HISTORICAL TRENDS

WATER QUALITY AND FISHERIES: ALBEMARLE-PAMLICO SOUNDS

With Emphasis on the Pamlico River Estuary

Donald W. Stanley

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
COASTAL OCEAN OFFICE
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A Report to the
National Ocean Pollution Program
and the
National Sea Grant College Program

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September 1992

U.S. DEPARTMENT OF COMMERCE
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This publication is sponsored by the National Ocean Pollution Program, National Oceanic and Atmospheric Administration, U.S. Department of Commerce. The project was administered under grant NA86AA-D-SG046 as project R/SF-2 through the UNC Sea Grant College Program, North Carolina State University, Raleigh, NC. Additional support came from Texasgulf Chemicals, Inc., and from East Carolina University.

Additional copies of this publication are available from UNC Sea Grant, Box 8605, North Carolina State University, Raleigh, NC 27695-8605. Order UNC-SG-92-04.

This document should be referenced as:
Stanley, Donald W. 1992. Historical Trends: Water Quality and Fisheries, Albemarle-Pamlico Sounds, With Emphasis on the Pamlico River Estuary. University of North Carolina Sea Grant College Program Publication UNC-SG-92-04. Institute for Coastal and Marine Resources, East Carolina University, Greenville, NC. 215 pp.

Cover Illustration: Drawn by Steve Daniels, and reproduced from Doug Young (editor). 1980. North Carolina and the Sea, *prepared by the North Carolina Marine Science Council, N.C. Office of Marine Affairs, N.C. Department of Administration, Raleigh, NC.*

Contents

Preface

Despite great interest in — and large expenditures for — estuarine water quality and fisheries management, there have not been evaluations of long-term trends in conditions of most of our estuaries. Consequently, little is known about the effectiveness of past and present management programs.

This is one of several products of a study of long-term trends in water quality and fishery resources in three important U.S. estuaries: 1) Narragansett Bay, Rhode Island, 2) the Albemarle-Pamlico Sound system in North Carolina, and 3) Galveston Bay, Texas. The project had four specific objectives:

1. To document long-term trends in water quality and, where possible, identify causes, consequences and significance.

2. To assess whether problems are similar or unique to each estuary.

3. To assess whether progress is being made in improving conditions in water quality and fishery resources and whether there are examples of success that would be useful for estuarine managers and researchers elsewhere.

4. To glean examples of the useful integration of research and policy.

The three estuaries chosen for this study have sufficient long-term data to permit trend analyses and inter-estuarine comparisons. In two of them, monitoring programs have been carried out for at least two decades. The Texas Department of Health and the Texas Water Commission and its predecessors, the Water Quality Board and the Department of Water Resources, have been monitoring dissolved oxygen, nutrients, metals and bacteria at many stations in Galveston Bay and along the Houston Ship Channel since the late 1960s. Likewise, there is a twenty-five year record of water quality from 20-30 stations in the Pamlico River Estuary in North Carolina. In the third estuary, Narragansett Bay, no routine monitoring program has been carried out, but enough independent studies have incorporated water quality parameters to permit construction of a comparable long-term data set. In addition to water quality data bases, there are catch statistics and records of management efforts for important fisheries in each bay.

These estuaries are characterized by a range of pollution problems, some of which are unique to each, while others are shared by all. Narragansett Bay and Galveston Bay represent heavily industrialized, urban estuaries with a long history of pollution. They are subjected to intense port and shipping activities, massive industrial discharges and major domestic sewage loadings from urbanized centers of population: Houston in Galveston Bay; and Providence, Central Falls and East Providence in Narragansett Bay. In contrast, the Albemarle-Pamlico Sound system is a relatively undeveloped estuary without major shipping lanes, industrial activity or a densely urbanized coastline. Instead, it is characterized by extensive wetlands along its shoreline with agriculture and forests as the major land use types within its watershed. Yet it also is perceived as having a history of water quality problems.

This is one of three separate — but comparable — reports that have been prepared on trends in pollutant loadings, water quality and pertinent fisheries for each of the estuaries. The other two are:

Stanley, Donald W. 1992. Historical Trends: Water Quality and Fisheries, Galveston Bay. University of North Carolina Sea Grant College Program Publication UNC-SG-92-03. Institute for Coastal and Marine Resources, East Carolina University, Greenville, NC. 100 pp.

Desbonnet, A. and V. Lee. 1991. Historical Trends: Water Quality and Fisheries, Narragansett Bay. The University of Rhode Island Coastal Resources Center Contribution No. 100 and National Sea Grant Publication #RIU-T-91-001. Graduate School of Oceanography, Narragansett, RI. 101 pp.

Three major topics are covered in this report: 1) nutrient production in the drainage basin, 2) estuarine water quality, and 3) fisheries. Preceding the first of these are two introductory chapters. The first gives some basic information about the physical setting, hydrology, uses, and living resources of the Albemarle-Pamlico estuarine system. Chapter 2 briefly summarizes the major environmental issues for the estuary. In Chapter 3 I attempt to develop an estimate of changes in potential point and nonpoint source nutrient loading to the estuary over the past century. Actually, this part of the study was not included in the original research plan. Rather, it evolved from a combination of my curiosity about what nutrient loading rates to the estuary might have been in the past, before "cultural" eutrophication, and my frustration resulting from the lack of adequate riverine nutrient concentration data upon which to base a direct estimate of historical loading trends.

Chapter 4 deals with historical trends in water quality within the estuary. For a number of reasons, water quality sampling in the Albemarle-Pamlico region has been very uneven. Only one sub-estuary, the Pamlico River, has been sampled intensively on a continuous basis over the past two decades. Two others, the lower Chowan River and the Neuse River, have been sampled intensively during studies lasting 2-to-5 years, and infrequently at other times. The open waters of Albemarle Sound were sampled intensively for a two-year period in the early 1970s, but there has never been an intensive water quality sampling for the open waters of Pamlico Sound. Because the Pamlico River data set is, by far, the most comprehensive, I have decided to restrict my analysis of trends in water quality to this sub-estuary.

One of the most widely-held perceptions about the Pamlico River is that it has worse bottom-water dissolved "problems" now than in the past, and that this is adversely impacting the estuary's fishery resources. Hence, Chapter 5 addresses the factors responsible for low dissolved oxygen episodes in the estuary. Chapter 6 summarizes some information about comparisons between the Pamlico River and other estuaries, in terms of nutrient and phytoplankton concentrations.

Historical records of commercial landings of finfish and shellfish are available on a county-by county basis for all of the Albemarle-Pamlico region. Unfortunately, however, the data reflect where the fish were brought to shore, not where they were caught, so that it is impossible to equate landings in counties around the Pamlico River Estuary to catch in the estuary. Thus, in Chapter 7 report, which examines trends in fisheries, I was forced into looking at the Albemarle-Pamlico region as a whole, rather than focusing on individual sub-estuaries.

Primary funding for this research was provided by the National Ocean Pollution Program Office of the National Oceanic and Atmospheric Administration, U.S. Department of Commerce. The project was administered as Grant R/SF-2 through the UNC Sea Grant College Program, North

Carolina State University, Raleigh, NC. Additional support came from Texasgulf Chemicals, Inc. and from East Carolina University.

