharge (t/yr)
Neuse[1]	14,504	172.6 (5.4 km^3/yr)	2.35×10^5
Pamlico	11,137	152.8 (4.8 km^3/yr)	2.08×10^5
Roanoke[1]	25,035	251.0 (7.9 km^3/yr)	3.43×10^5
Chowan[1]	12,802	130.2 (4.1 km^3/yr)	1.77×10^5

Most of the sediment that enters by way of rivers is silt and clay with high organic content. The absence of sand can be attributed to a combination of 1) low-lying drainage basins with extensive marsh and swamp forests, 2) flow velocities that are generally below the competency level for transporting sands, and, in the case of the Roanoke River, and 3) upstream impoundments that capture most of the coarse sediments (Meade and Trimble, 1974).

The major source of coarse sediment is erosion of shorelines by direct wave attack. Figure 2 shows that a fetch of 70 km is possible when winds are aligned with the axis of Albemarle Sound and 100 km when aligned with the axis of Pamlico Sound. Along the shallow margins of Albemarle Sound, erosion rates of 0.5-1.0 m/yr (Bellis et al., 1975; Copeland et al., 1983) are sufficient to supply an apron of sand out to the break in subaqueous slope at a depth of 1-2 m. Along the shallow margins of Pamlico Sound, erosion rates of 1-3 m/yr (Stirewalt and Ingram, 1974; Copeland et al., 1984) are sufficient to create beaches. The greatest supply of sand is from high banks and bluffs which are undercut during storms, then collapse as slump blocks onto the beach.

Most of the sand in central and eastern Pamlico Sound, as well as in Core Sound to the south, is derived from barrier islands and offshore (Duane, 1964; Pickett and Ingram, 1969). The similarity in texture between sound and barrier island sediments and the decreasing landward percentage of garnet and yellow quartz are usually cited as evidence for barrier island rather than riverine sources (Duane, 1964; Meade, 1969; Pickett and Ingram, 1969). Three of the five APES inlets, Ocracoke, Hatteras, and Oregon Inlets (Fig. 1), are high-energy wave-dominated openings which have offshore-derived sand bodies in the form of flood tidal deltas. These tidally winnowed deposits are locally important sand bodies that account for approximately half of the medium sand in the system. Extensive washover fans and former inlets have also contributed offshore sand to nearly all of Core Sound (Moslow and Heron, 1978; Heron et al., 1984).

The total contribution of biogenic material to the Albemarle-Pamlico estuarine system is unknown. Based on calcium carbonate content (weight of shell fragments), Pickett and Ingram (1969) found that percentages ranged from less than 2% throughout much of Pamlico Sound to greater than 16% at Ocracoke, Hatteras, and Oregon Inlets where shell fragments were transported from the Outer Banks littoral environment (Fig. 4). High concentrations of shell fragments in the central basin and seaward of the Pamlico and Neuse Rivers were attributed by Pickett (1965) to preferential growth of oysters in these regions of high organic content.

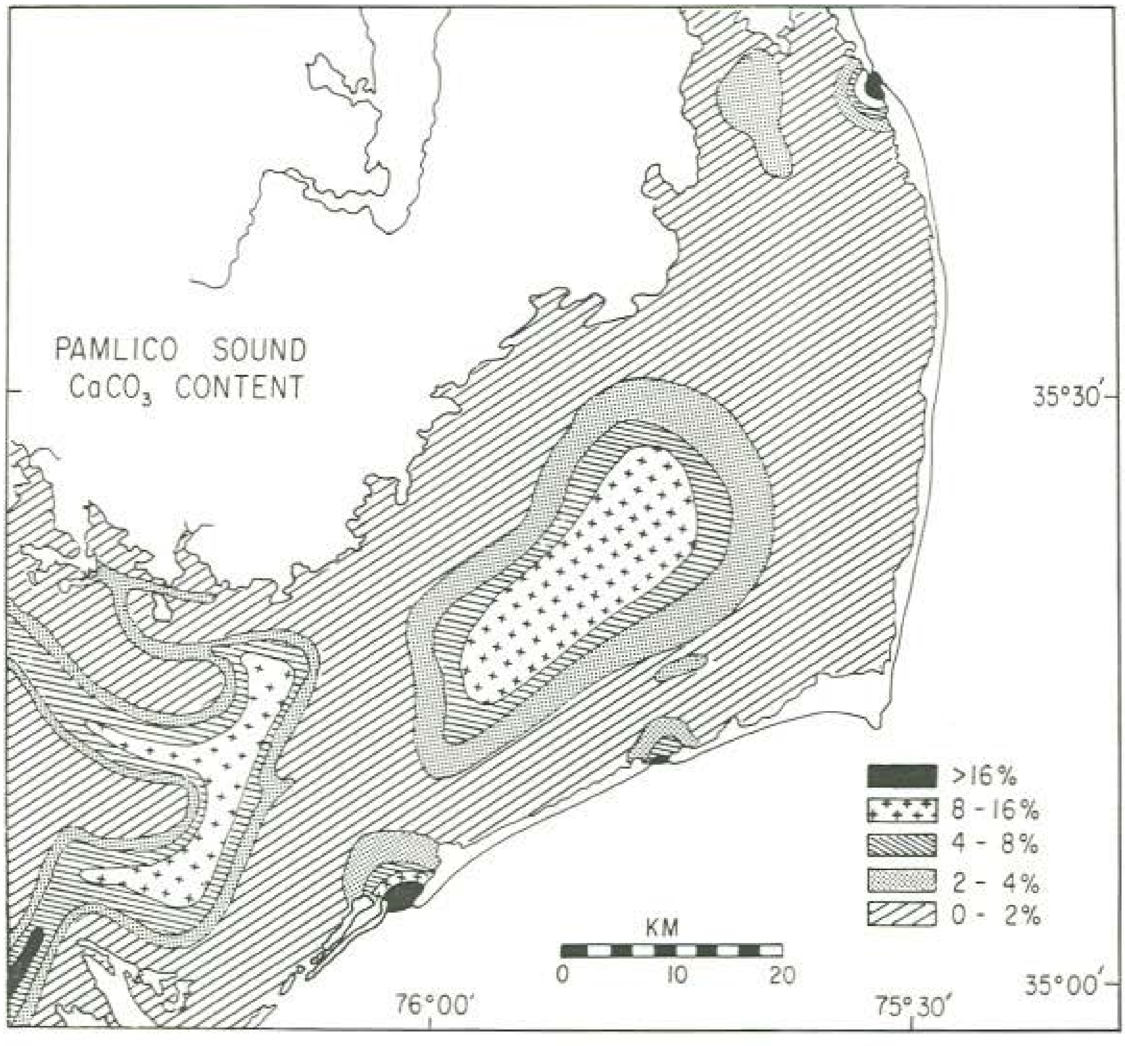

Figure 4. Distribution by weight (%) of calcium carbonate. Highest concentrations occur at inlets where shell fragments are transported from the littoral zone (figure modified from Pickett, 1965).

Grain Size and Mineralogy

Particle size and mineralogy have been extensively researched in most of the APES region, including the tributary estuaries and lowermost freshwater reaches of the river systems. Table 3 provides a complete summary of literature citations, areas sampled, total number of samples collected and analyzed, and the type of analyses performed. A total of 3300 samples have been taken since the mid 1950s: 862 of these were subjected to a sieve, pipette, or hydrometer analysis and the remainder were examined microscopically, through x-ray diffraction analysis, or left unanalyzed.

Figures 5 and 6 show the spatial distribution of bottom samples. Perhaps the most significant feature is that virtually the entire system has been sampled at one time or another during the last several decades. Nearly 20% of the samples were taken in the small APES subset consisting of the Newport River, North River, Beaufort Inlet, and Cape Lookout Bight. The number of data points in Figures 5 and 6 is less than shown in Table 3 because samples from some studies were collected but not analyzed (e.g. Skean, 1959), and several studies were conducted in upstream, freshwater and transitional segments of the river systems (e.g. Filer, 1979; Erlich, 1980; Davis, 1981; Witner, 1984). A complete listing of all bottom samples referenced in Table 3 is available from the North Carolina Department of Natural Resources and Community Development.

