# III. WATER QUALITY

Written by

B.J. Copeland, Director, UNC Sea Grant College Program, NC State University, Raleigh, NC
Hans Paerl, Professor, Institute of Marine Sciences, University of North Carolina at Chapel Hill, Morehead City, NC
Jerad D. Bales, Hydrologist, US Geological Survey, Raleigh, NC
Donald W. Stanley, Professor, Institute for Coastal and Marine Resources, East Carolina University, Greenville, NC
Edward Kuenzler, Professor, Department of Environmental Sciences and Engineering, University of North Carolina at Chapel Hill, Chapel Hill, NC
Alan Klimek, Planner, Division of Environmental Management, Department of Health, Environment and Natural Resources, Raleigh, NC

# CHAPTER III: WATER QUALITY

## CHAPTER III: FIGURES and TABLES

## A. WATER QUALITY ISSUE IDENTIFICATION

### A. 1. Freshwater Drainage and Estuarine Circulation

There are five major hydrologic pathways by which water and chemical constituents can enter the Albemarle-Pamlico (A/P) system. These pathways are (1) atmospheric deposition, (2) direct discharge of waste materials into the estuary, (3) inflow through tidal inlets, (4) groundwater discharge to the system, and (5) surface drainage via tributaries and runoff. Within the estuaries, physical and chemical transformations also occur that may effectively remove certain constituents from the water or may release substances which were previously biologically unavailable.

The primary focus of this section is surface drainage of freshwater into the Albemarle-Pamlico system. Riverine inflows and local, or nonpoint-source, inputs from lands surrounding the estuarine waters are discussed separately. Surface drainage processes are physically linked to hydrologic-transport mechanisms within the estuaries -- mechanisms which affect essentially all of the physical and chemical processes and many of the biological processes occurring in the sounds. Consequently, discussion of estuarine transport, particularly the mixing of fresh and brackish water, in the context of surface drainage, is also warranted.

Groundwater discharge directly into the estuaries and tidal exchange through inlets are important hydrologic processes affecting Albemarle-Pamlico water quality, however, there is essentially no available information on these processes for the system. A Sea Grant study currently underway in Oregon and Ocracoke Inlets may provide this information (Dr. L.J. Pietrafesa, NC State University, Personal Communication), however, the discussion of groundwater contributions to the Albemarle-Pamlico System and of tidal exchange through the inlets in this presentation is quite limited. Atmospheric deposition of chemical constituents is discussed in Section A.2. Metals and toxins are discussed in A.3. Sediments are discussed in A.4. Information on point source discharges is presented in Section A.5.

**A. 1. a. Riverine Issues.** Maintenance of an acceptable level of estuarine water quality is dependent, to a large extent, upon the quality of the inflowing rivers. Rivers supply the estuary with freshwater, nutrients, sediment, and other substances. The proper balance of riverine inputs and ocean water produces a setting which is favorable for living resources. Estuarine water quality management must involve knowledge and management of these riverine inputs.

Freshwater is the most important product that upland rivers supply to the estuary. Temporal variations in riverine inputs determine the spatial patterns of salinity and water density in the estuary. These, in turn, control the longitudinal patterns of distribution of plants and animals, the vertical patterns of dissolved oxygen, and other important characteristics of the estuary. Water transports, in solution, in suspension, and along the stream bed, a variety of substances that govern estuarine water quality. There are several important issues related to riverine freshwater inputs and sound water quality management. Some of these issues have been addressed to the extent that current information is useful for management decisions:

1. The seasonal and geographic distributions of freshwater inflows to the estuaries are important for determining constituent loadings, evaluating water budgets, estimating the duration and extent of salinity intrusion, managing the fishery resource, etc.

2. Information on the relation between upstream river flows and the potential for the occurrence of estuarine algal blooms may be used for variable-discharge permitting of point-source discharges.

3. An understanding of the relation between river flow and inputs of sediments and chemical constituents is important for managing upstream inputs and estuarine wasteload allocations. Infrequent, high-flow events, in particular, may remove large amounts of sediment and associated constituents from storage in the rivers and transport them into the estuaries. (Simmons 1988)

4. Flow diversion and management of reservoir releases are significant issues in the Roanoke and Neuse River basins. The existence of major reservoirs in those basins offers possibilities for flow regulation to enhance water quality and fishery resources if the relationship between flow and other processes are well established.

5. Watershed modeling has been attempted in the Chesapeake basin. This capability may allow the evaluation of the cumulative effects on the estuaries of upland land-use conversions and land management strategies. Physical and chemical modeling of rivers would also be required to link upland surface drainage processes to estuarine inputs.

**A. 1. b. Local Drainage Issues.** The Albemarle-Pamlico estuarine system has an extensive shoreline. Lands along this shoreline support a number of uses including agriculture, silviculture, residential and urban development, and marina operations. Investigations over the last 15 to 20 years have established that drainage from urban and agricultural lands can significantly contribute to the degradation of rivers and streams (Paerl 1983).

Tributary freshwater inflow rates can exert a direct influence on Albemarle-Pamlico water quality, apart from chemical constituents carried by the inflows. For example, the increase of low flows from the Roanoke River above natural conditions has apparently resulted in a decrease in the magnitude and frequency of saltwater intrusion into western Albemarle Sound (NC Division of Environmental Management 1982). The decrease in saltwater intrusion may, in turn, have resulted in an increase in nuisance algal blooms in the area (NC Division of Environmental Management 1982). This relation has been documented by Christian et al. (1986) who showed that the occurrence of blue-green algal blooms in the Neuse River estuary was directly related to Neuse River flow rates.

Much of the land surrounding the Albemarle-Pamlico estuary must be drained to accommodate agriculture, silviculture, and other types of development due to a naturally high water table, relatively high rainfall (between about 50 and 55 inches per year, depending upon location), and the flat terrain of the region. More than 20 miles of field ditches, collector canals and main canals are typically present in each square mile of agricultural land (Heath 1975; Daniel 1978). The ditches, designed to remove runoff from a 2 inch rainfall within 24 hours (Heath 1975), may increase the rate and volume of runoff (Skaggs et al. 1980; Daniel 1981).

There is some argument about long-term and undesirable decreases in salinity of the tidal creeks and bays resulting from the increased drainage. Sholar (1980), for example, estimated that salinity in northwestern Pamlico Sound decreased at an annual rate of about 0.2 ppt between 1948 and 1980. On the other hand, between 1968 and 1986, Stanley (1988b) detected a slight increase in surface salinity near the mouth of the Pamlico River and a decrease of about 0.13 ppt per year in the bottom salinity near the mouth. Most of these changes appear to have occurred between 1968 and 1975.

In contrast to the estuaries of Texas and California, in which hypersaline conditions often exist, parts of the Albemarle-Pamlico estuarine system appear to be affected by excessive rates of freshwater inflow, especially during the spring. For example, Pate and Jones (1981) linked the impairment of nursery area function to high freshwater inflow rates associated with artificial drainage ditches. Important issues concerning local drainage of freshwater into the estuaries include the following items:

1. Rate measurements, including temporal and spatial variations, of freshwater drainage from various land uses around Albemarle-Pamlico waters are required for many of the same reasons that riverine inflows are needed. The effect of land use, artificial drainage, channelization, and water-control practices on drainage to estuarine waters will allow better informed management of land use conversion activities and management of existing drainage systems.

2. Effects of freshwater drainage, from both altered and natural areas, on the salinity regime of receiving waters may be used to evaluate the effect of existing drainage outlets, to manage pumped-drainage systems and to better protect important nursery areas.

3. Identification of lands and nursery areas of significance and areas which would suffer major adverse effects from drainage activities, along with a solid basis from which to evaluate the effects of drainage on receiving waters, is also vital to the protection of aquatic living resources.

4. If areas of ecological or economic significance are found to be adversely affected by drainage activities, mitigation of the effects or restoration of altered lands may be an option. Information on expected benefits of such mitigation/restoration activities, plus the cost of mitigation/restoration, will allow more informed decisions to be made.

5. Effects of a single land use conversion or drainage activity within a small area on receiving waters are certainly difficult to quantify. Yet, management decisions require information on the net, or cumulative, effect of numerous small, individual changes on overall receiving water quality.

6. Global climate change and the related sea-level rise are topics of intense scientific speculation and discussion. Because of the low elevations and flat terrain of the Albemarle-Pamlico shoreline, sea-level rise would have a dramatic effect on the entire estuarine system, including freshwater drainage processes.

In Back Bay, Virginia, there has been concern over the local (and usually short-term) effects of the saltwater pumping operation at Little Island, a project that was designed to have counteracted the effects of the construction of a line of dunes (the dunes have successfully prevented overwash events form occurring for nearly 20 years, and so have altered the salinity of Back Bay). A significant saltwater plume, however, was produced, the adequate dispersion of which was dependent upon wind-driven tides, and the flushing regime of the Bay was altered. Operations of the station were recently brought to an end in the midst of much controversy over the desired character of the waterbody.

A. 1. c. Estuarine Transport Issues. Riverine inflows and local drainage waters are mixed by hydrodynamic and transport processes within the estuary. These processes also directly or indirectly affect, among other things, the re-suspension, transport, and deposition of sediments, advection and mixing of dissolved substances, exchange of oxygen and volatile organics across the air-water interface, the formation and movement of algal blooms, and the movement of the larval stages of several fish and shellfish species.

In general, estuarine transport rates cannot be determined directly except over a small area for a short period of time. The usual procedure is to measure tidal elevations, wind speed and direction, inflow rates, and the upstream and downstream salinity variation over time. These data are utilized, along with information about bathymetry, to compute transport rates throughout some region of interest. Short-term measurements of velocity fields may be used to insure that the computations provide reasonable results for the conditions under which the measurements were made.

**A. 1. d. Availability of Information.** Williams et al. (1973) stated, "Bits of information on currents, salinities, temperatures, effects of storms, and other events (including engineering projects) are scattered widely in the literature, from historical narratives to modern scientific papers, but effective physical description of these bodies of water has seldom been accomplished." This 18-year-old statement about the Albemarle-Pamlico system is still generally true. Most of the existing data for the Albemarle-Pamlico estuarine system is, by virtue of the objectives and methods of the data collection, more suited for analysis of processes occurring under a particular set of circumstances than for use in the assessment of temporal and spatial trends. Bales and Nelson (1988) compiled a bibliography of works concerning hydrology and water quality in the Albemarle-Pamlico region, which is useful for identifying available data.

Freshwater inflows to the Albemarle and Pamlico sounds are gaged by the US Geological Survey (USGS). Ragland et al. (1987) summarized the existing USGS stream-gaging network in North Carolina, however, most of the gaging stations are located well upstream of the mouths of the Albemarle-Pamlico tributary rivers. Flow from about 63% of the 4,940 square-mile Roanoke River basin is measured; flow from only about one-half of the 4,300 square-mile Tar-Pamlico River basin and the 5,600 square-mile Neuse River basin is gaged. In addition a few of the smaller tributaries to the sounds are gaged, but in general, freshwater inflow rates to the Albemarle-Pamlico system are not well defined.

Based on frequency curves for annual mean discharge (Wilder et al. 1978) of the Blackwater, Roanoke, Tar, and Neuse Rivers, there is a 50% chance that annual mean flow in any year will be 0.8 cfs/sq mi or less in the Blackwater and Roanoke Rivers. The comparable flows for the Neuse and Tar Rivers, on the other hand, are about 1.05 cfs/sq mi. Low flow frequency values were similar for all streams except the Roanoke (Wilder et al. 1978). Natural flows in the Roanoke are augmented by releases from Kerr and Gaston Reservoirs. During 30-day, 10-year low flow conditions (flows which are not exceeded for 30 consecutive days and occur, on the average, once every 10 years) about 75% of the total inflow to the Albemarle-Pamlico estuarine system consists of flow from the Roanoke River basin, which constitutes only about 48% of the total Albemarle-Pamlico drainage basin.

Historical tidal-elevation records exist for numerous sites around the Albemarle-Pamlico estuarine region. A synoptic array of tidal-elevation gages was installed along the Pamlico and Neuse Rivers during February 1988 by the US Geological Survey (Figure III-1) and in Albemarle Sound in 1990. US Army Corps of Engineers' (COE) needs are typically project-specific and, as a consequence, COE gages tend to be short-duration installations. Short-duration historical records also exist from numerous National Ocean Service (NOS) gages in North Carolina. Chronologies of COE and NOS tidal-elevation stations are available. About 6 years of record for eight sites located on the Chowan River are also available for the late 1970s and early 1980s (Daniel 1977). In addition, tidal-elevation data, with periods of record on the order of months, have been obtained by other researchers, such as Pietrafesa et al. (1986). Useful publications for tidal information include the following tide tables published annually by the US Department of Commerce: NOS publications "Index of Tide Stations, United States of America and Miscellaneous Other Locations", "Sea Level Variations for the United States 1985-1980 (Annual Revision)", "Products and Services Handbook", Ho and Tracey (1975), Harris (1981) and Ebersole (1982).

By contrast, there have been relatively few measurements of tidal velocity in Albemarle-Pamlico estuarine waters. One potential difficulty with utilizing much of the available velocity data is that important ancillary information, such as tidal stage, salinity, and wind field, were not obtained in conjunction with velocity measurements. Several sets of velocity measurements have been taken at Oregon Inlet and Ocracoke Inlet (Giese et al. 1985). These COE data typically were taken at various times throughout a single tidal cycle. One set of velocity data was collected at Hatteras Inlet during flood flow.

Dye releases for the measurement of time of travel have been made in the Chowan River (Daniel 1977), the Neuse River (Woods 1969; Christian et al. 1986), and the Pamlico River (Horton et al. 1967).

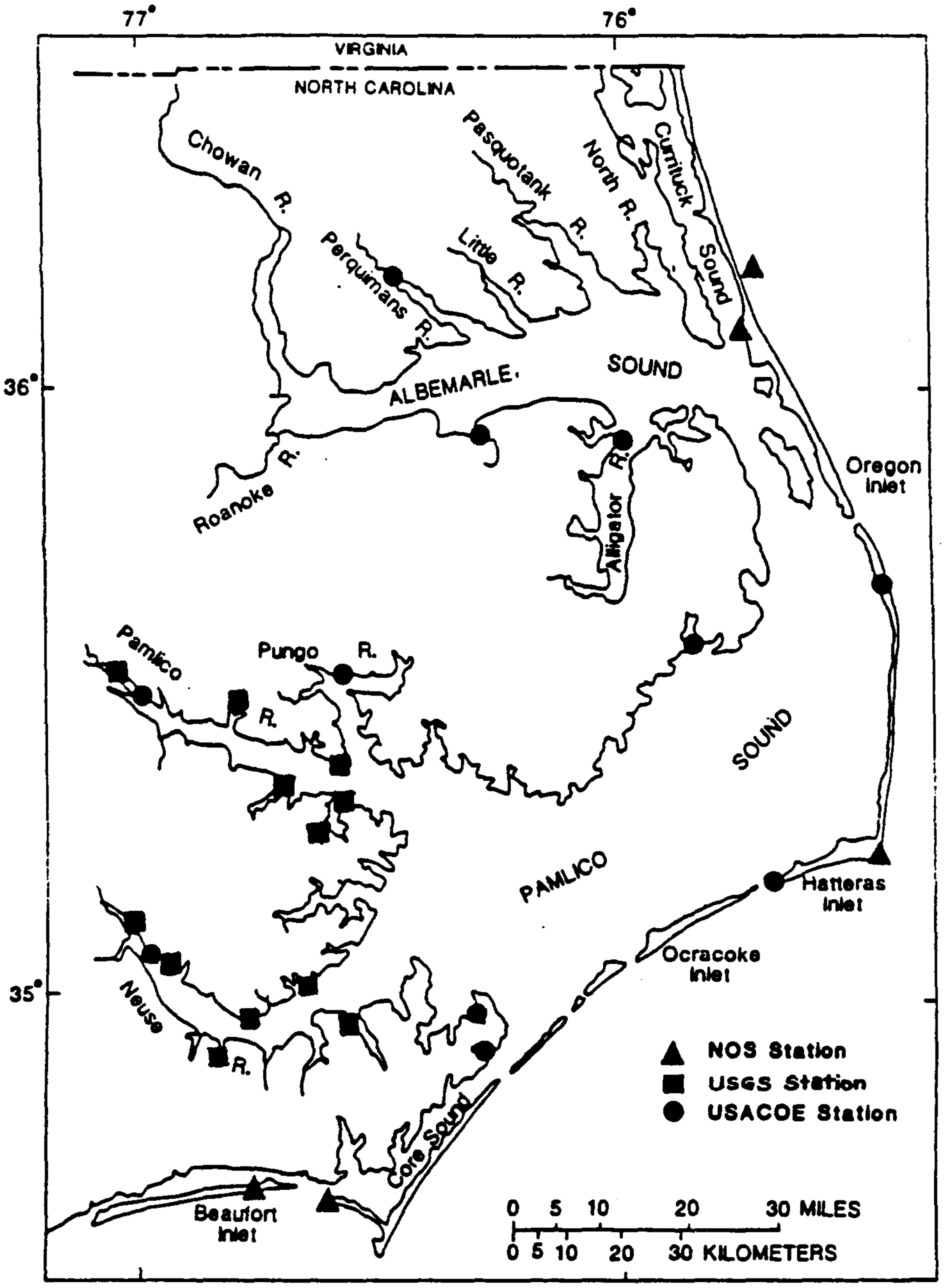


Fig. III-1. Tidal Elevation Gage Sites in the Albemarle-Pamlico Estuarine System, March 1989. From J.D. Bales, USGS, Personal Communication.

Instantaneous discharge measurements were made in the upper reaches of the tide-affected portion of the Chowan River (Jackson 1968). Longer term velocity data were obtained from seven recording velocity meters that were moored in the Neuse River for 38 days (Knowles 1975). Perhaps the most comprehensive set of hydrodynamic data were obtained from seven moored, recording velocity meters, two tidal-elevation gages, and five thermographs located near Oregon Inlet (Singer and Knowles 1975).

Salinity is physically linked to the flow field by the pressure gradients generated from the salt distributions, yet, salinity has typically been measured as a conservative tracer (i.e., without regard to flow conditions), which renders the data of little use for assessing transport processes. In addition, salinity fluctuations are so rapid, great, and erratic that samples collected at monthly, or even daily, frequencies may only be suitable for obtaining seasonal trends.

Giese et al. (1985) provided a detailed analysis of historical data on saltwater intrusion in Albemarle-Pamlico tributary rivers. Summaries of Albemarle-Pamlico estuarine system salinity data have been given by Marshall (1951), Roelofs and Bumpus (1953), Hobbie (1970b), Schwartz and Chestnut (1973), Williams et al. (1973), and Sholar (1980). Salinity distributions were observed in Albemarle Sound and the Chowan River for several months in 1981 and 1982 and have been reported, along with estimates of the frequency of occurrence of various salinities in Albemarle Sound (NC Division of Environmental Management 1982). Based on several years of observations, Wilder et al. (1978) developed cumulative frequency curves of specific conductance for sites on the Pasquotank, Perquimans, Chowan, Scuppernong, Pamlico and Neuse Rivers, and Albemarle Sound. Singer and Knowles (1975) obtained some vertical profiles of salinity with their velocity data measured near Oregon Inlet.

Despite the polymictic nature of the Albemarle-Pamlico estuarine system, periodic vertical salinity and/or thermal stratification occurs (on an hourly to daily basis) and occasionally persists for days or weeks in the central basins and main stems of tributaries and estuaries (Matson et al. 1983; Paerl et al. 1984). Significant hypoxia/anoxia can accompany stratification and salt wedges which may extend up into ordinarily highly productive meso- to oligohaline segments of slow-moving rivers (Chowan, Pamlico, Neuse). During these events deposited organic matter is entrained and rapidly decomposed and converted to inorganic nutrients (including phosphates and ammonia) in hypolimnetic, near-bottom, saline waters. Salt wedges are not permanent features; hence, regenerated inorganic nutrients are eventually redistributed and assimilated by photosynthetic primary producers throughout the shallow water column.

Giese et al. (1985) used long-term records at the downstream-most gaging stations and drainage-area ratios to develop a gross monthly water budget for Albemarle and Pamlico Sounds (Tables I-3 and I-4). Pietrafesa et al. (1986) also developed a gross monthly water budget for Pamlico Sound, which is similar to that of Giese et al. (1985). Likewise, a similar water budget was also developed for Albemarle Sound by the NC Division of Environmental Management (1982).

For the period 1970-1988 Harned and Davenport (1990) found a statistically significant increase in salinity in the upper Pamlico River, in the central portion region of Albemarle Sound, and in the Pasquotank River. A decline in salinity was found in the lower Pamlico River. No statistically significant trend in salinity was found elsewhere in the Albemarle or Pamlico sounds or tributaries. Data from National Weather Service meteorological stations are published monthly in the National Oceanographic and Atmospheric Administration (NOAA) report "Climatological Data -- North Carolina" and are stored at the National Climatological Data Center in Asheville, North Carolina. Meteorological data are also recorded at the Cherry Point Marine Corps Air Station (MCAS) and at several of the US Coast Guard stations in the region. USGS is measuring windspeed and direction at three open water sites in support of hydrodynamic modeling activities. Analysis of long-term meteorological data has been provided by, among others, Carney and Hardy (1967) and Pietrafesa et al. (1986).

**A. 1. e. Extent and Status of Understanding.** The hydrology of the Albemarle-Pamlico Estuary, particularly the wetlands and artificially drained lands, is quite complex. Moreover, the natural hydrology of much of the region has been altered by construction of vast networks of drainage ditches and canals (Heath 1975). It had been speculated that artificial drainage activities would not significantly alter the annual water budget (Heath 1975); the primary effect, it was assumed, would be a slight increase in surface runoff as a result of a lowering of the water table. Indeed, recent investigations reveal that annual surface runoff from drained agricultural lands in the Albemarle-Pamlico region exceeds runoff from undisturbed lands by about 10% (Skaggs et al. 1980; Daniel 1981; Gilliam et al. 1985). This increase in runoff was attributed to the difference in evapotranspiration rates between agricultural and natural lands (Gilliam et al. 1985).

The effect of artificially drained systems on runoff from individual events is apparently more pronounced than changes in the annual water budget (Skaggs et al. 1980; Daniel 1981; Gregory et al. 1984). Peak outflow rates tend to occur sooner and be of greater magnitude on lands with man-enhanced drainage than on natural lands (Skaggs et al. 1980; Gregory et al. 1984).

Some results from investigations in the Coastal Plain of the effects of stream channelization on flows and the lowering of water tables may be extrapolated to describe changes that might occur because of artificial drainage. Both maximum and minimum rates of flow are typically more extreme as a result of channelization (Figure III-2), but the total annual runoff volume appears to change very little from natural conditions (Winner and Simmons 1977; Gregory et al. 1984). Lowering natural water tables by artificial drainage also reduces recharge to the deep aquifers; thus, saltwater encroachment into the deep aquifer, which is a continuing process, may be increased (Heath 1975).

"Drainage density" is the ratio of total length of all stream segments in the basin to the basin area. Drainage density indicates the efficiency with which water is removed from an area by surface runoff. Drainage densities are about 2.5 miles per square mile for the Piedmont and about 1.5 miles per square mile for undisturbed Coastal Plain lands (Heath 1975). By comparison, artificial drainage systems in lands between Albemarle and Pamlico Sounds typically have about 20 miles of channel per square mile of basin. There is some argument about whether artificial drainage has resulted in long-term and undesirable decreases in salinity of receiving waters. It has been estimated that freshwater drainage from the Albemarle-Pamlico peninsula accounts for about 6% of the inflow to Albemarle Sound and about 8% of the inflow to Pamlico Sound (Heath 1975). Consequently, drainage activities probably do not significantly affect overall salinities in the sounds. Artificial drainage does, however, under certain meteorological conditions, result in changes to the salinity regime in small tidal creeks and bays (in many cases the end points for drainage canals) (Overton et al. 1988).

In addition to carrying fresh water to the sounds, drainage ditches and canals also act as conduits for the upstream movement of brackish water. Because the bottoms of many ditches and canals are below sea level, estuary water may move inland, particularly during periods of low freshwater runoff. Many low-lying areas, which were once agriculturally productive, have become contaminated by salt as a result of the movement of salt water inland through the canals. The onset of the anticipated increase in the rate of sea-level rise will likely focus greater attention on this process. Water control structures placed in drainage ditches allow the land user to exert some control over the level of the water table in fields. This process can result in more efficient drainage and may improve water quality draining to receiving waters. Two studies, currently underway, should result in better understanding of the effects of water-control structures on off-site water quality (Dr. Wayne Skaggs, NC State University; Dr. Jerad Bales, US Geological Survey).

There have been several efforts to investigate various aspects of artificial drainage and salinity changes in receiving waters. In a study of tributary tidal creeks to South River, Kirby-Smith and Barber (1979) found that drainage from Open Ground Farm sometimes decreased surface salinities, but that the bottom salinities were unaffected. Drainage from Mattamuskeet Canal lowered surface salinities in the

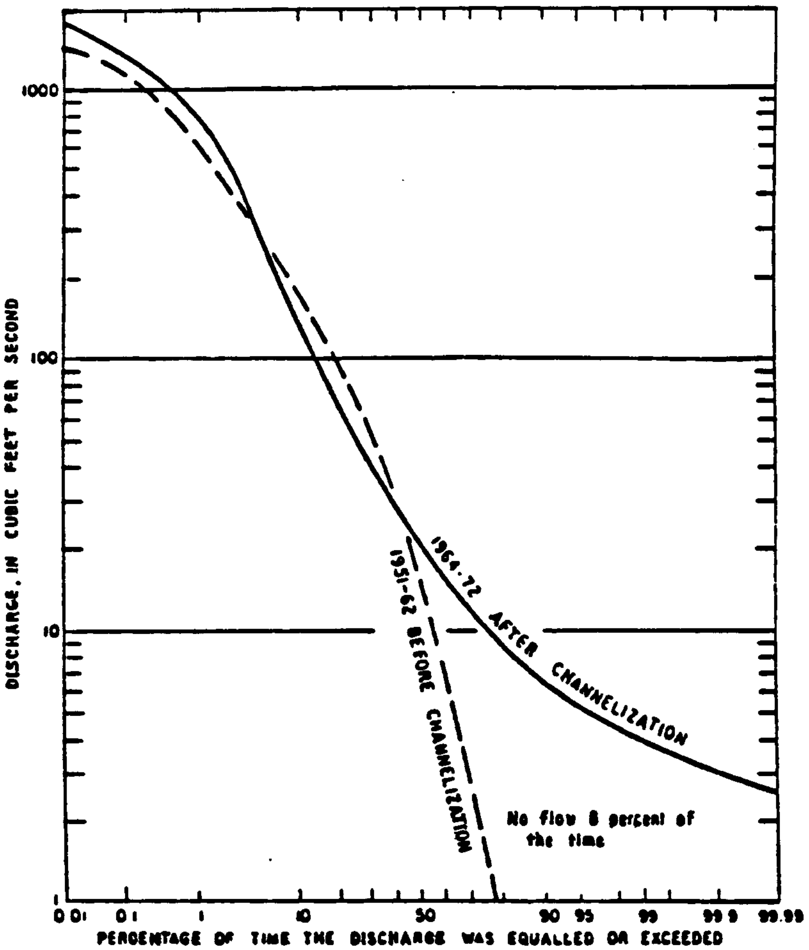


Fig. III-2. Flow Duration Curves for Ahoskie Creek at Ahoskie Before and After Channelization. From Winner and Simmons (1978).

upper portions of Rose Bay (Gilliam et al. 1985), but salinity at the mouth of Rose Bay appears to be controlled by wind-induced circulation and tidal exchange processes. Salinity in Broad Creek changed in response to the changing availability of freshwater, a product of winds pushing saltier water away from the canal (Overton et al. 1988). The effects of freshwater drainage and the associated salinity changes on the living resources of nursery areas are not entirely clear.

Controlled drainage affects both nitrate and phosphorus losses from agricultural fields. Nitrate export is reduced by as much as 50% when a high water table is maintained in the field by placing a control structure across the field ditch outlet. This reduction is due to a greater opportunity for denitrification (which occurs in anaerobic environments) in a saturated soil profile (Gilliam et al. 1978). While nitrate export may be decreased by controlled drainage, losses of organic nitrogen may be increased, and organic nitrogen is less biologically available than nitrate (Gilliam et al. 1985). On the other hand, because there is less water storage capacity in the more saturated soil, surface runoff and associated sediment and phosphate loads may be increased with the use of drainage control, especially in comparison to fields with well-drained soils or with good subsurface drainage systems.

Improved subsurface drainage may be the most effective method for reducing peak outflow rates in drainage ditches (Gilliam et al. 1985). Water is stored in the soil and is released slowly by evapotranspiration and/or lateral movement to drainage ditches. Recent results indicate that total nutrient export from agricultural fields is affected more by the drainage outflow volume than by the type of drainage system present in the field (Evans et al. 1987).

A cooperative investigation of the off-site effects of water control structures on the flow and water conditions of canals in Hyde County is currently being undertaken by the US Geological Survey and NC Division of Environmental Management (Dr. Jerad Bales, US Geological Survey; Personal Communications). Preliminary data indicate that fresh water may be released more slowly from ditches controlled by tidegates than from uncontrolled ditches (Figure III-3). Mean salinity in the tidegate controlled canal was 3 ppt. compared with a mean of roughly 5 ppt. of adjacent canals under uncontrolled conditions. Salinities of greater than 18 ppt. were observed in the uncontrolled Hyde County canals (Treece and Bales, 1990). There is widespread recognition that additional assessment of off-site effects of water control structures is needed. The Albemarle-Pamlico Estuarine Study Work Plan accorded high priority to the need to evaluate "best management practices" in coastal situations. Proper implementation of control strategies will depend on these types of evaluations. It is of equal priority to gain an understanding of the off-site effects of agricultural water management. "Research in this area [off site effects] needs to be significantly increased if we are to be successful in designing and managing systems to satisfy both agricultural and off site objectives" (Skaggs, 1987).

### A. 2. Nutrients

A. 2. a. Eutrophication. Nutrient loading is the process that usually controls the rate at which primary production increases in water bodies. Eutrophication is the process by which excessive nutrient loading causes an array of symptomatic changes in a water body among which are high rates of primary production and high levels of algal biomass. From a management perspective, eutrophication is frequently equated with the rate at which fertility increases and the manifestation of such increases in terms of water quality. Primary production is the biochemical conversion of inorganic carbon ($CO_2$) into organic matter, a process mediated by photosynthetic and chemosynthetic microorganisms and higher plants in aquatic ecosystems. In essence, this process represents the initial input of organic matter at the base of the food chain, supporting all higher ranked consumers of organic matter, ranging from simple heterotrophic bacteria and fungi to invertebrates, fish and, ultimately, man.