Several persons in North Carolina and Virginia state agencies provided courteous and friendly assistance as I collected the information needed for the study. They include:

Mr. David Clawson, District Sanitarian, Shellfish Sanitation Program, Division of Marine Fisheries, North Carolina Department of Natural Resources and Community Development, Morehead City;

Mr. George Gilbert, Assistant Supervisor, Shellfish Sanitation Program, Division of Marine Fisheries, North Carolina Department of Natural Resources and Community Development, Morehead City;

Mr. Jeff French, Marine Biologist, Division of Marine Fisheries, North Carolina Department of Natural Resources and Community Development, Morehead City;

Ms. Katy West, Division of Marine Fisheries, North Carolina Department of Natural Resources and Community Development, Morehead City;

Staff of the U.S. Government Documents Section of the North Carolina State University Library, Raleigh;

Staff of the Virginia State Library, Richmond; and

Ms. Renee Hawkins of the Virginia State Water Control Board, Richmond.

Many hundreds of hours were spent transcribing data from the printed records into computer files. East Carolina University students and staff involved in this task included Ray Taft, Jeff Taft, Sharon Reid, Colleen Reid, Deborah Daniel, Anne Anderson and Kay Evans. I thank M. Brinson, J. Dorney, and K. Evans for reviewing an earlier draft. Mark Hollingsworth provided invaluable assistance in the preparation of the final draft.

Greenville, North Carolina D.W.S.
December, 1991

CHAPTER 1

Profile of the Albemarle-Pamlico Estuarine System

It is not the purpose of this chapter to provide a comprehensive analysis of the ecology of the Albemarle-Pamlico Estuary. Rather, it is a brief sketch intended to focus the reader's attention on the system's features which are most relevant to the water quality and fisheries data that will be presented below. Details of the ecology of the Pamlico River Estuary and Albemarle Sound can be found in two *Estuarine Profiles* by Copeland et al. (1983; 1984). Giese et al. (1979) provide details of the hydrology of each of the major sub-estuaries in the Albemarle-Pamlico Sound system.

Say "coast" in North Carolina, and everybody thinks beach, specifically the broad, sandy aprons of the barrier islands. Everything west of the beach is merely something through which to pass en route to the water. And there is plenty of water.

It sometimes seems as if nature created the Coastal Plain so water would have something to lap against and sky would have something to rest upon. The Coastal Plain is a beautiful mosaic: sun-bleached tidal marsh as broad as the eye can follow; level beach planing into the surf; mullet skipping on the water of the sound; boats of every size, shape and design; and magnificent flights of ducks and geese. Arrow-straight highways where rows of crops flicker past the window like pickets on a fence. You can plow it, graze it, till it, timber it, fish it, trap it, swim it, and sail it. Bask in its warmth, boat it, run it, drive it and follow it through centuries by reading its history in church graveyards.

It is, above all, a land in community with water and plow, where the good earth and bountiful sea provide all the rewards needed to those who spill their sweat.

G. Morris (1985)

The Physical-Chemical Environment

The Pamlico Sound covers an area of about 5,335 km^2, making it the largest sound formed behind the barrier beaches along the Atlantic Coast of the United States. Giese et al. (1979) estimate that the total volume of water in the sound averages about 26 billion m^3, or about 21 million acre-feet. The average depth is only about 4.9 m, and the maximum depth is only 7.3 m (Figure 1.1 and Table 1.1).

There are numerous tributaries and embayments along the western shore of the Pamlico Sound. Two of these — the Tar-Pamlico River Estuary and the Neuse River Estuary — are by far the largest. The Tar-Pamlico extends approximately 65 km from near the town of Washington, NC to its confluence with Pamlico Sound. Actually, the Tar River and the Pamlico River are one in the same. The Tar River is the major freshwater source for the estuary, but downstream from Washington, the name Pamlico River has traditionally been used. The combined surface area of the Tar-Pamlico Estuary and its sub-tributaries is about 582 km^2. However,