Figure 7 shows sediment texture in Currituck, Albemarle, Croatan, Pamlico, and Core Sounds (compiled primarily from Skean, 1959; Pickett, 1965; Pels, 1967; O'Connor et al., 1972). The most striking features are the overall abundance of fine sand, the simplicity of distributional patterns, and the sharpness of textural transitions. In Albemarle Sound, where the input of terrigenous sand is almost nil, organic sediments derived from marshes and swamps are the dominant material (Copeland et al., 1983). The fine to medium sand that is concentrated around the margins grades into deeper-water brown-to-black silt and clay that contains up to 15% organic matter (Pels, 1967; Giese et al., 1979; Copeland et al., 1983). The lower Chowan and Roanoke Rivers consist of peaty sediments that have been accumulating for the last 5000 years at average rates of 15 cm/century (Erlich, 1980; Witner, 1984). Widespread sand deposits at the eastern end of the sound and in Croatan Sound were probably derived from the Outer Banks (Folger, 1972a,b).

Bottom sediments in Pamlico Sound, in contrast to those described above, consist primarily of fine sand but range in size from medium sand to clay (Pickett, 1965; Park, 1971; Folger, 1972a,b). The distinct textural differences between Albemarle and Pamlico Sounds can be explained by sediment sources. Whereas Albemarle Sound received large amounts of sediment (several million tons/yr) before upstream impoundments (Folger, 1972b), Pamlico Sound derived its sediments (sand) from barrier islands and from shore erosion.

Table 3. Summary of literature that provides information on bottom sediments of Albemarle and Pamlico Sounds and the surrounding estuaries.

Reference	Area	Samples Total (Sieved[1])	Data type[2,3]
Allen, 1964	Pamlico River Tar River[6]	17 (0) 13[6] (0)	XR,M,GS[4,5]
Batten, 1959	Beaufort Inlet	202 (76)	GS,M
Benson, 1965	coastal NC	54 (0)	XR,GS[5]
Brett, 1963	Bogue Sound Newport River	39[7] (39)	GS
Custer and Ingram, 1974	Pamlico Sound Pamlico River Neuse River Core Sound Newport River	~140 (~140)	GS
Davis, 1981	Roanoke River Neuse River	29 (0)	SS,GS[4]
Dobbins, 1967	Pamlico River	20 (20)	XR,GC,GS[5]
Duane, 1962[8]	Pamlico Sound Ocracoke Inlet Pamlico River Pungo River Neuse River Core Sound	165 (165)	GS,M,XR
Edwards, 1961	North River	265 (72)	GS,M,XR
Edzwald, 1972	Pamlico River	23[9] (0)	XR
Erlich, 1980	Roanoke River	81 (0)	GS,M,XR
Filer, 1979	Neuse River	185 (~80) ~55[6]	GS,M
Griffin and Ingram, 1955	Neuse River	24 (0)	XR,M,GS
Harding, 1974	Pamlico River	68 (0)	GC,GS[5]
Helwig, 1969	Back Sound Bogue Sound Newport River Beaufort Inlet	40 (40)	GS
Johnson, 1959	Newport River	184 (12)	GS,M,XR
Katuna and Ingram, 1974	Pamlico Sound Pamlico River Neuse River Core Sound Newport River	148[9,10] (0)	SS

Table 3. Continued.

O'Connor, Riggs and Winston, 1972	Croatan Sound Roanoke Sound north Pamlico Sound	132 (0)[4]	GS
Park, 1971	Albemarle Sound Roanoke Sound Croatan Sound Pamlico Sound Pamlico River Neuse River Core Sound Back Sound North River Newport River Bogue Sound	160[11] (0)	M,XR,GS[5]
Pels, 1967	Albemarle Sound Chowan River Roanoke River	~350 (12)	GS,M[12]
Petree, 1974	Neuse River	21 (21)	GS,M,XR
Pickett, 1965	Pamlico Sound	~528[13] (28)	GS,M,SS,XR
Skean, 1959	north Core Sound	244 (74)	GS,M
Wells, 1988	Cape Lookout Bight	24 (24)	GS,SS
Wells, this study	Alligator River Currituck Sound North River North Landing River Pasquotank River	59 (59)	GS
Witner, 1984	Chowan River	30 (0)	GS,M,XR

1 Number of samples analyzed by sieve and/or pipette or hydrometer. Samples not analyzed by these methods were examined microscopically, using the methods described by Ingram (1965), unless otherwise noted.
2 GS = grain size, M = mineralogy, SS = sedimentary structure, GC = geochemistry, XR = clay mineralogy.
3 Listed in order of importance.
4 Sands are described in a manner not apparent from methods.
5 Samples were wet sieved to separate sands from fines.
6 Not included in this review.
7 Samples taken 5 times at the same locale were combined into one and analyzed.
8 A subset of the data was published in an article on skewness by Duane (1964).
9 Grain size was not examined.
10 Samples are probably in the same locations used by Custer and Ingram (1974). Custer analyzed grab samples, Katuna analyzed cores.
11 Samples were from a Geology Department collection (University of North Carolina at Chapel Hill) except for "additional samples collected ... in Albemarle Sound and along the Outer Banks." The author maps 59 samples from these locales.
12 Performed on 75 samples.
13 Includes 28 cores used to describe sedimentary structures.

Pickett (1965) and Pickett and Ingram (1969) identified by grain size eleven environments of deposition. They found that 1) the median diameter decreases away from cross-lagoon and finger shoals toward the center of the sound and also toward quiet-water environments such as lagoons near river mouths and protected mainland embayments, 2) most sediments in Pamlico Sound are fairly well sorted because of its orientation relative to prevailing wind directions, and 3) environments subjected to winnowing have size distributions that are negatively skewed whereas those not subjected to constant wave and current action are positively skewed. Duane (1962; 1964) also noted that skewness was environmentally sensitive and could be used in Pamlico Sound to discriminate beach, littoral zone, and inlet sediments from those that were more sheltered.

The lower Pamlico and Neuse River estuaries have muddy bottoms from fine-grained sediments that have been derived from deeply weathered Piedmont soils (Brown and Ingram, 1954; Filer, 1979; Giese et al., 1979; Copeland et al., 1984). Figures 8 and 9 are summaries of several textural studies which show that transitions from channel-flank sands to channel-bottom muds are extremely sharp in the estuaries. In some data sets (e.g. Custer and Ingram, 1974), adjacent samples differ in sand content by 99%. As in Albemarle Sound, the fine-grained sediments are clearly confined to the deep axis of the estuary and sands on the channel margins are supplied from local shoreline erosion. One of the problems in preparing composite textural maps, highlighted especially in the Neuse and Pamlico estuaries, is that relatively few studies contain comparable grain size measures. If fact, it was not unusual to find APES textural data of the 1950s and 1960s reported in descriptive rather than quantitative terms.

Clay mineral analyses in the Neuse and Pamlico Rivers (Table 4) show a downstream increase in illite and decrease in kaolinite (Brown and Ingram, 1954; Griffin and Ingram, 1955; Allen, 1964; Petree, 1974). Controversy exists over whether the change in abundance of these clay minerals is a result of differential settling (grain-size effects), differences in stability (illite more stable than kaolinite), or simple dilution by oceanic illite (Allen, 1964; Edzwald, 1972; Petree, 1974). Kaolinite, which accounts for as much as 80% of the fine fraction, is relatively more abundant in Albemarle Sound than any other estuary from which samples have been analyzed on the Atlantic coast (Folger, 1972a).

Quartz is the most abundant constituent of sand in both Albemarle and Pamlico Sounds. Coarse fraction analyses indicate that sediments are composed of 60-90% quartz, 1-15% heavy minerals, 2-20% shell and wood fragments, and up to 10% mica (Pickett and Ingram, 1969; Park, 1971; Folger, 1972a,b). X-ray radiographs of cores from Pamlico Sound show that these sands, together with their fine-grained components, accumulate in diverse depositional environments that display 13 different types of physical structures and 7 types of biogenic structures (e.g. laminations, grading, scour and fill, and burrows; Katuna and Ingram, 1974).