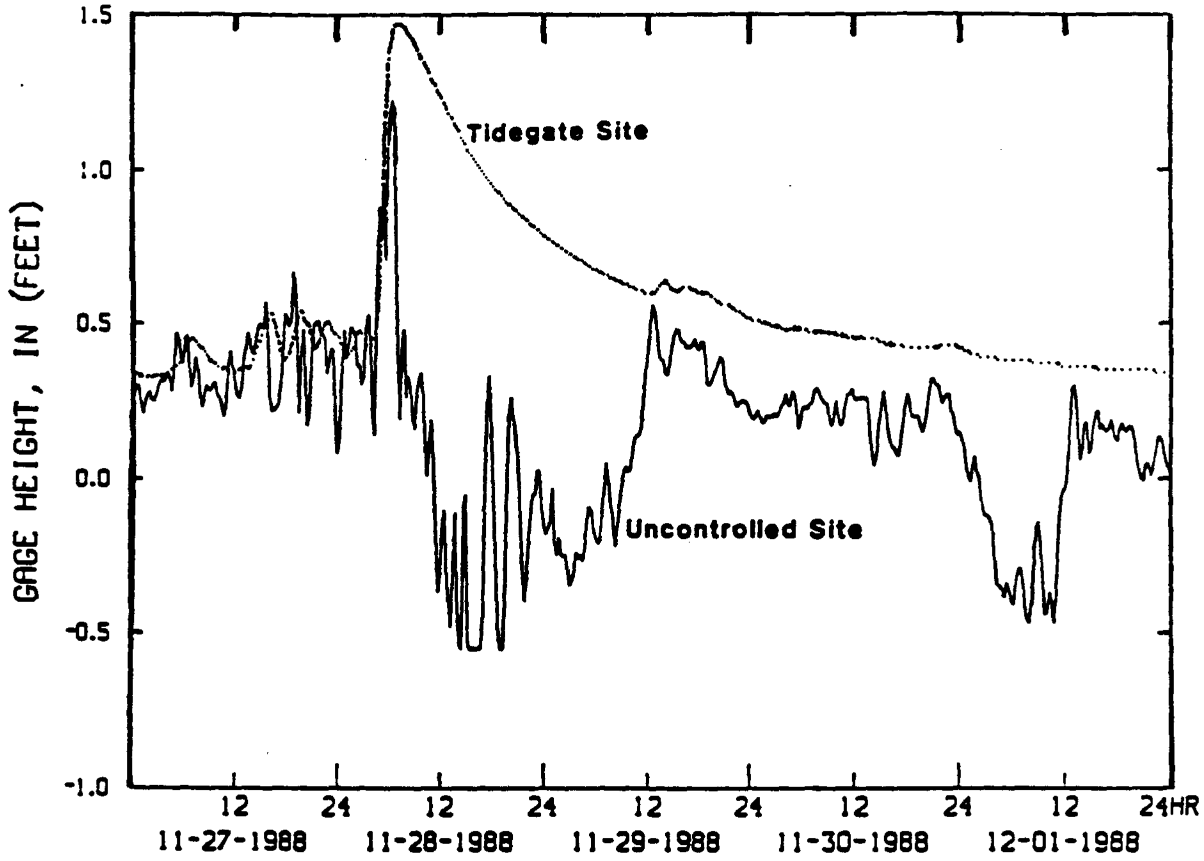


Fig. III-3. Water Level Response to Rainfall at a Tidegate Site versus an Uncontrolled Site. From J.D. Bales, USGS, Provisional Data.

Eutrophication in and of itself should not a priori be construed as an undesirable process. Limnologists, marine biologists and ecologists recognize this process as a natural phenomenon in aquatic ecosystems (Ruttner 1963; Vollenweider 1968; Likens 1972a; Wetzel 1975). Due largely to human interference with this process, events have led to undesirable (often termed "cultural") eutrophication. Eutrophication is the ominous process frequently associated with perceptible water quality degradation (Hasler 1947; Likens 1972b).

Primary production is regulated by the fundamentally important physical and chemical factors of: (1) photosynthetically available light, (2) water circulation, (3) temperature and (4) nutrients. A variety of secondary factors, including biological and geochemical nutrient regeneration, biological fixation, and conversion of essential nutrients, also play roles in mediating primary production rates. This secondary set acts on nutrients once they have already been discharged into a system and accordingly reflects the productive, or trophic, characteristics. It is the set of primary factors which most directly determine eutrophication trends. Of those factors nutrients are most critical, for it is the chronic (and, in the case of highly polluted systems, acute) nutrient loading characteristics that invariably determine eutrophication and trophic characteristics of receiving water bodies. Physical factors, such as light and temperature regimes, morphometry, water residence time, and vertical-horizontal circulation all reflect geological and climatological/latitudinal conditions which, over time, fluctuate slowly relative to nutrient inputs. A flow diagram depicting the diagrammatic relationships in an ecosystem is given in Figure III-4.

Eutrophication is a natural process of ecosystem "aging", where chronic nutrient loading results from combined erosional, hydrological, and terrestrial biogeochemical processes in a watershed, and leads to gradual accumulation of biologically-available nutrients in sediments and the water column. Human activities in watersheds have, in many cases, changed nutrient loading patterns and characteristics by altering the above-mentioned processes (Beeton 1965; Schelske and Stoermer 1971; Schindler 1974, 1977).

Specific problem areas involving anthropogenic nutrient/sediment inputs that contribute to accelerated eutrophication include:

1. Land Use. Activities which have, over the past two decades, been shown to be major nutrient contributors are: a) conversion of forests to agricultural, municipal, and industrial land, b) conversion of native forests to managed forests (silviculture), c) conversion of wetlands and marshes to agricultural, municipal, industrial, and recreational regions, d) agricultural clearing and tilling practices, and e) use and application of fertilizers. These alterations and uses constitute major nonpoint and point nutrient/sediment sources. Their relative contributions of nitrogen and phosphorus need to be quantified and considered in overall management strategies aimed at regulating eutrophication in the Albemarle-Pamlico estuarine system.

2. Nutrient Discharge Patterns. Both the magnitude and timing of nutrient discharges require careful consideration and appropriate controls. Based on the hypothesis that enhanced spring discharge of nutrients is instrumental in supporting subsequent summer nuisance algal blooms in oligohaline portions of several major tributaries (especially the Chowan and Neuse Estuaries), the timing of discharge events and their relative importance as nutrient sources are critical in controlling unwanted aspects of eutrophication. Allowable point and nonpoint discharges must exit the mesohaline portions of tributaries prior to the late-spring early-summer "slow down" (increased residence time) periods when initiation of nuisance blooms is most likely. This aspect of basin-wide nutrient management should accompany formulations for total annual nutrient input constraints in order to most effectively stem nuisance bloom potentials.

3. Freshwater Runoff. In addition to its role in mediating nutrient loadings (especially spring freshwater runoff events), freshwater dilution of seawater plays a critical role in determining

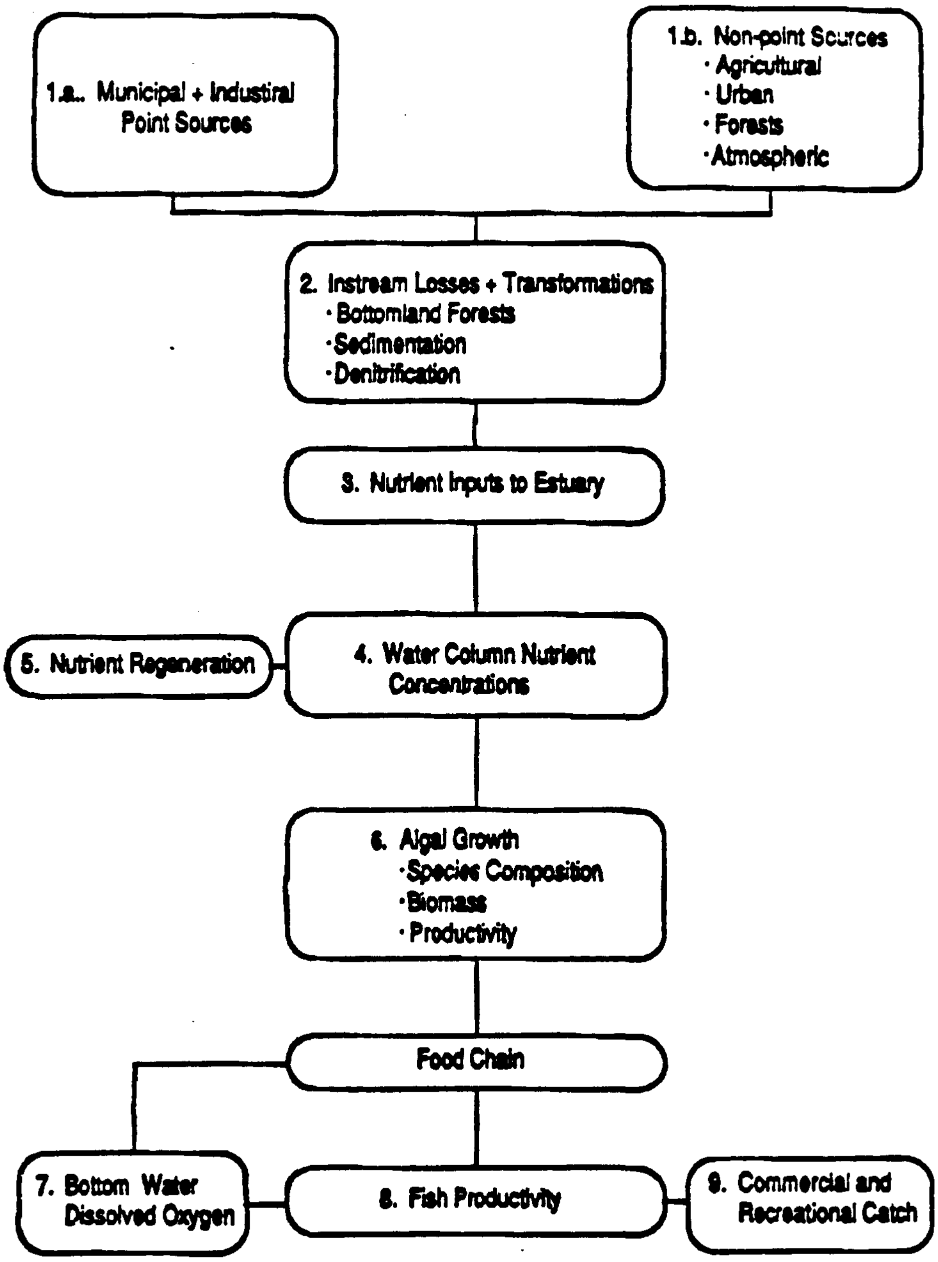


Figure III-4. Compartmentalized Model of Events leading to Consequences of Eutrophication. From D.W. Stanley, East Carolina University, Personal Communication.

the nature, extent, and duration of nuisance algal bloom events in receiving estuaries. Previous work (Witherspoon et al. 1979; Paerl 1982a, 1983; Paerl et al. 1984) has shown that the combined presence of high nutrient loading and low salinities (<5 ppt) greatly enhance nuisance bloom potentials in both the Chowan and Neuse River Estuaries. The blooms observed under these conditions have been dominated by cyanobacterial nitrogen fixing (Anabaena, Aphanizomenon) and non-nitrogen fixing (Microcystis, Oscillatoria) taxa. At salinities exceeding 5 ppt these taxa rapidly lose their dominance, and are generally replaced by mesohalophillic flagellates and dinoflagellates. In nutrient enriched waters, the latter can be responsible for chlorophyll a concentration frequently exceeding 50 ug/l (Paerl 1987; Stanley 1988b).

Impacts of freshwater salinity dilution on phytoplankton species composition and biomass have been examined further downstream at the meso-euhaline intersection of the Neuse Estuary-Pamlico Sound (Mallin et al. 1991), it can be stated with certainty that such dilution events in oligo- to mesohaline portions of certain Albemarle-Pamlico estuarine system tributaries are key determinants of both the nature and magnitude of algal blooms (Paerl 1982a, 1983, 1987 and Mallin et al. 1991). It can also be concluded that enhanced freshwater runoff and associated nutrient loads increase the risk of cyanobacterial blooms extending and proliferating further downstream in the estuaries (Paerl et al. 1984). Accordingly, freshwater runoff dynamics (magnitude and timing) will require careful scrutiny in future water quality management plans for the Albemarle-Pamlico estuarine system. It is predictable that alterations in freshwater runoff characteristics will yield profound impacts on rates of eutrophication in localized regions of the Albemarle-Pamlico estuarine system.

4. Erosion and Sedimentation. Sediment loading from the watersheds yields a diverse array of impacts on receiving estuarine-sound waters. The mineralogical and organic sediments periodically discharged into the estuaries represent a source of nutrients, both in adsorbed and subsequently desorbed, and particulate forms. The specific roles of sediments and soluble nutrients (non-sediment associated) in eutrophication mechanisms have not been adequately addressed and are the subject of proposed research. It is safe to assume, even at this early stage of investigation, that sediments will play a central role in the long-term nutrient transport and loading cycles. Sediment loading during spring runoff, when erosional products are transported significant distances into the lower estuaries and open sounds, is of particular concern with respect to long-term eutrophication trends. Such runoff events represent particularly effective means of dispersing nutrients which can subsequently be made soluble and available, during ensuing summer months and perhaps future years, as an algal nutrient source. Certainly, the well-mixed characteristics of the Albemarle-Pamlico estuarine system ensures the circulation of such released nutrients in the water column where effective algal assimilation seems certain.

   It should be recognized that suspended sediments affect water column transparency, often decreasing it by factors of 2 to 3. In assessing the overall eutrophic effects of sedimentation, the positive effects of associated nutrient enrichment must be weighed against the potential negative impacts of decreased light availability on phytoplankton. Settling generally reduces sediment-related turbidity shortly after acute erosional-runoff events, but leaves soluble nutrient loads in the water column after sedimentation. Given the ability of phytoplankton to readily intercept such nutrients in euphotic well-mixed waters, it is likely that nutrient enrichment far outweighs reduced transparency in an overall consideration of eutrophic impacts of sediment loadings.

5. Precipitation (Acid Rain). While attention has focused on land-borne nutrient runoff as a main factor involved in estuarine and coastal eutrophication, virtually no attention has been paid to atmospheric sources of nutrients, specifically nitrogen-enhanced acid rain. As a source

of freshwater runoff and dilution, precipitation has historically been recognized as a factor qualitatively and quantitatively affecting eutrophication. Until recently, however, precipitation has not been considered a highly significant nutrient source. Even in the mid-1970s, precipitation-related nutrient inputs were thought to be only 9-10% for nitrogen and less than 5% for phosphorus (NC Division of Environmental Management 1989a). Our recent awareness of the magnitudes and frequencies of nitrogen-enriched acid rain altered our appreciation for and concern about this important nutrient source affecting the Albemarle-Pamlico estuarine system (Paerl 1985). Recent experimental work has shown that naturally-occurring amounts of rainfall can stimulate primary production in estuarine and coastal waters through the addition of nutrients (mainly nitrogen) contained in the rainwater (Paerl 1985, Paerl et al. 1990).

In the North Carolina shallow coastal habitats, much of the nitrogen loading is rapidly assimilated by oligohaline and mesohaline phytoplankton populations that typically reside in the upstream portions of estuaries. These populations act as biological "filters", stripping out biologically-available nitrogen before it enters the larger meso- to euhaline segments of the estuaries, sounds (Albemarle and Pamlico), and Atlantic coastal waters. As a result, these vast water bodies remain chronically nitrogen deficient. Because riverine nitrogen inputs are often stripped in upper portions of estuaries, direct nitrogen inputs from precipitation become an increasingly important source of biologically-available nitrogen downstream. While rainfall nitrogen accounts for about 10-20% of annual nitrogen inputs in the upper portions of estuaries, it may account for as much as 30-40% of the annual nitrogen supplied to the lower estuaries and sounds (Paerl 1985). These calculations are based on annual rainfall nitrogen loading originating from "non-acid" rain events. Typically $NO_3^-$, which is the largest nitrogen constituent in North Carolina rainfall, ranges in concentration from 5 to 10 umoles per liter during "non-acid" rain events (pH >4.5). By contrast, during "acid" rain events (pH <4.5) $NO_3^-$ concentrations can exceed 100 umoles per liter (Paerl 1985). Considering acid rain derived $NO_3^-$ loading values, direct nitrogen loading from precipitation could account for as much as 50% of the total annual nitrogen loading in the open sounds and coastal waters. This estimate may, in fact, be conservative since dry deposition of nitrogen has not been included in these calculations. This largely ignored source of nitrogen can, at times, account for a bulk of the nitrogen input into these waters.

__A. 2. b. Impact of Nutrients.__ Of all the nutrients essential for primary production, nitrogen and phosphorus have been of most concern as "limiting factors" controlling eutrophication (Likens 1972a; Schindler 1977; Hecky and Kilham 1988). Both are frequently perceived to be the primary anthropogenic nutrient inputs. As constituents in key structural and functional molecules (including proteins, lipids, sugars and nucleic acids), nitrogen and phosphorus are in high demand by primary producers (Stewart 1974). This, along with the fact that availability of these nutrients is often restricted (compared to plentiful supplies of carbon, hydrogen, oxygen, sulfur, silicon, and a variety of trace metals), implies that nitrogen- and/or phosphorus-limited growth commonly characterizes aquatic ecosystems (Hecky and Kilham 1988). In general, nitrogen has been considered most limiting in marine and coastal waters (Ryther and Dunstan 1971; Carpenter and Capone 1983), while phosphorus is a dominant limiting nutrient in freshwater (Likens 1972b; Schindler 1977). In estuaries, both nitrogen and phosphorus play key roles in limiting growth (Neilson and Cronin 1981; D'Elia et al. 1986; Nixon 1986), and it is clear that the Albemarle-Pamlico estuarine system is no exception.

Accelerated eutrophication is of environmental and economic concern. Frequently, serious water quality degradation in the form of "runaway" or uncontrolled nuisance algal blooms, periphytic and/or macrophytic growths accompany accelerated eutrophication. Secondary effects of such unwanted growth may include:

1. Toxicity to members of resident food chains caused, for example, by blooms of cyanobacteria (blue-green alga) and/or dinoflagellates (red tide);

2. Toxicity of drinking water, fish, and shellfish affecting recreational users (including domesticated animals and humans) of degraded waters;

3. Hypoxia and/or anoxia of hypolimnetic (non-mixed subsurface) and near bottom waters, resulting from increased biological and chemical oxygen demands caused by decomposition of micro-algal blooms and macrophytic growth. Both forms of oxygen depletion lead to intolerable living conditions, toxicity and death of invertebrate, shellfish, and finfish species in affected waters and sediments;

4. Resultant alterations of planktonic and benthic food chains due to either poor food values (due to the shape or size of colonial nuisance algae) or avoidance of primary producers (due to toxicity or undesirable taste);

5. Increased incidence and stress-related promotion of fish and shellfish diseases; and

6. Foul smells, unacceptable tastes, and poor aesthetic values of affected waters.

To varying extents, symptoms as well as fully developed cases of the above-mentioned manifestations of accelerated eutrophication have affected some tributaries of the Albemarle-Pamlico estuarine system. In all cases, enhanced sediment and soluble nutrient loadings have been identified as causative agents for these forms of water quality degradation.

Coastal nutrient-related water quality problems, ranging from gradual eutrophication to massive algal blooms, represent serious short- and long-term threats to commercial, recreational, and aesthetic values of affected freshwater and estuarine habitats in eastern North Carolina (Paerl 1982a, 1983, 1987). It is clear that eutrophication-related problems have caused persistent negative impacts on the economic and environmental well-being of the Albemarle-Pamlico estuarine system. Technically, relevant questions of concern include:

1. Are inorganic nutrients limiting and hence regulating phytoplankton growth in the Albemarle-Pamlico system?

2. Which nutrients act as growth limiting factors?

3. Is anthropogenic nitrogen and/or phosphorus enrichment a detectable problem in the Albemarle-Pamlico system?

4. Is accelerated eutrophication, resulting from such enrichment, occurring in the Albemarle-Pamlico system?

5. What are the symptoms of eutrophication?

6. Does nutrient-related eutrophication represent a threat to fisheries, recreational and aesthetic resources in the Albemarle-Pamlico system?

7. If the above are true, can we properly manage a system of such size and scope and successfully arrest and reverse long-term water quality degradation?

**A. 2. c. Availability of Information.** It is intuitively obvious that increased estuarine nutrient loading ought to occur with increasing human population, increasing use of nitrogen and phosphorus fertilizers, and continued conversion of forest lands to agriculture. Scores of annual nitrogen (N) and phosphorus (P) loading estimates have been made for various estuarine drainage basins, including the Neuse, Chowan, and Tar-Pamlico River estuaries. However, actual estuarine nutrient loadings have not increased at rates similar to those of population growth.

A study (Stanley 1988a) was conducted to use existing data to estimate N and P loading rates for the Neuse basin over the past 100 years. Trends in land use and nutrient loading in the Neuse River basin were estimated for the period 1880 through 1985 by summing computed estimates of annual point and nonpoint source loadings for each county in the basin. The procedure was a modification of that used by Craig and Kuenzler (1983). Nonpoint sources considered included: (1) six categories of farm animals, (2) agricultural cropland, (3) idle cropland, (4) forestland, (5) pastureland, and (6) urban land area. Data on harvested acreage of individual crops were tallied and summed to give the total cropland acreage. Results of this study are given in Section C.1.b.

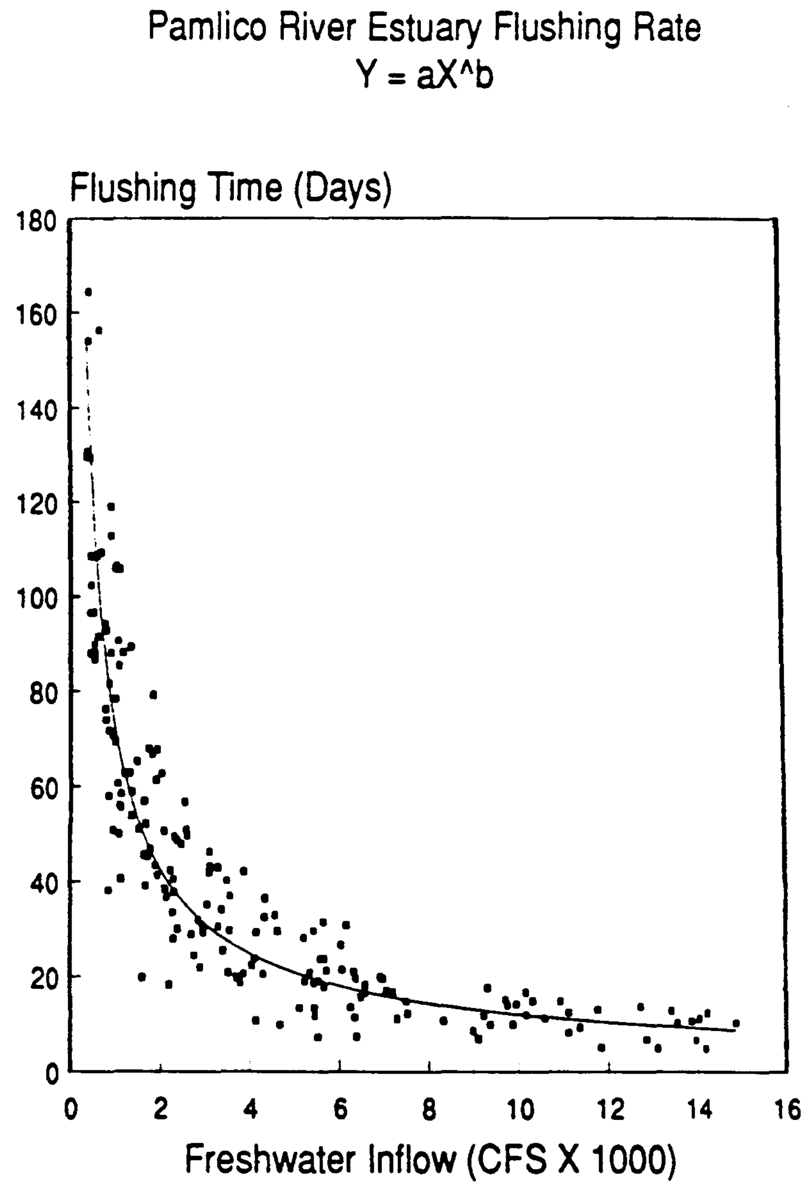
Harned and Davenport (1990) used seasonal Kendell test to evaluate trends in Water Quality data, including nutrients, collected at 296 locations in the Albemarle-Pamlico system in 1945 and 1988.

Another study was made to synthesize twenty years of water quality data for the Pamlico River Estuary (Stanley 1988b). Data for the analyses came from several sources. Most of the nutrient and hydrographic data were from two long-term monitoring projects, covering the periods 1967-1973 and 1975-1986, with additional data from two short-term research projects in the mid-1970s. Phytoplankton studies during two periods (1966-1968 and 1982-1985) gave species composition, cell density and biomass data that were used in the analyses. Details of the methodology and the results of this study are presented in Section C.1.c.

An extensive survey of the nutrients and their fates was conducted in Albemarle Sound during the 1970s (Bowden and Hobbie 1977). Albemarle Sound is suggested to have adequate supplies of both phosphorus and nitrogen for abundant phytoplankton growth, sometimes exceeding the levels thought to be the threshold for undesirable eutrophication. Studies have been completed on the Chowan system for nutrient uptake, recycling and phytoplankton response (Craig and Kuenzler 1983; Kuenzler et al. 1982; Stanley and Hobbie 1977).

High concentrations of nitrogen and phosphorous were found to be consistent problems in Virginia's Back Bay. Releases from hog operations' storage lagoons have had significant impacts on water quality, resulting in "excessively high" ammonia nitrogen, phosphorous, and fecal coliform concentrations as well as fish kills in the receiving waterways (Mann Associates 1984). Data from Virginia's Back Bay also indicate a nearly direct relation between suspended solids and total phosphorous, clearly demonstrating the influence of erosion on nutrient concentration of nutrients and water quality.

**A. 2. d. The Status and Extent of Understanding.** Water residence characteristics are also factors to be considered in susceptibility to accelerated eutrophication. Winter and early spring (November-March) traditionally represent the rainy period in North Carolina, with between 50-75% of annual precipitation falling during this interval (NC State University Climatological Report 1988). Relatively high flushing, high discharge, and short water retention characterizes the tributaries and sounds at this time. Typically, water residence times vary from a few weeks to 2 months in major tributaries (Chowan, Pamlico, Neuse Estuaries); nitrogen-rich (and to a lesser extent phosphorus-enriched) discharge is common. After May during a "normal" rainfall year, hydrological conditions abruptly change; discharge decreases substantially (on the order of 2-3 fold for most tributaries) while retention times dramatically increase from 1 to 3-4 months (Figure III-5). During the spring, summer, and fall estuarine tributaries frequently exhibit lake-like characteristics (i.e., lengthy retention with ephemeral mixed/non-mixed conditions) (Paerl 1987). If the transitional "slowdown" discharge period is abrupt enough, a situation arises in which nutrient and sediment laden spring runoff waters will, in varying degrees depending on the tributaries in question, still reside in oligo- and mesohaline portions of estuaries (Showers et al. 1990). This overlap between



a=16830; b=-.786
FW Inflow = Tarboro Flow X 2.04

Fig. III-5. Flushing Time of the Pamlico River Estuary versus Freshwater Inflow. From D.W. Stanley, ECU, Unpublished Data.

nutrient enrichment, increasing water temperatures, stability, and residence time, and day length (light availability) represents excellent conditions for phytoplankton macrophyte growth. Persistent summer-fall low-flow conditions following high spring runoff events appear to set the stage for optimal phytoplankton biomass development and persistence (Christian et al. 1986). In oligohaline waters this scenario appears to have precluded blooms of some of the most problematic nuisance blue-green algae (both non-nitrogen fixing and nitrogen fixing) (NC Division of Environmental Management unpublished data; Paerl 1982a, 1983, 1987; Christian et al. 1986), while mesohaline microflagellate/dinoflagellate blooms frequently thrive under these conditions (Paerl et al. 1984; Stanley 1988a).

The nutritional status and phytoplankton populations of the Pamlico River estuary have been intensively studied for the past two decades (Hobbie 1970a, 1970b, 1971, 1974; Hobbie et al. 1972; Copeland and Hobbie 1972; Davis et al. 1978; Kuenzler et al. 1979; Harrison and Hobbie 1974; Copeland et al. 1984; Stanley 1988b). Phosphate concentrations are relatively high in the middle reaches of this oligo-mesohaline (2-15 ppt salinity), shallow, turbid estuary, especially in the summer. By comparison, inorganic nitrogen concentrations are low relative to phytoplankton needs, except for periods of abundant nitrate in the upper reaches during winter and early spring. Most of the particulate nitrogen and particulate phosphorus appears to be phytoplankton (Kuenzler et al. 1979). Dinoflagellates dominate the phytoplankton, especially during winter blooms of Heterocapsa triquetra. Primary productivity and rates of uptake of nitrate, ammonium, and phosphate were measured by Kuenzler et al. (1979). Phytoplankton showed a marked "preference" for ammonium over nitrate; ammonium provided 82% of the nitrogen taken up annually. There was evidence that algal abundance and primary productivity increased in the Pamlico River estuary during the 1970s, although phytoplankton species composition did not change significantly (Kuenzler et al. 1979). The lower, mesohaline part of the Neuse River estuary has been studied less extensively (Hobbie and Smith 1975; Stanley 1983, 1988a; Christian et al. 1986, 1987), but the data indicate many similarities to the Pamlico River estuary.

Little, however, is known about the dynamics of and susceptibility to algal blooms in the open waters of Albemarle-Pamlico sounds. Moreover, it is not known whether nuisance blooms of cyanobacteria, microflagellates or dinoflagellates occur and/or proliferate in these waters. The potential for such blooms and the factors regulating their development and persistence are the subjects of a current study (Paerl, H.W. et al. 1990) Studies in poorly but occasionally stratified estuaries like Chesapeake and Delaware Bays indicate that microflagellates and dinoflagellates often thrive in shallow (3-5 m) waters. Especially important are findings that both nitrogen and phosphorus enrichment lead to enhanced growth of these apparently opportunistic taxa (Steidinger 1983). Therefore, it is prudent to assume that a similar scenario for periodic microflagellate and dinoflagellate blooms exists in the open sound components of the Albemarle-Pamlico estuarine system.

Two very important points are frequently overlooked in assessments of the vulnerability of North Carolina's estuaries to accelerated eutrophication. First, the light/temperature climate is such that rapid proliferation of plant growth is assured given adequate nutrition. On average, Eastern North Carolina experiences a wealth of sunlit days. Approximately 80-90% of days (disregarding thunderstorm events) during spring, summer, and fall months are sunny. This assures adequate supplies of photosynthetically available radiation and leads to maximum water column heating. Second, waters periodically receive nitrogen-enriched acid rain generated in upwind (north, northwest and west), urban, and industrial regions as far as 1,500 miles away (National Acid Precipitation Assessment Program 1988). The shallow confined nature of the Albemarle-Pamlico Estuarine System makes it particularly susceptible to eutrophication impacts of acid rain, since dilution of this nutrient source is minimal. Added to locally-generated point sources and nonpoint sources, acid rain represents an increasingly significant nitrogen source in a system known to be nitrogen sensitive.

The limnological literature abounds with examples of nutrient impacted, shallow, ephemerally stratified (but on average well-mixed) water bodies of becoming victims of accelerating eutrophication. Although the Albemarle Pamlico estuarine system is not a freshwater system, its morphological, hydrological and physical characteristics resemble polymictic large lake conditions in many ways. The main basins of the Albemarle-Pamlico Estuarine System and its major tributaries (Chowan-Roanoke, Pamlico-Tar, and Neuse Rivers) are shallow and well-mixed, facilitating dispersal of loaded nutrients and sediments and efficient nutrient-sediment exchange between benthic and planktonic regions. These characteristics ensure optimal nutrient availability to both planktonic and sessile primary producers. Transparency is restricted in the turbid, highly colored waters, in part due to humics and fluvics, and in part to biogenic production. Extinction coefficients range from 2 to >6 hours, but frequent and thorough vertical mixing of a few minutes to <1 hour for the entire water column, promotes optimal exposure to available light leading to high photosynthetic production. Recent productivity studies employing a light-field-simulator designed to mimic phytoplankton residence in a highly-variable (mixed) light regime revealed resident phytoplankton to be well-adapted to such illumination regimes. Higher rates of primary production were observed in rapidly-mixed conditions (15-20 min for total water column mixing) than in longer high-light conditions (M. Mallin and H.W. Paerl 1991). While the physiological basis for optimal transient light regime photosynthesis requires further investigation, it can be concluded that resident phytoplankton communities are well adapted to a rapidly-mixed, turbid water column.