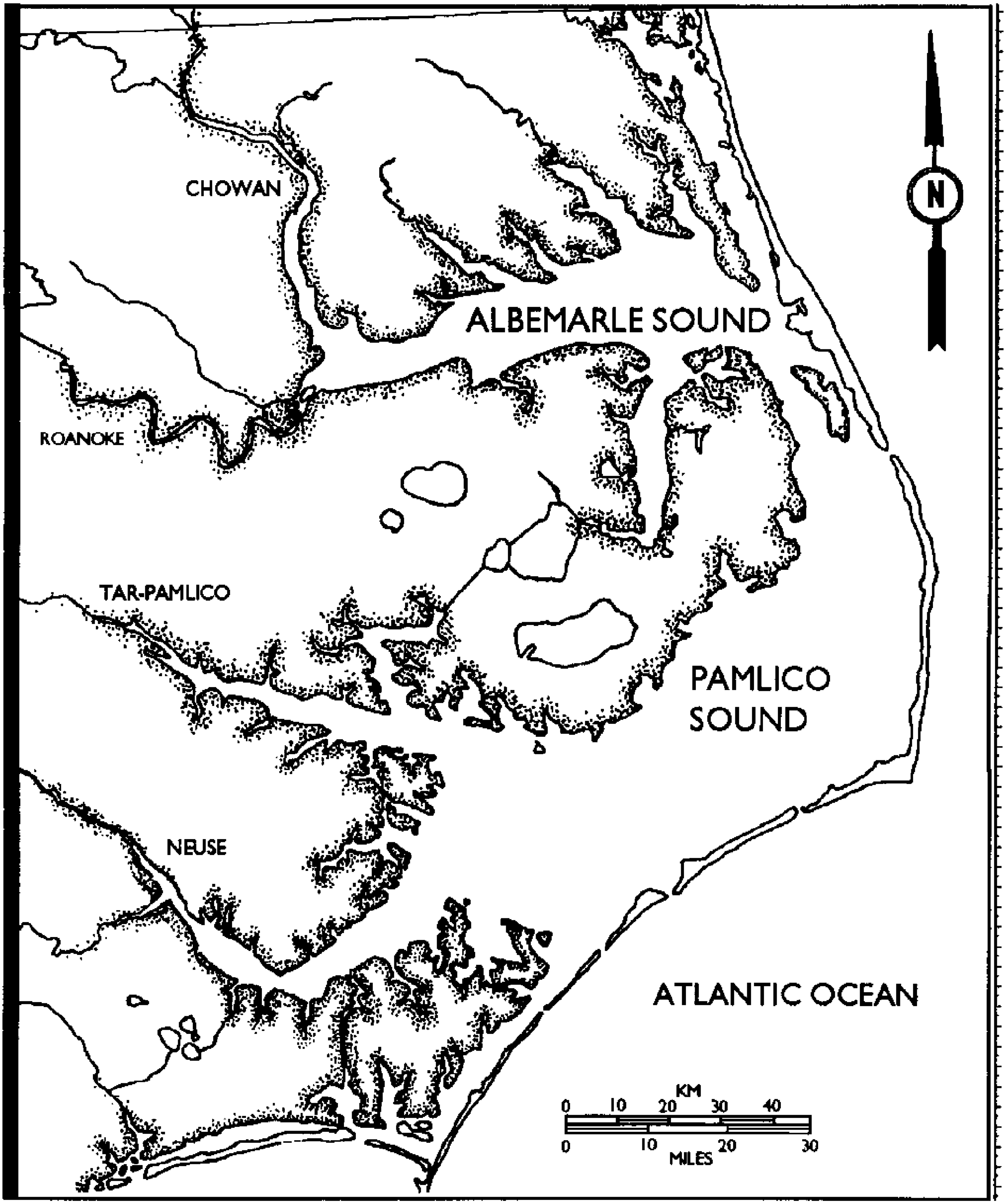


Figure 1.1. *Map of the Albemarle-Pamlico Estuarine System.*

depths are shallow, averaging only about 3.4 m. The other important Pamlico Sound tributary embayment is the Neuse River Estuary. Beginning near the confluence of the Neuse River and the smaller Trent River at New Bern, NC, the Neuse River Estuary extends 65 km to the mouth in the southwest corner of Pamlico Sound, only a short distance south of the mouth of the Tar-Pamlico River estuary. The Neuse Estuary is similar in size and depth to the Tar-Pamlico. The Neuse covers approximately 394 km^2, and averages 3.6 m in depth.

The Albemarle Sound, extending about 88 km from the mouths of the Roanoke and Chowan Rivers eastward to the outer banks, covers an area of about 2,419 km^2. It averages about 11 km wide, and has a maximum depth of nearly 9 m, but most of the central area of the bay is little more than 5.5 m deep. Its volume is about 5,310,000 acre feet (Giese et al. 1979).

Table 1.1. *Hydrologic data for Albemarle and Pamlico Sounds (from Giese et al. 1979).*

A. *Drainage area*				
Albemarle Sound	**17,879**	**mi^2**	**46,309**	**km^2**
Chowan River	**4,943**	**mi^2**	**12,802**	**km^2**
Roanoke River	**9,666**	**mi^2**	**25,035**	**km^2**
Other	**3,288**	**mi^2**	**8,516**	**km^2**
Pamlico Sound	**10,460**	**mi^2**	**27,092**	**km^2**
Tar-Pamlico River	**4,300**	**mi^2**	**11,137**	**km^2**
Neuse River	**5,598**	**mi^2**	**14,499**	**km^2**
Other	**562**	**mi^2**	**1,456**	**km^2**
Total	**28,357**	**mi^2**	**73,445**	**km^2**
B. *Surface area*				
Albemarle Sound & tributaries	**934**	**mi^2**	**2,419**	**km^2**
Pamlico Sound & tributaries	**2,064**	**mi^2**	**5,335**	**km^2**
Pamlico River estuary	**225**	**mi^2**	**582**	**km^2**
Neuse River estuary	**152**	**mi^2**	**394**	**km^2**
Total	**2,998**	**mi^2**	**7,765**	**km^2**
C. *Volume*				
Albemarle Sound	**5,310,000**	**acre-ft**	**6.5**	**km^3**
Pamlico Sound	**21,000,000**	**acre-ft**	**26**	**km^3**
Pamlico River estuary	**662,308**	**acre-ft**	**0.82**	**km^3**
Neuse River estuary	**1,082,306**	**acre-ft**	**1.34**	**km^3**
D. *Average Depth*				
Albemarle Sound	**15**	**ft**	**4.6**	**m**
Pamlico Sound	**16**	**ft**	**4.9**	**m**
Pamlico River estuary	**11**	**ft**	**3.4**	**m**
Neuse River estuary	**12**	**ft**	**3.6**	**m**

Geological Origin and Evolution

The Albemarle-Pamlico system began to form sometime after 17,000 years BP, when the last major glacial ice advance reached its maximum development. At that time sea level was as much as 130-160 m lower than today. Consequently, the shoreline was far out on the continental shelf. Sand dunes were built up along the shore by winds blowing toward the land. As the ice melted and sea level rose again, between 17 thousand and 5 thousand years ago, these dunes were separated from the shore in places, thus forming a string of barrier islands. Breaching during storms caused inlets to develop and lagoons to be flooded and eventually become wide, shallow sounds. Further sea level rise, as well as continual wave action, caused the islands to migrate toward the land (Gade and Stillwell 1986). Today some of these barrier islands (popularly known as the *Outer Banks*) are moving landward each year at up to 3 m, while sea level is rising about 0.3 cm per year (Pilkey et al. 1978).

The sounds are underlain with sediments and sedimentary rock of marine origin. These sediments were deposited over at least the past 100 million years while the ocean covered portions of the coastal plain (Brown et al. 1972). The uppermost veneer of unconsolidated sediments were laid down 25 to 1 million years ago in the Miocene and Pliocene epochs. These are extremely varied and include gravels, sands, clays, peats, and all possible combinations (Copeland et al. 1984). The present day surface sediments of the estuaries are composed primarily of fine sand, silts and clays. Pickett (1965) noted that fine sand covers most of the bottom of Pamlico Sound, with silt present primarily in the deep areas of the northern basin and in the channels extending into the sound from the mouths of the Neuse and Pamlico rivers. Medium sand covers the higher energy areas near shoals and the tidal inlets from the ocean. Similarly, Pels (1967) found the bottom sediments of Albemarle Sound to consist mainly of fine-to-medium sand around the margins of the sound, with a gradation southward to silt and clay in the deepest areas.

Table 1.2. *Water Budget for the Albemarle-Pamlico Sound system (from Giese et al. 1979).*

Process	Value
Albemarle Sound	
A. Freshwater Inflow	
Chowan River	4,600 cfs
Roanoke River	8,900 cfs
Other	2,900 cfs
Total	**16,400 cfs**
B. Precipitation on Albemarle Sound and associated open-water areas	3,400 cfs
C. Evaporation from Albemarle Sound and associated open-water areas	2,600 cfs
D. Total outflow of Albemarle Sound into Pamlico Sound: D = A + B - C	17,200 cfs
Pamlico Sound	
A. Freshwater Inflow	
Tar-Pamlico River	5,400 cfs
Neuse River	6,100 cfs
Other	500 cfs
Total	**12,000 cfs**
B. Inflow from Albemarle Sound to Pamlico Sound	17,200 cfs
C. Precipitation on Pamlico Sound	8,250 cfs
D. Evaporation from Pamlico Sound	5,740 cfs
E. Net inflow to Pamlico Sound: E = A + B + C - D	31,710 cfs

Climate

North Carolina lies within a general climatic region known as Humid Subtropical. Moisture is adequate throughout the year to support forest as well as a variety of agricultural crops, with only limited, localized needs for irrigation or artificial drainage. Temperatures are moderate with long summers and brief winters. An extended summer drought may result from dominance of the Bermuda high pressure off the east coast. Warm, moist air from the tropics dominates summer conditions while cooler, drier continental polar air controls winter weather (Gade and Stillwell 1986).

Daily mean air temperatures over most of eastern North Carolina and southeastern Virginia range between 5°C and 10°C in January, the coldest month, and between 24°C and 27°C in July, the warmest month. Annual precipitation averages about 127 cm/year throughout the basin, but in some years it may be very much lower or higher than this. For example, at New Bern, NC, the annual precipitation over the past 100 years has ranged between 88 and 203 cm/year (Wilder et al. 1978). In northeastern North Carolina, evapotranspiration averages about 86 cm per year, and results in the return of roughly two thirds of the rainfall back to the atmosphere. Generally, except in spring and early summer, precipitation exceeds evapotranspiration (Wilder et al. 1978).