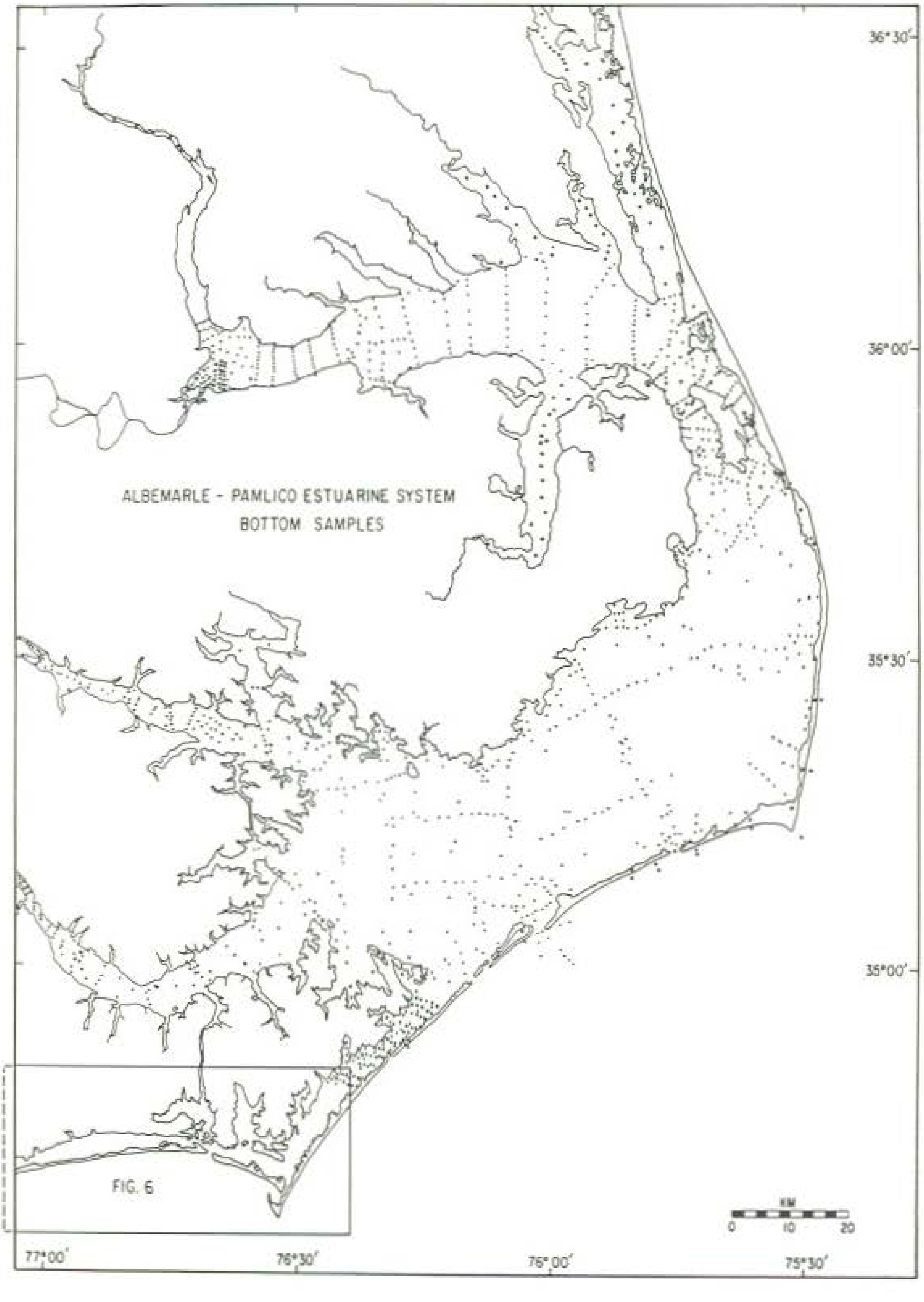

Figure 5. Composite distribution of bottom samples taken by approximately 25 investigators over the last 3 decades.

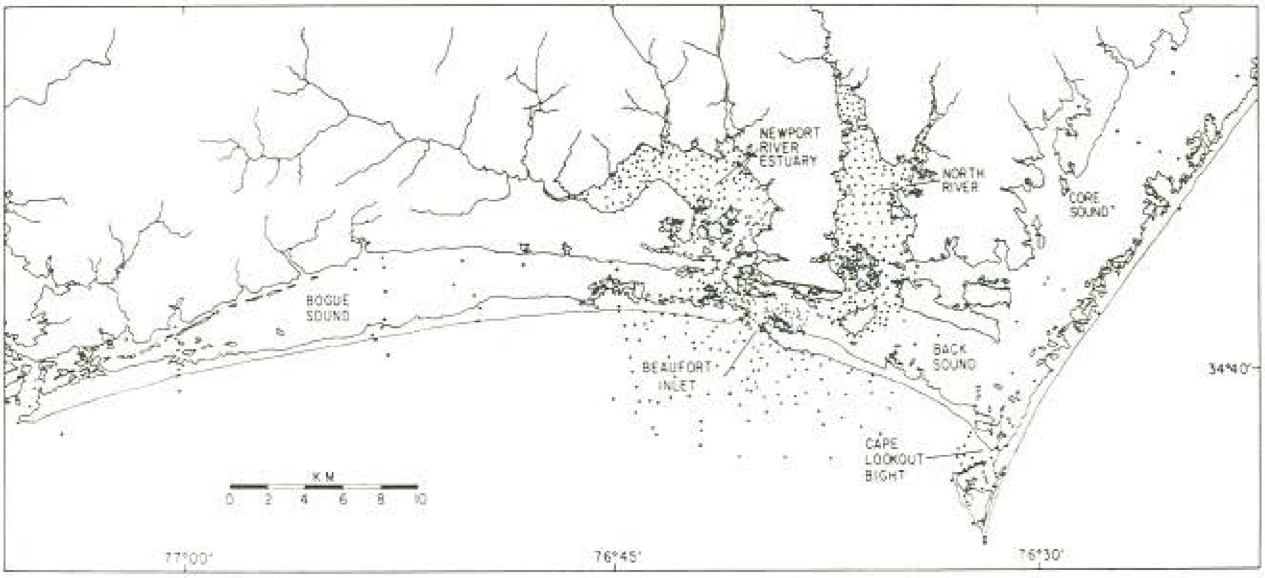

Figure 6. Composite distribution of bottom samples taken along the southern margin of the APES region.

Pickett (1965) has shown that the muddier parts of the mainland side of Pamlico Sound are characterized by sediment mottled by the mixing of sand and mud layers by burrowing organisms. The central deeper part of the sound is characterized by sediment which is homogeneous because of a dearth of sand and burrowing organisms. The barrier side and the sandy mainland finger shoals are characterized by indistinct banding of sandy and muddy sediment that Pickett (1965) ascribes to differences in wave and current intensity and general lack of burrowing organisms. Although bedforms have been reported in the Neuse River (Filer, 1979) and Roanoke River (Erlich, 1980) and probably exist in other shallow, sandy environments, the openwater areas of Albemarle and Pamlico Sounds apparently lack the large sand wave fields that characterize many estuaries and shallow seas (e.g. Chesapeake Bay and Delaware Bay).

Four environments along the southern margin of the Albemarle-Pamlico system have been extensively researched (with respect to sediment texture; Fig. 10): North River, Newport River, Beaufort Inlet, and Cape Lookout Bight. Sediments in

Table 4. Relative percentages of clay minerals in Albemarle-Pamlico estuarine system (Park, 1971).