Despite the scarcity of open-water nutrient and productivity data from the past decade, a reasonably diverse and comprehensive data bank has been established for the main tributaries and some estuaries. Included are the major freshwater input sources for the Albemarle Sound (Chowan, Pasquotank and Roanoke Rivers) and the drainage basins emptying into Pamlico Sound (Pamlico-Tar and Neuse Rivers). Some generalized findings and characteristics appear to apply to the cycling and seasonal concentrations of nitrogen and phosphorus sources and inputs in these tributaries. The dominant form of inorganic nitrogen in virtually all tributaries is nitrate ($NO_3^-$) (Hobbie et al. 1972; Harrison and Hobbie 1974; Stanley and Hobbie 1977; Paerl 1983). The major source of $NO_3^-$ (Table III-1) appears to be agricultural runoff (Gilliam et al. 1978) and land development, including deforestation and channelization (Skaggs et al. 1980). Together with natural (wetland forest) drainage, such nonpoint sources of $NO_3^-$ (and $NO_2^-$) contribute as much as 62% of total annual nitrogen inputs in the Chowan system (Craig and Kuenzler 1983) and at least 50% of the total nitrogen inputs into the Neuse and Pamlico River systems (NC Division of Environmental Management 1989b; Harrison and Hobbie 1974; Stanley 1988a, 1988b). Ammonia inputs from nonpoint sources constitute a relatively small fraction (5-15%) of total nitrogen inputs in these tributaries and estuaries. It is generally believed that $NH_3$ is relatively more important as "internally cycled" nitrogen. It is periodically released from oxygen-depleted and anoxic sediments (Matson et al. 1983; Kuenzler et al. 1984) and rapidly reassimilated by phytoplankton during spring and summer growth periods (Harrison and Hobbie 1974; Stanley and Hobbie 1977; Kuenzler et al. 1979; Stanley 1983). Consequently, seasonal $NH_3$ concentrations are consistently low and fairly uniform and are more or less independent of major hydrological events such as runoff or drought (Harrison and Hobbie 1974; Paerl 1983, 1987). In contrast, $NO_3^-$ loading and concentrations reveal dynamic seasonal fluctuations, ranging from generally high and abundant levels during high discharge winter and spring months to significantly lower, and at times undetectable, levels in summer and fall phytoplankton growth periods (Hobbie et al. 1972; Harrison and Hobbie 1974; Kuenzler et al. 1979; Tedder et al. 1980; Paerl 1983, 1987; Stanley 1988b).

Estuarine sediment chemistry is quite complicated. Many elements are directly or indirectly involved in nutrient transformations and fluxes. The species and concentrations of these elements vary in space and time. Concentrations often change over short distances (centimeters) with depth in the sediment, but other patterns of spatial change extend the entire length of the estuary. The most important temporal changes in nutrient concentrations, forms, and fluxes range from a few days (for some anoxic events) to annual periodicities, although shorter and longer cycles may exist. The concentrations of many elements are tightly linked to the redox state of the sediments and the end-members can thus be recognized: oxic sediments contain elements predominantly in their oxidized forms ($O_2$, $SO_4^=$, $NO_3^-$, $Fe^{+++}$, etc.); whereas, anoxic sediments are dominated by elements in their reduced forms ($CO_2$, $HS^-$, $NH_4^+$, $Fe^{++}$, etc.). Linked closely to inorganic biogeochemistry are the enormous number of species of

Table III-1. Nonpoint Source Impacts in the Estuarine Portion of the Albemarle-Pamlico Estuaries (NC Division of Environmental Management 1989b).

| Parameter | Acreage | Percentage |
|---|---|---|
| WATER QUALITY RATING | | |
| Support | 1,738,761 | 93.1 |
| Partial and Nonsupport | 128,739 | 6.9 |
| MAJOR SOURCES OF DEGRADATION* | | |
| Point Source | 38,290 | 29.7 |
| Nonpoint Source | 90,369 | 70.2 |
| Agriculture | | |
| Feedlots | 1,462 | 1.1 |
| Runoff | 83,011 | 64.5 |
| Urban | | |
| Runoff | 1,664 | 1.3 |
| Finger Canals | 0 | 0.0 |
| Land Disposal | | |
| Sludge | 0 | 0.0 |
| Septic Tanks | 3,143 | 2.4 |
| Other | | |
| Marinas | 1,089 | 0.8 |
| Natural | 0 | 0.0 |
| MAJOR CAUSES OF DEGRADATION* | | |
| Fecal Coliform | 9,579 | 10.6 |
| Dissolved Oxygen | 400 | 0.4 |
| Chlorophyll _a_ | 44,030 | 48.7 |
| Sediment | 3,300 | 3.7 |
| Multiple | 33,060 | 36.6 |

* Partially-supporting and Non-supporting Areas Only. From EPA Source Codes.

organic chemicals and microbially mediated reactions, almost none of which have been studied in North Carolina estuaries.

Definitive studies of estuarine nutrients and productivity began in North Carolina during the early 1970s. Although much has been done, large gaps still exist in our knowledge of causes and effects. Pilot nutrient studies were conducted for Albemarle Sound (Bowden and Hobbie 1977) and the Neuse River Estuary (Hobbie and Smith 1975). A much longer-term nutrient study has been underway in the Pamlico River Estuary since the late 1960s (Hobbie et al. 1972; Hobbie 1974; Stanley 1988b).

While the North Carolina Division of Environmental Management has been conducting periodic (monthly or quarterly) ambient water quality monitoring in North Carolina's estuarine water for several years, a comprehensive monitoring and data management program in the sounds is needed. In response to the need for monitoring information, the North Carolina Division of Environmental Management and the US Geological Survey, in cooperation with the Albemarle-Pamlico Citizens Monitoring Program, have initiated a network of physical, chemical and biological information of maximum utility for researchers and managers (Holman 1989). The monitoring plan includes: 1) emergency response capabilities; 2) continuous monitors of water quality parameters at risk locations; 3) expansion of the existing ambient water quality monitoring; 4) fish tissue toxicants and sediment; 5) one-time synoptic water quality survey; 6) sediment oxygen demand; and 7) citizens' monitoring program.

**A. 2. e. Impact of Nutrient Loading on Phytoplankton Biomass and Productivity.** Phytoplankton production in the Chowan, Pamlico, and Neuse Rivers, generally relies heavily on the availability of inorganic nitrogen during peak summer growth periods. The fact that nitrogen-fixing blue-green algal species can periodically exert dominance and bloom during mid- to late-summer months in the lower Chowan River (Witherspoon et al. 1979; Paerl 1982a, 1982b) serves as testimony that periods of nitrogen limitation occur in this system. On the Pamlico, late summer flagellate-dominated blooms are effective in locally depleting inorganic nitrogen in broad, oligohaline segments (Hobbie et al. 1972; Harrison and Hobbie 1974; Hobbie 1974; Stanley 1988b). It is believed that nitrogen constitutes a limiting nutrient at certain times of the year (Hobbie 1974). During spring and summer months, the Neuse River receives relatively high $NO_3^-$ loading and exhibits hypereutrophic conditions with respect to $NO_3^-$ and $NH_3$ concentration compared to the phytoplankton demands (Paerl 1983, 1987; Paerl and Bowles 1986). In the summer, low flow blue-green algal bloom conditions can lead to significant inorganic nitrogen "drawdown", resulting in periodic nitrogen limitation. This has been substantiated with in situ bioassays (Paerl 1983; Paerl and Bowles 1986)

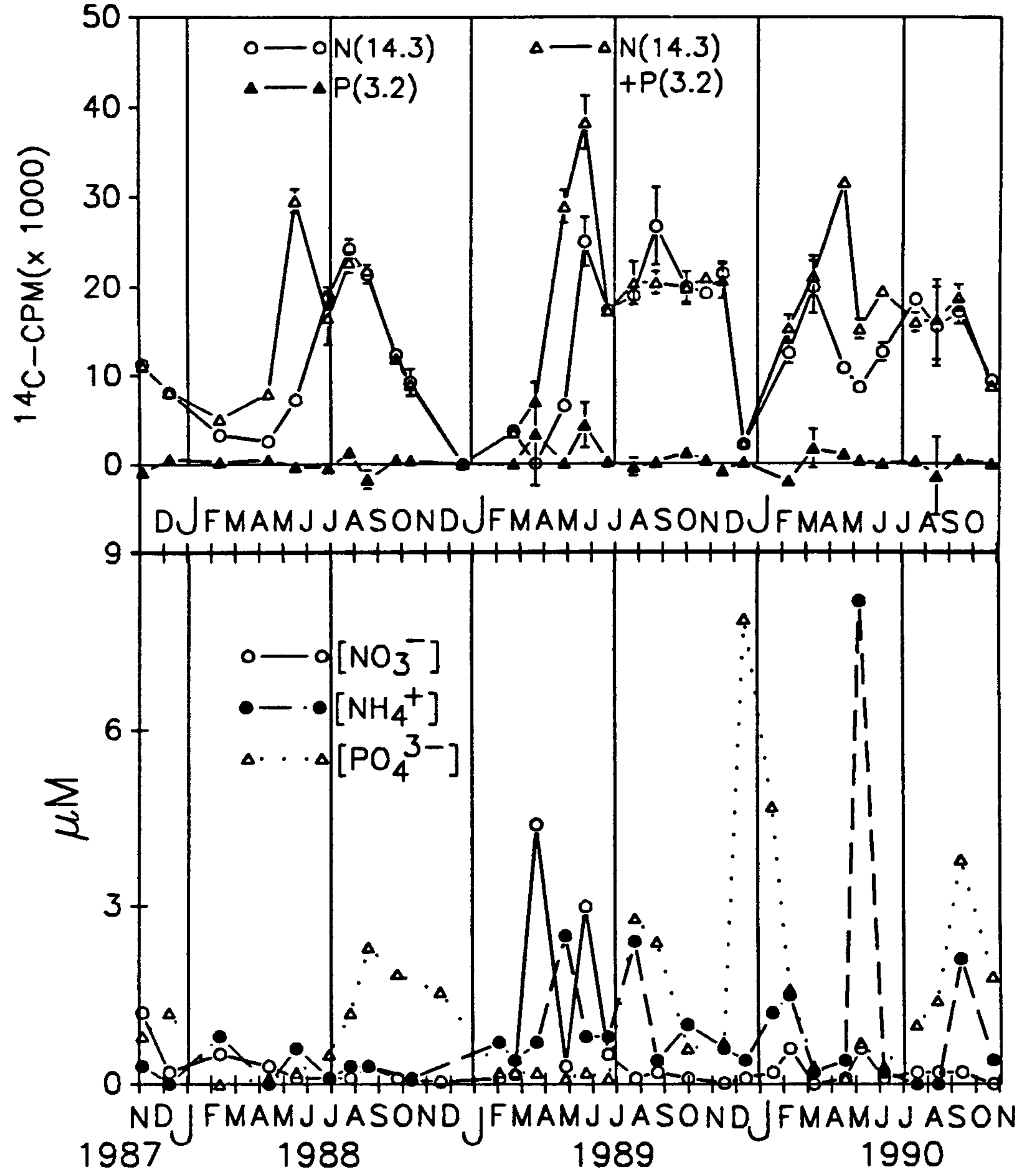
Point source inputs, such as sewage treatment plants and industrial discharges, play a relatively important role in maintaining nitrogen availability during the summer months, largely because agricultural, rural, and urban runoff-related inputs are minimized during these relatively dry, low nonpoint discharge months. At such times it is estimated that point source N inputs can account for as much as 60-70% of total nitrogen entering these river systems (NC Division of Environmental Management, 1985). Hence, on a seasonal basis, point source nitrogen inputs constitute a critical source of nitrogen during times when nitrogen limitation appears most severe. A rather extreme case for the relative importance of a point source discharge in maintaining summer phytoplankton growth and bloom activity was documented for C.F. Industries (Farmers Chemical Co.), a major discharger of nitrogenous waste located at Tunis on the Chowan River. It was widely believed that spring and summer nitrogen discharge from this plant in the early 1970s was responsible for aggravating and intensifying already problematic summer algal blooms, dominated by blue-green nuisance species (NC Division of Environmental Management in-house report; Kuenzler et al. 1982).

Further downstream in typical oligo- to mesohaline estuaries, strong inverse relationships commonly exist between $NO_3^-$ concentration and phytoplankton standing crops (Hobbie 1974; Paerl 1982a). Significant flagellate and dinoflagellate blooms, during which chlorophyll a content exceeds 40 ug/l, have occurred during late winter, early spring, and late summer in these regions, where $NO_3^-$ concentrations and loading are effectively "stripped" out of the water column within a relatively short segment of the estuary. It is generally agreed that such blooms are promoted by relatively long water residence times as the estuaries broaden downstream (Hobbie 1974; Paerl 1983, 1987). Increased clarity due to the settling of previously suspended riverine sediments alleviates light limitation on photosynthesis (Hobbie et al. 1972; Hobbie 1974; Paerl 1982a). These oligo- and mesohaline blooms have been observed on a regular spring-fall basis in both the Pamlico (Hobbie et al. 1972; Hobbie 1974; Stanley and Daniel 1985) and Neuse (Paerl 1982a) estuaries. Blooms act as "biological filters" by stripping ambient waters of $NO_3^-$ content. In the Pamlico and Neuse River Estuaries nitrate-laden upstream waters containing from 200-500 ug $N\text{-}NO_3^-/l$ enter the oligohaline bloom regions. Waters leaving this region commonly contain nearly undetectable concentrations (<10 ug/l of N and $NO_3^-$) of N and $NO_3^-$ (Hobbie et al. 1972; Harrison and Hobbie 1974; Paerl 1982a; Showers et al. 1990; Rudek et al. 1991). Recently, water column $NO_3^-$ concentrations have been significantly and strongly correlated with phytoplankton productivity in the mesohaline Neuse River Estuary (Mallin et al. 1991). Such findings strongly imply that availability of $NO_3^-$ is limiting the development and proliferation of algal blooms during most of the year.

In a recently completed study by Paerl and co-workers, phytoplankton primary production and its environmental regulation were examined at three stations representative of the lower Neuse River Estuary near the Pamlico Sound interface (Paerl et al. 1990, Rudek et al. 1991). *In situ* nutrient addition bioassays indicated that the estuary experienced a general state of nitrogen limitation with especially profound limitation during summer periods. Bioassays during spring months showed increased algal biomass and production stimulation with the addition of nitrogen and phosphorus over that found with nitrogen addition alone. While seasonal patterns predominated, the algal community responded during any season to increased flow and concomitant nutrient loadings by increasing biomass and production levels, often very rapidly. This was most dramatically demonstrated by a large *Heterocapsa triquetra* bloom during late winter of 1989-1990. Dissolved inorganic nitrogen levels were generally low, except during periods of high flow when heavy nutrient loading occurred. Dissolved inorganic phosphorous levels followed a seasonal pattern of high summer and fall values and low winter and spring values. The highest inorganic phosphorous concentrations were, however, measured during the winter 1989-1990 loading event (Figure III-6).

Upstream, $NH_3$ concentrations entering the bloom region are generally low (<20-30 ug $N\text{-}NH_3/l$) relative to $NO_3^-$), therefore, $NH_3$ supplied via stream inputs are not thought to be strong determinants in regulating magnitudes of phytoplankton production in these estuarine regions. On the other hand, $NH_3$ does play an important role in the maintenance of phytoplankton and bloom populations by being a chief component of "regenerated" nitrogen (i.e., nitrogen which is recycled between sediments and the water column). Regenerated nitrogen may be particularly important in maintaining net phytoplankton production during low discharge periods when $NO_3^-$ inputs from watersheds are greatly reduced and resultant nitrogen limitation is evident. Evidence for the ecological importance of nitrogen regeneration, chiefly as released and reassimilated $NH_3$, has been obtained from the Chowan (Stanley and Hobbie 1977), Pamlico (Harrison and Hobbie 1974) and Neuse (Stanley 1983) River Estuaries. Interestingly, salinity was determined to be the limiting factor to algal growth in Virginia's Back Bay (Mann Associates 1984).

In summary, loading and cycling of nitrogen, chiefly as $NO_3^-$, are strong determinants in the regulation and ultimate limitation of primary production and bloom development in all the freshwater tributaries and diverse estuaries examined to date. Accordingly, understanding nitrogen loading and flux rates, as well as the magnitude, timing, and location of inputs, is of vital importance in assessing productive and eutrophication processes in the estuarine portions of the Albemarle-Pamlico estuarine system.



ERROR BARS=POOLED SAMPLE SEM (n=3)

Fig. III-6. Top panel: 14C assimilation (CPM = counts per minute as measured on scintillation counter) of selected nutrient addition treatments minus controls, averaged over the four days of each bioassay. N(14.3) = addition of 14.3 ugN/l as $NO^{3}$-. P(3.2) = addition of 3.2 ugP/l as $PO_4^{3}$-. Error bars not visible are smaller than symbol.
Bottom panel: Nitrate ($NO^{3}$-), Ammonium ($NH_4^{+}$), and Phosphate ($PO_4^{3}$-) concentrations of surface waters at station site in the lower Neuse River Estuary. No error bars plotted. From Rudek et al. (1991).

Phosphorus loading, cycling, and utilization by phytoplankton are quite different from those of nitrogen. There is virtual agreement, based on previous studies and monitoring efforts, that the combination of both natural and anthropogenically derived sources of phosphorous loading lead to high (by both freshwater and marine standards) standing concentrations of phosphate in North Carolina coastal waters (Copeland and Hobbie 1972; Hobbie et al. 1972; Hobbie 1974; Kuenzler et al. 1979; Kuenzler et al. 1982). Whereas, inorganic nitrogen is often rapidly depleted during summer phytoplankton growth periods, phosphate concentrations act in a much more conservative fashion, indicating both excess supplies and a general lack of phosphorus limitation. Furthermore, phosphorus is effectively recycled between the sediments and the water column (Kuenzler et al. 1982), assuring the maintenance of sufficient supplies of phosphate during periods of maximum phytoplankton demand. Bioassay studies (Figure III-5) conducted by a variety of investigators on diverse riverine and estuarine habitats have come to the conclusion that, phosphate limitation is rare (Copeland and Hobbie 1972; Hobbie 1974; Paerl 1983; Paerl and Bowles 1986). The single exception may be the Chowan River during bloom periods. Phytoplankton biomass development during blooms can, at times, lead to concurrent depletion of inorganic nitrogen (as evidenced by development and dominance of nitrogen fixing blue-green algae) and phosphorus (Sauer and Kuenzler 1981; Paerl 1982a, 1982b; MacKintosh 1979). However, such phosphorus limited periods are extremely ephemeral, lasting only a few weeks during maximal bloom development.

Phosphorus discharge sources include: 1) natural erosion and dissolution of rocks, sediments, and soils in tributary basins, 2) industrial discharges, 3) sewage treatment plants, and 4) phosphate mining operations (in the Pamlico River Estuary). North Carolina's Piedmont and Coastal Plains soils are generally rich in phosphate (Hobbie 1970b) and are responsible for appreciable natural leaching of phosphate. It comes as no surprise that actively-tilled agricultural soils can contribute a majority of the phosphorus loading to the estuaries (NC Division of Environmental Management 1989b). Unlike nitrate-nitrogen loading, which is often maximized during early spring high runoff periods, phosphate loading generally proceeds more steadily, with appreciable spring loading (erosion related) as well as substantial summer loading (from the continuous discharge of sewage treatment plants). In this manner, adequate phosphorus loading is usually assured throughout the year, and so ensures that summer phytoplankton phosphorus demands will be met.

Clearly, arresting current water quality deterioration associated with eutrophication and periodic nuisance blooms in tributaries as well as more incipient symptoms of accelerated eutrophication (such as increased incidence of violations of chlorophyll a standards, periodic microflagellate and dinoflagellate blooms, ephemeral anoxia, and associated fish kills) will involve more closely monitoring, controlling nutrient inputs, and elucidating mechanisms and dynamics of nutrient-growth/bloom interactions. Those interactions in particular, must be dealt with and addressed with long-term (5-10 years) research efforts aimed at lower estuarine-open sound waters, about which so little is known.

**A. 2. f. Sediments and Their Role in Nutrient Cycling.** Bottom sediments play an important role in nutrient cycling in most estuaries. The hydrology of North Carolina's estuaries causes them to be traps for suspended sediments and nutrients, resulting in bottom deposits of sand and mud. High productivity of phytoplankton, and sometimes bordering salt marshes and macrophyte beds, generates abundant particulate organic matter which is eventually deposited on the bottom. Microbial degradation of this organic matter, especially in summer when re-aeration is slow, creates low redox potential in the sediments, a condition which affects many aspects of the cycling of nitrogen, phosphorus, sulfur, iron, and other elements. Mass balance models of phytoplankton nutrition in both the Chowan and the Pamlico Rivers indicated that nutrients delivered to these estuaries by upland runoff alone were insufficient to support the observed rates of phytoplankton primary productivity (Stanley and Hobbie 1977; Kuenzler et al. 1979). This initiated investigations of the importance of the sediments as internal sources of nutrients for estuarine phytoplankton production (Matson et al 1983, Kuenzler, et al. 1984, and Albert 1985).

A number of the biogeochemically important elements in estuaries are delivered to the bottom in particulate form and returned to the water in soluble form. In Back Bay, Virginia, the concentration of suspended solids has been correlated nearly directly with total phosphorous, indicating the direct relation between erosion and water quality (Mann Associates 1984). The basic aspects of nitrogen and phosphorus cycling are known well enough to make the following generalizations regarding sediment cycling and regeneration of carbon, nitrogen and phosphorus (Figure III-7):

1. Large amounts of particulate organic carbon, nitrogen, and phosphorus derived from phytoplankton and allochthonous organic matter sink through the water column and are deposited on the bottom. The quantity of organic matter is, however, relatively small compared to the amount of inorganic sediments deposited annually.

2. Microbial metabolism of the organic matter consumes oxygen--if re-aeration and/or vertical mixing are poor, the sediments may become anoxic. Under anoxic conditions, metabolic byproducts such as carbon dioxide, ammonium, and phosphate diffuse upward and into the water (Figures III-8 and III-9). The concentration gradients in the sediments drive the diffusive flux (Figure III-10). The bottom then constitutes a source of these chemical forms to the overlying water. Reduced sediments are a sink for oxygen and, during periods of thermal or salinity stratification of the water, hypoxic or anoxic bottom waters become rich in phosphate and ammonium (Figure III-11).

3. When stratification is weak, the bottom water maintains sufficient oxygen for an oxidized zone to exist at the sediment surface. Microbes at the sediment surface oxidize ammonium to nitrate (Table III-2), which then diffuses upward into the water or downward where it is denitrified to $N_2$ gas which is then transported to the atmosphere. Under oxic conditions, phosphate tends to be precipitated or sorbed with ferric iron and is thus immobilized in the sediments until anoxic conditions return.

4. In a study of the Pamlico River, it was discovered that although the rates of nutrient regeneration in bottom sediments were high, the total quantities of inorganic nitrogen and phosphorus returned to the overlying water were less than 25% of the annual needs for Pamlico River estuary phytoplankton production (Table III-3). Thus, it was concluded that water column regeneration, sediment regeneration and external sources (e.g., watershed runoff, precipitation, wastewaters and seawater advection) (Table III-4) are all important sources of phytoplankton nutrients in the Pamlico River estuary (Kuenzler et al. 1984).

<u>A. 2. g. Availability of Information.</u> There have been at least five investigations of bottom sediment characteristics, elemental cycling, and exchanges of materials between sediments and overlying waters in three North Carolina estuaries in this decade (Table III-5). A considerable body of knowledge of sediment characteristics and elemental cycling has been acquired. Research questions, experimental design, and methods of sampling and analysis differed among the studies. For example, Matson et al. (1983) calculated nutrient exchanges from concentration profiles in the sediment; whereas Kuenzler et al. (1984) measured changes in concentrations in benthic chambers. Albert (1985) measured primarily concentration profiles and chemical transformations within sediment cores.

Soil erosion, on its own, can also cause significant water quality degradation by increasing the turbidity of the receiving waters, clogging the gills of fish and larvae, and decreasing the potential for photosynthesis. In Back Bay, Virginia, soil erosion has been cited as a major source of nonpoint source pollution. Twelve thousand tons are estimated to enter the estuarine system every year.

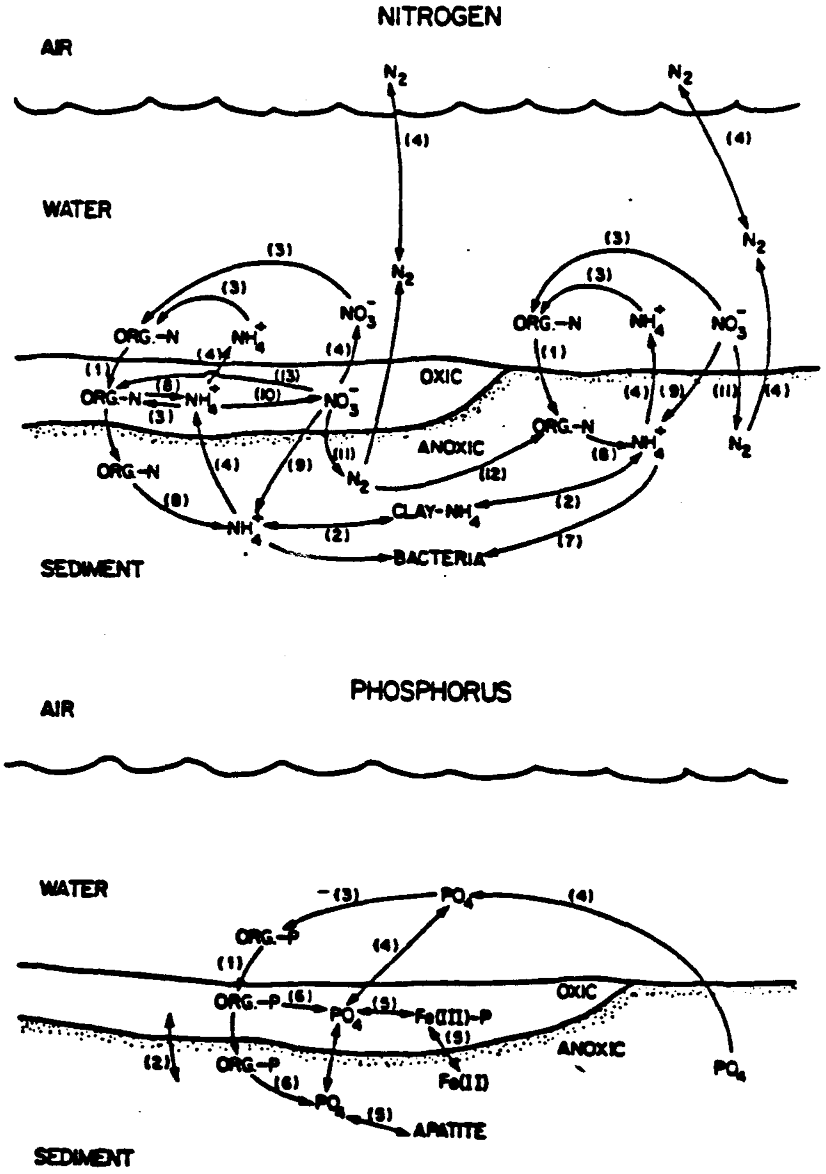


Fig. III-7. Major Pathways of Phosphorus and Nitrogen Cycling in Estuaries. 1) Sedimentation, 2) Sorption, 3) Assimilation, 4) Diffusion, 5) Precipitation-Dissolution, 6) Heterotrophic Regeneration, 7) Immobilization, 8) Ammonification, 9) Dissimilatory Nitrate Reduction, 10) Nitrification, 11) Denitrification, 12) Nitrogen Fixation, and 13) Assimilatory Nitrate Reduction. From Kuenzler et al. (1984).

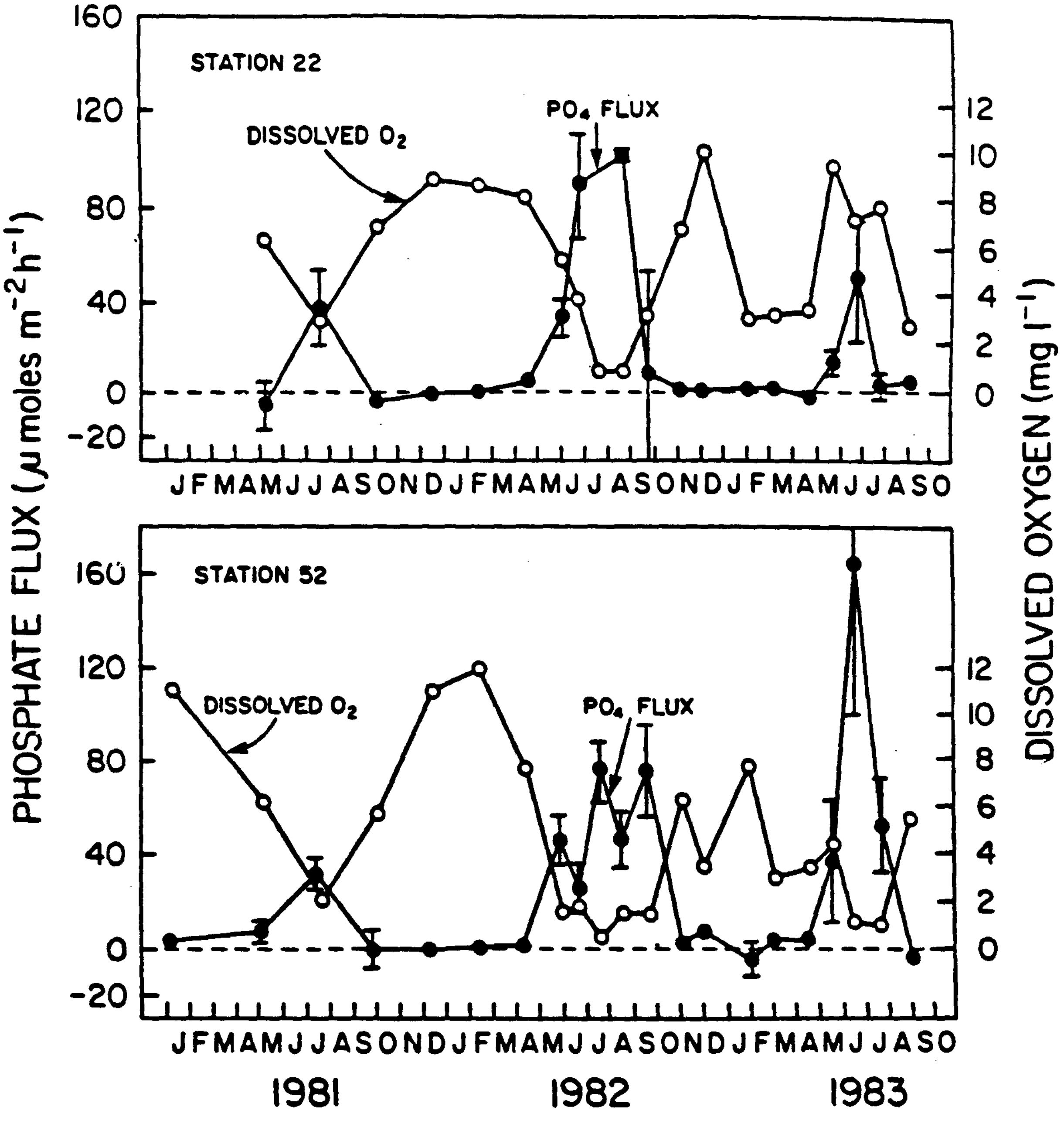


Fig. III-8. Seasonal Pattern of Bottom Water Dissolved Oxygen and Sediment Phosphate Flux in the Pamlico River Estuary. From Kuenzler et al. (1984).