Freshwater Inflows

Most of the freshwater for the Albemarle and Pamlico Sounds comes from four large rivers: the Chowan, Roanoke, Tar, and Neuse. The Roanoke and Chowan, which are the two major rivers in the Albemarle basin, drain 25,035 km^2 and 12,802 km^2, respectively, in northeastern North Carolina and southern Virginia. The Roanoke basin extends to the foothills of the Appalachian Mountains. The Tar and Neuse

Rivers, which supply most of the freshwater to the Pamlico Sound, have watershed areas equal to 11,137 km^2 and 14,499 km^2, respectively.

The total freshwater discharge from these rivers into the Albemarle and Pamlico Sounds cannot be measured, because the low stream slopes and tidal influence near the river mouths make measurement of stream flow by conventional techniques impossible in these areas. Consequently, the most downstream gauging stations operated by the U.S. Geological Survey lie in the higher areas to the west. Wilder et al. (1978) showed that the data that are available from the gauging stations can be extrapolated to give reasonably accurate estimates of runoff from the whole Albemarle-Pamlico watershed. They found that on a long-term basis, average flows on a unit basis through all of the major rivers are within narrow limits, ranging from 0.80 cubic feet per second (CFS) per mi^2 for the Roanoke River to 1.05 CFS/mi^2 for the Neuse River. Thus, multiplication of these unit discharge rates times the total basin area yields estimates of the total freshwater input.

Giese et al. (1979) presented estimates of inflow calculated by this method, along with data on precipitation and evaporation, in their detailed monthly and annual gross water budgets for the two sounds (Table 1.2). The runoff is highest in the late winter and lowest in the late summer and fall. This is out of phase with the annual precipitation cycle described earlier (higher rainfall in the summer than in the winter). The explanation for the discrepancy is that evapotranspiration rates are much higher in the summertime than in winter.

Tidal Exchange, Circulation, and Flushing

Pamlico Sound is connected with the ocean through several relatively small openings in the Outer Banks, primarily Ocracoke, Hatteras, and Oregon Inlets. This limited access, in combination with the broad expanse of the sound, results in ocean tides being dampened to less than 6 cm, except near the inlets (Roelofs and Bumpus, 1953; Giese et al. 1979). Often, wind-driven tides are dominant over lunar tides in both the sound and adjoining tributary estuaries. The large size of Pamlico Sound allows ample opportunity for wind setup over long fetches. U.S. Geological studies in the Neuse and Tar-Pamlico estuaries, summarized in Giese et al. (1979), indicate these wind tides are normally in the range of 0.3 to 0.6 m.

The Albemarle Sound system has no direct outlet to the ocean. Instead, it connects to Pamlico Sound and Oregon Inlet through Croatan and Roanoke Sounds; hence, dampening of lunar tides is even greater in the Albemarle than in the Pamlico. Normal wind tides in the sound average about the same as in Pamlico Sound, and the water level can change relatively rapidly with shifting wind directions and velocities accompanying frontal storm passage (Giese et al. 1979).

On a short-term basis, wind driven currents are often dominant over riverine flows in both the sounds and adjoining estuaries. Within the estuaries, the velocity of wind-driven currents may be increased because of funneling effects. A second factor which contributes to the relative importance of wind-driven currents in the system is that velocities due to freshwater inflow are low. Pamlico Sound and its estuaries are drowned river valleys. Consequently, the river channels are oversized for the amount of water they now carry, resulting in low velocities. In the long term, however, freshwater inflow is more important than wind in affecting net flow because the effects of winds blowing from various directions tend to cancel each other over time. This is true throughout the Albemarle-Pamlico system (Giese et al. 1979).

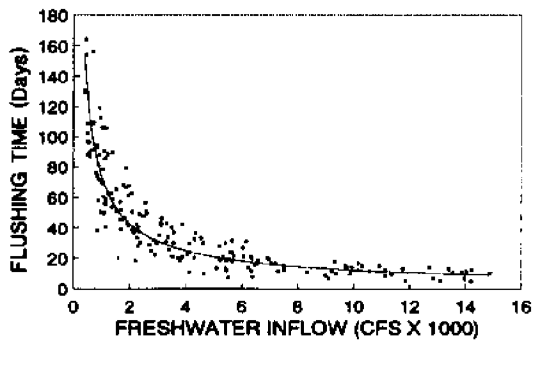


Figure 1.2. *Flushing times for the Tar-Pamlico estuary as a function of river flow. Tar River flow gauged at Tarboro, NC.*

Giese et al. (1979) computed estimates of the replacement time for freshwater in the Albemarle and Pamlico Sounds by comparing the estimated freshwater input per month with the volumes of the sounds. On average, it would take about 11 months for the flow into Pamlico Sound to equal the volume of the sound. Based on their monthly inflow estimates, the water replacement times would vary between 19 and 6 months. Actually, the range is greater than this because of extremes in inflow that occur in some years. Similar estimates for Albemarle Sound range between 9 and 3.5 months with a mean of about 5.5 months. These estimates suggest that the Albemarle flushes about twice as rapidly as the Pamlico.

A more realistic estimate of estuarine residence times requires taking into account tidal exchange effects. To do so, one may use the method of Ketchum (1950) to calculate the amount of freshwater in the estuary based on the salinity of the system. One then computes the amount of freshwater it would take to flush that freshwater from the system (Pilson 1985). Using this procedure, I calculated flushing times for the Tar-Pamlico River estuary as a function of freshwater inflow. The results are that the residence times for this estuary range from around 10 days under high flow conditions up to around 100 days for low flow conditions (Figure 1.2). The average flushing time, based on long-term flow data, is about 24 days for the Tar-Pamlico.

Salinity and Nutrients

Salinities are generally lower in the Albemarle system than in the Pamlico system for two reasons. First, the freshwater input:sound volume ratio for Albemarle Sound is larger than that for Pamlico Sound. The higher current strength resulting from this more effectively blocks saline water intrusion. Secondly, seawater that does reach Albemarle Sound has already been diluted in Pamlico Sound (Giese et al. 1979). Consequently, western Albemarle Sound is essentially a freshwater system, and even the eastern-most areas of the sound typically have salinities less than 5 ppt. Pamlico Sound salinities decrease from around 30 ppt near the barrier island inlets to approximately 15 ppt at the Pamlico River and Neuse River sub-estuary mouths (Giese et al. 1979; Stanley 1988b). Giese et al. (1979) contend that wind velocity and direction are the dominant short-term influences on salinity in the sounds, whereas variations in freshwater inflows are the primary influence on the seasonal salinity patterns.