Region	Kaolinite	Illite	Chlorite-intergrade	Chlorite	Smectite
Neuse River	46	23	17	8	5
Pamlico River	41	30	16	7	7
Pamlico Sound	28	40	12	11	8
Core Sound	19	60	8	7	5
Albemarle Sound	40	32	22	5	1

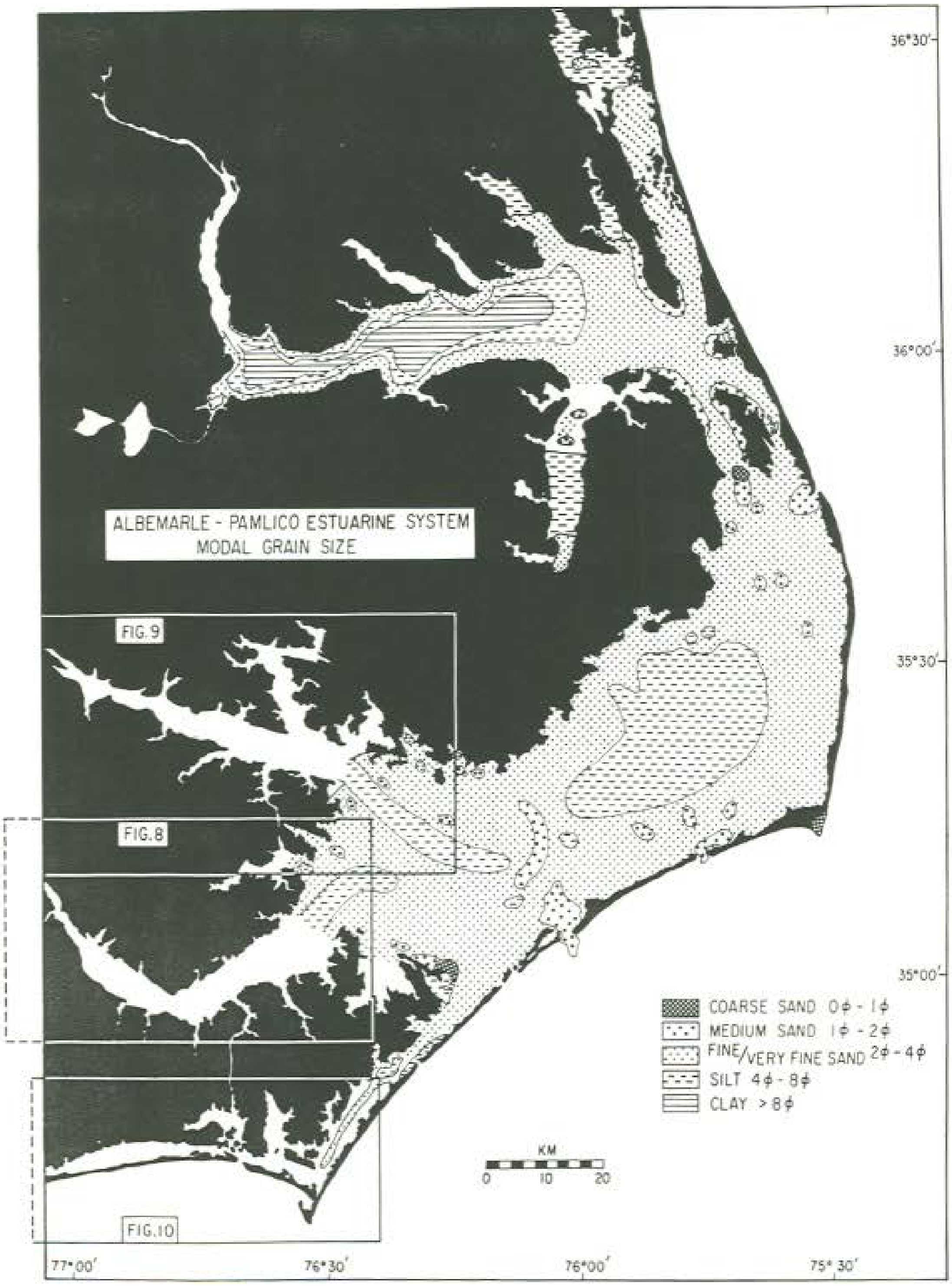

Figure 7. Distribution of modal grain sizes, following the Wentworth classification, as synthesized from the literature.

North River are moderate to well sorted, very fine to fine sands, which grade into medium sands along the narrow beaches and into silt and clay in the less energetic deeper waters. This distribution of sediments reflects reworking of Pleistocene deposits rather than the influence of sediment sources, since tributaries to the North River are insignificant sources of sediment (Edwards, 1961). Sands consist almost entirely of quartz and the most abundant clay mineral is illite (Edwards, 1961). Organic matter, consisting of decayed marsh vegetation, was found only in the finer sediments. Calcium carbonate content is controlled by presence or absence of shell fragments and was relatively high in areas of poor sorting such as tidal channels.

Sediments in the Newport River estuary (Fig. 10) are similar in lithology and texture to those of North River, but differ in that they are supplied partially at the upstream end by a tributary stream and at the downstream end by Beaufort Inlet. Fine to coarse sand along the shorelines grades into well sorted, fine to very fine sand in the shallow southern half of the embayment, then into progressively finer silts and clays in the northern and western sections of the estuary (Johnson, 1959). Near the tidal inlet at Beaufort, clean coarse sand, transported from offshore or from adjacent barriers, is present. Sands are predominantly quartz grains and clays are illite and diagenetic chlorite (Johnson, 1959). Several areas of the estuary that are near small freshwater sources have muddy sediments with an abundance of wood fragments. In common with much of the APES region, distribution and sorting of sediments are primarily from strong wind-driven currents.

Beaufort Inlet, which forms a seaward extension of the Newport River, is the only tidal inlet in the APES study area that has been extensively sampled. Batten (1959) identified six types of bottom sediments on the basis of grain size. Five of these environments were sands that decreased in size away from the inlet gorge; the sixth was a discontinuous silty environment in approximately 10 m of water. The relatively simple textural distributions (Fig. 10) are probably a result of longshore sediment sources and strong tidal currents in the inlet. Essentially all of the silt and clay has been winnowed out of the inlet throat and the poorly sorted, negatively skewed sediment containing large amounts of shell debris is indicative of inlet lag deposits. Farther offshore within the zone of wave action, sediments grade into finer components because of increasing water depths and hence less impingement of wave energy on the bottom.

Cape Lookout Bight is unusual morphologically, and thus sedimentologically, in that it forms a small basin at the distal end of Barden Inlet (Fig. 10). Surficial sediments range in mean grain size from medium sand to very fine silt. Frequency curves show that samples are naturally grouped by environment of deposition and that each environment has a narrow range of grain sizes (Wells, 1988). The shallow margin surrounding the center of the bight contains the coarsest sediment, which can be classified as medium sand. The center of the bight is composed of rapidly deposited (10 cm/yr) silts that have apparently been trapped due to the configuration of the bight. X-ray analyses indicate that the fine-grained sediments are illite, kaolinite, and very fine silt-sized quartz.

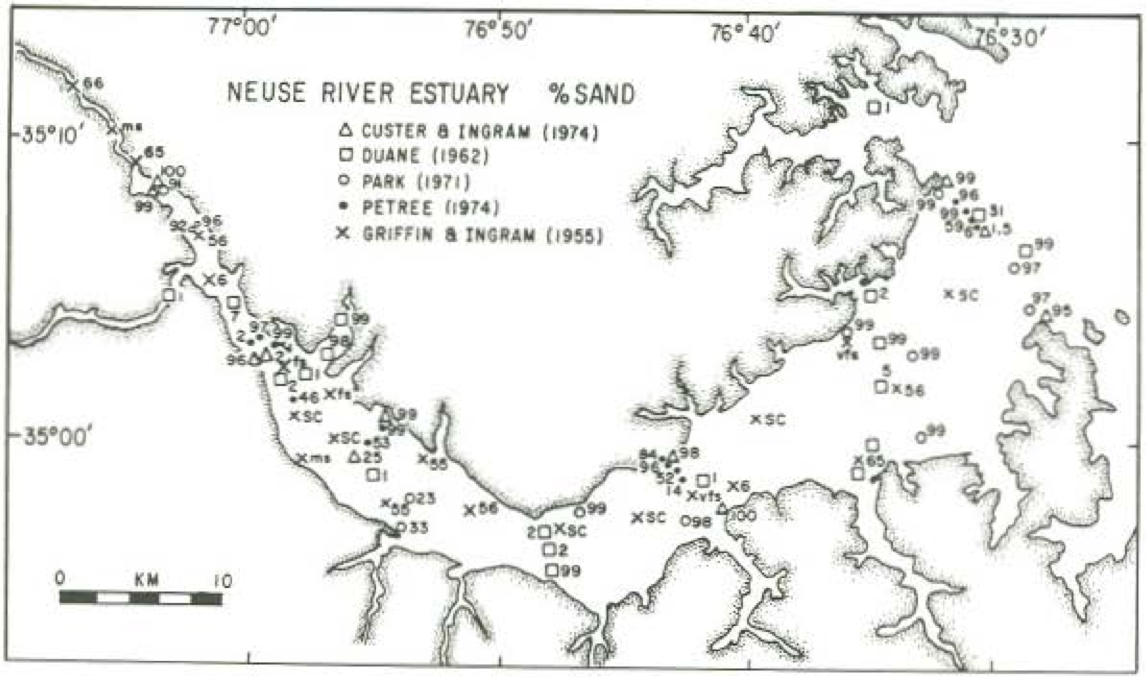

Figure 8. Percent sand in the Neuse River estuary (sc = silty clay, vfs = very fine sand, ms = medium sand).