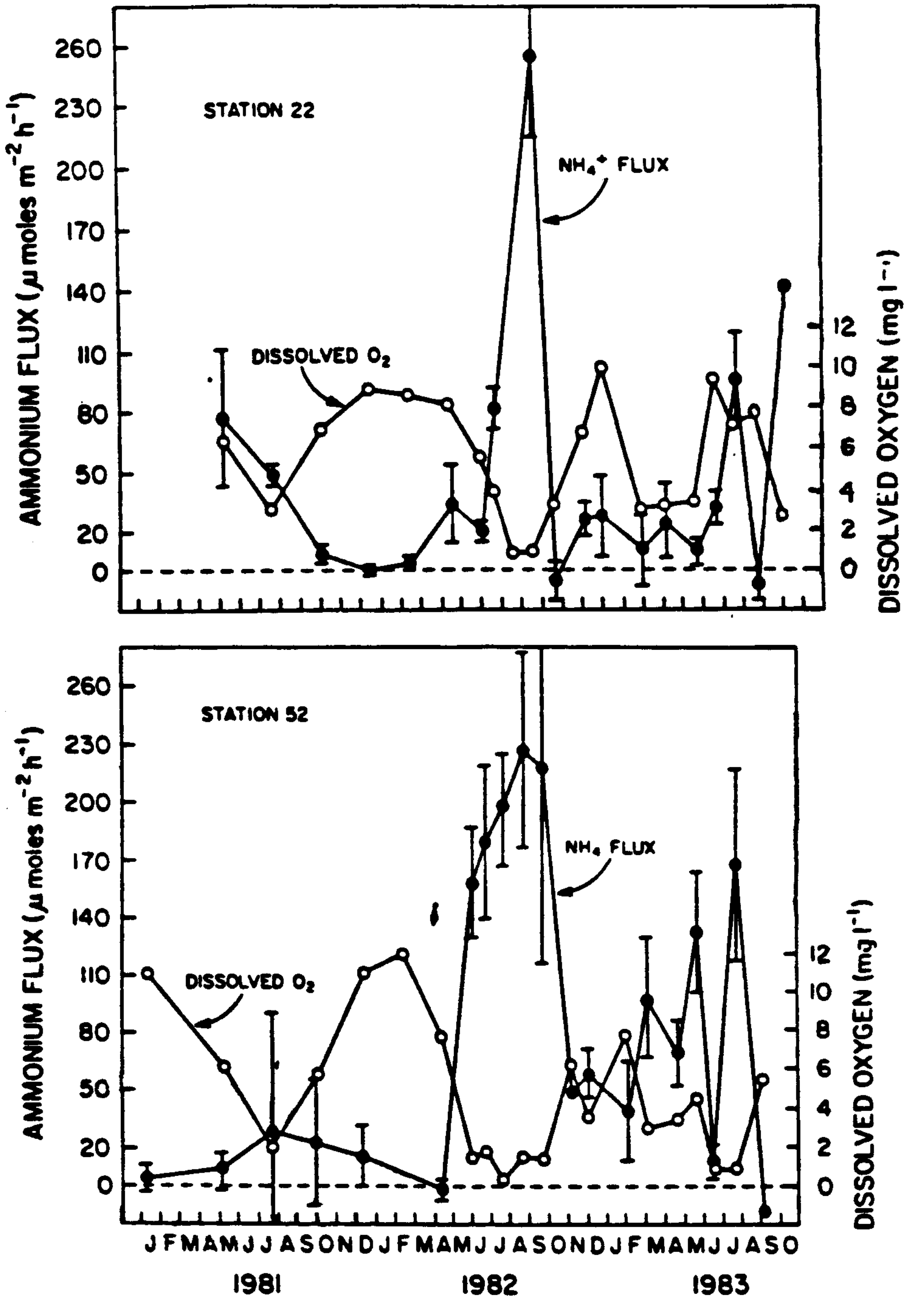


Fig. III-9. Seasonal Pattern of Dissolved Oxygen Concentration and Sediment Ammonium Flux in the Pamlico River. From Kuenzler et al. (1984).

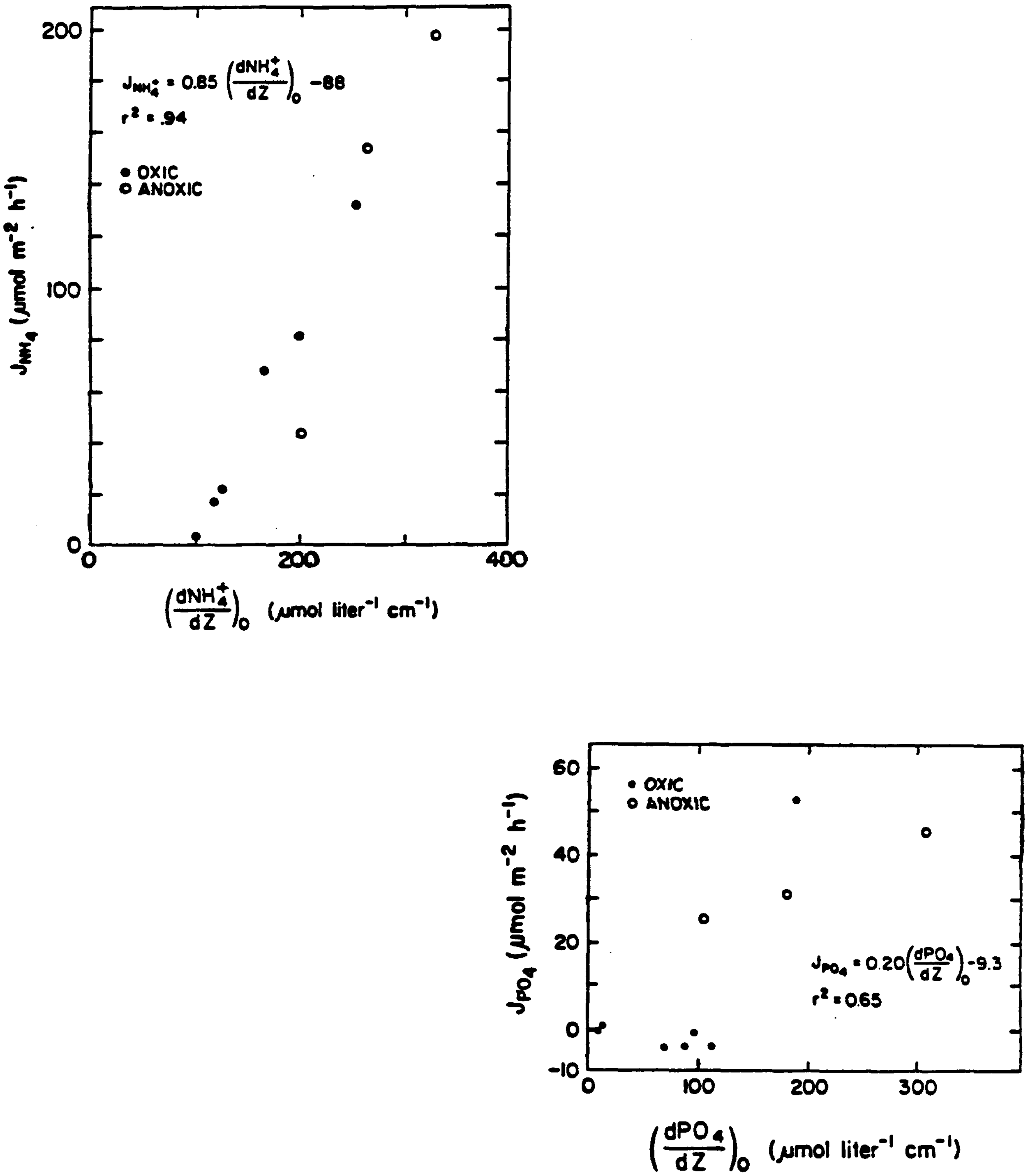


Fig. III-10. Ammonium and Phosphate Flux in Relation to the Pore-Water Concentration Gradient at the Sediment Interface in the Pamlico River. From Kuenzler et al. (1984).

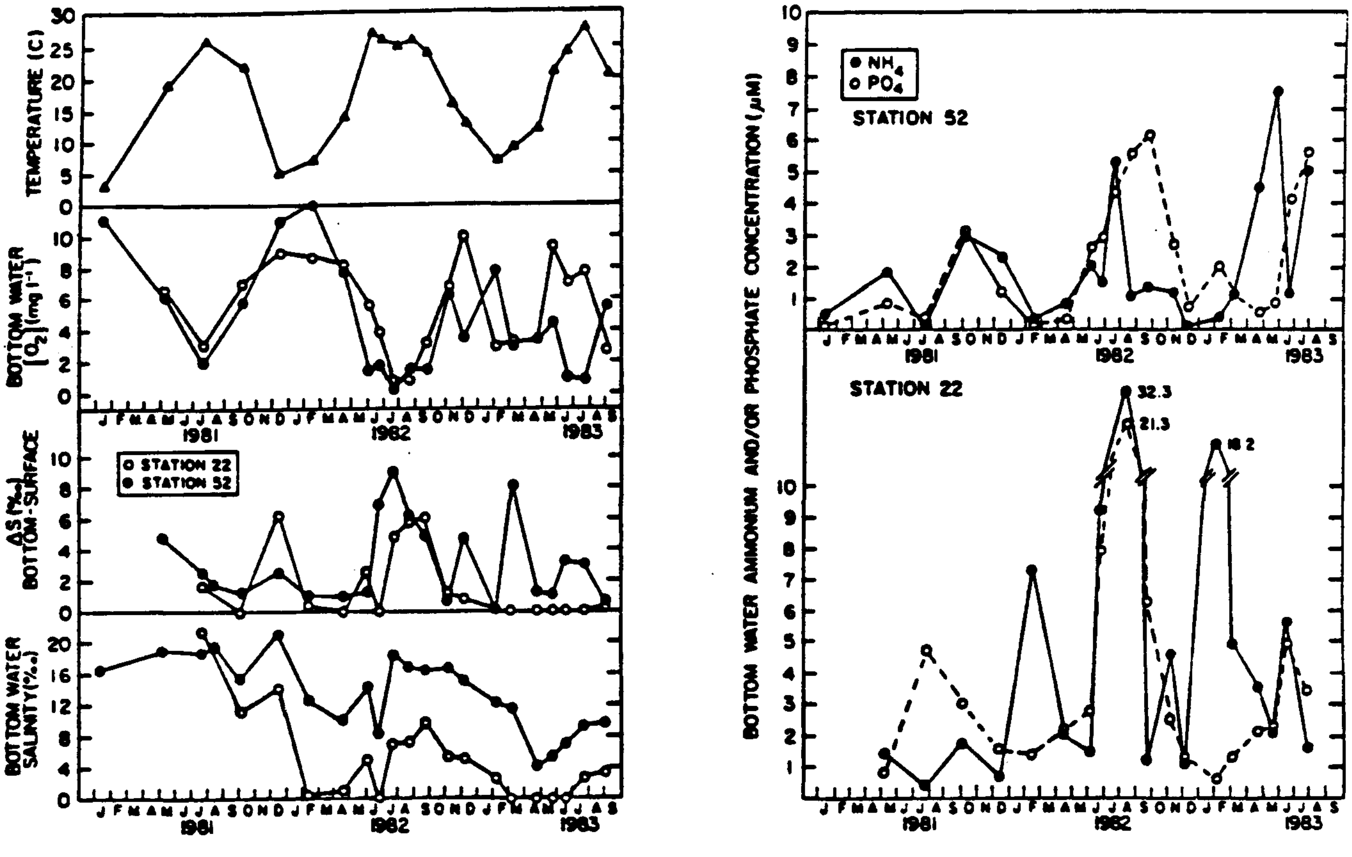


Fig. III-11. Annual Patterns of Bottom Water Temperature, Dissolved Oxygen, Salinity, Salinity Difference between Surface and Bottom, Ammonium, and Phosphate in the Pamlico River. From Kuenzler et al. (1984).

Table III-2. Nitrification potential rate (x + sd) at four depths in the sediment during 1982-83 in the Pamlico River estuary (rates in nmoles $NH_4^+$ oxidized $cm^{-3}d^{-1}$; integrated rates in nmoles $cm^{-2}d^{-1}$). From Kuenzler et al. (1984).

| Depth | Aug | Sept | Nov | Dec | Feb |
|---|---|---|---|---|---|
| 0-1 cm | 20 | 7 + 3 | 15 + 4 | 41 + 42 | 12 + 9 |
| 1-2 cm | 36 | 11 + 4 | 14 + 3 | 50 + .5 | 21 + 3 |
| 2-4 cm | 0 | 12 + 13 | 12 + 9 | 20 + 2 | 6 + 2 |
| 4-6 cm | 0 | 0 | 2 + 1 | 7 + 2 | 3 + 1 |
| Integrated Rate | 56 | 42 | 57 | 145 | 51 |

| Depth | Mar | Apr | May | June | July |
|---|---|---|---|---|---|
| 0-1 cm | 4 + 2 | 1 + 2 | 4 +.04 | 28 + 11 | 33 + 17 |
| 1-2 cm | 10 + 6 | 2 + 2 | 0 | 1 + 1 | 0 |
| 2-4 cm | 6 + 9 | 3 + 4 | 3 + 5 | 2 + 2 | 14 + 14 |
| 4-6 cm | 6 + 5 | 0 | 3 + 4 | 1 + 2 | 5 + 1 |
| Integrated Rate | 38 | 9 | 16 | 35 | 71 |

Table III-3. Phosphate, dissolved inorganic nitrogen (DIN), and oxygen fluxes (umole $m^{-2}h^{-1}$) from sediments in the Pamlico River estuary compared to phosphate, DIN and carbon uptake by phytoplankton. From Kuenzler et al. (1984).

| Element | Algal Uptake | Flux | Flux as % of uptake | C Based** |
|---|---|---|---|---|
| Annual Average Rates | | | | |
| Phosphate | 225 | 19.1 | 8.5 | 43 |
| DIN | 807 | 51.4 | 6.4 | 7.2 |
| Oxygen | - | 275 | 5.8* | - |
| Carbon | 4760 | - | - | - |
| Summer Average Rates | | | | |
| Phosphate | 142-175 | 30-42 | 21-24 | 31 |
| DIN | 795-1240 | 66-90 | 8.3-8.6 | 6.0-7.4 |
| Oxygen | - | 150-422 | 1.8-5.8* | - |
| Carbon | 7240-8110 | | | - |

* Percent of carbon fixed that could be respired to $CO_2$ by the observed oxygen uptake of the sediments.

** Based on Redfield stoichiometry to predict net nitrogen and phosphorus uptake relative to carbon uptake.

Table III-4. Nitrogen and phosphorus loading (MT/yr) of the Pamlico River estuary (1976-77) compared to phytoplankton needs. From Kuenzler et al. (1979).

| | Sources | | | | Algal |
|---|---|---|---|---|---|
| Chemical Form | Watershed | Precip | TGI | Pamlico So. | Ann.Needs |
| Nitrogen | | | | | |
| Ammonium | 206 | 67 | | 505 | 22,900 |
| $NO^{-3}$ + $NO^{-2}$ | 316 | 76 | | 325 | 4,230 |
| Dis. Org. N | 1,860 | 85 | | 5,580 | |
| Part. N | 1,430 | | | 1,860 | |
| Total N | 3,812 | 228 | | 8,270 | 27,100 |
| Phosphorus | | | | | |
| Filt. Reac. P | 84 | 13 | 843 | 184 | |
| Filt. NonR. P | 57 | 4 | | 103 | |
| Part. P | 190 | | | 190 | |
| Total P | 331 | 17 | 843 | 477 | 10,640 |

Table III-5. Recent Studies of Bottom Sediment Characteristics, Benthic Nutrient Cycling and Relationships to Overlying Water in North Carolina Estuaries

| Estuary | Sediment Characteristics | | | | References |
|---|---|---|---|---|---|
| | Measurements* | Stations | Samples | Elements | |
| Chowan | A to G | 115 | 143 | N,P,$O_2$ | Kuenzler et al. 1982 |
| Pamlico | B to F, H to I | 6 | 62 | N,P,C,S,Cl,Si | Matson et al. 1983 |
| Neuse | B to F, H to I | 6 | 63 | N,P,C,S,Cl,Si | Matson et al. 1983 |
| Pamlico | G, J to M | 2 | 22 | N,P,C,$O_2$ | Kuenzler et al. 1984 |
| Pamlico | A to C, N to Q | 2 | >20 | S,Fe | Albert 1985 |

* A = Organic C; B = TKN; C = TP; D = Sand; E = Silt; F = Clay; G = Bulk Density; H = Exchangeable $NH_4$; I = Extractable P; J = Percent Water; K = LOI; L = $NO_3$; M = $NH_4$; N = Extractable Fe; O = Total Fe; P = Acid-vol. S; Q = Pyrite S.

### A. 3. Metals and Toxicants in the Water Column and in the Sediments

A. 3. a. Introduction. Heavy metals and other elements are normal constituents of most estuarine ecosystems. Natural concentrations, however, are being supplemented and the normal ratios among them are being altered by the activities of man. The dual role of many trace elements in biological systems (i.e., some act as required nutrients and all, at some level, are potentially toxic) is well documented (Crounse et al. 1983a, 1983b).

Many factors affect the availability, transport, and concentration of metals and toxins into and through the coastal system. Accessibility of an element in the abiotic environment for incorporation into the biosphere is referred to as "bioavailability". The bioavailability of any given element depends on a host of factors, sometimes too numerous and complex to test and/or model. Principal among these factors are (1) the feeding habits, stage of life cycle, and age and condition of organisms involved; (2) the chemical form and manner in which a particular element is incorporated into the sediments; and (3) the physical and chemical conditions of the environment.

The transient nature of estuarine water column characteristics and the dilution of point source discharges often maintain trace metal concentrations in water below toxic or even detectable limits. The sedimentary regime, on the other hand, is much less transient and metals can become incorporated into sediments by several different mechanisms and partitioned among a variety of sedimentary phases. Consequently, concentrations in sediments are often several orders of magnitude greater than those in the overlying waters (Wolfe and Rice 1972). It has been well established that fine-grained sediments are the primary reservoir for heavy metals in estuarine systems (Renfro 1973). As a result, sediments are often envisioned as the ultimate sink for much of the soluble and most of the particulate matter entering the estuary.

The Albemarle-Pamlico estuarine system acts as a large settling basin for sediments, organic matter, heavy metals and organic toxins derived from agriculture, urbanization and industrialization within the drainage basin (Copeland et al. 1983, 1984). In addition to the normal runoff and stream drainage mechanisms for transporting materials to the estuary, there are several historic waste disposal sites around the estuary. These virtually unknown and often poorly sited facilities contribute unknown amounts of toxic and hazardous materials into the groundwater and into nearby marshes and lowlands. Since many of these facilities predate the time of environmental awareness, their potential effects on the estuarine system could be significant (Riggs et al. 1989).

A. 3. b. Availability of Information. The first detailed study of the metals and toxins in the Albemarle-Pamlico estuary is currently underway. The US Fish and Wildlife Service has sampled a large number of estuarine animals for the presence of toxins and is currently evaluating results. The first phases of the study, an analysis of heavy metal pollutants in organic-rich muds of the Pamlico and Neuse River estuarine systems, have been completed (Riggs et al. 1989, in press). Analysis and mapping have been completed for eight of the EPA "priority pollutant metals" (Arsenic, Cadmium, Chromium, Copper, Lead, Mercury, Nickel, and Zinc) plus fluoride and phosphorus in the sediments. Permitted point discharges and nonpoint sources were identified as contributors of significant concentrations of metals to the estuary. A similar evaluation of the Albemarle Sound is currently underway.

Dioxin has been found in the tissue of fish taken from the Roanoke. Health advisories have been posted to warn against eating fish taken from the area. Moreover, accumulations of heavy metals have been found in the sediments of Albemarle Sound (Bales 1991).

S. Riggs et al. (1989, in press) conducted studies to determine the concentrations of heavy metals in the organic rich sediments of the Pamlico and Neuse Rivers. Anthropogenic sources are believed to be largely responsible for heavy metal enrichment within the Neuse River estuarine system. In the Neuse River study 203 stations were cored and the cores analyzed to determine the vertical and lateral distribution of 15 critical trace elements (CTEs). Riggs et al. compared the trimmed mean of all surface samples with the individual samples from locations affected by or in close proximity to known point source dischargers. Sediments in the vicinity of known point source discharges were significantly enriched in specific metals compared to sediments in other portions of the Neuse River. Surface sediments have been enriched up to and occasionally in excess of 100 times the elemental concentrations occurring in sediments deeper in the cores, inferred to represent pre-man conditions. Riggs et al. identified 17 areas of "enrichment", areas in which one or more CTEs exceeded the control levels by a factor of two or more. In six of these areas, three or more of the CTEs were found to be enriched; in eleven of these areas, only one or two CTEs were found to be enriched.

The results of the similar Pamlico River study (Riggs et al., 1989) determined that heavy metal enrichment was generally less severe; the trimmed means of 10 CTEs were lower in the Pamlico River than in the trimmed mean of the same CTEs in the Neuse River estuarine system. Only arsenic, cobalt, and titanium exceeded the levels found in the Neuse. Individual waste water treatment plants, marinas, industrial plating facilities, and military facilities were identified as probable sources of CTE enrichment (Riggs, in Press).

Low concentrations of toxic heavy metals in discharge waters or in estuarine water columns are not indications that the estuaries are free from metal contamination. Due to rapid changes in estuarine water chemistry, high absorption characteristics of omnipresent inorganic clay mineral on the chemical process associated with metal complexing and organic matter, many trace metals are often enriched in the sediments at levels that are orders of magnitude above acceptable water level concentrations. Enrichment of trace metals continues as storms, biological processes, and man routinely resuspend the mud sediments into the water column. Consequently, the cumulative effect of large discharge volumes with low concentrations can result in significant enrichment of the sediments (Riggs, in press).

## A. 4. Point Sources and Nonpoint Sources

__A. 4. a. Introduction.__ Sources of pollution are generally grouped into two categories: point sources and nonpoint sources. Point sources of pollution enter a stream at a discrete location, usually a discharge pipe, and include municipal and private wastewater treatment facilities. These facilities must obtain a permit from the North Carolina Division of Environmental Management (or the Virginia Water Control Board) which limits the amount of pollution that may be discharged to a given stream. In contrast to point source pollution, nonpoint source pollution is that which enters waters mainly as a result of precipitation and subsequent runoff from land•primarily from what has been disturbed by man's activities. Examples include runoff from urban areas, septic tanks, agricultural lands, and construction sites. Nonpoint source pollution is addressed through a combination of regulatory, cost incentive, and voluntary programs.

North Carolina adopted its first comprehensive, modern water pollution control law in 1951. The essentials of the 1951 law (originally entitled State Stream Sanitation Act and renamed in 1967 the Water and Air Resources Act) remain in effect as an important part of the legal basis for North Carolina's water pollution control program. The Water and Air Resources Act provided for a program of pollution abatement and control based principally on classifications and water quality standards applied to the surface waters of the State.

Two principles are involved in defining the quality to be maintained in a water body: (1) the desired use of a body of water, called its "classification" and (2) the levels of contaminants that can be tolerated without impairing the desired use, called its "standards". Twenty-five years ago, the Albemarle-Pamlico study area had some streams that were classified "E", which designated the best use as agricultural and industrial processing and for transporting wastewaters. The corresponding standards were only stringent enough to protect against human health hazards. Still other streams were classified "D", which had standards sufficient to allow fish to survive but not to allow fish to propagate. Today, all waters are classified "C" or better, indicating water quality that permits the propagation of fish.

The major river basins of the Albemarle-Pamlico area were systematically classified in response to the 1951 law. Each basin was surveyed by the State Stream Sanitation Committee, with the results and classification recommendations summarized in what were termed Pollution Survey Reports. These reports included information on the point sources in each basin, and were published in the following order:

| | |
|---|---|
| Chowan River Basin | 1955 |
| Roanoke River Basin | 1956 |
| Neuse River Basin | 1959 |
| Pasquotank River Basin | 1960 |
| Tar-Pamlico River Basin | 1961 |

The original classifications resulting from these surveys have been modified in response to stricter federal requirements, improved wastewater treatment and new state initiatives. The standards have also been significantly expanded in response to increased research on the effects of pollutants on aquatic life and human health.

**A. 4. b. Point Sources.** The current program for control of wastewater discharges to streams is based primarily on the Federal Water Pollution Control Act of 1972. Allowable discharge must meet the more stringent of two separate requirements:

1. Maintenance of the receiving water's quality as specified in State water quality standards, ideally a quality suitable for "the protection and propagation of fish, shellfish and wildlife" and for "recreation in and on the water".

2. Minimum treatment requirements which are imposed uniformly nationwide and are based on the type, age, and size of the discharging facility.

These requirements are enforced through a permit program called the National Pollutant Discharge Elimination System (NPDES). The US Environmental Protection Agency (EPA) manages the NPDES program, although it may delegate program administration to qualified State agencies. In 1975 North Carolina received a delegation from EPA which allows the Division of Environmental Management to administer the NPDES program.

The major pollutants discharged from point sources include those wastes that deplete the dissolved oxygen in the water as they decompose, cause disease in man, stimulate undesirable growths of plants or algae in the water, and are toxic to fish, wildlife or humans. The efforts of the 1950s and 1960s focused primarily on the first two types of pollutants; organic matter which depleted the dissolved oxygen in the water and pathogenic bacteria.

The decomposition of organic substances in wastewater by aquatic organisms consumes dissolved oxygen. Significant reductions in the amount of dissolved oxygen can hinder fish propagation and, in more severe cases, can result in fish kills and odor problems. Wastewater facilities are generally classified according to the percentage of carbonaceous organic matter that is removed during treatment, which can be roughly summarized as follows:

| Type | Percent Removed |
|---|---|
| No treatment | 0 |
| Primary | 40 |
| Secondary | 85 |
| Tertiary | 90 |
| Advanced | 95 |

In 1960, there were about 200 point sources in the North Carolina portion of the Albemarle-Pamlico area with a combined flow of 115 million gallons per day (mgd). Roughly one half of these facilities provided no treatment, a little over one third provided only primary treatment, and roughly 10% provided secondary treatment. The combined organic waste reduction was only about 13%. Today there are about 400 facilities with a combined flow of about 250 mgd. All facilities must provide at least secondary treatment and many are required to provide tertiary or advanced levels of treatment.

A variety of pathogenic bacteria exist in raw domestic wastewater. Waterborne diseases (such as typhoid fever, hepatitis, dysentery and cholera) are caused by bacteria in drinking water supplies that are contaminated by inadequately treated wastewater. Some bacterial maladies result from body contact in contaminated recreational waters. Waterborne diseases can also be spread when shellfish ingest pathogens that are then passed on to humans. Because so much untreated wastewater was being discharged in 1960, the Pollution Survey Reports recommended that numerous areas be closed to the taking of shellfish and cited unsafe conditions in several recreational areas such as Pantego Creek, Silver Lake, Pamlico River near Washington, Shallowbag Bay, sections of the Perquimans and Pasquotank Rivers, the Neuse River near New Bern, and the Colerain and Tuscorora Beaches. Disinfection is now required of all wastewater discharges with domestic components. While some areas in the vicinity of dischargers are closed to shellfishing as a safety precaution against accidents, no new domestic discharges are allowed in shellfishing waters. The emerging problems with new shellfish closures are generally related to nonpoint source inputs such as septic tanks, urban runoff, or agricultural operations.

Eutrophication has become a serious problem in several of the estuaries of the Albemarle-Pamlico area. The Chowan River was the first to experience massive algal blooms in the early 1970s, although less spectacular algal problems had been documented on the Tar-Pamlico system even earlier. The lower Neuse River began experiencing problems in the late 1970s. Point sources contribute about 15% of the North Carolina nutrient input to the Chowan, about 50% to the Neuse, and about 18% nitrogen and 75% phosphorus to the Tar-Pamlico. Strategies to reduce nutrients to the Tar-Pamlico, Chowan, and Neuse rivers have been adopted. Industrial point sources are also very important. For example, Texasgulf Inc. (TGI) is a major discharger of phosphate in the middle reaches of the Pamlico River estuary (Table III-4). Union Camp pulp mill in Virginia releases very large volumes of water to the Chowan River during winter, increasing the conductivity, color, turbidity, ammonium concentration, and phosphate concentration of the waters below their outfall (Kuenzler et al. 1982). Nine of the ten municipalities in the Chowan basin have gone to land disposal, eliminating their nutrient inputs. All dischargers over 0.5 mgd in the Neuse must reduce their phosphorus input by 1992.

"Toxic substances" include a variety of materials such as heavy metals (e.g., mercury, zinc, cadmium, lead, chromium, nickel and copper), pesticides (e.g., DDT, parathion, toxaphene, endrin, malathion and others), and many organic chemicals (e.g., polychlorinated biphenyls (PCB) and phthalate esters). Unlike oxygen-demanding wastes which degrade over time, toxic substances are often environmentally persistent and are classified as conservative pollutants. Toxicants are addressed in a comprehensive manner through the use of whole effluent toxicity testing. These tests employ sensitive aquatic species to determine if a wastewater discharge would be toxic to the receiving stream. There are currently 80 dischargers in the Albemarle-Pamlico estuarine area which are required to monitor their wastewater for toxicity. Of these facilities, 36 have permit limits for toxicity. The remaining 44 have permits, but no associated limits.

<u>A. 4. c. Nonpoint Sources.</u> Nonpoint source pollution (NPS) means pollution which enters waters mainly as a result of precipitation and subsequent runoff from lands that have been disturbed by man's activities. Obviously, there is the potential for wide variations in pollutant loadings with runoff from different types of land use under a variety of management regimes. This diversity and corresponding complexity, which arises in studying NPS pollution, makes it very difficult to accurately determine the magnitude of pollutants originating from diffuse sources. However, using a large watershed or river basin approach, pollution loading and land-use categories can be correlated in relatively quick and simple, first-cut NPS investigations (Novotny and Chesters 1981). After a preliminary land-use analysis is conducted for a watershed, more complicated efforts can be undertaken to further differentiate the diffuse sources of pollution.

<u>A. 4. d. Availability of Information.</u> In 1988, the Division of Environmental Management (North Carolina Department of Natural Resources and Community Development) conducted a water quality assessment of the Albemarle-Pamlico study area as part of the statewide Nonpoint Source (NPS) Assessment Report in order to determine impacts from nonpoint sources of pollution (NC Division of Environmental Management 1989a, 1989b). The assessment concentrated on waterbodies which fail to or only partially support their designated uses because of NPS pollution. Following is a description of methods employed to identify NPS pollution problems in the Albemarle-Pamlico estuarine study area.

Two types of information were utilized in the NPS Assessment Report in order to obtain an overall water quality rating which could be assigned to streams and stream segments. The first level is "monitored" waters and is based on current site-specific ambient data. The second level is "evaluated" waters and is based on information other than site-specific data, such as citizen complaints or best professional judgements. By using "evaluated" segments, a much broader, but less precise, picture of nonpoint source pollution can be developed.

The most recent source of "monitored" data used in the NPS Assessment Report was the 1986-87 305b Report (NC Division of Environmental Management 1989a, 1989b). In preparing the 305b Report, all available chemical and biological data from North Carolina's ambient biological and chemical monitoring network in the area were reviewed. Biological data collected during special benthic macroinvertebrate surveys were also utilized.

Another source of information which was used as a reference for the NPS Assessment Report was the Water Quality Assessment Document, which summarizes biological and chemical data (NC Division of Environmental Management 1985). Analyses for this document were based on benthic macroinvertebrate data from many point and nonpoint source studies, one-time surveys on benthic macroinvertebrates, recent research reports, fish collection records, wildlife resources survey and classification reports, and questionnaire results from fisheries biologists in various state agencies. Some references in the 1985 assessment report date back to the 1960s.