Salinity in turn influences to some extent the concentrations of dissolved plant-growth nutrients in the estuary. For example, in the lower freshwater tidal areas of the rivers, nitrate nitrogen (NO_3-N) generally exceeds 20 μM, but decreases rapidly downstream with increasing salinity. Part of this decrease is due simply to dilution by low-nitrate ocean water, so that in the open areas of Pamlico Sound, the nitrate concentrations are probably less than 1 μM most of the time. Other forms of nitrogen and phosphorus also are generally most concentrated in the upper ends of the estuaries (Stanley 1988b; Bowden and Hobbie 1977; Hobbie and the

Smith 1975). Of course, rates of biological uptake and remineralization, and rates of input from the watershed also are factors regulating the estuarine nutrient concentrations. Because there are so many dynamic processes affecting estuarine nutrients, their concentrations vary widely, both spatially and temporally, and it is difficult to generalize.

Annual nutrient loading rates have been estimated for several of the Albemarle-Pamlico sub-estuaries (NCDNRCD 1982, 1983, 1987b). While detailed comparisons must be made with caution, since no uniform methodology was used to construct the budgets, several general conclusions seem obvious (Table 1.3). First, there are not drastic differences in the nonpoint areal N and P loading rates from one basin to another. For N the range is from 216 kg/square km in the Tar-Pamlico to 365 kg/square km in the Neuse. The nonpoint P loading varies from 21 kg/square km in the Chowan to 33 kg/square km in the Neuse. Second, point-source N loading (on an areal basis) is highest in the Neuse and lowest in the Tar-Pamlico, but in all cases is only about 20% of the total N load. Point sources contribute about half the total P loading, except in the Pamlico where they

Table 1.3. *Nutrient loading estimates for sub-basins of the Albemarle-Pamlico Sound system.*

Basin	Land Area (km^2)	N Annual Loading (kg/sq. km)	N Annual Loading (kg x 10^3)	P Annual Loading (kg/sq. km)	P Annual Loading (kg x 10^3)
Chowan	12,673		4,197		443
Point			881		165
Nonpoint		261	3,316	21	278
Roanoke	25,063		5,436		486
R.R. Res.	21,780		3,845		279
Bel. Res.	3,283				
Point			593		133
Nonpoint		303	998	22	73
Tar-Pamlico	11,650		3,223		933
Point			625		201
Nonpoint		216	2,522	26	312
Texasgulf			76		419
Neuse	15,979		7,358		962
Point			1,513		430
Nonpoint		365	5,845	33	532
Total	**65,365**		**20,214**		**2,824**
Point					
Nonpoint		290		27	

Notes:
1. Roanoke and Chowan data from NCDNRCD (1982)
2. Tar-Pamlico dat from NCDNRCD (1987)
3. Neuse data from NCDNRCD (1983)
4. "R.R. Res." refers to the Roanoke River Reservoir
5. "Texasgulf" refers to discharge from the Texasgulf phosphate mining facility

are two-thirds of the total because of the large input from Texasgulf Chemicals, which accounts for about one-half the total P going into the Tar-Pamlico. Finally, except for the Tar-Pamlico phosphorus loading, none of the Albemarle-Pamlico tributary areal loading rates are unusually high in comparison to other U.S. river basins for which estimates have been made (e.g., Clesceri et al. 1986; Rast and Lee 1983).

Principal Uses

Settlement and Population Growth

The Albemarle-Pamlico region was the first area of North Carolina to be settled by Europeans, but the development proceeded slowly until recent times, so that at present the area remains one of the State's most rural. Sir Walter Raleigh explored the Pamlico Sound, landing at Roanoke Island in 1584. In 1587, Raleigh appointed John White governor of what was to become the "Lost Colony" on Roanoke Island. Settlements in the Jamestown, Virginia area after 1607 became the nucleus for the colonization of northeastern North Carolina. Early communities began north of Albemarle Sound in the mid and late 1600s, and migration farther south led to the establishment of the town of Bath on the Pamlico River estuary in 1704. At the time of the first United States census in 1790, the total basin population was about 380,000. The Roanoke and Chowan sub-basins in the northeastern part of North Carolina and southern Virginia contained about three-fourths of the total, with 140,000 and 100,000 inhabitants, respectively (Figure 1.3).

Southern and western migration continued with the founding of New Bern at the head of the Neuse estuary in the early 18th century (Lefler 1965). By 1850 there were over 600,000 persons in the basin, with most of the growth having occurred in the western Roanoke basin and in the Tar-Pamlico and Neuse basins to the south. The population was overwhelmingly rural at this time. There were only two small urban areas, New Bern at the head of the Neuse River estuary and Raleigh in the upper Neuse basin. Each had about 4,500 inhabitants.

Since 1850 there has been only modest population growth in the Chowan Basin, but much more rapid growth in the Roanoke, Tar-Pamlico, and Neuse basins (Figure 1.3). In 1987, it was estimated that 2.37 million persons lived in the Albemarle-Pamlico basin, with most of these in the

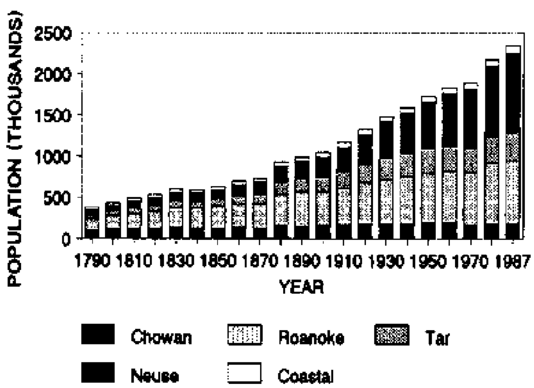


Figure 1.3. *Growth of human population in each of the major Albemarle-Pamlico estuarine system sub-basins.*

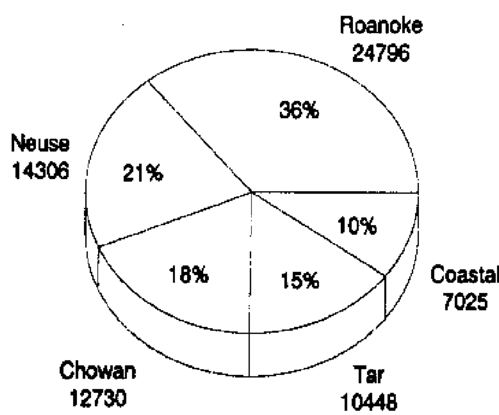


Figure 1.4. *Distribution of Albemarle-Pamlico land areas (square kilometers) among the major sub-basins.*

Roanoke and Neuse basins.

Most areas immediately adjacent to the Sounds are sparsely populated in comparison to more inland areas. For example, although 10% of the Albemarle-Pamlico watershed drains directly into the sounds (i.e., is downstream from the mouths of the four major rivers), those "coastal" areas contain only about 5% of the total basin population today (Figures 1.3 and 1.4). However, present growth rates in three of the coastal counties — Dare, Currituck and Carteret — are among the highest in the State, and this trend is projected to continue in the near future (Tschetter 1989). Nevertheless, the Albemarle-Pamlico basin in general, and the immediate coastal area in particular, continue to be more rural than areas surrounding most of the large estuaries farther north along the Atlantic coast.

The coastal counties experience wide fluctuations in population due to seasonal tourism. Tschetter (1989) estimated that Dare County's population increased to over 4 times that of the permanent population during the peak seasonal day in 1987. Other coastal counties and some counties on the west side of the sound experience smaller population fluctuations, perhaps in the 20-50 percent range. Counties farther inland in the AP basin experience little or no effect from seasonal visitors (Tschetter 1989).