Suspended Sediment Dispersal and Vertical Flux

In common with most estuaries and lagoons, the Albemarle-Pamlico system may be expected to retain within its boundaries a major fraction of the sediment supplied, regardless of source. Because of the shallow water and significant wind stresses, most of the sediments will be deposited and resuspended many times before coming permanently to rest on the bottom. Commercially available satellite imagery has provided one method of obtaining a basin-wide glimpse of suspended sediments under different environmental conditions which, in turn, may provide important clues to the hydrodynamic processes that operate in the APES area.

The only published account of regional suspended-sediment distribution is given by Khorram and Cheshire (1983). Using a single Landsat scene and surface measurements of total suspended solids taken at the time of satellite overpass, they developed a regression model for the southern one-third of the APES region. The concentration of suspended solids (in late September) was 5-

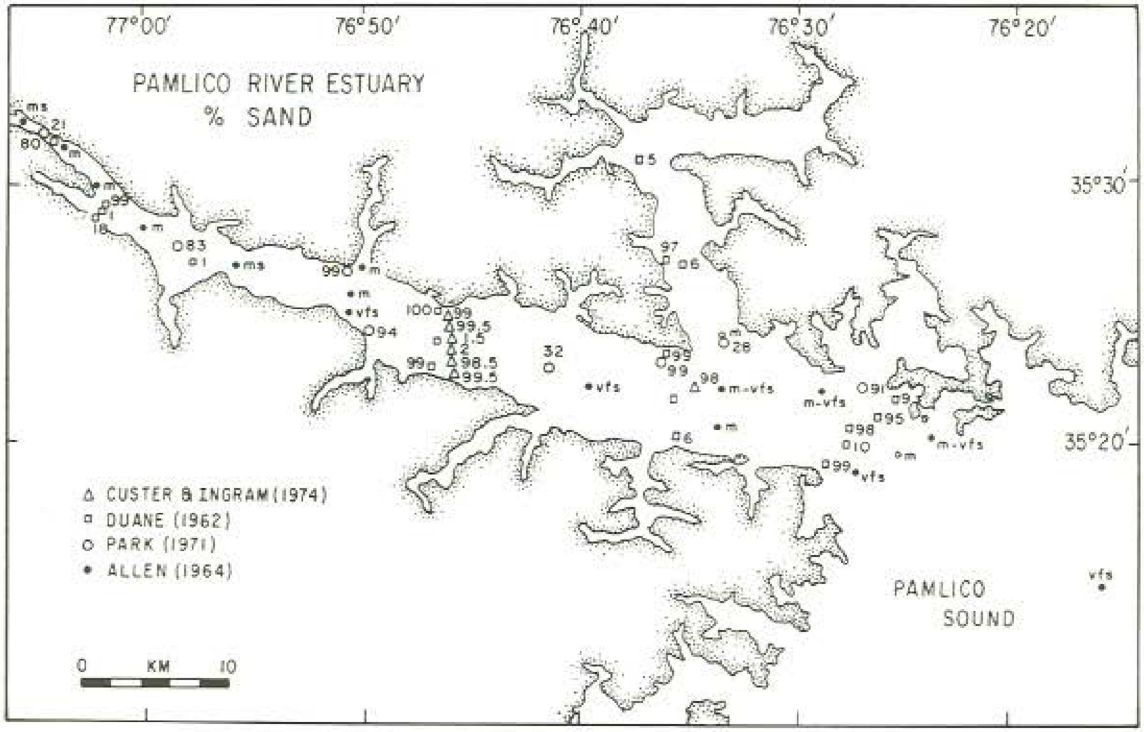

Figure 9. Percent sand in the Pamlico River estuary (m= mud, vfs = very fine sand, ms = medium sand).

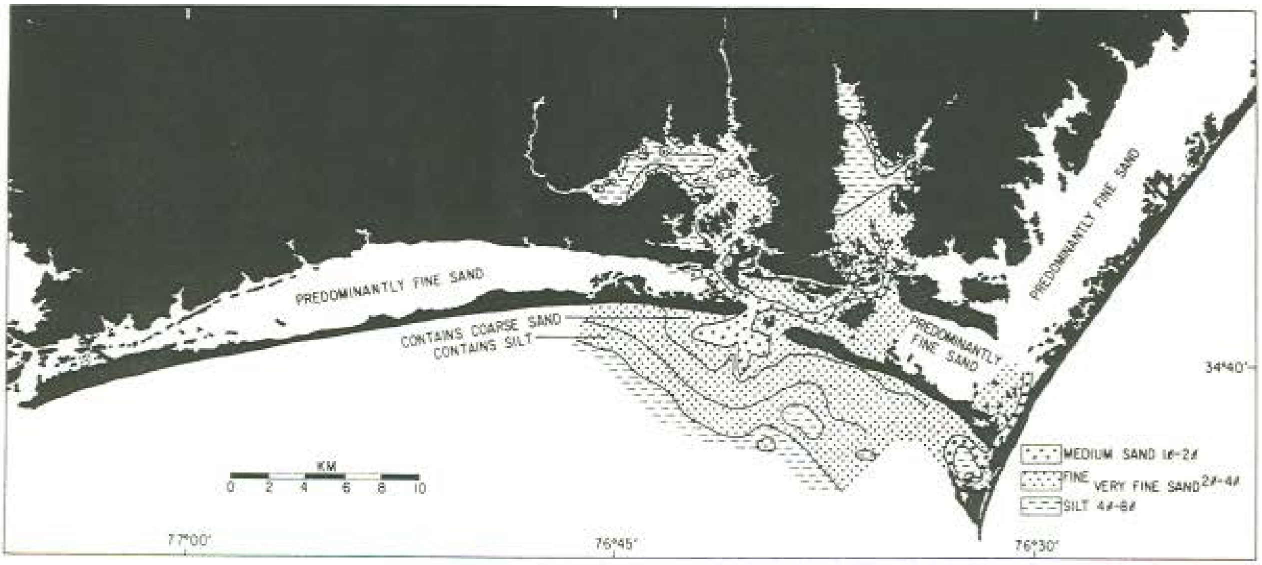

Figure 10. Distribution of modal grain sizes, following the Wentworth classification, as synthesized from the literature for the southern margin of the APES region.

Figure 11A. Landsat Thematic Mapper image (Band 2) taken on April 1, 1985 showing the northern half of the APES region. High concentrations of suspended sediments are generally indicated by the high radiance values (white areas). Depth of penetration is dependent upon sediment concentration and actual values of turbidity cannot be determined without ground truth data at the time of satellite overpass. However, in shallow well mixed areas the bottom patterns may be similar to observed surface patterns. The fact that the open waters of Pamlico Sound have higher sediment concentrations than either Albemarle Sound or the tributary rivers suggests that wind-generated currents are the dominant process in resuspension, mixing, and advection.

Figure 11B. Landsat Thematic Mapper image (Band 2) taken on April 1, 1985 showing the southern half of the APES region. High concentrations of suspended sediments are generally indicated by the high radiance values (white areas). Depth of penetration is dependent upon sediment concentration and actual values of turbidity cannot be determined without ground truth data at the time of satellite overpass. However, in shallow well mixed areas the bottom patterns may be similar to observed surface patterns. The fact that the open waters of Pamlico Sound have higher sediment concentration than the Neuse River suggests that wind-generated currents are the dominant process in resuspension, mixing, and advection.

Figure 11C. Landsat Thematic Mapper image (Band 2) taken on October 7, 1984 showing the northern half of the APES region. High concentrations of suspended sediments are generally indicated by the high radiance values (white areas). Depth of penetration is dependent upon sediment concentration and actual values of turbidity cannot be determined without ground truth data at the time of satellite overpass. However, in shallow well mixed areas the bottom patterns may be similar to observed surface patterns. The fact that the open waters of Pamlico Sound have higher sediment concentrations than either Albemarle Sound or the tributary rivers suggests that wind-generated currents are the dominant process in resuspension, mixing, and advection.