To determine overall water quality ratings, older chemical information from 1978 to 1985 was also used when appropriate. Additional chemical water quality data available from the U.S. Geological Survey (USGS) and other sources were gathered and added in order to obtain as much information about use-support as possible. In addition, workshops were held for federal, state, municipal, and county representatives and the general public. One goal of the workshops was to gather either data or educated judgments (evaluations) for streams, lakes and estuaries not rated at that time. Information was also obtained regarding point and nonpoint sources and causes of the partially supporting and non-supporting ratings (e.g., sediment or dissolved oxygen). All data, evaluations, and source information were added to the water quality monitoring data and overall water quality ratings were assigned to streams and stream segments.

Information was used to determine ratings in the order described below.

1. Biological Ratings generally were preferred over any other source of information since this is a direct measurement of long-term effects of water quality on aquatic life. Chemical data, however, were used to determine ratings for water supply segments.

2. Chemical Ratings were given second preference.

3. Workshop "Evaluations" or Best Professional Judgement were given third preference.

4. Assessment Document information was used when no other more recent information was available.

After overall ratings were assigned, sources of pollution (point or nonpoint) for partially supporting and non-supporting streams were sought (Tables III-6, III-8), as were the actual pollutants or causes of degradation (e.g., sediment, toxicants; Table III-7). The NC Division of Environmental Management Regional offices or workshops provided much of the information used for the monitored segments. Information on point sources, such as permit compliance records, was reviewed in order to find major dischargers potentially impacting streams. The Biological Assessment Group and the Aquatic Toxicology Unit of the Environmental Sciences Branch were consulted to identify facilities known to have toxic effects based on chronic and acute bioassays. Groundwater and precipitation were also considered as sources of nutrients and other substances.

The Shellfish Sanitation Branch within the North Carolina Department of Health and Human Resources is responsible for determining the status of shellfishing waters and keeps a historical record of the opening and closing of waters to the collection of shellfish. This is extremely valuable use-support information. With respect to this information, partially supporting waters are those that are permanently closed to shellfishing while support-threatened waters are those that are temporarily opened. Waters closed to shellfishing are considered partially supporting because they still support recreational and other aquatic life uses. Non-supporting areas are those with excessive algal blooms as noted by NC Division of Environmental Management regional offices and documented through special studies.

The NC Division of Environmental Management maintains chemical ambient monitoring stations in estuarine waters. Data from these stations were treated and rated in the same manner as the 1986-1987 chemical data for rivers and streams. It should be noted, however, that for saltwater, violations of metal standards were not used to determine use-support ratings since chemical analyses for metals are extremely sensitive to salinity levels.

Only rarely did shellfishing and chemical data conflict for a saltwater segment in determining overall ratings for estuarine areas. These ratings were reviewed by the NC Division of Environmental Management Water Quality regional staff, the NC Division of Shellfish Sanitation (Morehead City, NC), and during the workshops. Ratings were then modified accordingly. Evaluated areas (areas lacking data) were assigned the same use-support rating as the closest monitored areas within about 15 miles. Only the middle and northern Currituck Sound and the central portion of the New River were "evaluated"; the remaining estuarine areas were "monitored". Distribution of nonpoint source impacts on the estuary are given in Table III-1.

Workshops provided information on sources and causes of pollution for degraded areas. Other data or information used to determine sources and causes for degradation were the NC Division of Shellfish Sanitation Surveys, regional office special studies and data, and special water quality reports and studies. Sources of pollution that were suggested in the NC Division of Shellfish Sanitation Surveys or in other sources were evenly weighted to determine acres degraded. The actual pollutants or causes of degradation were either listed as the most important cause (often using best professional judgement)

Table III-6. Water Quality Ratings in the Streams of the Albemarle-Pamlico Estuarine Area. From the NC Division of Environmental Management (1989b).

| Water Quality Rating | Cumulative Length of Streams | Percentage of Total Stream Length |
|---|---|---|
| Support | 4,427.1 | 48.7 |
| Partial and Nonsupport | 3,613.1 | 39.7 |
| Not Evaluated | 1,054.5 | 11.6 |
| Total | 9,094.7 | 100.0 |

Table III-7. Major Causes of Degradation in the Streams of the Albemarle-Pamlico Estuarine Area. From the NC Division of Environmental Management (1989b).

| Causes of Degradation | Extent of Degradation (mi) | Percentage of Degraded Miles |
|---|---|---|
| Sediment | 1,762.6 | 48.7 |
| Fecal Coliform | 36.1 | 1.0 |
| Dissolved Oxygen | 41.8 | 1.2 |
| Metals | 124.0 | 3.4 |
| pH 0.0 | 0.0 | |
| Ammonia | 0.0 | 0.0 |
| Chlorophyll a | 0.0 | 0.0 |
| Phosphorus | 0.0 | 0.0 |
| Multiple | 501.9 | 13.9 |
| Unknown | 1,155.7 | 31.9 |

Table III-8. Sources of Nonpoint Pollution Impacts in the Streams of the Albemarle-Pamlico Estuarine Area. From the NC Division of Environmental Management (1989b).

| Sources of Degradation* | Mileage+ | Percent of Total Degraded Stream Mi.** |
|---|---|---|
| Nonpoint Sources (total) | 3,489.1 | 96.6 |
| Point Sources (total) | 441.6 | 12.2 |
| Agriculture (total) | 2,415.6 | 66.9 |
| Runoff | 510.7 | 14.1 |
| Animal Waste | 480.6 | 13.3 |
| Miscellaneous | 240.0 | 6.6 |
| Forestry (total) | 93.2 | 2.6 |
| Harvest | 94.5 | 2.6 |
| Forest Management | 5.3 | 0.1 |
| Construction (total) | 284.0 | 7.9 |
| Highways and Bridges | 0.0 | 0.0 |
| Land Development | 71.6 | 2.0 |
| Urban (total) | 376.8 | 10.4 |
| Sewers | 61.4 | 1.7 |
| Runoff | 104.4 | 2.9 |
| Miscellaneous | 17.4 | 0.5 |
| Mining (total) | 0.0 | 0.0 |
| Land Disposal (total) | 144.6 | 4.0 |
| Landfills | 63.6 | 1.8 |
| Septic Tanks | 89.5 | 2.5 |
| Miscellaneous | 39.8 | 1.1 |
| Hydromodification (total) | 227.9 | 6.3 |
| Channelization | 4.0 | 0.1 |
| Miscellaneous | 27.0 | 0.7 |
| Unknown | 591.8 | 16.4 |

* Partially and Non-supporting Streams Only. From EPA Source Codes.

\+ Point source and nonpoint source impacted stream mileages were compiled from independent workshops and field research projects, so sub-totals may not correlate perfectly.

** Some double-counting of sources of degradation occurred, so percentages may not correlate perfectly.

or listed as one of multiple causes. In addition to the nonpoint source pollutants considered in freshwater streams, freshwater inflows to estuarine waters were considered as a nonpoint source pollutant. It should be noted that use classifications were based on "actual" use criteria, rather than "desired" use criteria, and that "supporting use" merely means that a body of water or stream has not been degraded enough to violate the actual use criteria.

## B. STATUS OF MANAGEMENT ACTIVITIES

### B. 1. Introduction

Several attempts have been made to limit nutrient inputs into the estuaries as a means of controlling eutrophication. This technique, however, is replete with problems. For phosphorus to be growth-limiting for phytoplankton of the Neuse River, for example, it has been estimated that input reductions of up to 60-80% of current levels would have to be achieved (Paerl and Bowles 1986; Paerl 1987). This is a formidable, if not impossible, task since perhaps 30-40% of the Neuse's phosphorus inputs can be considered as having natural, non-anthropogenic origins. The Neuse River system represents a somewhat extreme case in that ambient $PO_4^{3-}$ concentrations are generally the highest of any major tributary emptying into the Albemarle-Pamlico estuarine system; levels of 100 to 450 ug/l P-$PO_4^{3-}$ are commonly found throughout the year (Paerl 1987). The Tar and Pamlico Rivers also contain quite high $PO_4^{3-}$ concentrations (Stanley 1988b), but concentrations are somewhat diluted (50-300 ug/l P-$PO_4^{3-}$) by the time the rivers discharge into the Pamlico River Estuary. In either case, $PO_4^{3-}$ appears in excess of phytoplankton demands in the estuaries throughout much of the year.

The fact that $PO_4^{3-}$ does not occur in concentrations that would limit growth, as do $NO_3^-$ and $NH_3$, does not necessarily mean that generally high levels of $PO_4^{3-}$ discharge are not problematic. If, for example, $NO_3^-$ input reductions are initiated as a means of controlling eutrophication in the form of nuisance blooms of the non-nitrogen-fixing blue-green alga Microcystis aeruginosa, it is conceivable that nitrogen fixing blue-green algae such as Anabaena and Aphanizomenon will replace M. aeruginosa. To control the growth and proliferation of nitrogen fixing blue-green algae, only one feasible management option remains--concurrent phosphorus input constraints. Hence, dual nutrient (nitrogen and phosphorus) input controls should be practiced in this as well as other systems susceptible to blue-green algal blooms.

Another argument for dual nutrient input control is based on recent findings (Paerl et al. 1990 and Rudek et al. 1991) concerning high runoff during spring months which combine the influences of excessive nitrogen loading (chiefly as $NO_3^-$) and dilution of phosphorus by rainfall. This combination can result in periods of phosphorus and nitrogen co-limited growth conditions in the lower Neuse River Estuary-Pamlico Sound region (see Figure III-6). It would appear that the combined impacts of heavy and, since the 1940s, increasing nitrogen fertilization, increased atmospheric nitrogen loading in rainfall (due to the enhanced generation of the oxides of nitrogen), and more recently, improved sewage treatment and a phosphate detergent ban decreased phosphorus loading to the region. All contribute to a phosphorus limited period in the estuaries. Whether or not such a phosphorus limited period characterized the Albemarle-Pamlico estuarine system in previous decades is unknown.

Besides studying land-use trends and their potential relationships to water quality, it is interesting to note the evolution of efforts to control NPS pollution. In addition to the National Estuary Program (Section 320 of the Water Quality Act of 1987), there are eight major initiatives that have been taken to understand and control NPS pollution within the Albemarle-Pamlico estuarine system area. These initiatives represent a trend toward increasing responsibility at the federal, state, and local levels to implement the proper mix of regulatory and voluntary controls.

### B. 2. Section 208

Traditionally, pollution control efforts were directed toward point sources. In 1972, however, Section 208 of the Federal Water Pollution Control Act Amendments (Area-wide Waste Treatment Management) emphasized both point and nonpoint source pollution control. States were directed to develop plans that would specify actions needed to upgrade water quality on a statewide basis and recommend management agencies that would be responsible for plan implementation. These management plans were to be used by the implementing agencies to direct their efforts in water pollution control. The State of North Carolina developed water quality management plans for agriculture, construction, forestry, mining, on-site wastewater treatment, solid waste, and urban stormwater management.

### B. 3. Sedimentation Control

The North Carolina General Assembly enacted the Sedimentation Pollution Control Act in 1973. The Act authorized the establishment of a sediment control program to prevent accelerated erosion and off-site sedimentation caused by land-disturbing activities other than agriculture, forestry, and mining. The Land Quality Section of the NC Division of Land Resources is responsible for administration and enforcement of the requirements of the Act under the authority of the NC Sedimentation Control Commission. The sediment control program requires, prior to construction, the submission and approval of erosion control plans on all projects disturbing one or more contiguous acres. On-site inspections are conducted to determine compliance with the plan and to evaluate the effectiveness of the best management practices (BMPs) that will be used. The intent is to offer permanent downstream protection for stream banks and channels from damages caused by increased runoff velocities. If voluntary compliance with the approved plan is not achieved and violations occur, the Land Quality Section will pursue enforcement through civil penalties and injunctive relief.

### B. 4. Coastal Area Management Act

In order to foster protection of sensitive coastal areas, the North Carolina General Assembly enacted the Coastal Area Management Act (CAMA) in 1974. One major goal of the Act was to provide protection of areas of environmental concern (AEC) by requiring permits for development in these areas. The NC Division of Coastal Management (NC DEHNR) is responsible for administration of the program. Ideally the program is a cooperative effort between state and local governments. State and local governments are both responsible for enforcement of the Act while local governments hold the initiative for planning.

There are three major areas of responsibility for the NC Division of Coastal Management in implementing CAMA. First, land use plans are to be developed by each coastal jurisdiction under supervision of the state for the protection and appropriate development of AECs. Second, a permit is required for all development or land disturbing activity in an AEC. A "major" permit is required if the development is in excess of 20 acres, requires drilling or excavation on land or underwater, or the structure is greater than 60,000 sq. ft. in size. Anything other than "major" development requires a "minor" permit, which is administered by the local government. Finally, a consistency review is made of federal projects to ensure that the policy and provisions of CAMA are satisfied.

### B. 5. Nutrient Sensitive Waters

To address the need for limiting nutrients in certain waters, the NC Environmental Management Commission (EMC) adopted a nutrient sensitive waters (NSW) classification in May of 1979. This classification gave the EMC the authority to limit the input of nutrients into waters experiencing or subject to excessive growths of microscopic or macroscopic vegetation. If necessary, the NSW classification could include all waters in a river basin. Because of a history of algal blooms, the Chowan River was designated NSW in September 1979 and the lower Neuse River (below Falls Lake) in May 1988.

### B. 6. Agriculture and Forestry Cost Share Programs

Two nonpoint source cost share programs evolved from the NSW classification with the purpose of reducing nonpoint source pollution for water improvement. The North Carolina General Assembly appropriated funds in 1984 to assist landowners from 16 counties within the NSW watersheds of the Chowan River, Falls Lake, and Jordan Lake to implement BMPs. The NC Environmental Management Commission designated these watersheds "NSW" due to severe eutrophication problems caused by point and nonpoint sources. Each watershed was seriously affected by soil erosion from agricultural lands and by corresponding nutrient and sediment problems. A general statute (NCGS Article 21, Chapter 143) expanding the program to include 17 counties in the Albemarle-Pamlico region was added in 1986. The program was expanded in 1989 to include all counties in North Carolina. It should be noted that the program currently covers the entire Albemarle-Pamlico estuarine area.

In targeted areas, the cost share program will pay up to 75% of the cost of implementing a system of approved BMPs. Technical assistance is available to the landowners or users that would provide the greatest benefit for water quality protection.

The NC General Assembly also appropriated funds in 1984 to establish a Forestry Cost Share Program to compliment existing programs to control point source discharges, agricultural runoff, and urban runoff. The purpose of the program is to protect the quality of soil and water resources in watersheds through the use of accepted forestry BMPs. The Division of Forest Resources is responsible for administering the program, which will pay landowners up to 75% of the cost of implementing BMPs.

### B. 7. Food Security Act of 1985 and 1990 Farm Bill

Several provisions authorized by the Food Security Act of 1985 (FSA) and 1990 Farm Bill offer excellent opportunities for the abatement of agricultural nonpoint source pollution in the Albemarle-Pamlico Estuary area. The FSA makes the goals of the US Department of Agriculture farm and conservation programs more consistent by encouraging the reduction of soil erosion, the reduction of production of surplus commodities, and the protection of wetlands. The provisions can also serve as tools to remove from production those areas which critically degrade water quality by contributing to sedimentation. The provisions are known as the Conservation Reserve, Conservation Compliance, Sodbuster, Swampbuster, and Conservation Easement.

The <u>Conservation Reserve Program</u> (CRP) is administered by the U.S. Department of Agriculture Agricultural Stabilization and Conservation Service (ASCS) and the US Soil Conservation Service. Other cooperating agencies include the NC State University Agriculture Extension Service, NC Division of Forest Resources, and Local Soil and Water Conservation Districts. The CRP was established to encourage the removal of highly erodible land from crop production and to promote planting long-term permanent grasses and tree cover. The ASCS will share up to half of the cost of establishing protective cover. The intention of the Program is to protect the long term ability of the United States to produce food and fiber by reducing soil erosion, improving water quality, and improving habitat for fish and wildlife. Additional objectives are to curb the production of surplus commodities and to provide farmers with income supports through rental payments over a 10-year contract period for land entered under the CRP. The 1990 Farm Bill extended this contract period to 30 years. Vegetative filter strip establishment has been incorporated into the CRP and has great potential for environmental benefits. Some of the benefits include improved water quality and wildlife habitat. Active steps have been initiated to obtain farmer participation in the Program.

The Conservation Compliance provision of the FSA discourages the production of crops on highly erodible cropland where the land is not carefully protected from erosion. Highly erodible land is defined as land where the potential erosion (erodibility index) is eight times or greater than the rate at which the soil can maintain continued productivity. This rate is determined by the US Soil Conservation Service. A conservation plan must be developed by January 1, 1990 and fully operational by January 1, 1995. If a soil survey is not available, the farmer has two years after soil mapping is completed to develop and begin applying a conservation plan. If a conservation plan is not developed and implemented, the farmer loses eligibility in price and income supports, crop insurance, Farmers Home Administration loans, Commodity Credit Corporation storage payments, farm storage facility loans, Conservation Reserve Program annual payments, and other programs under which US Department of Agriculture makes commodity-related payments.

The Sodbuster provision of the FSA is directed toward discouraging the conversion of highly erodible land for agricultural production. It applies to highly erodible land that was not planted in annually tilled crops during the period 1981-85. As with other provisions of the FSA, the US Soil Conservation Service determines if a field is highly erodible. If a highly erodible field is planted in an agricultural commodity without an approved conservation system, the landowner (or farmer) becomes ineligible for certain US Department of Agriculture program benefits.

The purpose of Swampbuster is to discourage the conversion of wetlands to cropland use. Wetlands are defined as areas that have a predominance of hydric soils which are inundated or saturated by surface water or groundwater at a frequency or duration sufficient to support a prevalence of hydrophytic (water-loving) vegetation. It is the responsibility of the US Soil Conservation Service to determine if an area is a wetland. Like the other provisions of the FSA, a farmer will lose eligibility for certain US Department of Agriculture program benefits on all the land farmed if a wetland area is converted to cropland.

The Conservation Easement provision encourages producers whose Farmers Home Administration (FHA) loans are in or near default to place their wetland, highly erodible land and/or fragile land in conservation, recreation or wildlife uses for periods of at least 50 years. The producer benefits by having the FHA loan partially cancelled. Environmental benefits include reducing the level of soil disturbing activities and the threat of agricultural pollutants.

The Wetlands Reserve Program of the 1990 Farm Bill was established to restore 1 million acres of former wetlands over a five year period. The federal government will compensate owners of the previously converted cropland, rangeland, and pastureland who voluntarily transfer their property rights as permanent conservation easements to the reserve. The conditions of the conservation easements should prohibit the landowner from further development or alteration of the land. Also, much of the cost of improvements to these lands to enhance their wetlands functions will be paid by the federal government.

### B. 8. Coastal Stormwater Management Regulations

Coastal stormwater control has become an increasingly important issue as development continues. The initial debate focused primarily on stormwater and the closure of shellfish waters. In November 1986, the EMC adopted rules which required new development in a limited zone (575 feet) around Class SA (shellfish) waters to control stormwater either by limiting density or completely controlling a 4.5 inch, 24-hour storm with the use of a stormwater treatment system. The regulations applied to development activities which required either a CAMA major permit (through the NC Division of Coastal Management) or a Sediment/Erosion Control Plan (through the NC Division of Land Resources). The design storm, low-density limits, and areal coverage were all quite controversial and the adopted rules represented a compromise by all parties. A sunset provision was added to the rules to force the NC Division of Environmental Management (and Commission) to reconsider the rules after a year. The original rules expired December 31, 1987.

New stormwater regulations with an effective date of January 1, 1988 were subsequently adopted with similar requirements except the design storm was changed to the 1.5 inch, 24-hour storm. The new regulations apply the stormwater controls to development activities within all 20 CAMA coastal counties, and so includes those counties surrounding the Albemarle-Pamlico estuary system. While the near-water impact of stormwater is very important, as addressed in the original rules, the cumulative impact of stormwater runoff throughout the coastal zone also needed to be addressed. Therefore, the expanded area of coverage helps provide protection of both shellfish waters and general coastal water quality.

Other major items specified in the new rules address the sizing of stormwater treatment systems, innovative infiltration systems, and low-density options. For developments adjacent to SA waters, infiltration systems must be able to retain runoff from 1.5 inches of rainfall in 24 hours; whereas, development in other areas must control only 1 inch of rainfall. Wet detention ponds are not allowed for stormwater control near SA waters and must be sized for 85-90% total suspended solids removal in other areas. Porous pavement is considered an innovative infiltration system (only five are to be allowed until they are proven to work), but evidence regarding its effectiveness in coastal areas has not yet been provided. A low-density option of the new regulations applies a "built-upon" limit of 25% for SA areas and 30% for other coastal areas. Development exceeding these levels is required to have an engineered stormwater system.

### B. 9. Section 319

The federal Water Quality Act (WQA) of 1987, which was essentially the reauthorization of a similar act passed in 1972, emphasized nonpoint source pollution control as well as conventional point source control. According to Section 319 of the WQA, each state must develop strategies for managing nonpoint source pollution. In North Carolina, the Water Quality Section of the NC Division of Environmental Management was designated as the coordinating agency for nonpoint source pollution management.

Two reports were prepared in fulfillment of Section 319 (NC Division of Environmental Management 1989a, 1989b). The first report focuses on identifying the causes and sources of nonpoint source (NPS) pollution for impaired waterbodies in the Albemarle-Pamlico Estuarine area. The second report emphasizes management strategies and programs to address the nonpoint source problems identified in the assessment report. The NPS Management Program balances two priorities. One priority is to implement the overall NPS Program which includes regulations, technical and financial assistance, and educational efforts. The second priority involves targeting specific watersheds to improve degraded water quality or minimize nonpoint source impacts on high quality waters. Ideally, the watersheds selected are ones which can demonstrate water quality benefits from NPS projects within the four-year time span mandated in Section 319 of the Water Quality Act of 1987. It is recognized, however, that the time needed to demonstrate water quality improvements may often exceed four years.

The approach of controlling NPS pollution in the Albemarle-Pamlico estuarine area (and throughout North Carolina) is through a combination of land-use controls and technology-based BMPs. In urban areas, the preferred method of treatment is land use control through low-density development because of the long-term maintenance requirements associated with structural BMPs. In situations where low-density development is not feasible, stormwater controls devices (BMPs) are allowed. Nonpoint source strategies for other categories of pollution (e.g., agriculture, construction, or mining) depend more on the implementation of BMPs such as setbacks or filter strips, and waste reduction/management systems. The installation of these BMPs and management systems may be voluntary or required by regulations.

## C. EVALUATION OF TRENDS

### C. 1. Historical Perspective and Current Trends

**C. 1. a. General Statement.** Accelerated nutrient loading, particularly over the past 2 to 3 decades, has ushered in some ominous and increasingly common symptoms of eutrophication which, to the best of our knowledge, were extremely rare prior to World War II. Prior to the late 1960s virtually no field surveys yielding quantitative data on nitrogen and/or phosphorus concentration or loading characteristics can be documented for North Carolina's coastal waters, including major river systems and estuaries.

Several early reports describe hydrologic, hydrographic, and very limited chemical characteristics of specific waters (Dubach 1977). The first extensive field surveys specifically oriented towards identifying concentrations, sources and sinks as well as some bio-geochemical cycling characteristics of nitrogen and phosphorus occurred in the 1960s and 1970s (Copeland and Hobbie 1972; Hobbie et al. 1972; Harrison and Hobbie 1974; Kuenzler et al. 1982) for the Pamlico River Estuary. Bowden and Hobbie (1977) initially described nutrient characteristics of the Albemarle Sound, Hobbie and Smith (1975) examined nutrients in the Neuse River, while Stanley and Hobbie (1977) reported on nitrogen cycling in the lower Chowan River.

During the mid 1970s the NC Division of Environmental Management and the US Geological Survey developed and deployed monitoring networks in coastal regions that included nutrient analyses. Relevant river and estuarine systems included were the Chowan-Albemarle, Roanoke, Tar-Pamlico and Neuse. Throughout the 1970s and early 1980s more specific and goal-oriented nutrient/eutrophication studies on these systems and their watersheds were initiated. Included were examinations of nutrient uptake kinetics of phytoplankton in the Pamlico (Kuenzler et al. 1982), Chowan (Stanley and Hobbie 1977; Kuenzler et al. 1982), and Neuse (Stanley 1983) Rivers, and determinations of algal growth requirements including nutrient limitations through the use of bioassays in the Chowan (Witherspoon et al. 1979; Sauer and Kuenzler 1981; Paerl 1982a, 1982b) and Neuse (Paerl 1983) Rivers.

Origins, processing, and runoff characteristics of agricultural field sites were likewise investigated by Gilliam et al. (1978), while Kirby-Smith and Barber (1979) evaluated the potential estuarine water quality impacts of converting forest to intensive agriculture, with particular reference to nutrient discharge alterations. Skaggs et al. (1980) have more recently monitored effects of land development on the chemical characteristics of drainage water in Eastern North Carolina. Matson et al. (1983) and Kuenzler et al. (1984) examined biogeochemical processing and cycling of nitrogen and phosphorus compounds in sediments of the Neuse Estuary, while Kuenzler et al. (1982) addressed similar questions in the Chowan River. Meanwhile, water quality models (based in large part on nutrient dynamics) were being developed for the Chowan (Amein and Galler 1979) and Pamlico (Lauria and O'Melia 1980)

Rivers. More recent modeling efforts have incorporated both physical (flow, discharge, salinity stratification, light) as well as nutrient factors into predicting trophic states and nuisance bloom characteristics of coastal rivers (Christian et al. 1986; Lung and Paerl 1988). Information is extensive for the Pamlico system but limited for the Albemarle.

Recognition of quantitatively important nutrient input sources, refinement of research techniques, and discovery of additional nutrient discharge and cycling factors have led to recent studies in the areas of nitrogen losses from agricultural drainage areas (Jacobs and Gilliam 1983), strategies for reducing agricultural nonpoint input sources (Humenik et al. 1983), and identification and partitioning of point and nonpoint nutrient inputs within watersheds (Craig and Kuenzler 1983). Bioassay techniques have been developed to facilitate potentially limiting nutrients under highly enriched hypereutrophic conditions (Paerl and Bowles 1986; Paerl 1987) and to help prioritize and set specific target levels for future nutrient reduction levels effective in curbing "runaway eutrophication" and associated nuisance blooms.

C. 1. b. Neuse River Estuary Water Quality Trends: Basin Land Use and Nutrient Loading. An important analysis of the land uses and nutrient loading in the Neuse River basin was completed by Stanley (1988a). The summary below was taken from that study. According to estimates made in the study, basin-wide changes in acreages of major land use categories have been small in the Neuse region during the past century (Figure III-12). Total agricultural cropland acreages have varied somewhat since 1930, ranging from highs of 25-27% of the total basin area in 1945 and 1980 to a low of 16% in 1970. Forestland declined gradually from around 75% of total basin area in the late 1800s to around 64% of the total by the 1930s and has changed little since then. A detailed county-by-county analysis showed that cropland acreage has increased substantially in recent years in some of the coastal areas, while declining in the Piedmont areas.

The percentage of total land area in the watershed devoted to cropland has remained nearly constant at around 20-25%, but some crops are much more economically important now than in the past, while others have become less important over the years. In terms of acres harvested, corn has been dominant in the Neuse basin throughout the past century, accounting for between 290,000 and 450,000 acres (115,000-175,000 ha), or roughly 40-50% of the total cropland. Soybeans, the second most widely planted crop today, were first planted in significant acreages in the 1930s and 1940s, but until about 1960 never made up more than 5-10% of the total. By 1985, however, there were 290,000 acres (117,450 ha) of soybeans, roughly one-third of the total harvested cropland (Stanley 1988a).

On the other hand, acreages of tobacco and especially cotton have declined in the Neuse basin. Annual tobacco plantings peaked in the 1930s and 1940s at around 230,000 acres (93,000 ha), but now are down to around 60,000 acres (24,300 ha), or approximately 7% of total cropland. Cotton production in the basin was very important up until the 1930s, but then it declined rapidly and had practically ceased by about 1970. At it's peak in the 1920s, cotton was the second most widely planted crop, taking up as much as 35% of the total cropland in some years. Wheat and other small grains have never been dominant crops in this area. In 1985 only about 15% of the Neuse basin cropland (120,000 acres or 48,600 ha) was devoted to wheat. Hay crops are a minor part of the total cropland use today (<5% of total). This crop was slightly more important in the past, but was never dominant (Stanley 1988a).

In every census since 1880, swine have been the most numerous large farm animal in the Neuse basin (Figure III-13). Between 1880 and 1940, the swine inventory fluctuated between 150,000 and 200,000 head, but since 1945 it has risen steadily so that currently there are about 500,000 of these animals. Cattle numbers, on the other hand, have ranged between 25,000 and 75,000, but with no particular pattern; the numbers in recent years are no higher than those 100 years ago. Inventories of mules peaked in the 1940s at around 50,000, but they, along with horses and sheep, have become an insignificant part of the total in the past two decades. Thus, the overall pattern of change in large farm

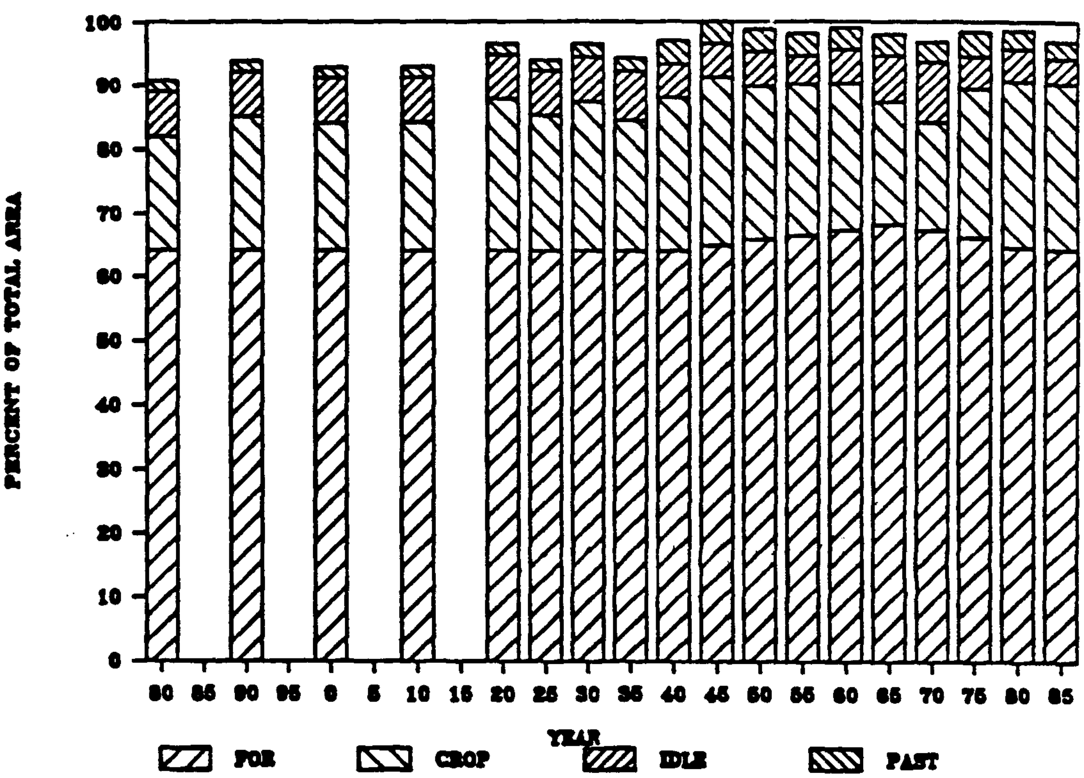


Fig. III-12. Land Use in the Neuse River Basin, 1880-1985. From Stanley (1988a).