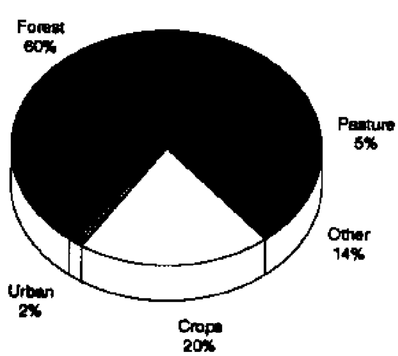


Figure 1.5. *Land use within the Albemarle-Pamlico estuarine system watershed (1985).*

Land Use

Current land use patterns in the Albemarle-Pamlico also reflect its rural nature. The region is predominantly forested and agricultural (Figure 1.5). Forest lands comprise 60% of the total basin area, and about 20% of the land is in crops. The percentage of the basin that is urbanized is estimated to be no more than about 2%. There are modest differences in land use among the sub-basins of the system (Figure 1.6). The forest land coverage ranges from 54% in the Neuse River, Tar-Pamlico River, and Albemarle Sound "coastal" basins to 63% and 67% in the Roanoke River and Chowan River basins, respectively. Conversely, the cropland acreage is highest in the Neuse, Tar-Pamlico and Albemarle Sound regions (25-28%) and lowest in the Roanoke River basin (14%). The Neuse Basin as a whole is more urban (4%) than any of the other sub-basins, but of course almost all of this is in the upper end of the basin, in the Raleigh-Durham area.

Commercial Fisheries

The Albemarle-Pamlico system is a major contributor to the commercial fisheries catch in North Carolina, as evidenced by the fact that about 80% of the total edible harvest each year is landed there. Pamlico Sound is very different from Albemarle Sound, however, both in terms of the commercial catch poundage and the composition of the catch. It has been estimated that in 1980, for example, Pamlico Sound contributed 78% of the total inshore catch, in contrast to Albemarle Sound, which contributed only 14% of the total commercial catch (Copeland et al. 1984).

Freshwater and anadromous species of finfish dominate the catch in Albemarle Sound and its tributary rivers, the Chowan

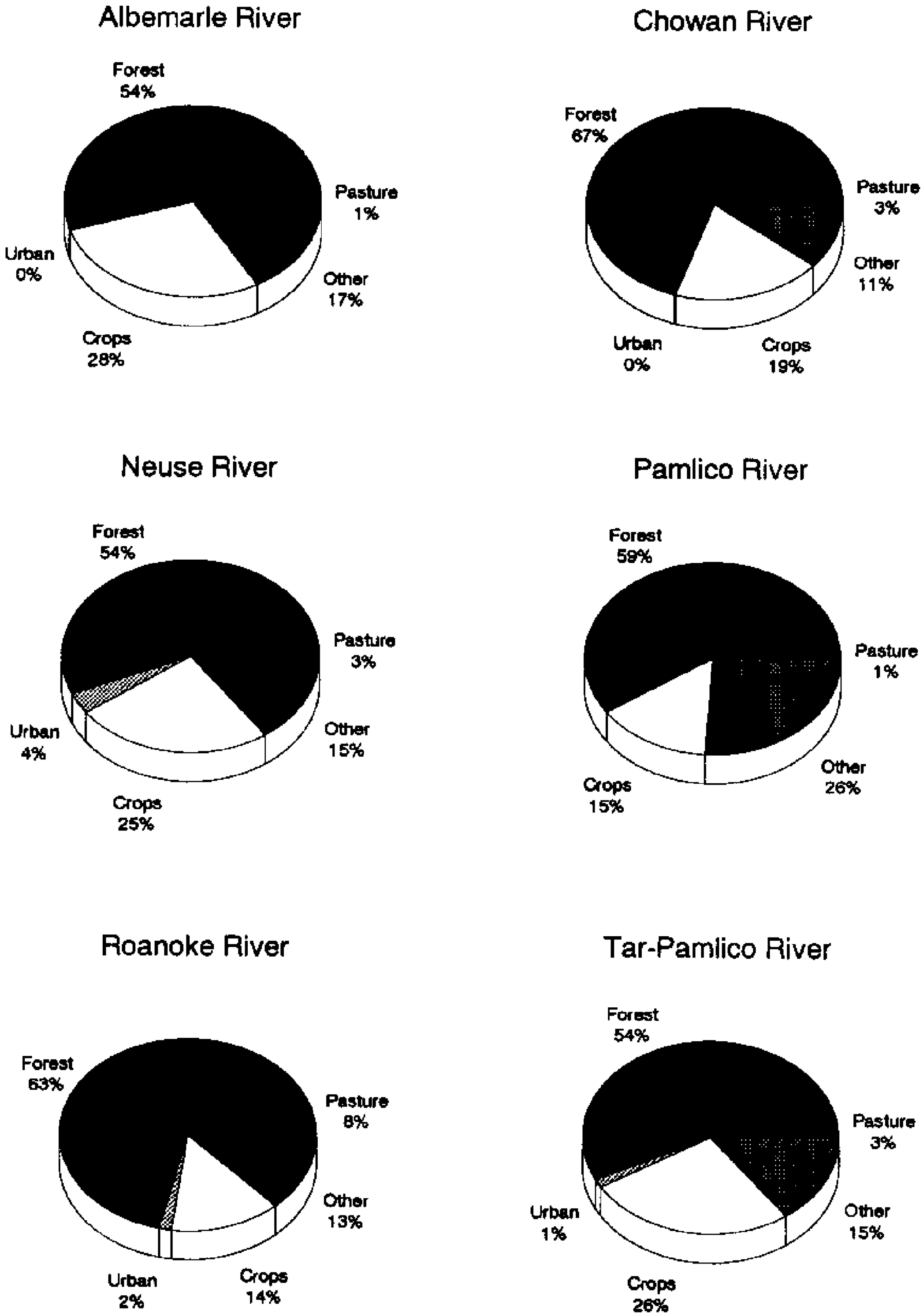


Figure 1.6. *Land use within each of the major sub-basins of the Albemarle-Pamlico estuarine system watershed.*

and the Roanoke, where most of the catch is made during the spring spawning runs. In recent years the most important anadromous species have been the alewife (*Alosa pseudoharengus*) and blueback herring (*Alosa aestivalis*). In the official landing statistics of the National Marine Fisheries Service, these two species are combined as "alewives." Another common name is "river herring" (Godwin et al. 1971). American shad (*Alosa sapidissima*) and striped bass (*Morone saxatilis*) are two other anadromous species in the Albemarle. The shad were once very abundant, but the catch declined drastically in the early 1900s. Striped bass is perhaps the best known, and certainly the most studied, finfish in the Albemarle region. A modest commercial fishery for resident species of catfish and bullheads (genus *Ictalurus*) has developed in the last 25 years or so (Epperley and Ross 1986; Godwin et al. 1971).