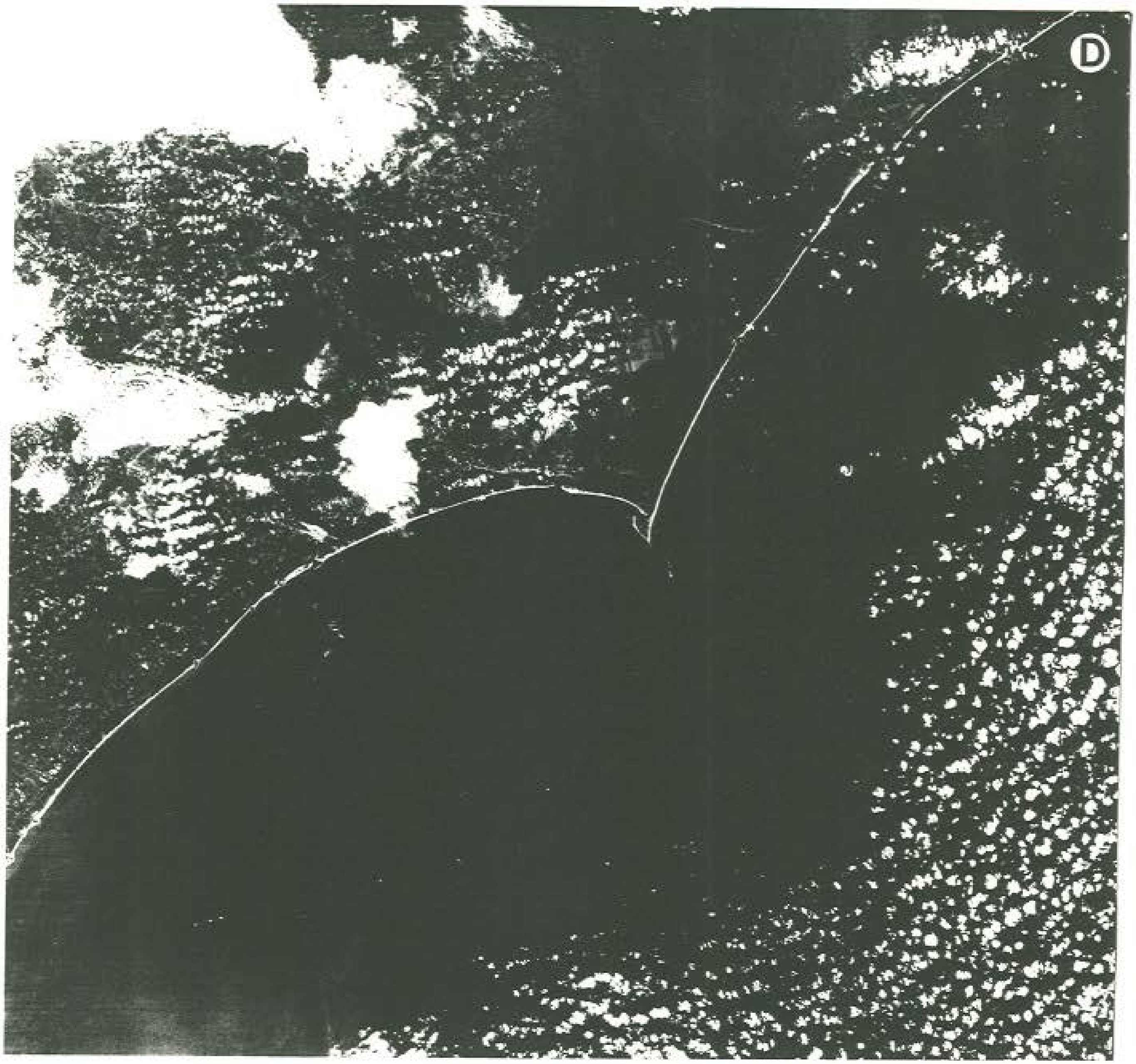

Figure 11D. Landsat Thematic Mapper image (Band 2) taken on October 7, 1984 showing the southern half of the APES region. High concentrations of suspended sediments are generally indicated by the high radiance values (white areas). Depth of penetration is dependent upon sediment concentration and actual values of turbidity cannot be determined without ground truth data at the time of satellite overpass. However, in shallow well mixed areas the bottom patterns may be similar to observed surface patterns. The fact that the open waters of Pamlico Sound have higher sediment concentrations than the Neuse River suggests that wind-generated currents are the dominant process in resuspension, mixing, and advection.

15 mg/l throughout the lower Neuse River and generally greater than 15 mg/l in Pamlico Sound (south of 35°10′) and in Core Sound. Close examination of two TM (Band 2) scenes acquired as Kvpart of this study has revealed three features that may be important to suspended-sediment flux. First, highest turbidities, as shown by the saturated white returns in Figure 11, occurred in Pamlico Sound. This appears to be true regardless of wind direction or stage of the major rivers. For example, winds were blowing from the southwest during flood stage in Figures 11A and B, whereas they were from the northeast during low river stage in Figures 11C and D. Second, within Pamlico Sound the suspended-sediment concentrations, at least in surface waters, appeared to be highest over the muddy central basin, despite the fact that these are the deepest waters in the sound and therefore experience the least amount of bottom stress from waves. Third, the surface turbidity patterns were extremely complex, particularly in Pamlico Sound. It is unclear whether the complexity is a result of differential sediment resuspension, water column mixing processes, or simply a result of eddies that have formed from wind-induced movement of surface waters.

Without ground-truth data taken at the time of satellite overpass, the actual suspended-sediment concentrations cannot be determined. However, data from two 25 hr anchor stations in the lower Neuse River, taken during the month of September, showed that the range in suspended-sediment concentration in this part of the system was 2-17 mg/l (generally in agreement with Khorram and Cheshire, 1983) and that the concentrations were essentially unrelated to either tidal phase or current speed within the observed range of 5-30 cm/s (Wells and Kim, 1989). These data were taken as part of a 2-yr sedimentation study to characterize the turbidity maximum and determine its role in the accumulation of toxic substances that may be adsorbed onto the surfaces of the fine-grained sediments. Measurements further showed that estuarine circulation with opposing surface and bottom layers and strong stratification with a sharp halocline at about 0-2 m was present at both anchor stations. Although peaks in suspended sediment concentration did not coincide with peak current speeds, the highest concentrations were usually at the bottom, thus providing the opportunity for upstream transport and concentrating sediments in a turbidity maximum.

The pattern of higher concentrations in bottom waters has also been observed in monthly suspended-sediment transect data from the same study (Fig. 12; Wells and Kim, 1989). The range in suspended-sediment concentration was 7-13 mg/l at the surface and 6-22 mg/l near the bottom, averaged along a 30-km section downstream from New Bern. Maximum and minimum concentrations occurred in March/April and June/October, respectively. The lack of correlation to river discharge suggests that other factors, perhaps winds, control the turbidity levels in the Neuse. During most months a weak turbidity maximum was observed near the upper limit of salt penetration. The best examples were in March and April (Fig. 13), but even during these months the concentrations were only 3 times the surrounding turbidity levels and in April a second region of higher concentrations occurred upstream of the 1 ppt isohaline.

DISCUSSION

The most striking features of bottom sediments are 1) an overall abundance of fine sand from shoreline erosion, 2) a simple sand/mud distribution pattern that is related primarily to sediment sources, and 3) sharp textural transitions that suggest a lack of well-defined dispersal pathways (Fig. 7). Of particular interest here is the distribution of the most mobile sediments, the organic-rich muds, which are concentrated mainly in two environments of deposition: 1) fresh-to-brackish estuarine waters associated with riverine sources, and 2) the deep central basin of Pamlico Sound. Figure 7 shows that these two accumulation sites are not connected; rather, they have discrete boundaries and are separated by a region of fine sand.