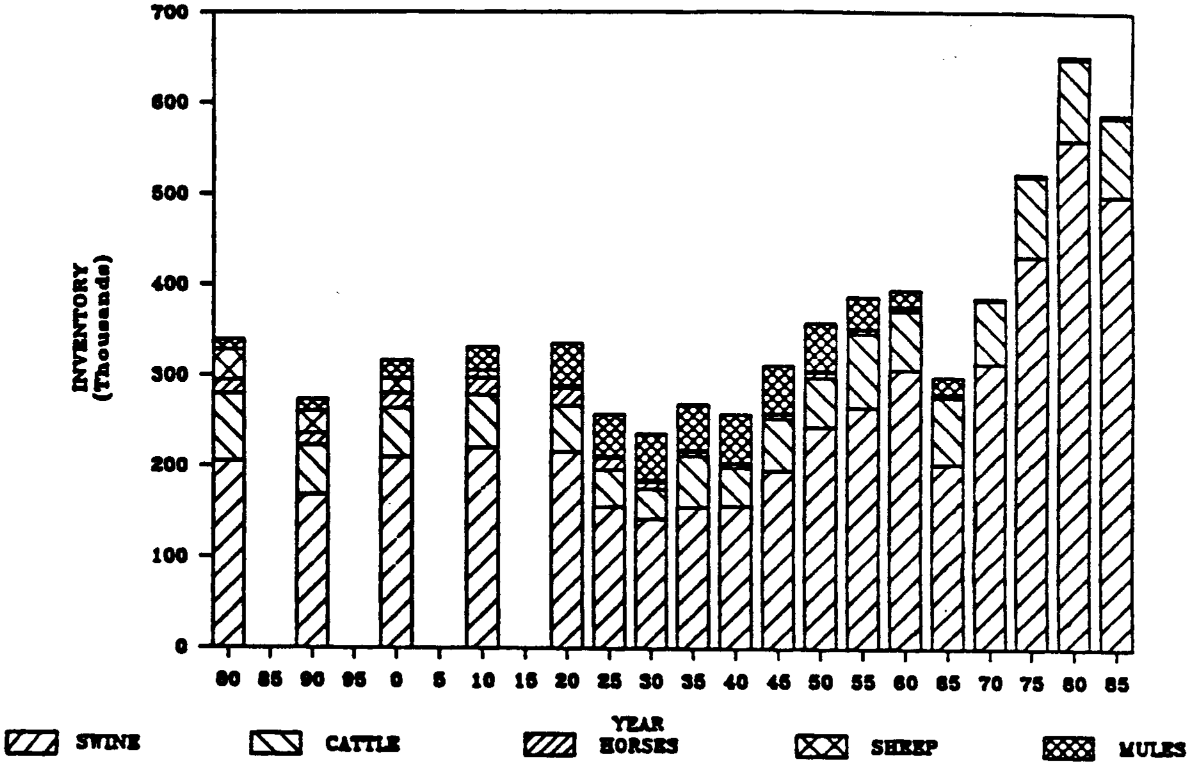


Fig. III-13. Inventory of Large Farm Animals, 1880-1985, in the Neuse River Basin, Poultry not Included. From Stanley (1988a).

animals inventory in the Neuse basin during the past century is dominated by the doubling in swine numbers (Stanley 1988a).

Poultry numbers in the Neuse basin have increased dramatically in the past two decades. The total poultry inventory (broilers, chickens, and turkeys) grew slowly from around 0.4 million in 1880 to approximately 1.6 million in 1960. Since then, however, poultry inventories have increased at an amazing rate, so that by 1985 there were over 8 million.

The estimated sewered population in the Neuse basin has increased steadily over the past century to 440,000 in 1985 (Stanley 1988a). Most of these people live in the upper half of the watershed, particularly in the Durham-Raleigh area. Conventional secondary treatment removes little phosphorus and only about 25-45% of the nitrogen (Gakstatter et al. 1978). When these treatment efficiencies are combined with historical data on the types of treatment practiced by municipal plants in the Neuse basin, it becomes clear that before 1950 there was no significant nitrogen or phosphorus removal from wastewater discharged into the river. As secondary treatment came into widespread use in the 1950s and 1960s in the Neuse basin, the overall nutrient removal efficiencies increased, but there has been little additional improvement in the last 10 years because further increases in treatment efficiencies have not occurred. Consequently, even now only about 27% of the Neuse basin total point source nitrogen and less than 2% of the total point source phosphorus are removed by treatment.

Total annual phosphorus loading from all Neuse basin sources (point and nonpoint) is estimated to have increased about 60% over the past century, from 1.04 million kg/year in 1880 to 1.7 million kg/year in 1985 (Figure III-14). Most of that increase has occurred during the past 40 years and appears to be due primarily to increases in point source phosphorus (i.e., increases in sewered population). In 1880, point sources accounted for only about 2% of the total load, compared to 42% from forests, 24% from cropland, 12% from farm animals, 18% from idle cropland, and 2% from pastures. In 1985 the point source phosphorus was 30% of the total. The farm animal contribution also has increased, from 0.13 million kg/year in 1880 to 0.25 million kg/year in 1985. Phosphorus from the other sources (cropland, forests, idle cropland and pastures) has not increased significantly; this is not surprising since the acreages of these land use types have not increased.

Total annual nitrogen loading is estimated to have increased 70% during the past 100 years, from 4.6 million kg/year in 1880 to 7.8 million kg/year in 1985 (Figure III-15). Like phosphorus, the rate of increase in nitrogen loading has not been constant. The loading increased until the mid-1950s, then declined slightly before increasing rapidly in the 1970s and 1980s. This pattern can be explained, in part, by improvements in nitrogen removal at waste treatment plants in the 1950s and 1960s, which tended to slow increases in point source loading that were occurring as the sewered population grew. But with no further improvement in the nitrogen removal efficiency since the mid-1970s, the nitrogen loading began to increase sharply as population continued to increase. Another factor leading to reductions in nitrogen loading in the late 1960s was the temporary reduction in cropland acreages which reduced cropland nitrogen runoff.

Point source increases have contributed significantly to the increased nitrogen loading. In 1880, only 2.5% of the total nitrogen was from point sources, compared to 55% from croplands, 19% from forests, 14% from farm animals, and the remainder from pasturelands and idle croplands. By 1985 the point source nitrogen contribution had increased to 24% of the total. Farm animal nitrogen also had nearly doubled and made up 14% of the estimated total.

The 1985 estimated total nitrogen and phosphorus loadings presented here (Stanley 1988a) are consistent with estimates prepared recently by the NC Division of Environmental Management (1989b). The NC Division of Environmental Management (DEM) calculated, by methods similar to those used by Stanley, that current total annual nitrogen and phosphorus loadings are 6.24 million kg/year and 1.0 million kg/year, respectively. DEM estimates are only 80% and 68%, respectively, of Stanley's nitrogen

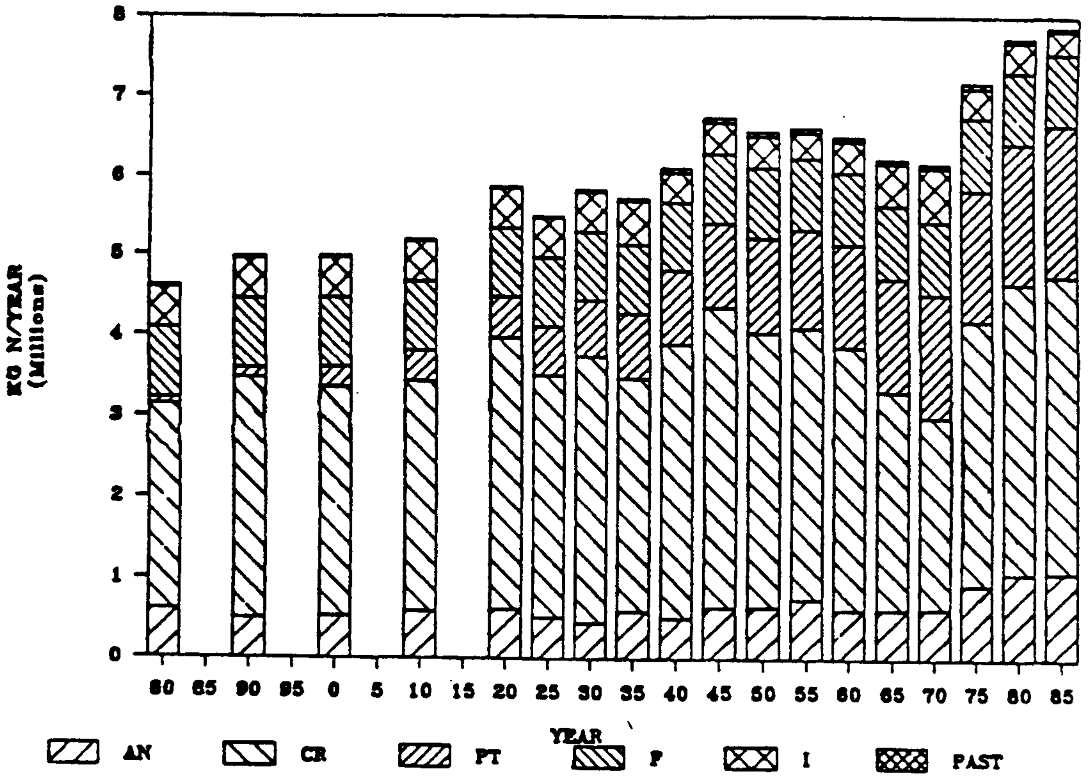


Fig. III-14. Estimated Nitrogen Loading to the Neuse River Estuary, 1880-1985. AN = Farm Animals, CR = Cropland, PT = Point Sources, F = Forestland, I = Idle Cropland, and PAST = Pastureland. From Stanley (1988a).

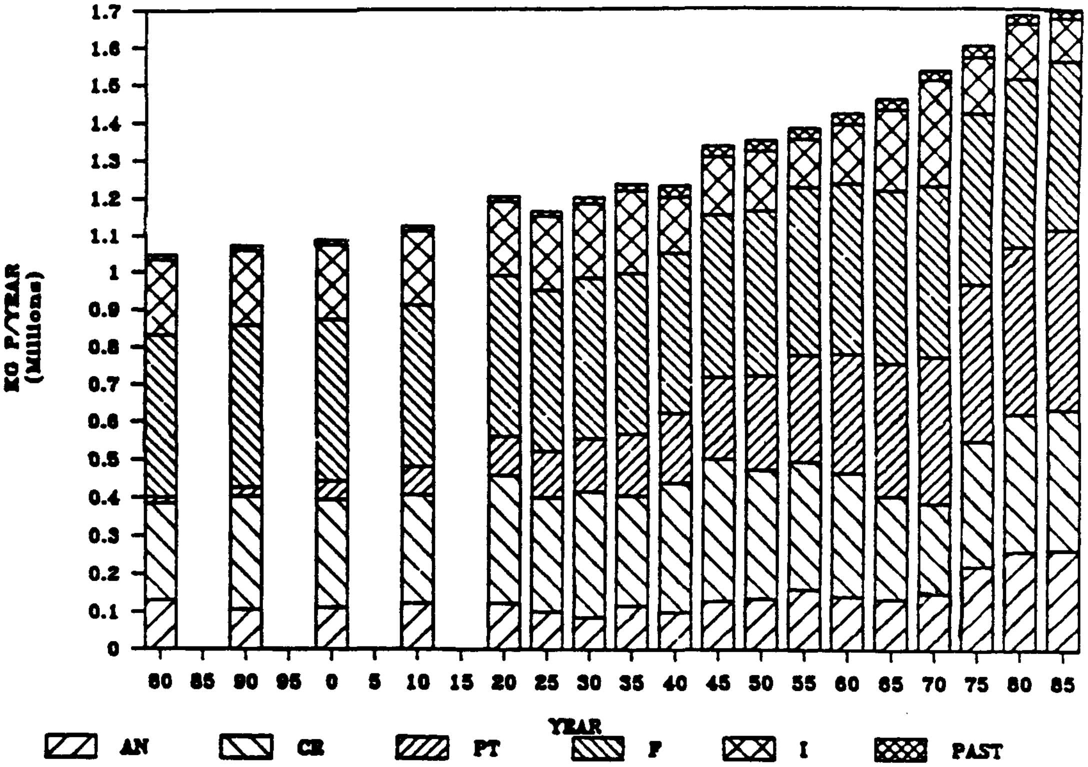


Fig. III-15. Estimated Phosphorous Loading to the Neuse River Estuary, 1880-1985. Symbols same as in Fig. III-14. From Stanley (1988a).

and phosphorus loading estimates. DEM, however, did not include that part of the basin downstream from New Bern (about 24% of the total) nor did they present historical estimates for additional comparisons.

Although there are no good historical instream data that could be used as a check on the estimates presented by Stanley (1988a), there are some recent instream data for comparison. Christian et al. (1987), working in the lower Neuse River above New Bern, multiplied nitrogen and phosphorus concentrations from grab samples by mean daily river flows to give total annual instream loading estimates. Their results, 3.5 million kg/year of nitrogen and 0.8 million kg/year of phosphorus, are about twice the estimates of expected loading developed by Stanley (1988a). This difference is similar to what Craig and Kuenzler (1983) found in a similar comparison for the Chowan River. Their explanation was that lowland swamp forests along these coastal rivers represent a major sink for nutrients; removing, for example, 83% of the total nitrogen and 51% of the total phosphorus from water draining into the lower Chowan. Such losses are within the range of values derived from detailed input-output studies of swamp forests within the Southeast (Craig and Kuenzler 1983).

Stanley (1988a) noted that his estimates of nitrogen and phosphorus loading in the past may have been too low because he did not take into account the large increase in fertilizer use that has occurred in the Neuse basin over the past 50 years. Phosphorus fertilizer use increased in the 1930s and 1940s, but has remained nearly constant since. Meanwhile, however, there has been a very rapid rise in the amount of nitrogen fertilizer sold. In fact, annual sales have increased about 10-fold during the last half-century, from 6 million kg/year in 1933 to about 60 million kg/year in 1984. The increases in fertilizer usage probably have increased the annual losses of the nutrients from croplands. The loading coefficients that Stanley used are based mostly on recent studies under high fertilization rate conditions. Actual loading coefficients were probably lower in the past when less fertilizer was being applied to the croplands. For example, assuming that only 5% of the additional fertilizer applied to crops is lost to the streams draining the farmland, the 50 million kg/yr difference in nitrogen used in 1932 and in 1984 would result in a 2.5 million kg/year difference in loss of nitrogen from croplands. In other words, the actual loss of nitrogen from croplands in 1932 might have been 2.5 million kg/year less than Stanley estimated (i.e., actually 0.2 million kg/year rather than the 2.7 million kg/year estimated). Of course, crop yields have increased dramatically over the past 50 years, and a substantial fraction of the added fertilizer went into the increased harvest. There is no way to be sure what percentage of added nutrient is actually lost in runoff.

One way to deal with the effects of changing fertilizer use and harvest is to construct mass balance models for each crop, rather than to simply use a constant loading coefficient as Stanley did in his calculations. Craig and Kuenzler (1983), and others, have used the mass balance approach to identify all the significant inputs, storage, and outputs of a particular nutrient within a defined system (e.g., cropland, pasture or forest). The advantages of this approach are obvious, but there are disadvantages associated with having to make estimates of numerous process rate coefficients such as those for denitrification, erosion, and nitrogen fixation.

It is clear from the historical trend information presented above that the rapidly increasing farm animal numbers, particularly swine and poultry, in the Neuse basin, could lead to greatly increased nitrogen and phosphorus loading. Stanley assumed that only 5% of the nutrients produced by farm animals is lost to the Neuse River drainage, however, if the loss were increased to 10 or 15%, there would be a substantial impact on the total nutrient loads. Such an increase may not be unrealistic, given that many of these animal operations involve the use of feed lots or buildings in which hundreds (swine) to tens-of-thousands (poultry) of animals are confined in very small areas. In such cases, these could become point discharges and, indeed, the wastes are now often treated by aeration lagoons or other techniques similar to those employed by conventional municipal treatment plants. Unfortunately, the animal waste treatment facilities are not as strongly regulated as municipal point sources, but North

Carolina State officials are becoming increasingly aware of the potential problems (NC Division of Environmental Management (1989a).

Pyhtoplankton community composition, productivity, and biomass characteristics of the mesohaline lower Neuse River Estuary were assessed monthly from May 1988 through February 1990 (Mallin et al. 1991). An incubation method which considered water column mixing and variable light exposure was used to determine phytoplankton primary productivity. The summer productivity peaks in the shallow estuary were stimulated by increases in irradiance and temperature (Figure III-16), however, dissolved inorganic nitrogen loading was the major factor controlling ultimate yearly production. Dynamic, unpredictable rainfall events determined magnitudes of seasonal production pulses through nitrogen loading and helped determine phytoplankton species composition. Dinoflagellates occasionally bloomed and were present in moderate numbers, but rainfall events produced large pulses of cryptomonads, and dry seasons and subsequent higher salinities led to dominance by small centric diatoms. Daily production was strongly correlated ($r = 0.82$) with nitrate concentration and inversely correlated ($r = -0.73$) with salinity, while nitrate and salinity were inversely correlated ($r = -0.71$), emphasizing the importance of freshwater input as a nutrient loading source to the lower Neuse River Estuary. During 1989, mean daily areal phytoplankton production was 938 mgC/m$^2$, mean chlorophyll a was 11.8 mg/m3, and mean phytoplankton density was $1.56*10^3$ cells/ml. Estimated 1989 annual areal phytoplankton production for the lower estuary was 343 gC/m$^2$.

C. 1. c. Pamlico River Estuary Water Quality Trends. A detailed analysis of historical trends in nutrient data for the Pamlico River Estuary has been developed by Stanley (1988b). A non-parametric trend test (Kendall Seasonal Trend Test) gave information on the statistical significance and magnitude of trends over the last twenty years for each of the various water quality measures. Since no single station in the Pamlico has been monitored continuously since 1967, the estuary was divided into segments and monthly averages for each segment were used in the trend analysis. Data from upriver, mid-river, and downriver areas of the estuary were analyzed for trend. A review of the Pamlico sampling and analytical methods used since 1967 showed that ammonia nitrogen data from 1975-1979 could not be used in the trend tests, and that changes in total dissolved nitrogen and total nitrogen methods were substantial and might interfere with comparisons between the two major studies. Also, there was evidence that data from the two phytoplankton studies were not comparable. For the other hydrographic and nutrient parameters, the methodological changes were not deemed serious enough to interfere with the trend analyses.

Three climatic variables and Tar River discharge were tested for trends because such trends, if they existed, might be linked to trends in the water quality variables. However, air temperature, wind velocity, precipitation, and river flow either showed no trend or, in the case of air temperature, a very slight (0.13 °F) upward trend. There were, however, several 1- to 3-year periods of unusually high or low river flows.

The Seasonal Kendall test indicated no significant trends in surface or bottom water temperature. Trends in salinity were detected for some river segments, but the changes were very small (about 1 ppt during 20 years). The 20-year trend was much smaller than the shorter-term interannual variations associated with years of high and low Tar River discharge. These fluctuations were as high as 8 ppt between two successive years.

Nitrate nitrogen appears to have decreased in the upper estuary by about 25% since 1970, with most of the decrease probably occurring before 1975. Part of the change is likely to be related to changes in salinity, but exactly how much is unknown. Ammonia nitrogen abundance appears to have trended downward at a rapid rate in all areas of the estuary. Upriver, the decline has been about 60% over the past 17 years.

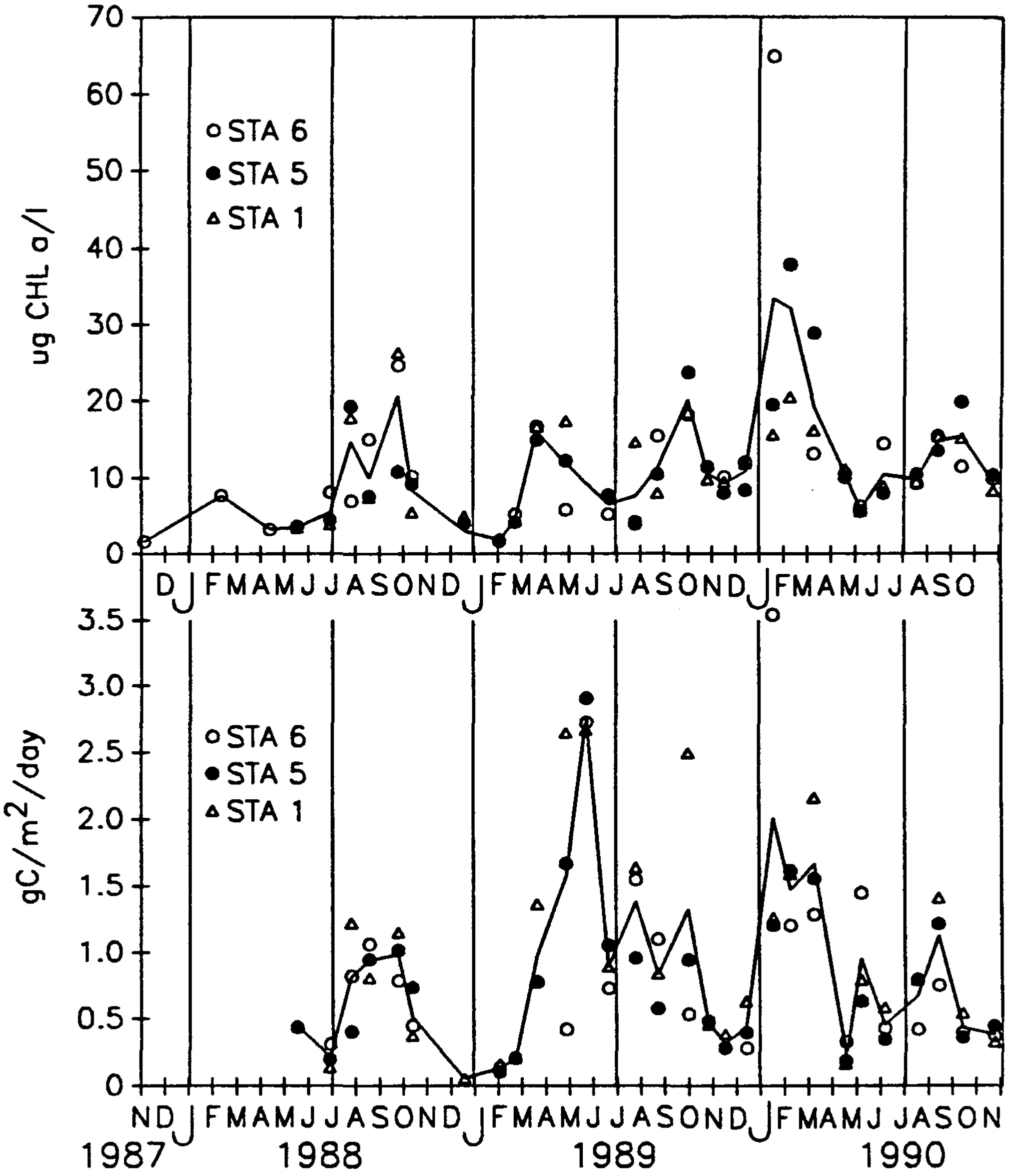


Fig. III-16. Top Panel: Surface measurements of chlorophyll a.
Bottom Panel: Aereal productivity values from stations 1, 5, and 6 in the lower Neuse River Estuary.
(Note: Line represents mean among stations measured.)

Total phosphorus levels in the middle of the Pamlico Estuary have doubled since 1967. There have been smaller increases in the upriver and downriver segments, but in the 1975-1986 period there was a significant increase in total phosphorus only in the downriver segment. Total dissolved and orthophosphate phosphorus have also increased significantly, particularly in the lower estuary. The fact that phosphorus abundance has not changed in the mid-river segment since 1975 probably reflects declining phosphorus loading from Texasgulf Chemicals counter-balanced, to some extent, by increased loading from the Tar River basin. Monthly loading of phosphorus from the plant site has apparently decreased by about two-thirds since the mid-1970s. This ought to have produced a significant downward trend in phosphate in the river, given that the Texasgulf discharge accounts for approximately 40% of the total phosphorus input to the Pamlico. But, the decreased Texasgulf load probably has been offset, to some large extent, by increased loading from the Tar River, so that the overall pattern is one of little change since 1975. Unfortunately, there are no historical Tar River loading data which could be used to test this hypothesis.

Chlorophyll a, an indicator of algal abundance, has increased in the middle and upper river segments, but not downriver. At the head of the estuary, the increase was about 50% during the 16-year period of record. Chlorophyll a values exceed the State standard of 40 ug/liter <1% of the time in some years up to about 10% in others (during the period April through November when the standard is in effect). But there has been no trend toward increasing frequency of the high values. In most years high chlorophyll concentrations were more frequent in the upper and middle river areas than in the lower estuary. Also, high values (>40 ug/liter) are usually more common in the winter than in the summer (Figure III-17). Actual phytoplankton species composition in the Pamlico appears not to have changed significantly over the past two decades. Nuisance blue-green algae are not an important component of the Pamlico flora, and clearly do not reach bloom proportions in the tidal freshwater areas of the Pamlico Estuary. This is in strong contrast to the lower Neuse River and the lower Chowan River, where significant blue-green algae blooms have occurred in several years over the past decade. Water

Water column nutrient ratios (dissolved inorganic nitrogen/orthophosphate) calculated for the Pamlico indicate that nitrogen is more likely than phosphorus to limit phytoplankton growth during the summer (Figure III-18). The ratios indicate that phosphorus could become limiting upriver during the winter, but other factors such as low temperatures and low light penetration into the water are probably more important in controlling algal growth then.

The Pamlico River Estuary has been compared (Nixon 1983; Stanley 1988b) to other well-studied estuaries in the United States in terms of: a) nutrient concentrations, b) bottom water dissolved oxygen, and c) phytoplankton. Except for higher orthophosphate phosphorus in the Pamlico there was little difference in salinity and nutrients between the Pamlico and the adjacent Neuse River Estuary. Inorganic nitrogen and phosphorus in the Pamlico shows temporal and spatial patterns similar to those in most temperate estuaries, although there are wide ranges in the concentrations, both within each of the systems, and among different systems. Phosphorus concentration in the Pamlico is higher than in most estuaries (but not the highest of those included in the survey), while nitrogen seems to be about average. Nitrogen, not phosphorus, is thought to be the nutrient most limiting algal growth in other estuaries that have been studied. Short-term hypoxia appears to be common in estuaries, but there is a great deal of uncertainty over the impact of cultural eutrophication. In other estuaries most of the oxygen depletion seems to be caused by the same factors operating in the Pamlico (i.e., water column stratification, wind and river flow). In only a few instances are there long-term data, and the interpretation of that data is not easy. Phytoplankton algal species composition and biomass in the Pamlico are not very different from that in most other estuaries in the region for which data are available. Annual primary production in the estuary is probably higher than average, but the data are inadequate to allow individual rankings. No such evaluation has been done for the Albemarle Sound region.

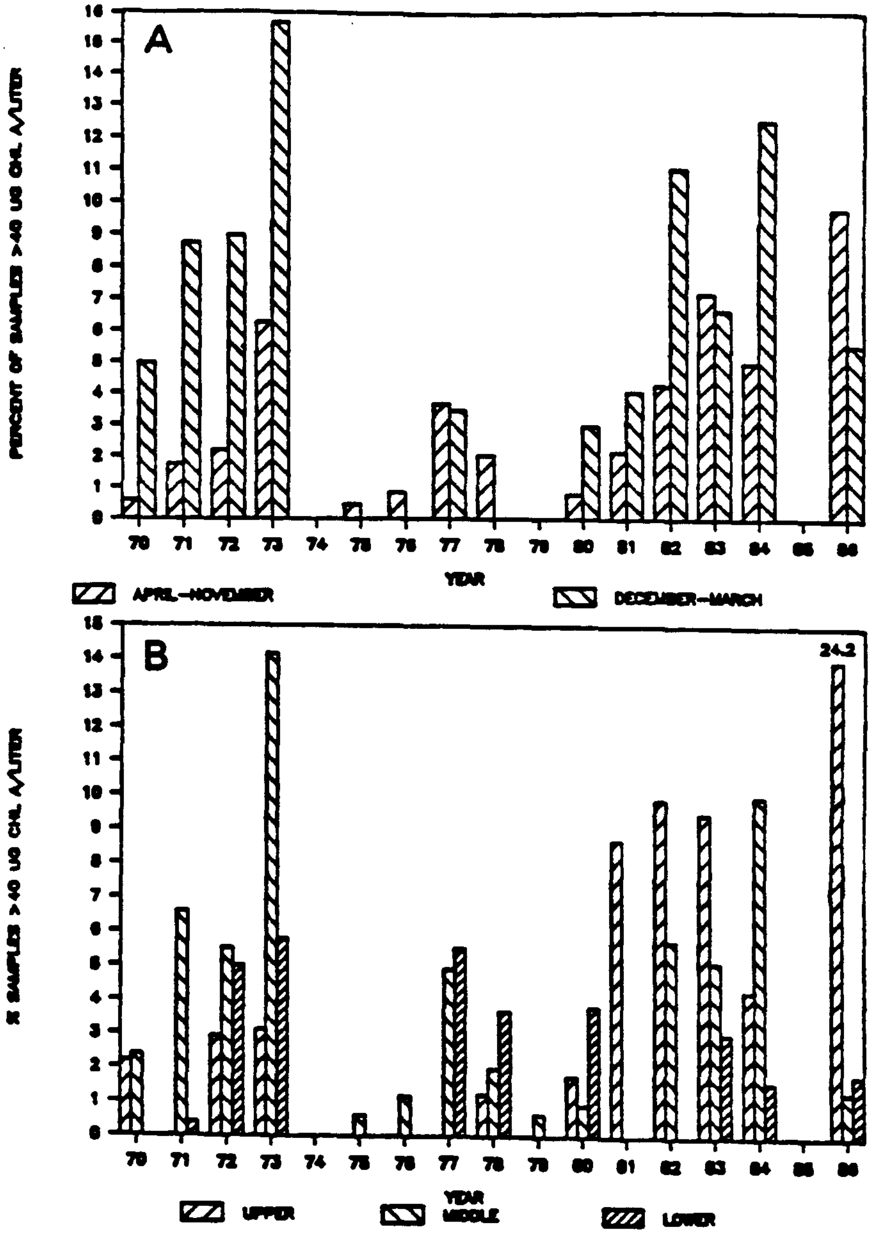


Fig. III-17. Pamlico River Estuary Chlorophyll a in Percentage of Sample Values Greater than 40 ug/l Each Year (1970-1986). A = Data grouped by April-November and December-March periods; B = Data grouped by Upper, Middle, and Lower river segments. From Stanley (1988b).