Farther south, in Pamlico Sound and its tributary estuaries, the commercial catch consists primarily of blue crabs (*Callinectes sapidus*), white, brown and pink shrimp (*Penaeus* sp.), oysters (*Crassostrea virginica*), hard clams (*Mercenaria mercenaria*), bay scallops (*Argopecten irradians*), and seasonally abundant species of edible marine finfishes. These include grey seatrout, or "weakfish" (*Cynoscion regalis*), flounder (mostly *Paralichthys dentatus* and *P. lethostigma*), Atlantic croaker (*Micropogon undulatus*), bluefish (*Pomatomus saltatrix*), spot (*Leiostomus xanthurus*) and mullet (*Mugil cephalus* and *M. curema*).

Between 1980 and 1987, the annual landings of edible finfish in the Albemarle-Pamlico system averaged 57.3 million pounds, and the shellfish harvest averaged

Table 1.4. *Albemarle-Pamlico Commercial landings catch composition (1980-1987 averages). Data are from N.C. Division of Marine Fisheries (1980-1987).*

Species	lbs/year	% of total catch	% of finfish catch	% of shellfish catch
Edible Finfish	57,298,432	60.2		
1. Grey Seatrout	12,325,898	12.9	21.5	
2. Flounder	10,071,075	10.6	17.6	
3. Croaker	9,678,043	10.2	16.9	
4. Alewives	6,578,158	6.9	11.5	
5. Bluefish	4,180,627	4.4	7.3	
6. Spot	3,593,872	3.8	6.3	
7. Mullet	1,312,485	1.4	2.3	
8. Catfish	1,108,679	1.2	1.9	
9. American Shad	261,034	0.3	0.5	
10. Striped Bass	230,140	0.2	0.4	
11. Other	7,958,421	8.4	13.8	
Shellfish	37,876,224	39.8		
1. Blue Crabs	30,311,632	31.8		80.0
2. Shrimp	4,969,160	5.2		13.1
3. Hard Clams (meat)	846,452	0.9		2.2
4. Oysters (meat)	533,781	0.6		1.4
5. Bay Scallops (meat)	533,781	0.6		1.4
6. Other (Squid, Sea Scallops)	962,270	1.0		2.7

about 38 million pounds (Table 1.4). Four species — grey seatrout, flounder, croaker and alewives — account for about two-thirds of the total edible finfish harvest. Averaging 30 million pounds landed per year, blue crabs have dominated the shellfish landings (80% of the total), and are the most abundant single species in the entire commercial edible harvest (32%). About 5 million pounds of shrimp are landed annually, along with lesser quantities of hard clams and other mollusks (.25-1 million pounds per year).

Atlantic menhaden (*Brevoortia tyrannus*) is an industrial finfish species that spends part of its life in the estuaries but is harvested offshore in the Atlantic. In terms of volume, no other fishery in North Carolina has ever come close to menhaden (Whitehurst 1973). In 1984, 178 million pounds of menhaden were landed at North Carolina ports (North Carolina Division of Marine Fisheries 1984).

Recreation

Tourism, already one of North Carolina's larger industries, is projected to grow even larger in the near future, surpassing three of the States traditional major industries: tobacco, textiles, and furniture. Dare County is by far the leader in tourism in the coastal region. Revenues there have increased at an explosive rate from just $11.6 million in 1971 to nearly $350 million in 1987 (both figures adjusted to 1984 dollars) (Tschetter 1989).

Fishing was the first major water-related recreational activity to develop in the Albemarle-Pamlico region, and today, recreational fishing is a major activity in the coastal region (see Chapter 7). Recent studies have quantified it in social and economic terms (Johnson et al. 1986). Also, Johnson and Perdue (1986) estimated the marina and marine manufacturing income attributable to recreational fishing. Unfortunately the ecological impact on the Sounds remains largely unknown. Other than for striped bass, there are essentially no historical ecological data upon which to base recreational fishing trend analyses.

Industry and Ports

North Carolina is currently the nation's eighth largest state in manufacturing employment. Manufacturing is fairly uniformly distributed throughout the state except in two areas where it is much less intense: the southwestern Mountain and northeastern Tidewater areas (Gade and Stillwell 1986). Large firms (with over 250 employees) are especially scarce in the Albemarle-Pamlico region; in 1980, there were fewer than 30 of them in the 14 counties adjacent to the Sounds (Wilms and Powell [no date given]). In fact, there are only three large water-dependent manufacturing plants that discharge directly into an estuary of the Albemarle-Pamlico system. Two are Weyerhaeuser pulp and paper mills; one on the lower Roanoke River at Plymouth, NC, and another above New Bern, NC, on the lower Neuse River. The third is a phosphate mine and manufacturing plant owned by Texasgulf Inc. on the south shore of the Pamlico River estuary.

In the early 1950s, large deposits of phosphate were discovered in Beaufort and Hyde Counties. The deposits were formed 25 million years ago as thick layers of small calcium phosphate pellets; they were subsequently covered with up to 30 meters of sand and clay. By 1966, the Texas Gulf Sulphur Company (now Texasgulf, Inc.) mine was in full-scale operation in an area immediately adjacent to the Pamlico River near Aurora, NC. At the Aurora facility Texasgulf concentrates the ore and uses part of it in the manufacture of phosphoric acid. The rest is sold to fertilizer manufacturers. The plant also discharges phosphorus and fluoride enriched freshwater into the estuary. Controversy surrounding the impact of Texasgulf on the Pamlico River has grown steadily over the past decade. The company's reputation has been tarnished by a series of Clean Air Act violations and small-scale chemical spills, some of which have led to hefty fines. Today fisherman and other local citizens, along with some North Carolina state officials and scientists, suspect that the discharges are responsible for widespread damage to the estuary, but so far, the evidence is mostly circumstantial.

The Albemarle-Pamlico probably has the lowest amount of port activity of any estuarine system, in its size category, in the nation. The only ports of any significance in North Carolina are to the south, at Morehead City and at Wilmington. Waterborne commerce, as reflected by shipping tonnage, is trivial in the sounds. In 1984, only 2 million tons of waterborne cargo were transported in the all of the sounds and rivers in the Albemarle-Pamlico system (Morehead City port activity not included). By way of comparison, during the same year the Port of Wilmington, NC, alone handled about three times as much cargo. And Wilmington is a very small port in comparison to Charleston, Norfolk, Philadelphia, etc.

Pamlico River tonnage rose rapidly in the mid-1960s, coincident with the opening of the Texasgulf phosphate mine, and today about half of the total Albemarle-Pamlico waterborne commerce is related to the mine. Liquid sulphur (17% of the total tonnage) is brought to the Texasgulf plant and fertilizer materials (34% of the total) are barged south to Morehead City for shipment out of the region. The third largest cargo in the sounds is pulpwood (25% of total tonnage) en route to mills on the lower Neuse and Roanoke Rivers and upstream in the Chowan River.

The fact that no significant port development occurred in the Albemarle-Pamlico region has been attributed to the difficulties of navigating the shallow, shifting inlets through the Outer Banks and the large expanse of shallow waters between the Banks and the mainland to the west (Gade and Stillwell 1986). Poor transportation between the coastal counties and other regions of the state may have been a factor also, but of course it is difficult to ascertain whether this was primarily a cause for, or effect of, the lack of port development.