Much of the fine-grained terrigenous sediment is apparently trapped in the lower courses of the Neuse and Pamlico Rivers by processes of estuarine circulation, even though sediments may be deposited and resuspended many times before coming permanently to rest on the bottom. Benninger and Martens (1983) found sediment accumulation rates to be <0.5 cm/yr over the last 60-100 years near New Bern, the approximate upstream limit of salt penetration, but essentially zero at the Neuse River entrance where salinities are typically 15-20 ppt. The 30-km seasonal migration of the 1-5 ppt isohalines in the Neuse probably plays an important role in the distribution of fine-grained sediments

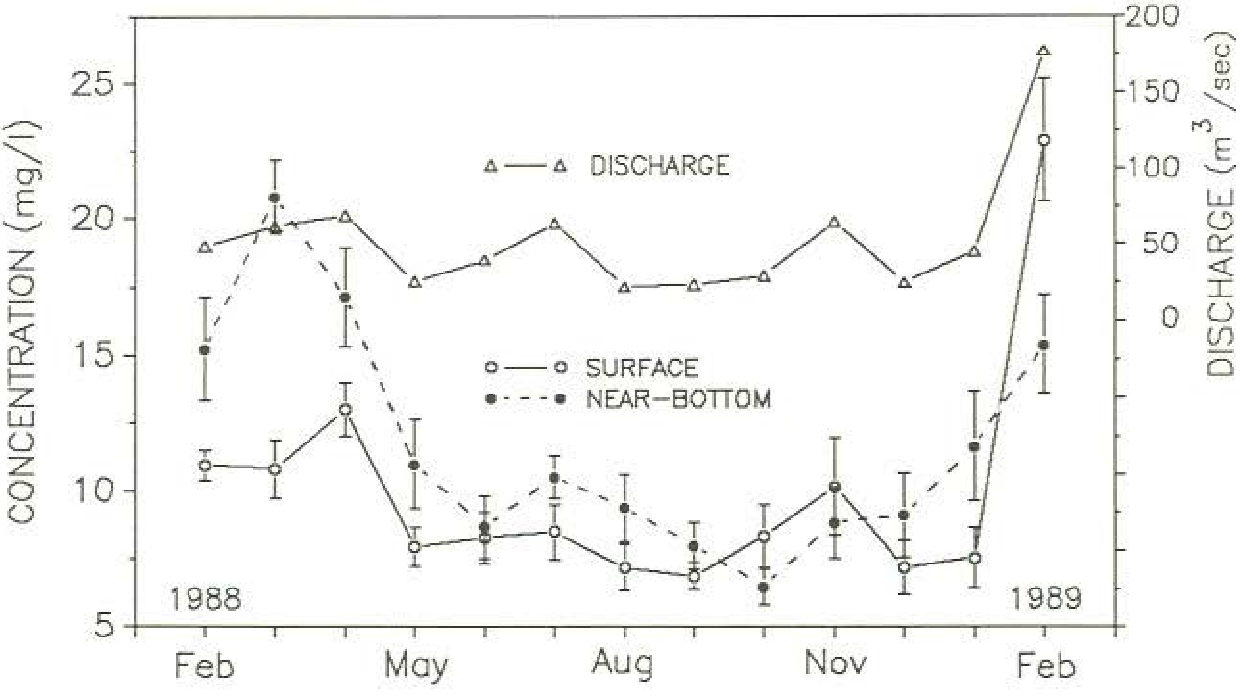

Figure 12. Monthly variation in suspended-sediment concentration averaged for surface and near-bottom waters of the lower Neuse River (typically 14 stations per average). Error bars are for 95% confidence limits. Discharge is from U.S.G.S. gauging station approximately 60 cm above New Bern.

since processes of electrochemical flocculation reportedly reach a maximum at these low salinities (Whitehouse et al., 1969; Edzwald and O'Melia, 1975). Thus the effects of enhanced settling of large flocculated particulate material, such as the marine snow previously documented in the sounds and estuaries of North Carolina (Wells and Shanks, 1987; Wells, in press), would be widely distributed rather than confined to a narrow stationary zone in the estuary (Nichols and Biggs, 1985).

On-going research (unpublished data of J.T. Wells and L.K. Benninger) shows that a poorly defined but identifiable turbidity maximum in the 1-5 ppt isohaline region (Fig. 13) most likely marks a transitory region of focusing for river-borne sediments in the Neuse estuary. Two hundred and thirty photographs of particulates taken during monthly transects in the Neuse River turbidity maximum in 1988 show that, despite low sediment concentrations, large particles are usually present near the bottom and perhaps throughout the water column. The abundance of aggregates with observed diameters up to 2000 microns accelerates the overall transport of material to the bottom at aggregate settling rates of 50-200 m/day. Distribution of particle-reactive tracers in box cores taken at seven locations along the axis of the lower Neuse River are consistent with the observed migration of the turbidity maximum, and hence of the locus of sediment deposition. Depth of penetration and inventory (total quantity per unit of sediment surface area) of 7-Be (half life 53.3 days) and 137-Cs (weapons fallout, maximum deposition in 1963) are taken as measures of short-term (< 1 year) and long-term (decades) interaction between suspended and bottom sediments. For both radionuclide tracers real differences in penetration and inventory were found along coring stations. However, these quantities do not vary in a systematic way between upstream and downstream locations; nor are the differences consistent between the short (7-Be) and longer (137-Cs) time scales. As the source of large particles moves up- and down-channel with the turbidity maximum, local factors (chemistry, biota, water depth) may significantly influence deposition.

Residence time of suspended particulate material is unknown. Rough estimates indicate, however, that material entering from the Neuse and Pamlico Rivers would take about one week to move through the estuarine sections of these tributaries, assuming that the material remained continuously in suspension and was transported at the approximate rate of river flow. In fact it is all but certain that the residence time would be substantially longer than this since 1) suspended material is deposited and resuspended many times within a given estuary, and 2) estuarine circulation can transport sediment particles upstream as they settle into the lower water column, thus trapping them in the estuary. Moreover, estuaries are not static systems and residence time may differ on a seasonal or annual basis.

Sediments that escape the Neuse and Pamlico Rivers apparently accumulate in a topographic low, referred to by Katuna