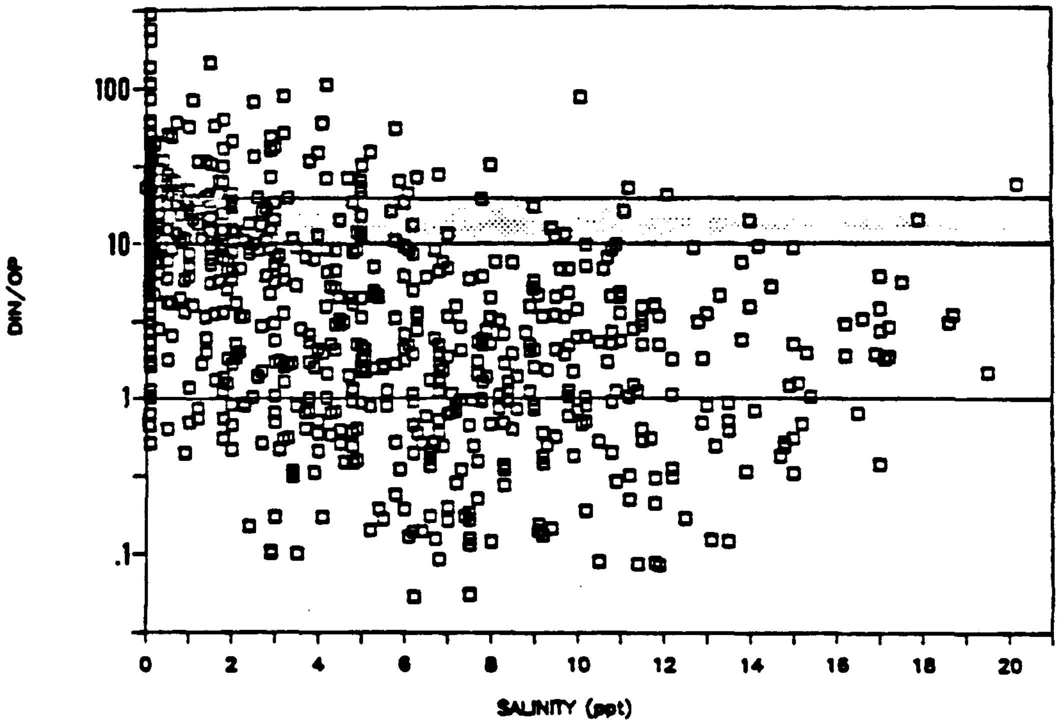


Fig. III-18. Dissolved Inorganic Nitrogen (DIN): Ortho-Phosphate (OP) Ratio Versus Salinity in the Pamlico River Estuary, 1979-1986. Shaded Area Indicates Usual Range of N:P Ratio in Algal Cells. From Stanley (1988b).

<u>**C. 1. d. Albemarle-Pamlico Water Quality Trends and Basin Characteristics**</u>. Harned and Davenport (1990) conducted an exhaustive analysis of water quality trends and basin characteristics in the Albemarle-Pamlico Sounds. The following is drawn directly from Harned and Davenport (1990). Wastewater discharges in the Neuse River basin have increased 650 percent since the 1950s. The Neuse River basin has the greatest total wastewater discharges of any of the basins in the study area, averaging about 200 million gallons per day in 1988. Wastewater discharges into the Neuse and Tar Rivers were nearly equal to the 7-day, 10-year low flows for these rivers. Data from seven stations of the US Geological Survey National Stream Quality Accounting Network were used to evaluate water quality for the major streams flowing into the Albemarle-Pamlico estuarine system. Water-quality data for 296 stations in the estuarine system were examined for the period 1945-88.

The statistical test used for trend analysis was the Seasonal Kendall test, the same as that used by Stanley (1986). This nonparametric procedure is useful for analyses of water-quality properties that show non-normally distributed frequency distributions. The Seasonal Kendall trend analyses of water-quality data indicate that change has occurred in the water quality of the Albemarle-Pamlico estuarine system from 1945 to 1988. Dissolved-oxygen concentrations increased at a mean rate of 0.1 milligram per liter per year throughout the estuarine system, except in the Chowan River where decreases of approximately 0.06 milligram per liter per year occurred. In general, pH increased in streams throughout the area at a mean rate of 0.04 pH units per year, except in the Pamlico River where pH decreased by 0.03 pH units per year. A general increase in pH and dissolved-oxygen concentrations (if daytime measurements) might be indicative of more productive estuary conditions for algal growth. Suspended-solids concentrations decreased throughout the area at a mean rate of 1.1 milligrams per liter per year, probably as a result of a general decrease in suspended inorganic material. Increasing trends of salinity concentrations, as much as 0.1 part per thousand per year, were detected in Albemarle Sound.

Total ammonia plus organic nitrogen concentrations decreased (-0.03 milligram per liter per year) in streams throughout most of the area but increased (0.02 milligram per liter per year) in the Pamlico River. However, ammonia nitrogen concentrations decreased (-0.0035 milligram per liter per year) in the Pamlico River; therefore, increases in organic nitrogen probably caused the observed increase in combined ammonia plus organic nitrogen concentrations. This probably results from increased eutrophication in the system and its associated increased production of plant biomass. Nitrogen concentrations generally increased downstream and were usually sufficient for development of algal blooms.

Total phosphorus concentrations increased (0.003 milligrams per liter per year) in the Pamlico River and decreased (-0.004 milligram per liter per year) elsewhere. There was a general pattern of decreasing phosphorus concentrations downstream for the Neuse and Pamlico Rivers; however, phosphorus concentrations in the Pamlico River peaked near Durham Creek.

Soluble nutrient concentrations, including ammonia nitrogen, nitrite plus nitrate, and dissolved phosphorus, are a net result of the effects of biological uptake, solution and dissolution of nutrients available in sediment, and new nutrient inputs. If plant biomass increases over time, this could be reflected in decreases in soluble nutrients such as observed ammonia nitrogen and phosphorus concentrations on the estuary system.

On the basis of annual median concentrations, nitrogen was the limiting nutrient for algal growth in the Neuse and Pamlico Rivers. Phosphorus was the limiting nutrient in most of the rest of the Albemarle-Pamlico system. Direct tests for specific nutrient limitations need to be made to confirm limitations at specific sites in the estuarine system.

Trends in chlorophyll-a concentrations increased in the Neuse River, upper Pamlico River, in the upstream end of Albemarle Sound, and near Bull Bay in Albemarle Sound (maximum rate, 1.0 microgram per liter per year). Chlorophyll-a concentrations decreased in the part of the Chowan River near Mount Gould. A pattern of increases in chlorophyll-a concentrations downstream in the Neuse, Chowan, and Alligator Rivers is apparent. Chlorophyll-a concentrations in the Pamlico River increased downstream, peaked in Durham Creek, and declined farther downstream. Chlorophyll-a concentrations were largest in the Pamlico (interquartile range 3-27 micrograms per liter) and Neuse Rivers (interquartile range 3-17 micrograms per liter) and in Currituck Sound (interquartile range 7-22 micrograms per liter).

## C. 2. Potential Effects of Current Trends

C. 2. a. Anoxia (Hypoxia) -- An Example. Bottom water dissolved oxygen concentration is controlled primarily by climatic and hydrologic factors in the Pamlico River Estuary. There has been no trend toward lower oxygen concentrations over the past 17 years (Stanley 1988b). Low bottom water oxygen (hypoxia) does not occur in the estuary when water temperatures are lower than around 20°C. Above 20°C, dissolved oxygen values of less than 1 mg/liter were found in about 20% of the samples from the upper estuary, but in only 4% of the samples from the lower estuary. In addition to high water temperature, another requirement for hypoxia development in the Pamlico is stratification. Salinity stratification prevents mixing of the bottom water with surface waters, which prevents aeration of the bottom water and leads to hypoxia. Two key factors controlling stratification in the Pamlico River Estuary are river flow and wind velocity. High summer flows favor development of stratification (and hence hypoxia) in the lower estuary, while preventing it in the upper estuary. Conversely, drought periods favor hypoxia development upriver but not downriver. Wind velocity is inversely correlated with hypoxia. That is, calm weather favors development of stratification and hypoxia. On the other hand, strong winds can de-stratify the water column in only a few hours and lead to mixing and re-aeration of hypoxic bottom waters, especially downriver where the fetch is greatest.

Although systematic information concerning the exact cause and effects of hypoxia are not available, one intensive study was made during the summer of 1976 (Davis et al. 1978) that sheds some light on short-term changes in oxygen in the river. This study showed that only a few days are required for hypoxia to develop, and that it can be broken up and reversed very quickly. In 1976 Davis and his coworkers measured surface and bottom water salinity, temperature, and dissolved oxygen at stations along the axis of the estuary at intervals ranging from a few days to two weeks. Two sequences illustrate the point, June 24 through July 20, 1976 and August 24 through August 31, 1976. The estuary was well mixed on June 24, but a period of calm on this and succeeding days led quickly to severe deoxygenation by June 29. Stratification and low concentrations of dissolved oxygen in the bottom water were also evident on July 14, following a week of calm or light winds, but the stratification was completely broken up by July 20 following a frontal passage and strong northeasterly winds on the previous day. A complete cycle of development and break-up of bottom water hypoxia in less than a week was detected in the August samples. Deoxygenation was just beginning to occur in the upper reaches of the estuary on August 24. Deoxygenation intensified during the next three days as calm weather persisted (a North Carolina air stagnation advisory was in effect on August 26 and 27), so that by August 27 deoxygenation was recorded throughout the estuary. But, during the night of August 30 and throughout the day on August 31, there were strong winds from the east and northeast, which were probably responsible for the downriver mixing apparent in the hydrograph of August 31 (Davis et al. 1978).

Stanley (1988b) conducted an analysis of over 10 years of data to determine the relative influences of factors affecting deoxygenation. One possible explanation for the lack of low dissolved oxygen in the winter is the lack of salinity stratification. Vertical salinity gradients greater than 1 ppt (an indication of stratification) are, however, just as common in colder water periods as in the summer, at both ends of the estuary. Thus, factors other than lack of vertical stratification must be responsible for the lack of hypoxia in the winter. Lower respiration rates in colder water seem to be the most likely explanation. Spearman Rank Correlation analyses were used to provide information about the factors which have the most influence on dissolved oxygen in the Pamlico during the summer. Several variables were tested for correlation with dissolved oxygen concentrations at four stations sampled between 1975 and 1986. The results indicated that three factors, vertical salinity gradient, water temperature, and wind velocity/direction, were statistically significantly correlated with bottom dissolved oxygen concentration (Figure III-19). The vertical salinity gradient (DSAL), the difference between bottom and surface salinities, gave the highest correlation coefficient. The oxygen-DSAL relationship was inverse and was strongest at the three stations farthest up the estuary. Bottom water temperature was also negatively correlated with oxygen. The only variable showing a significant positive correlation to bottom water dissolved oxygen was wind velocity, as either average velocity on the previous day or the mean velocity over the previous two days. Differences in the correlation coefficients among the four stations suggest that this factor is somewhat less potent in the upper half of the estuary than at the mouth. The correlations between bottom water dissolved oxygen and year, nitrogen, phosphorus and chlorophyll a were not statistically significant.

Additional Spearman analyses were used to test for correlations between vertical salinity gradient (VSG) and two factors that could influence the strength of the VSG (Figure III-20); i.e., river flow and wind velocity (Stanley 1988b). The river flow data are from Tarboro, the nearest gauging station on the Tar River, about 75 km above the estuary. Thus, there are varying time-lags, depending on flow, between the gaging station and even the most upriver estuary sampling station. There are no velocity estimates for the lower Tar to provide insight into this problem, so several lagged and averaged flow parameters were used. The computed correlation coefficients between flow and VSG were all about the same, regardless of the flow parameter used. A more interesting result was that the VSG-flow correlations were positive for the downriver stations and negative for the two upriver stations. In other words, high summer flows enhance development of anoxia downriver, while preventing it upriver. Conversely, drought periods favor anoxia development upriver but not downriver. This is an interesting example of spatial variability in the estuary that is not obvious without close examination of these interrelationships. Wind velocity on the date of sampling was significantly correlated with stratification, but only at the station farthest downriver. Lagged or 2-3 day averaged wind data gave no significant correlations with the VSG. Two conclusions might be drawn from these results. First, bottom water dissolved oxygen seems to respond very rapidly to changes in wind velocity. In other words, only brief periods of calm or windy weather are needed to induce or break up bottom water hypoxia. Second, the influence of wind on the VSG and bottom water dissolved oxygen apparently increases downriver. This seems logical, since the river width increases toward the mouth. Given this increase in fetch, mixing induced by wind waves ought to range more widely downriver than in the more protected areas upriver.

Nixon (1989) also analyzed the historical Pamlico River estuary oxygen data and came to the following conclusions:

1. In spite of the popular belief that there is a direct link between the size of the winter-spring phytoplankton bloom and the severity of low oxygen conditions or "dead water" in the Pamlico during the following summer, no evidence of such a relationship could be found. The data show that the dominant factor determining the extent and duration of hypoxic and anoxic bottom water in the Pamlico is the degree of vertical salinity stratification.

2. The development of strong vertical salinity stratification (greater than 2%) is common in the Pamlico River because the Outer Banks severely restrict the tidal mixing energy that can enter the estuary. As a result, vertical mixing is dependent on the vagaries of the wind. During summer, the prevailing winds blow northeast or southwest across the channel. Unfortunately, the frequency of cross-channel winds with enough strength to produce vertical mixing is low enough that the estuary is often left unmixed for periods greater than the approximately five days required to consume most or all of the oxygen in the bottom waters. It is the frequency or recurrence interval of the strong winds that determines the magnitude of the summer "dead water" problem.

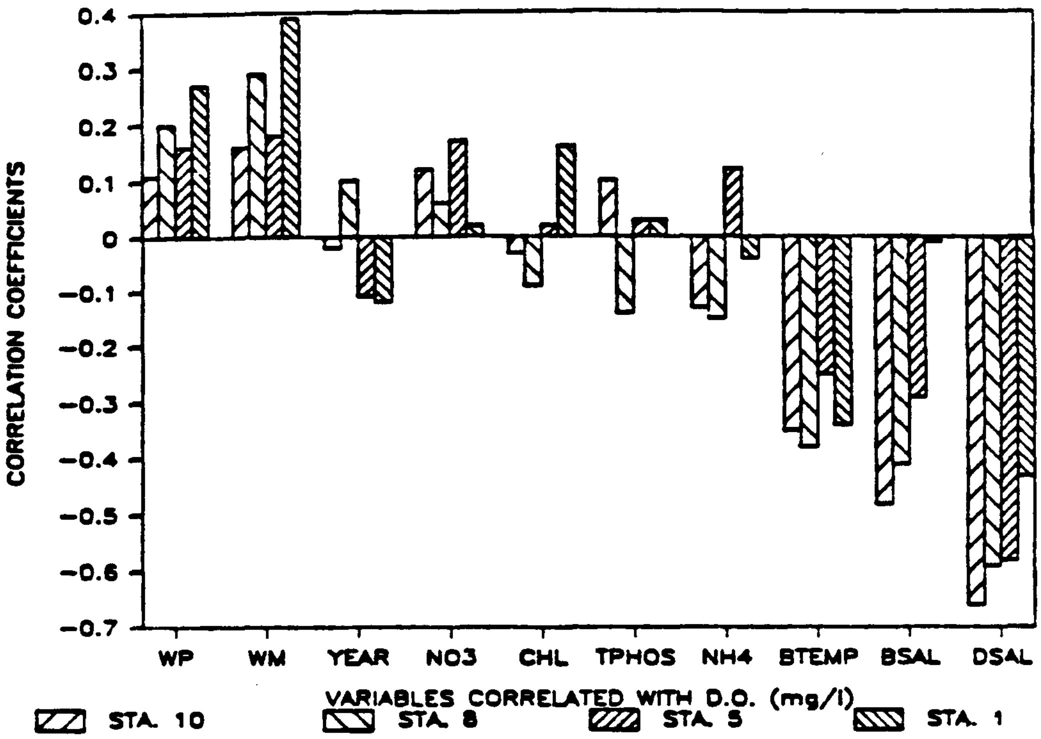


Fig. III-19. Spearman Rank Correlation between Bottom Water Dissolved Oxygen (mg/l) and Total Wind Miles on the Previous Day (WP), Average Total Wind Miles on the Sampling Date and the Previous Day (WM), Year, Nitrate Nitrogen ($NO_3$), Chlorophyll a (CHL), Total Phosphorus (TPHOs), Ammonia Nitrogen ($NH_4$), Bottom Water Temperature (BTEMP), Bottom Water Salinity (BSAL), and Vertical Salinity Gradient (DSAL) in the Pamlico River. From Stanley (1988b).

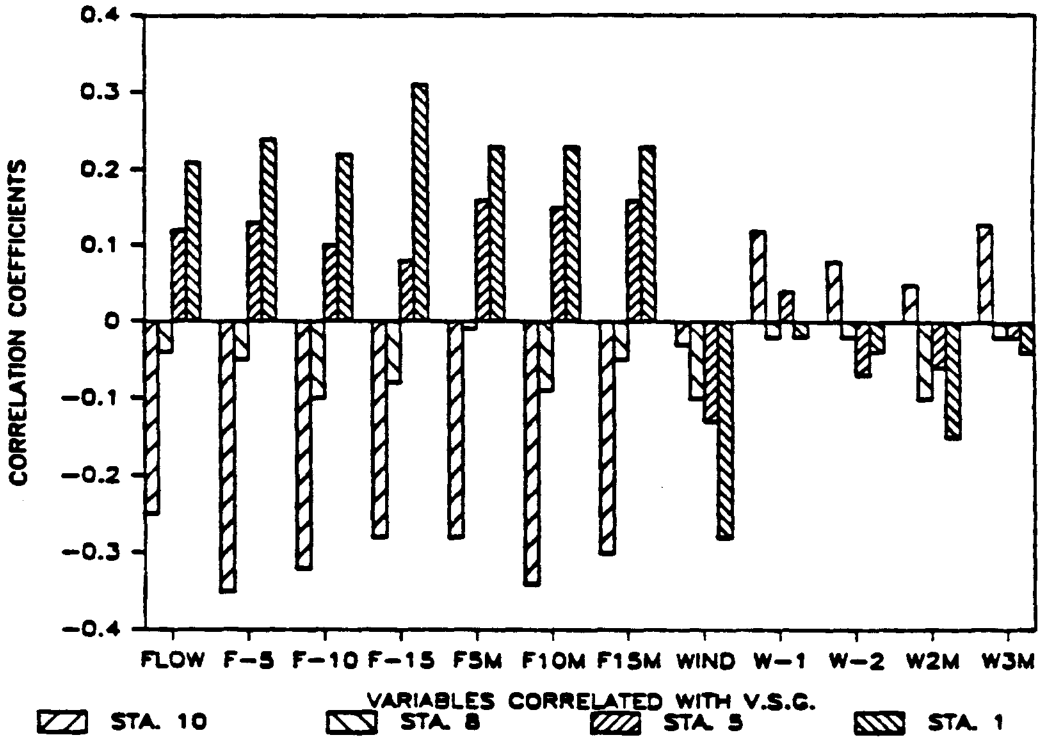


Fig. III-20. Spearman Rank Correlation between Vertical Salinity Gradient and River Flow on Sampling Date (FLOW), Flows 5 Days (F-5), 10 Days (F-10), and 15 Days (F-15)before Sampling, Average Flows for 5-Day (F5M), 10-Day (F10M), and 15-Day (F15M) Intervals before Sampling, Total Wind Miles on Sampling Date (WIND), Total Wind Miles 1 Day (W-1) and 2 Days (W-2) before Sampling Date, and Average Total Wind for 2-Day (W2M) and 3-Day (W3M) Intervals before Sampling in the Pamlico River. From Stanley (1988b).

3. The mechanism by which the stronger cross-channel winds produce vertical mixing appears to be by inducing upwelling along the lee shore of the estuary. During this process, surface water is carried across the estuary from the lee to the windward shore, and bottom water rises to replace it along the lee shore. As a consequence, surface waters may be cooler along the lee shore and benthic or bottom dwelling organisms along the lee side of the estuary may be exposed more frequently and for longer periods to bottom water that is lower in dissolved oxygen. During summer, the prevailing cross-channel winds blow toward the northeast more frequently than toward the southwest. This could explain why there have been more frequent reports of blue crab mortalities along the south shore of the Pamlico than along the north shore.

The general effect of hypoxia on the fauna of the Pamlico is difficult to assess. Anoxia or hypoxia in estuarine bottom waters obviously has the potential to seriously impact the biota either acutely via kills or chronically via physiological stress. The short-term effects were documented in the Pamlico during the late 1960s by Tenore (1970, 1972). He found that the macrobenthos in deeper waters of the estuary had low species diversity and density in the summer, and that variations in the density were correlated positively with anoxia/hypoxia. Large kills of the benthos occurred quickly in the affected areas following the onset of hypoxia, however, these areas were recolonized by the following winter (Tenore 1972). While these results seem dramatic, and are often cited to illustrate the Pamlico's oxygen "problem", they are probably typical for most estuaries (Stanley 1985).

There are no systematic data regarding fish and benthos kills in North Carolina estuaries, although most kills have been attributed to low dissolved oxygen. Most measurements have been made after a kill is reported so that precise determination of circumstances at the time of a kill is difficult. The implementation of the Pamlico Environmental Response Team (PERT) has the potential of enabling the NC Division of Environmental Management to gather more pertinent information. Stanley (1985) recently attempted an assessment of dissolved oxygen conditions in 23 estuaries in North Carolina, South Carolina and Georgia. One conclusion from this review was that none of these estuaries suffers from extended, widely-ranging hypoxia. Rather, the events appear to be of short duration and do not appear to have a serious impact on the estuaries, although benthic fauna are affected temporarily. Lack of long-term monitoring data for all these systems except the Pamlico River makes it impossible to determine exactly how much impact cultural eutrophication has had on the dissolved oxygen conditions. A study by Turner et al. (1987) showed that oxygen depletion in the bottom waters of Mobile Bay is caused by the same factors operating in the Pamlico River. They found that hypoxia was directly related to the intensity of water column stratification, which in turn was coincidental with low wind velocities. More than 80% of the dissolved oxygen variation in their samples was explained by variations in the vertical salinity gradient. An analysis showing a trend toward worsening dissolved oxygen conditions in the bottom waters of Chesapeake Bay (Officer et al. 1984) has been widely publicized, but the study results have come under recent attack by two bay-area scientists (Seliger and Boggs 1988) who have re-examined the data. Until a comprehensive analysis of the interacting factors leading to anoxia in the Albemarle-Pamlico estuarine system has been completed, the direct cause of low dissolved oxygen conditions will remain elusive. Currently, the predictive trend is that the conditions will remain sporadic and spatially limited.

<u>C. 2. b. Nutrient Enrichment.</u> <u>In situ</u> nutrient addition bioassays for nitrogen, phosphorus, and trace metals conducted on four to six week intervals have thus far proven valuable in identifying those nutrients responsible for regulating and limiting algal growth and algal community growth potentials (Paerl and Bowles 1986; Paerl 1987). Advantages of the <u>in situ</u> bioassay approach over the more traditional "standard" algal assays include: 1) the ability to examine nutrient enrichment responses by naturally occurring algal communities, 2) incubation and assay conditions which closely approximate light, temperature and turbulence regimes in the estuary, and 3) the utility of examining two parallel (and relevant) indicators of algal growth, carbon dioxide assimilation, and chlorophyll content, in highly replicated treatments.

Hans Paerl, University of North Carolina Institute of Marine Science, and co-workers have completed a three year study of nutrient addition and bioassys (November 1987-October 1990) in the lower Neuse River Estuary (Paerl et al. 1990). The bioassay results suggest a seasonal pattern in concert with estuarine phytoplankton biomass concentrations and productivity rates (Figures III-6 and III-16). Severe nitrogen limitation occurs in summer when algal biomass and production are high. There is somewhat less profound nitrogen limitation in fall and winter when biomass and production are at annual minima. Nitrogen and phosphorous co-stimulation (or synergism) occurs in the spring. With the exception of the winter 1989-90, these patterns repeated in years when flow and hence loading were low (1988), near average (1990), and high (1989).

The co-stimulation of phytoplankton biomass and production by nitrogen and phosphorus appears to be associated with periods of relatively high dissolved inorganic N:P (DIN:DIP) ratios in the water column which occurred during spring months. During periods when the DIN:DIP ratios were in excess of 10, phosphorus enrichment often played a synergistic role with nitrogen in stimulating phytoplankton growth potentials. Other estuaries have been found to exhibit seasonal variations in nutrient limitation. In the Patuxent River estuary, a tributary of the Chesapeake Bay, algal growth was found to be nitrogen limited during the summer, low-flow season and phosphorus limited during the late winter, high-flow season (D'Elia et al. 1986). As in the Neuse River Estuary, DIN:DIP ratios were elevated during phosphorus limitation. Graneli et al. (1990) also found phosphorus limitation in winter and nitrogen limitation in spring and summer in the coastal area of the southern Baltic Sea.

The bioassay results from the fall of 1989 through the spring of 1990 illustrate how the Neuse River Estuary is dependent on acute loading events to supply nutrients eventually needed for chronic nutrient recycling. The bioassays showed a progression from severe nitrogen limitation in the fall of 1989 (high $NO_3^-$ stimulation), to no stimulation in December during a nutrient loading event, to nitrogen limitation during a <u>Heterocapsa</u> <u>triquetra</u> bloom in January and February, to a nitrogen and phosphorus co-limited algal community in April and May after the bloom declines. The phytoplankton community in April and May may have been dependent upon nutrients regenerated from the organic matter previously transported to the bottom as a result of the bloom decline in March (Figure III-5).

However, despite the inter-annual variations in hydrologic and nutrient loading events during our study, it is striking how similar phytoplankton production and biomass levels were after the high flow season, when compared year to year (Figure III-16). The summer production and chlorophyll <u>a</u> levels from 1988-1990 were similar to estuarine averages ranging from 1.0 to 1.4 gC/m$^2$/day and from 15.4 to 20.6 ug chl<u>a</u>/l. the fate of the algal biomass produced in the winter-spring floods of 1989 and 1990 is not known, although some was likely converted to increased zooplankton biomass (Mallin, unpublished).

Trace metals added alone or in combination with nitrogen and phosphorus failed to exhibit any impacts upon growth potentials (data not shown) and so we concluded that natural availability of these metals exceeds phytoplankton growth requirements in the Neuse River Estuary. Diatoms may be limited by the availability of silica (Oviatt et al. 1989). Silica (1.5 ug/l) was added as a bioassay from April 1989 through October 1989, but silica did not seem to be limiting phytoplankton biomass or production in the Neuse River Estuary during the spring, summer, and fall of 1989.

The sounds of the Albemarle-Pamlico estuarine system have extremely limited tidal exchange with the off-shore waters. Given this, it would not bode well for the future of Albemarle and Pamlico Sounds if their tributary estuaries were being flushed or were transporting their nutrient loads as particulate matter downstream.

<u>C. 2. c. Sediment Conditions.</u> There is some evidence that the Albemarle-Pamlico estuarine sediments have been degraded from recent anthropogenic loadings and other human disturbances, but there is little or no evidence that any degradation has been due to changes in bottom sediment nutrient

processing routes or rates. We do not have a long-term data base which would support arguments regarding changes and trends in sediment characteristics and water quality impacts.

On the other hand, very poor water quality conditions in other Atlantic estuaries, such as the Potomac River, provide a warning signal. There is a need for more extensive knowledge of sediment-water interactions and for long-term monitoring of changes in sediment types and functioning. This is just now beginning under the Albemarle-Pamlico Estuarine Study (Riggs et al. 1989; Wells 1989). Standardized methods must be adopted for the primary monitoring program in order to compare results from different areas, different years, and different investigators. On the other hand, investigators should be supported and indeed be encouraged, to ask new questions and to develop new approaches to study old problems. It is important to adopt or develop comprehensive models of estuarine water quality which incorporate sediment interactions along with nutrient loadings, hydrology, insolation, temperature, and other controlling factors. Outputs of the model should aim to predict such variables as anoxic bottom waters, nutrient concentrations and phytoplankton productivity.

### C. 3. Identification of Needed Information

Considerable investment of manpower and funds have been directed towards accumulating information concerning water quality in the Albemarle-Pamlico estuarine system. Much of the work has been isolated in time and space, thus limiting attempts to build a total picture of functional characteristics of the trends in water quality. Several needs have been identified:

1. **Determine loadings of nitrogen and phosphorus (dissolved, particulate, organic, and inorganic) in the Albemarle-Pamlico estuarine system, and elucidate the cycling characteristics and ultimate fates of these loadings.** The ultimate utility of such information will be dictated by the consideration given to existing and future freshwater nutrient input data, sediment input and sedimentation/resuspension information, and water input/circulation/retention data for the Albemarle-Pamlico estuarine system. This effort should utilize a "grid approach" so as to obtain data with spatial and temporal integrity.

2. **Investigate the relative importance of nitrogen and phosphorus as potential limiting factors governing primary production.** This would link nutrient input, cycling, and fate information with in situ primary productivity, nutrient addition/dilution bioassays and nutrient uptake/cycling kinetics determinations. This effort should focus on locations bordering major estuarine input sources such as the Neuse, Pamlico, Chowan Rivers, as well as on several locations in the mid-Sound region.

3. **Conduct a comparative study aimed at delineating physical and chemical limitations on primary production in the Albemarle-Pamlico estuarine system.** Turbidity (sediment resuspension and water color) and temperature exert independent limitations on quantitative and qualitative aspects of primary production. It is well known that nutrients (most likely nitrogen) operate simultaneously to limit primary production. This study must address the relative importance of each type of limiting factor on a seasonal and temporal basis in all parts of the estuarine system. In all likelihood, a novel, non-monitoring oriented experimental approach should be employed in addressing this vital set of questions. Information generated from this project should be presented in such a manner as to be useful for both water quality management and flux/mass balance modeling efforts.

4. **Determine the presence of, and potential for, proliferation of phytoplankton considered undesirable from trophic, recreational, and aesthetic perspectives, in response to nutrient and sediment enrichment in the Albemarle-Pamlico estuarine system.** Specifically, blue-green algae and toxic dinoflagellates (red tides) should be investigated with the goal of establishing nutrient

input and concentration "thresholds", above which periodic dominance and blooms might be anticipated. Ancillary environmental factors known to play regulatory roles in nuisance bloom development, such as salinity, turbidity, thermohaline stratification, and humic substances, should receive parallel consideration in spatial and temporal evaluations of bloom development within the estuarine system.

5. **Investigate the incidence and impacts of enhanced hypolimnetic and sediment deoxygenation.** The interaction and impact of stratification, water movement, temperature and wind on the intensity and stability of deoxygenation needs to be characterized. In addition, the roles of enhanced nutrient loading from "internal" recycling processes and loading and the resultant eutrophication need to be identified and their relationship to hypoxia determined.

6. **Examine and evaluate potential trophic (food chain) impacts attributable to eutrophication.** It should be emphasized that such impacts may prove to be positive (i.e., enhanced production of desirable herbivore, fish and shellfish species due to enhanced production of desirable phytoplankton) or negative (i.e., decreases in production of utilizable commercial fish and/or shellfish species resulting from enhanced production of non-utilizable or toxic phytoplankton). This effort should incorporate both laboratory-oriented feeding and phytoplankton assimilation studies, and field evaluations of the utilization of primary producers (emphasizing potential nuisance species) by herbivorous zooplankton, larval and mature invertebrates, and commercially important fish.

7. **Develop a model to consider all factors which affect water quality.** Although sediment-water exchanges are important to nutrient cycling and metal storage in estuaries, these exchanges are only one of the fluxes that dominate cycling in certain places at certain times. A multidisciplinary evaluation of the physical, chemical, and biological interaction of inputs is the only way that the total picture can be determined.

8. **Conduct a long-term seasonal assessment of the phytoplankton productivity, biomass, and taxonomic structure of Pamlico Sound proper, and characterize the zooplankton community.** Currently, these data do not exist for Pamlico Sound proper, but are essential for any future assessment of the food chains there.

## D. CONCLUSIONS

1. The US Geological Survey has gathered abundant data on stream discharges in North Carolina over several decades. Groundwater discharge directly into the estuaries and tidal exchange through the inlets are also important hydrologic processes affecting Albemarle-Pamlico water quality. Yet, there is little information on these processes for the system.

2. Among the vast suite of nutrients essential for primary production, nitrogen and phosphorus have been of most concern as "limiting factors" controlling eutrophication. Accelerated eutrophication is of environmental and economic concern. Frequently, serious water quality degradation, in the form of uncontrolled nuisance algal blooms, accompanies accelerated eutrophication. To varying degrees, symptoms and fully developed cases of eutrophication have affected some tributaries of the Albemarle-Pamlico estuarine system. In all cases, enhanced sediment and soluble nutrient loadings have been identified or suspected as causative agents for some forms of water quality degradation.

3. Sources of pollution are generally grouped into two categories--point sources and nonpoint sources. Point sources of pollution enter a stream or estuary at a discrete location (or point), usually a discharge pipe. Point sources include municipal and private wastewater treatment facilities. These facilities must obtain a permit from the NC Division of Environmental Management which limits the amount of pollution that may be discharged to a given water body. In contrast to point source pollution, nonpoint source pollution is that which enters waters mainly as a result of precipitation and subsequent runoff from land -- primarily from what has been disturbed by man's activities. Examples include runoff from urban areas, agricultural lands and construction sites. Nonpoint source pollution is addressed through a combination of regulatory, cost incentive and voluntary programs.

4. The first detailed study of the metals and toxins in the Albemarle-Pamlico estuarine system is underway. The first phase, the evaluation of heavy metal pollutants in organic-rich muds of the Pamlico River Estuary, has been completed. The Neuse River and Albemarle Sound estuaries will be evaluated by late 1991.

5. There have been at least 5 investigations of bottom sediment characteristics, elemental cycling, and exchange of materials between sediments and overlying waters in the Chowan River, Pamlico River, and Neuse River estuarine systems.

6. In 1988, the NC Division of Environmental Management conducted a water quality assessment of the Albemarle-Pamlico study area as part of the statewide Nonpoint Source Assessment Report to determine impacts from nonpoint sources of pollution. Using information from "monitored" and "evaluated" stream segments, overall water quality ratings were assigned to nearly all stream and estuary segments. In the Albemarle-Pamlico study area, 49% of all stream segments were judged to be un-affected by nonpoint sources of pollution, nearly 40% were partially or seriously impacted, and 11% were not evaluated. In the estuarine portion of the study area, about 93% of the segments were un-affected by nonpoint sources.

7. Despite the scarcity of open-water nutrient and productivity data, a reasonably diverse and comprehensive data bank has been established for some of the main tributaries; the Chowan, Pamlico, and Neuse River Estuaries. The main forms of nutrient inputs are nitrates and phosphates; ammonia is more significant as an "internally cycled" nutrient. Nonpoint sources are thought to be the major contributors of both nitrates and phosphates, although point sources are more significant sources of phosphates than nitrates and during the summer nitrates from point sources become relatively more important.

8. Nitrogen loading and cycling (chiefly as nitrate) are strong determinants in the regulation and ultimate limitation of primary production as well as in bloom development in the freshwater tributaries and diverse estuaries examined to date. Accordingly, nitrogen loading and flux rates, and magnitude, timing, and location of inputs, are of vital importance in assessing production and eutrophication processes in the estuarine portions of the study area. Phosphorus loading, cycling and utilization by phytoplankton, on the other hand, present quite a different picture. There are, indeed, quite high standing concentrations of phosphate in North Carolina coastal waters. In the Pamlico River estuary the concentration is higher than in most similar systems in the country. Whereas inorganic nitrogen is often rapidly depleted during summer phytoplankton growth periods, phosphate concentrations act in a much more conservative fashion, indicating both excess supplies and a general lack of phosphorus limitation. Furthermore, phosphorus is effectively recycled between sediments and the water column, assuring the maintenance of sufficient supplies of phosphate during periods of maximum phytoplankton demand. Exceptions may occur, however, in the Chowan River during bloom periods when high algal biomass leads to parallel depletion of nitrogen and phosphorus. Phosphorus appears to have limiting effects during the high runoff spring months when rapid

dilution can occur, i.e., additions provide stimulation of productivity in the presence of nitrogen.

9. Accelerated nutrient loading, particularly over the past 2 to 3 decades, has ushered in some ominous and increasingly common symptoms of eutrophication, which apparently were extremely rare prior to World War II. However, eutrophication data prior to the mid-1960s do not exist. Trend analysis for the Neuse River Estuary indicates that total phosphorus loadings from all sources increased about 60% during the past century, primarily due to point sources, and total annual nitrogen loading was estimated to have increased about 70%, from both point and nonpoint sources. By contrast, total phosphorus levels in the middle of the Pamlico Estuary have doubled since 1967, with smaller increases in both upstream and downstream sections. Nitrogen concentrations are very similar to those of the Neuse River. No trend analyses have been performed on other estuaries in the study area. It is recommended that a long-term trend analysis be completed for the Albemarle Sound area.

10. Bottom water dissolved oxygen concentration is controlled primarily by climatic and hydrologic factors in the Pamlico River Estuary, the only area where studies have been conducted. There has been no trend toward lower dissolved oxygen concentrations over the past 17 years of record. Low oxygen bottom water (hypoxia) does not occur in the estuary when water temperatures are lower than about 20°C. Above 20°C, dissolved oxygen values of less than 1 mg/liter were found in about 20% of the samples from the upper estuary, but in only 4% of the samples from the lower estuary. Salinity stratification prevents mixing of the bottom water with surface water, which prevents aeration of the bottom water leading to hypoxia. Hypoxia can become established in a short period of time during summer and, conversely, can dissipate very quickly if mixing occurs. A monitoring program needs to be established to provide more consistent data upon which to model hypoxia.

11. There is little or no evidence to support the hypothesis that the Albemarle-Pamlico estuarine sediments are qualitatively much different today than they were in past centuries. Long-term data upon which to base arguments regarding changes and trends in sediment characteristics and subsequent water quality impacts are not available.

12. A model needs to be developed to consider all factors which affect water quality. Although sediment-water exchanges are important to nutrient cycling and metal storage in estuaries, these exchanges are only one flux that dominates cycling in certain places at certain times -- there are many others. A multidisciplinary approach to the physical, chemical and biological interaction of inputs and interactions is the only way that the total picture can be determined.

# LITERATURE CITED

Albert, D.B. 1985. Sulfate reduction and iron sulfide formation in sediments of the Pamlico River Estuary, North Carolina. PhD Dissertation, University of North Carolina at Chapel Hill, Chapel Hill, NC.

Amein, M. and W.S. Galler. 1979. Water quality management model for the lower Chowan River. WRRI Report No. 130. Raleigh: Water Resources Research Institute of the University of North Carolina.

Bales, J.D. and T.M. Nelson. 1988. Bibliography of hydrologic and water quality investigations conducted in or near the Albemarle-Pamlico Sounds region, North Carolina. Open-File Report 88-480, Raleigh: US Geological Survey.

Beeton, A.M. 1965. Eutrophication of the St. Lawrence Great Lakes. Limnology and Oceanography 10:240-254.

Bowden, W.B. and J.E. Hobbie. 1977. Nutrients in Albemarle Sound, North Carolina. Sea Grant Report No. 75-25. Raleigh: University of North Carolina Sea Grant Program.

Carney, C.G. and A.V. Hardy. 1967. North Carolina hurricanes, a listing and description of tropical cyclones which have affected the state. Washington: US Department of Commerce, Environmental Services Administration.

Carpenter, E.J. and D.G. Capone. 1983. Nitrogen in the Marine Environment. New York: Academic Press.

Christian, R.R., W.L. Bryant and D.W. Stanley. 1986. The relationship between river flow and Microcystis aeruginosa blooms in the Neuse River, NC. WRRI Report No. 223. Raleigh: Water Resources Research Institute of the University of North Carolina.

Christian, R.R., W.M. Rizzo and D.W. Stanley. 1987. Influence of nutrient loading on the Neuse River Estuary, North Carolina. In Proceedings of Marine Expo '87, Oceanography Symposium, ed. R. Y. George. Wilmington: University of North Carolina at Wilmington.

Christian, R.R., D.W. Stanley and D.A. Daniel. 1988. Characteristics of a blue-green algal bloom in the Neuse River, North Carolina. Sea Grant Report No. WP87-2. Raleigh: University of North Carolina Sea Grant College Program.

Copeland, B.J. and J.E. Hobbie. 1972. Phosphorus and eutrophication in the Pamlico River Estuary. WRRI Report No. 65. Raleigh: Water Resources Research Institute of the University of North Carolina.

Copeland, B.J., R.G. Hodson, S.R. Riggs and J.E. Easley, Jr. 1983. The ecology of Albemarle Sound, North Carolina: an estuarine profile. Report FWS/OBS-83/01. Washington: US Fish and Wildlife Service, Division of Biological Services.

Copeland, B.J., R.G. Hodson and S.R. Riggs. 1984. The ecology of Pamlico River Estuary, North Carolina: an estuarine profile. Report FWS/OBS-82/06. Washington: US Fish and Wildlife Service, Division of Biological Services.

Craig, N.J. and E.J. Kuenzler. 1983. Land use, nutrient yield, and eutrophication in the Chowan River Basin. WRRI Report No. 205. Raleigh: Water Resources Research Institute of the University of North Carolina.

Crounse, R.G., W.J. Pories, J.T. Bray and R.L. Mauger. 1983a. Geochemistry and man: health and disease. 1. Essential elements, p. 267-302. In Applied Environmental Geochemistry, ed. I. Thornton. London: Academic Press.

Crounse, R.G., W.J. Pories, J.T. Bray and R.L. Mauger. 1983b. Geochemistry and man: health and disease. 2. Elements possibly essential, those toxic and others, p. 309-330. In Applied Environmental Geochemistry, ed. I. Thornton. London: Academic Press.

Daniel, C.C., III. 1977. Digital flow model of the Chowan River Estuary, North Carolina. Water Resources Investigations Report No. 77-63. Raleigh: United States Geological Survey.

Daniel, C.C., III. 1978. Land use, land cover, and drainage on the Albemarle-Pamlico Peninsula, eastern North Carolina, 1974. Water Resources Investigations Report No. 78-134. Washington: United States Geological Survey.

Daniel, C.C., III. 1981. Hydrology, geology, and soils of pocosins -- a comparison of natural and altered systems, p. 69-108. In Pocosin Wetlands -- An Integrated Analysis of Coastal Plain Freshwater Bogs in North Carolina, ed. C.J. Richardson. Stroudsburg, PA: Hutchison Ross Publishing Company.

Davis, G.J., M.M. Brinson and W.A. Burke. 1978. Organic carbon and deoxygenation in the Pamlico River Estuary. WRRI Report No. 131. Raleigh: Water Resources Research Institute of the University of North Carolina.

D'Elia, C.F., J.G. Sanders and W.R. Boynton. 1986. Nutrient enrichment studies in a coastal plain estuary: phytoplankton growth in large-scale continuous cultures. Canadian Journal of Fisheries and Aquatic Science 43:397-406.

Dubach, H. W. 1977. North Carolina coastal zone and its environment. Report No. 147. Aiken: US Department of Energy, Savannah River Laboratory.

Ebersole, B.A. 1982. Wave information study for US coastlines; Atlantic Coast water level climate. Report No. 7, HL-80-11. Vicksburg: US Army Engineer Waterways Experiment Station.

Esch, G. and T. Hazen. 1983. The ecology of Aeromonas hydrophila in Albemarle Sound, NC. WRRI Report No. 153. Raleigh: Water Resources Research Institute of the University of North Carolina.

Evans, R.O., J.W. Gilliam, R.W. Skaggs and W.L. Lemke. 1987. Effects of agricultural water management on drainage water quality. Proceedings of the Fifth National Drainage Symposium, 210-219. St. Joseph, MO: American Society of Agricultural Engineering.

Gakstatter, J.H., M.O. Allum, S.E. Dominquez and M.R. Crouse. 1978. A survey of phosphorus and nitrogen levels in treated municipal wastewater. Journal of the Water Pollution Control Federation 50:718-722.

Giese, G.L., H.B. Wilder and G.G. Parker, Jr. 1985. Hydrology of major estuaries and sounds of North Carolina. Water Supply Paper 2221. Raleigh: US Geological Survey.

Gilliam, J.W., R.W. Skaggs and S.B. Weed. 1978. An evaluation of the potential for using drainage control to reduce nitrate loss from agricultural fields to surface waters. WRRI Report No. 128. Raleigh: Water Resources Research Institute of the University of North Carolina.

Gilliam, J.W., J.M. Miller, L.J. Pietrafesa and R.W. Skaggs. 1985. Water management and estuarine nurseries. Sea Grant Report No. WP85-2. Raleigh: University of North Carolina Sea Grant College Program.

Graneli, E., K. Wallstrom, U. Larson, W. Graneli, R. Elmgren. 1990. Nutrient Limitation of Primary Production in the Baltic Sea Area. Ambio 19:142-151.

Gregory, J.D., R.W. Skaggs, R.G. Broadhead, R.H. Culbreath, J.R. Bailey and T.L. Foutz. 1984. Hydrologic and water quality impacts of peat mining in the coastal zone of North Carolina. WRRI Report No. 214. Raleigh: Water Resources Research Institute of the University of North Carolina.

Harned, D.A. and M.S. Davenport. 1990. Water Quality Trends and Basin Activities and Characteristics for the A/P Estuary System, NC and VA. Open File Report 90-398. Raleigh: US Geological Survey, 164 p.

Harris, D.L. 1981. Tides and tidal datums in the United States. Special Report No. SR-7. Fort Belvoir: US Army Coastal Engineering Research Center.

Harrison, W.G. and J.E. Hobbie. 1974. Nitrogen Budget of a North Carolina estuary. WRRI Report No. 86. Raleigh: Water Resources Research Institute of the University of North Carolina.

Hasler, A.D. 1947. Eutrophication of lakes by domestic sewage. Ecology 28:383-395.

Heath, R.C. 1975. Hydrology of the Albemarle-Pamlico region, North Carolina: a preliminary report on the impact of agricultural developments. Water Resources Investigations Report No. 9-75. Raleigh: US Geological Survey.

Hecky, R.E. and P. Kilham. 1988. Nutrient limitation of phytoplankton in freshwater and marine environments: A Review of recent evidence on the effects of enrichment. Limnology and Oceanography 33:796-822.

Ho, F.P. and R.J. Tracey. 1975. Storm tide frequency analysis for the coast of North Carolina north of Cape Lookout. Report No. NWS HYDRO-27. Rockville, Maryland: National Weather Service, National Oceanic and Atmospheric Administration.

Hobbie, J.E. 1970a. Hydrography of the Pamlico River Estuary, NC. WRRI Report No.70-39. Raleigh: Water Resources Research Institute of the University of North Carolina.

Hobbie, J.E. 1970b. Phosphorus concentrations in the Pamlico River estuary of North Carolina. WRRI Report No. 33. Raleigh: Water Resources Research Institute of the University of North Carolina.

Hobbie, J.E. 1971. Phytoplankton species and populations in the Pamlico River estuary of North Carolina. WRRI Report No. 56. Raleigh: Water Resources Research Institute of the University of North Carolina.

Hobbie, J.E. 1974. Nutrients and eutrophication in the Pamlico River Estuary 1971-73. WRRI Report No. 100. Raleigh: Water Resources Research Institute of the University of North Carolina.

Hobbie, J.E., B.J. Copeland and W.G. Harrison. 1972. Nutrients in the Pamlico Estuary, NC, 1969-1971. WRRI Report No. 76. Raleigh: Water Resources Research Institute of the University of North Carolina.

Hobbie, J.E. and N.W. Smith. 1975. Nutrients in the Neuse River Estuary. Sea Grant Report No. 75-21. Raleigh: University of North Carolina Sea Grant Program.

Holman, R.E. 1989. Baseline water quality monitoring plan. Albemarle-Pamlico Estuarine Study Project 88-01/02. Raleigh: NC Department of Natural Resources and Community Development.

Horton, D.B., E.J. Kuenzler and W.J. Woods. 1967. Current studies in the Pamlico River and Estuary of North Carolina. WRRI Report No. 6. Raleigh: Water Resources Research Institute of the University of North Carolina.

Humenik, F.J., B.A. Young and F.A. Koehler. 1983. Investigation of strategies for reducing agricultural nonpoint sources in the Chowan River. WRRI Report No. 211. Raleigh: Water Resources Research Institute of the University of North Carolina.

Jackson, N.M., Jr. 1968. Flow of the Chowan River, North Carolina -- a study of the hydrology of an estuary primarily affected by winds. Open File Report. Raleigh: US Geological Survey.

Jacobs, T.C. and J.W. Gilliam. 1983. Nitrate loss from agricultural drainage waters: Implications for nonpoint source control. WRRI Report No. 209. Raleigh: Water Resources Research Institute of the University of North Carolina.

Kirby-Smith, W.W. and R.T. Barber. 1979. The water quality ramifications in estuaries of converting forest to intensive agriculture. WRRI Report No. 148. Raleigh: Water Resources Research Institute of the University of North Carolina.

Knowles, C.E. 1975. Flow dynamics of the Neuse River, North Carolina, for the period 7 August to 14 September, 1973. Sea Grant Report No. 75-16. Raleigh: University of North Carolina Sea Grant Program.

Kuenzler, E.J., D.W. Stanley and J.P. Koenings. 1979. Nutrient kinetics of phytoplankton in the Pamlico River, North Carolina. WRRI Report No. 139. Raleigh: Water Resources Research Institute of the University of North Carolina.

Kuenzler, E.J., K.L. Stone and D.B. Albert. 1982. Phytoplankton uptake and sediment release of nitrogen and phosphorus in the Chowan River, North Carolina. WRRI Report No. 186. Raleigh: Water Resources Research Institute of the University of North Carolina.

Kuenzler, E.J., D.B. Albert, G.S. Algood, S.E. Cabaniss, and C.G. Wanat. 1984. Benthic nutrient cycling in the Pamlico River. WRRI Report No. 215. Raleigh: Water Resources Research Institute of the University of North Carolina.

Lauria, D.T. and C.R. O'Melia. 1980. Nutrient models for engineering management of the Pamlico River. WRRI Report No. 146. Raleigh: Water Resources Research Institute of the University of North Carolina.

Likens, G.E. 1972a. Eutrophication and aquatic ecosystems. In Nutrients and eutrophication: The limiting-nutrient controversy, ed. G. E. Likens, 3-13. American Society of Limnology and Oceanography Symposium Vol. 1.

Likens, G.E., Ed. 1972b. Nutrients and eutrophication: The limiting-nutrient controversy. American Society of Limnology and Oceanography Special Symposium Vol. 1.

Lung, W.S. and H.W. Paerl. 1988. Modeling blue-green algal blooms in the Lower Neuse River. NC Water Resources 22:895-905.

MacKintosh, S.L. 1979. A bioassay study of nutrient limitation in the lower Chowan River, NC. Undergraduate Research Studies Report. University of North Carolina at Chapel Hill, Institute of Marine Sciences, Morehead City, NC.

Mallin, M.A. 1991. Zooplankton abundance and community structure in a mesohaline North Carolina estuary. Estuaries. (In Press).

Mallin, M.A. and H.W. Paerl. 1991. Effects of variable light on shallow-water estuarine phytoplankton productivity. (Submitted).

Mallin, M.A., H.W. Paerl, and J. Rudek. 1991. Seasonal phytoplankton composition, productivity, and biomass in the Neuse River Estuary, North Carolina. Estuarine and Coastal Shelf Science. (In Press).

Mann Associates, Inc. 1984. A Management Plan for Back Bay, City of Virginia Beach, Virginia. Volumes 1 and 2.

Marshall, N. 1951. Hydrography of North Carolina marine waters. In Survey of Marine Fisheries of North Carolina, ed. H. F. Taylor, 1-76. Chapel Hill: University of North Carolina Press.

Matson, E.A., M.M. Brinson, D.D. Cahoon and G.J. Davis. 1983. Biogeochemistry of the sediments of the Pamlico and Neuse River Estuaries, North Carolina. WRRI Report No. 191. Raleigh: Water Resources Research Institute of the University of North Carolina.

National Acid Precipitation Assessment Program. 1988. Annual Report to the President and Congress, January 13, 1989. Washington, D.C.

Neilson, B.J. and L.E. Cronin, Eds. 1981. Estuaries and Nutrients. Clifton, NJ: Humana Press.

Nixon, S.W. 1983. Estuarine ecology -- a comparative and experimental analysis using 14 estuaries and the MERL microcosms. Report to the US Environmental Protection Agency, Chesapeake Bay Program. Narragansett, RI.

Nixon, S.W. 1986. Nutrient dynamics and the productivity of marine coastal waters. In Marine Environment and Pollution, eds. R. Halwagy, D. Clayton and M. Behbehani, 97-115. New York: Alden Press.

Nixon, S.W. 1989. Water quality in the Pamlico River estuary -- with special attention to the possible impacts of nutrient discharges from TexasGulf, Inc. Report to TexasGulf, Inc. Raleigh.

NC Division of Environmental Management. 1982. Chowan/Albemarle action plan. Report to NC Environmental Management Commission. Raleigh.

NC Division of Environmental Management. 1985. Assessment of surface water quality in North Carolina. Report No. 8501. Raleigh: NC Department of Natural Resources and Community Development.

NC Division of Environmental Management. 1989a. North Carolina Nonpoint Source Management Program. Report No. 89-01. Raleigh: NC Department of Natural Resources and Community Development.

NC Division of Environmental Management. 1989b. North Carolina Nonpoint Source Assessment Report. Report No. 89-02. Raleigh: NC Department of Natural Resources and Community Development.

Novotny, V. and G. Chesters. 1981. Handbook of Nonpoint Pollution Sources and Management. New York: Van Nostrand Reinhold Company.

Officer, C.B., R.B. Biggs, J.L. Taft, L.E. Cronin, M.A. Taylor, and W.R. Boynton. 1984. Chesapeake Bay anoxia: origin, development, and significance. Science 223:22-27.

Overton, M.F., J.S. Fisher, J.M. Miller and L.J. Pietrafesa. 1988. Freshwater inflow and Broad Creek Estuary, North Carolina. Special Report. Raleigh: University of North Carolina Sea Grant College Program.

Paerl, H.W. 1982a. Environmental factors promoting and regulating $N_2$ fixing blue-green algal blooms in the Chowan River, NC. WRRI Report No. 176. Raleigh: Water Resources Research Institute of the University of North Carolina.

Paerl, H.W. 1982b. Factors limiting productivity of freshwater ecosystems. Advanced Microbial Ecology 6:75-110.

Paerl, H.W. 1983. Factors regulating nuisance blue-green algal bloom potentials in the lower Neuse River, NC. WRRI Report No. 188. Raleigh: Water Resources Research Institute of the University of North Carolina.

Paerl, H.W. 1985. Enhancement of marine primary production by nitrogen-enriched acid rain. Nature 316:747-749.

Paerl, H.W., P.T. Bland, J.H. Blackwell and N.D. Bowles. 1984. The effects of salinity on the potential of a blue-green algal bloom. Sea Grant Report No. WP84-1. Raleigh: University of North Carolina Sea Grant Program.

Paerl, H.W. and N.D. Bowles. 1986. Dilution bioassays: Their application to assessments of nutrient limitation in hypereutrophic waters. Hydrobiologia 146:265-273.

Paerl, H.W. 1987. Dynamics of blue-green algal (Microcystis aeruginosa) blooms in the Lower Neuse River, NC: Causative factors and potential controls. WRRI Report No. 229. Raleigh: Water Resources Research Institute of the University of North Carolina.

Paerl, H.W., M.A. Mallin, J. Rudek, and P.W. Bates. 1990. The potential for eutrophication and nuisance algal blooms in the Albemarle-Pamlico Estuary, NC. Albemarle-Pamlico Estuarine Study Project No. (EPA-CE 00470601).

Pate, P.P. and R. Jones. 1981. Effects of upland drainage on estuarine nursery areas of Pamlico Sound, North Carolina. Sea Grant Report No. WP81-10. Raleigh: University of North Carolina Sea Grant Program.

Pietrafesa, L.J., G.S. Janowitz, T.Y. Chao, R.H. Weisberg, F. Askari and E. Noble. 1986. The physical oceanography of Pamlico Sound. Sea Grant Report No. WP86-5. Raleigh: University of North Carolina Sea Grant Program.

Ragland, B.C., R.G. Garrett, R.G. Barker, W.H. Eddins and J.F. Rinehardt. 1987. Water resources data, North Carolina, water year 1987. Data Report No. 87-1. Raleigh: US Geological Survey. 542 p.

Renfro, W.C. 1973. Transfer of $^{65}$Zn from sediments by marine polychaete worms. Marine Biology 21:305-316.

Riggs, S.R., E.R. Powers, J.T. Bray, P.M. Stout, C. Hamilton, D. Ames, S. Lucas, R. Moore, J. Watson and M. Williamson. 1989. Heavy metal pollutants in organic-rich muds of the Pamlico River estuarine system: their concentration, distribution, and effects upon benthic environments and water quality. Albemarle-Pamlico Estuarine Study Report. Raleigh: NC Department of Health, Environment, and Natural Resources.

Riggs, S.R., J.T. Bray, E.R. Powers, C. Hamilton, D. Ames, D. Yeates, K. Owens, S. Lucas, J. Watson, and M. Williamson. In Press. Heavy metal pollutants in organic-rich muds of the Neuse River Estuary: their concentration and distribution. Albemarle-Pamlico Estuarine Study Report. Raleigh: NC Department of Health, Environment, and Natural Resources.

Roelofs, E.W. and D.F. Bumpus. 1953. The hydrography of Pamlico Sound. Bulletin of Marine Science of the Gulf and Caribbean 3: 181-205.

Rudek, J., H.W. Paerl, M.A. Mallin, and P.W. Bates. 1991. Seasonal and hydrological control of phytoplankton nutrient limitation in the Neuse River Estuary, NC. Marine Ecology Pro. Ser. (Submitted).

Ruttner, F. 1963. Fundamentals of Limnology. 3rd ed. Toronto: University of Toronto Press.

Ryther, J.H. and W.M. Dunstan. 1971. Nitrogen, phosphorus, and eutrophication in the coastal marine environment. Science 171:1008-1013.

Sauer, M.M. and E.J. Kuenzler. 1981. Algal assay studies of the Chowan River, NC. WRRI Report No. 161. Raleigh: Water Resources Research Institute of the University of North Carolina.

Schelske, C.L. and E.F. Stoermer. 1971. Eutrophication, silica depletion, and predicted changes in algal quality in Lake Michigan. Science 173:423-424.

Schindler, D.W. 1974. Eutrophication and recovery in experimental lakes: Implications for lake management. Science 184:897-899.

Schindler, D.W. 1977. Evolution of phosphorus limitation in lakes. Science 195:260-262.

Schwartz, F.J. and A.F. Chestnut. 1973. Hydrographic atlas of North Carolina estuarine and sound waters, 1972. Sea Grant Report No. SG73-12. Raleigh: University of North Carolina Sea Grant Program.

Seliger, H.H. and J.A. Boggs. 1988. Anoxia in Chesapeake Bay. Paper presented at the 1988 Ocean Sciences Meeting. American Geophysical Union and the American Society of Limnology and Oceanography. New Orleans.

Sholar, T.M. 1980. Preliminary analysis of salinity levels for the Pamlico Sound area. NC Division of Marine Fisheries Report. Morehead City, NC.

Showers, W.J., D. Eisenstein, H.W. Paerl and J. Rudek. In Prep. Stable isotope tracers of nutrient sources to the Neuse River, NC. Project Completion Report for the Water Resources Research Institute of the University of North Carolina. Raleigh.

Simmons, C.E. 1988. Sediment Characteristics of North Carolina Streams, 1970-19. Open File Report 87-701. Raleigh: US Geological Survey.

Singer, J.J. and C.E. Knowles. 1975. Hydrology and circulation patterns in the vicinity of Oregon Inlet and Roanoke Island, North Carolina. Sea Grant Report No. SG75-15. Raleigh: University of North Sea Grant Program.

Skaggs, R.W., J.W. Gilliam, T.J. Sheets and J.S. Barnes. 1980. Effect of agricultural land development on drainage waters in the North Carolina Tidewater region. WRRI Report No. 159. Raleigh: Water Resources Research Institute of the University of North Carolina.

Stanley, D.W. 1983. Nitrogen cycling and phytoplankton growth in the Neuse River, NC. WRRI Report No. 204. Raleigh: Water Resources Research Institute of the University of North Carolina.

Stanley, D.W. 1985. Nationwide review of oxygen depletion and eutrophication in estuarine and costal waters: southeast region. Report to Brookhaven National Laboratory and the US Department of Commerce. Washington, D.C.

Stanley, D.W. 1988a. Historical trends in nutrient loading to the Neuse River estuary, NC. In Proceedings of the Coastal Water Resources Symposium, ed. W.L. Kyle and T.J. Hoban, 155-164. Wilmington, NC: American Water Resources Association.

Stanley, D.W. 1988b. Water quality in the Pamlico River estuary, 1967-1986. Report 88-01. Greenville, NC: Institute of Marine and Coastal Resources, East Carolina University.

Stanley, D.W. and D.A. Daniel. 1985. Seasonal phytoplankton density and biomass changes in South Creek, North Carolina. Journal of the Elisha Mitchell Society 101(2):130-141.

Stanley, D.W. and J.E. Hobbie. 1977. Nitrogen recycling in the Chowan River. WRRI Report No. 121. Raleigh: Water Resources Research Institute of the University of North Carolina.

Steidinger, K.A. 1983. A re-evaluation of toxic dinoflagellate biology and ecology. Progress in Phycology Research 2:147-188.

Stewart, W.D.P. 1974. Algal Physiology and Biochemistry. Oxford: Blackwell Scientific Publishers.

Tedder, S.W., J. Sauber, J. Ausley, and S. Mitchell. 1980. Neuse River Investigations 1979. Working Paper. NC Division of Environmental Management. Raleigh.

Tenore, K.R. 1970. The macrobenthos of the Pamlico River estuary, North Carolina. WRRI Report No. 40. Raleigh: Water Resources Research Institute of the University of North Carolina.

Tenore, K.R. 1972. Macrobenthos of the Pamlico River estuary, North Carolina. Ecological Monographs 42:51-69.

Treece, M.W. and J.D. Bales. 1990. Hydrologic and water quality effects of artificial drainage control. In NC Department of EHNR Project Abstracts for 1990; A/P Study Project No. 90-18; Raleigh, N.C.

Turner, R.E., W.W. Schroeder and W.J. Wiseman, Jr. 1987. The role of stratification in the deoxygenation of Mobile Bay and adjacent shelf bottom waters. Estuaries 10:13-19.

Vollenweider, R.A. 1968. Scientific fundamentals of eutrophication of lakes and flowing waters, with particular reference to nitrogen and phosphorus as factors of eutrophication. Report No. DAS/CSC/68.27. Paris: OECD.

Wells, J.T. 1989. A scoping study of the distribution, composition, and dynamics of water-column and bottom sediments: Albemarle-Pamlico estuarine system. Albemarle-Pamlico Estuarine Study Report on Project 89-05. Raleigh: NC Department of Health, Environment, and Natural Resources.

Wetzel, R.G. 1975. Limnology. Philadelphia: Saunders Publishing Company.

Wilder, H.B., T.M. Robison and K.L. Lindskov. 1978. Water resources of northeast North Carolina. Water-Resources Investigations Report No. 77-81. Raleigh: US Geological Survey.

Williams, A.B., G.S. Posner, W.J. Woods and E.E. Deubler. 1973. A hydrographic atlas of larger North Carolina Sounds. Sea Grant Report No. SG73-02. Raleigh: University of North Carolina Sea Grant Program.

Winner, M.D. and C.E. Simmons. 1977. Hydrology of the Creeping Swamp watershed, North Carolina, with reference to potential effects of stream channelization. Water Resources Investigations Report No. 77-26. Raleigh: US Geological Survey.

Witherspoon, A.M., C. Balducci, O.C. Boody and J. Overton. 1979. Response of phytoplankton to water quality in the Chowan River system. WRRI Report No. 129. Raleigh: Water Resources Research Institute of the University of North Carolina.

Wolfe, D.A. and T.R. Rice. 1972. Cycling of elements in estuaries. Fisheries Bulletin 70:959-972.

Woods, W.J. 1969. Current study in the Neuse River and Estuary of North Carolina. WRRI Report No. 13. Raleigh: Water Resources Research Institute of the University of North Carolina.