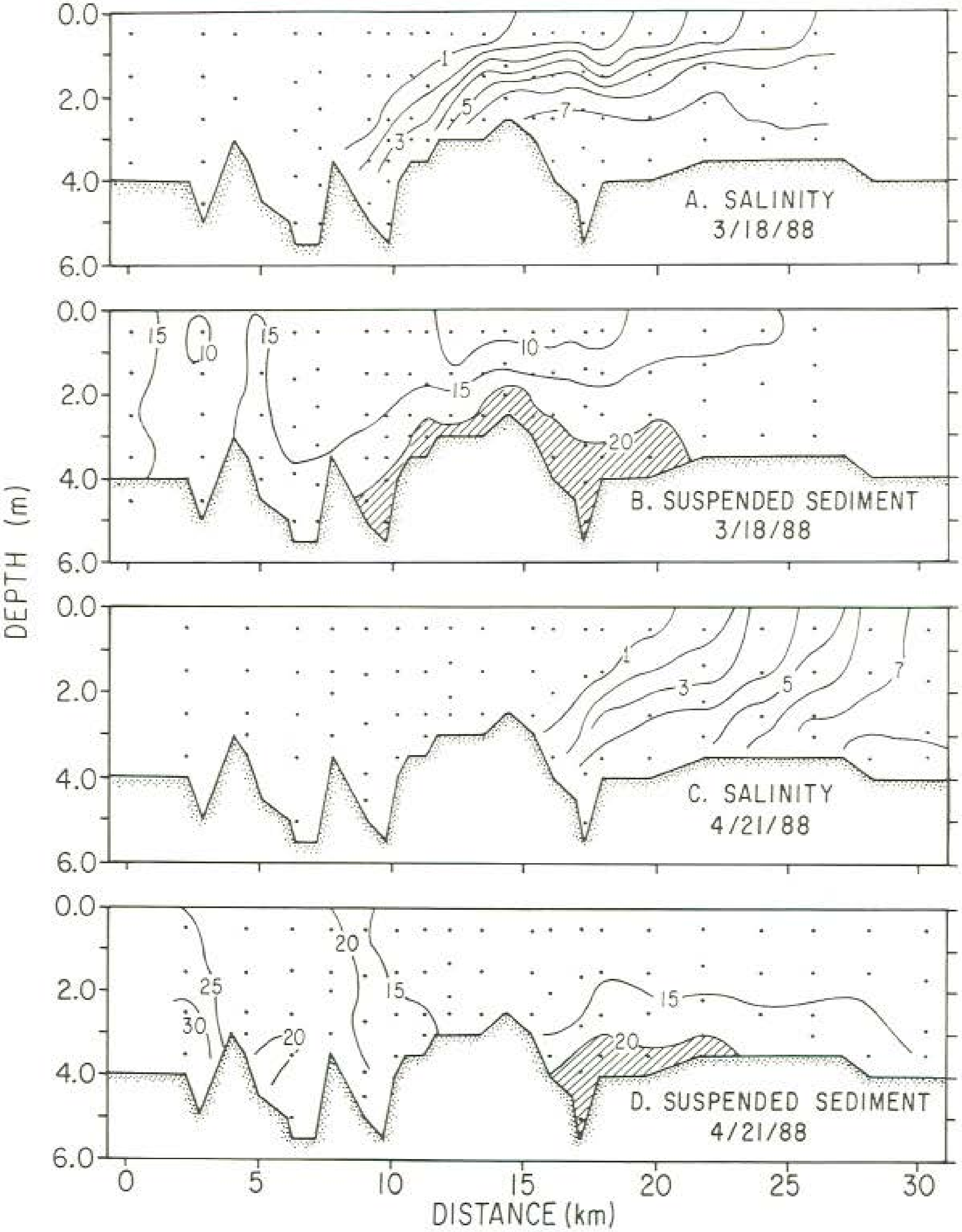

Figure 13. Relationship between suspended sediments (turbidity maximum) and salinity distribution for the lower Neuse River in (A) March, and (B) April, 1988. In April a second, upstream region of highly turbid bottom water is also present.

and Ingram (1974) as the deep central basin of Pamlico Sound. The two accumulation sites (estuary and central basin) are not connected; rather, they have discrete boundaries and are separated by a region of fine sand (Fig. 7). These two environments, which have been shown to be lithologically quite similar (Pickett, 1965; Custer and Ingram, 1974), represent two quite different processes of sedimentation. Whereas sediments in the Neuse and Pamlico Rivers are products of rapid sedimentation from deposition of flocculated (either biological or electrochemical) particulates, muds in the deep basin are presumably the products of slow sedimentation from many cycles of deposition and resuspension and include only those particles which have permanently escaped the estuarine "trap."

Once in Pamlico Sound most of the silts and clays are probably confined by the Outer Banks barrier islands and by the extremely limited tidal exchange with the shelf, although loss through tidal inlets has never been quantified. Thin laminae of mud deposited over the broad sand blanket during periods of high sediment discharge are most likely winnowed from shoal areas by storm waves. However, waves function mainly as a sorting mechanism since, without strong and persistent residual flow, there is little or no net transport. Thus, muds which bypass the rivers are apparently confined by, and recycled in, Pamlico Sound until they ultimately end up residing in the deep basin. It can be hypothesized, then, that 1) the 7-m deep topographic depression in Pamlico Sound is the final repository for fine-grained sediments that leave the tributary estuaries, 2) accumulation rates in this deep basin (100 yr time scale) are higher than those at the mouth of the Neuse River where little or no deposition is presently occurring, and 3) that Pamlico Sound basin already provides a pollution history that can be interpreted in light of historical patterns of watershed development.

Transition Zones and Sediment Dispersal

The sharpness of the textural transition zones (Figs. 7-10) suggests that well-defined dispersal pathways do not exist. This is primarily because transport of sediments along a well-defined dispersal route from a point source is more likely to provide a textural gradient than a textural truncation. The sharp contact between channel-flank sands and channel-bottom muds (Figs. 8 and 9) is a good example of two sources of sediment with little mixing (dispersal) across environmental boundaries. A reasonable hypothesis is that net advection of sediment is limited to the very fine particles which are transported to the deep basin (as discussed above) and that the very coarse particles (medium sands) are transported through the inlets and accumulate as flood tidal deltas. In terms of sediment volume, most material undergoes little net transport and is responding to slow basin- to global-scale processes such as sea level rise and barrier island migration.

There is much evidence for lack of large-scale dispersal.

There is much evidence for lack of large-scale dispersal. First, tide range is small and bottom current speeds are low. Any basin-wide residual flow patterns, if present, have not as yet been observed. Second, sediments are well sorted and have not been "smeared" across bathymetric gradients. The clear relationship between grain size and bathymetry or location indicates that particles undergo local transport only. Third, large bedforms, which are common under unidirectional flow and often vary systematically along dispersal pathways, are apparently absent in the Albemarle-Pamlico region. Calculations based on linear wave theory (CERC, 1973) reveal that maximum horizontal orbital speeds at the bottom can exceed 50 cm/s under the storm-wave conditions (waves 1-2 m high with periods of 5-10 s) that are prevalent during the winter (Fig. 2). However, waves function mainly as a sorting mechanism since, without strong and persistent residual flow, there is little net transport.

Order-of-magnitude calculations of volume input (based on the assumption that 1.0 metric ton = 1.0 m^3 of sediment) relative to total volume of APES basins (Table 1) reveal that 1) annual sediment infilling, on average, is 0.15 mm/yr and, neglecting dramatic short-term variations in sediment input or long-term climatic changes, then 2) 34,000 years would be required to fill the APES system from river input alone. Even assuming a very modest sea level rise of only 1 mm/yr, this estuarine system will never reach a sediment-filled state, unless river input changes drastically or the input from other sources exceeds river input by 6 times. Our present state of knowledge is insufficient to allow speculation on the timing of major climatic changes which may affect river discharge, sediment loads, or sediment types.

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LIST OF PATENTS AND PUBLICATIONS

Patents: none

Publications:

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Appendix 1. Sediment sample size statistics, APES basins.

SAMPLE #	MEANSIZE	SORTING	SKEWNESS	KURTOSIS
1	2.21	1.06	-4.83	31.00
2	2.67	0.90	-4.42	32.91
3	3.70	1.55	-3.46	12.80
4	1.47	1.02	-4.35	26.57
5	3.46	1.23	-4.47	22.63
6	3.45	1.12	-4.70	26.05
7	1.55	1.30	-2.83	10.11
8	3.83	1.59	-3.43	11.82
9	5.40	2.91	-0.98	-0.28
10	4.55	2.40	-1.59	1.84
11	5.31	2.88	-1.05	-0.07
12	5.05	2.54	-1.37	0.80
13	6.46	3.07	-0.50	-1.23
14	1.04	2.43	-3.26	8.75
15	1.88	2.94	-2.43	3.81
16	4.44	2.08	-2.07	3.55
17	3.60	1.19	-4.30	22.24
19	4.14	2.09	-1.95	3.65
22	3.91	1.99	-2.19	4.84
23	3.61	1.78	-2.31	6.22
24	2.91	0.97	-5.52	38.12
25	4.67	2.76	-1.08	0.25
26	4.78	2.52	-1.27	0.75
27	2.30	1.39	-3.96	19.05
28	1.00	1.24	-3.89	20.30
29	5.39	2.94	-0.81	-0.44
30	0.97	2.44	-3.45	9.90
31	7.31	2.97	-0.07	-1.48
32	7.40	3.10	0.26	-1.10
33	7.32	3.22	0.29	-1.07
34	7.58	3.00	0.47	-0.48
35	2.19	1.25	-2.50	14.94
36	6.17	2.90	-0.65	-0.89
37	5.16	2.72	-1.26	0.30
38	5.89	2.88	-0.65	-0.78
39	2.09	1.04	-4.71	30.71
40	4.54	2.59	-1.32	0.80
41	1.02	2.37	-3.30	9.04
42	5.76	2.97	-0.60	-0.57
43	1.74	2.75	-2.68	4.91
44	5.70	2.31	-0.81	-0.04
45	6.39	2.94	-0.36	-1.05
46	6.52	3.24	0.08	-0.79
47	6.89	2.73	-0.30	-1.15
48	6.94	2.72	-0.20	-1.00
49	7.13	2.66	-0.27	-1.31
50	5.59	2.71	-0.89	-0.34
51	3.64	1.84	-2.12	5.09
52	2.99	1.48	-3.19	12.33
53	3.35	1.35	-3.74	15.62
54	3.69	1.30	-4.33	19.72
56	7.26	3.61	0.58	-0.82
57	8.46	2.99	1.14	0.75
58	7.90	2.96	0.46	-0.93
59	6.63	3.63	0.03	-1.42
60	7.12	3.15	-0.05	-1.37
61	2.68	0.94	-5.12	35.48
62	2.76	1.05	-2.93	17.83
63	3.76	1.47	-3.41	12.79