CHAPTER 2

Major Environmental Concerns

> *A decade after the environmental movement spawned a great surge of new laws and commitments to clean up and protect threatened resources, the people of North Carolina are losing the battle against water pollution. Meanwhile, the life of our coastal waters continues to ebb away, choking on mud, algae, chemical poisons and the threat and promise of ever more. State regulators say the pollution problems confronting the coast are so complex, they are struggling just to understand them, let alone implement controls.*
>
> P. Haskins (1981)

During the past decade, concerns about the environmental health of various parts the Albemarle-Pamlico system have been voiced more and more frequently in magazine and newspaper articles, on television news reports, and by environmental groups, scientists and government agency personnel. At the present time, the estuary is being studied more intensively than ever before because of the U.S. Environmental Protection Agency's ongoing Albemarle-Pamlico Estuarine Study (APES). The *APES 5-Year Study Plan* (NCDNRCD 1987b) lists a number of so-called "major environmental concerns" for the Albemarle-Pamlico. A draft *Status and Trends Report* for the Albemarle-Pamlico estuarine system includes much more detailed information on some of these topics (Copeland 1989). The following summary is based, in part, on material from that document. Several of the concerns are addressed in other Chapters of this report; hence, they are discussed only briefly here.

Eutrophication — As Evidenced by Blue-Green Algal Blooms

Blooms of noxious phytoplankton are often a very obvious indication of cultural enrichment of estuarine waters with nutrients, primarily nitrogen and phosphorus. Such blooms have occurred during some, but not all, recent summers along the lower Chowan and Neuse Rivers. The most spectacular blooms in the Chowan occurred in 1972, 1978, and 1983 (NCDNRCD 1987b). Neuse blooms were documented in 1980, 1981, and 1983 (Christian et al. 1986). The Chowan blooms were largely composed of the nitrogen-fixing species *Aphanizomenon flos aquae, Anabaena spiroides* and *Anabaena flos aquae*, while in the Neuse *Microcystis aeruginosa* has been the dominant blue-green (Paerl 1982, 1987).

Fortunately, the blooms have been limited to the riverine and freshwater tidal portions of the estuaries because the blue-green species comprising them cannot tolerate saltwater. In the Chowan, the blooms extended over a 30 km stretch between Holiday Island and the river's mouth near Edenton, NC. The Neuse blooms persist for a period ranging from several weeks to months. Chlorophyll *a* levels typically are several hundred µg/liter (NCDNRCD 1982; Christian et al. 1986).

Research has improved our knowledge of several factors contributing to the blooms, but scientists have not yet integrated all the information needed to explain when and where the blooms will occur. The relationship between increased nitrogen and phosphorus and blue-green blooms is well established for freshwater lakes, but is not nearly so well understood for estuaries like the Chowan and Neuse. Generally, estuarine algal growth is considered to be more nitrogen limited than phosphorus limited (Boynton et al. 1982), but trying to quantify this has proven very difficult, for several reasons. For one thing, the flow-through nature of estuaries causes them to behave like rivers sometimes, when freshwater input is high, and like lakes at other times when inflow is low. This hydrologic variability causes problems in predicting water and nutrient flushing rates, as well as algal concentrations. For the Neuse, Christian et al. (1986) showed that blue-green blooms could not form unless water temperature is high and river discharge is low, because otherwise the water is swept into Pamlico Sound before the blue-green algae densities have time enough to build up to bloom levels. This probably explains why blooms develop only in low-flow summers, despite the fact that plenty of the nutrients are present every year.

There is much uncertainty whether the blue-green problem is worse now than in past decades. It is said that the blooms are more frequent now (e.g., NCDNRCD 1987b), but there is no historical systematic sampling record to confirm this. It is certainly possible that blooms were just as common earlier, but, like most other symptoms of environmental degradation, were paid little attention. This is unfortunate, because such a record would give support to the popular opinion that reduction of nutrient loading (and presumably nutrient concentration) in the estuaries will reduce or eliminate the blooms in the future.

The Pamlico River Estuary has been monitored for nutrients and algae longer, and more regularly, than any other estuary in North Carolina (Stanley 1988b). In fact, it is one of the few areas of the Albemarle-Pamlico system for which there is a complete enough record to permit an analysis of historical trends (*see* Chapter 4).

Wetlands Loss

Although the Albemarle-Pamlico region is relatively undeveloped, human activities in the area have altered and destroyed habitats that are part of, or tightly-linked to, the estuarine ecosystem. Dredging, draining and filling are the activities causing most of the changes and these activities are usually associated with one of three industries: agriculture, residential housing development, or commercial forestry. Reproductive, migratory and feeding patterns for a wide variety of aquatic and terrestrial organisms are thought to be affected, but details are lacking for most species. Thus, the relative values of the wetlands are poorly known and, in most cases, restoration or mitigation for impacted areas has yet to be evaluated on an economic basis.

Adams et al. (1989) recently prepared a report on the status and trends of the wetlands in the Albemarle-Pamlico region; some of their findings are summarized below.

A. *Tidal Salt Marshes*: In 1962, there were estimated to be a total of 4,897 hectares of salt marsh in Pamlico Sound, and none in the Albemarle Sound. Most of the marsh area was in Carteret County (83%), with the remainder in Hyde (13%) and Dare (4%) Counties (Wilson 1962). A more recent estimate is not available. Tidal salt marshes are of direct benefit for humankind due to their function in supporting finfish and shellfish fisheries, waterfowl populations, and aesthetics. These benefits have been appreciated for at least three decades; thus, salt marshes are afforded a relatively high level of protection in most states, including North Carolina.

B. *Nontidal Brackish Marshes*: These are eight times as extensive as salt marshes in Pamlico Sound; in 1962, there were about 40,000 hectares. Carteret County had 15,621 hectares (39% of total), and most of the rest was in Hyde, Pamlico and Dare Counties (Wilson 1962). Traditionally, these marshes have been altered to create impoundments to attract waterfowl, with little attention being paid to the costs of such alteration. Despite their large areal coverage, less is known about the ecological functioning of these marshes than is known for tidal salt marshes. In addition, large areas of marsh were altered in the past by digging ditches for mosquito control, a practice that elicited a call for a moratorium on ditching (Kuenzler and Marshall 1973). The ditching no longer occurs, but the potential for these areas to recover to their original, unaltered condition is not known. The brackish marshes are protected by the same mechanisms used for other wetlands.

C. *Fringe Swamps*: These are forested wetlands that occupy the shorelines of Albemarle Sound and the mouths of some of its major tributaries. They represent a transition between aquatic ecosystems and interior wetlands. Near the shoreline, they are characterized by groves of dead or dying cypress trees under permanently flooded conditions, a very common — and picturesque — sight in the Albemarle region. Brinson (1989) estimates that they occupy about three-fourths of the southern shoreline of Albemarle Sound and almost all the shoreline of the Alligator River. They were harvested for timber in the past, but no studies have been made to document the effects of the harvesting on the ecology of the swamps.

D. *Nontidal Freshwater Marsh*: Most of this marsh type (3,500 hectares) occurs in the northern part of Currituck Sound, which has a long history of water quality problems and is undergoing rapid development and land use changes. It is thought to be functionally similar to the nontidal brackish marsh, although obviously the plant and animal species composition is somewhat different. Where it is abundant, much importance is given to waterfowl and sports fishing resources. A relatively large number of permits were issued allowing alteration of wetlands in the Currituck Sound area between 1970 and 1984 (Stockton and Richardson 1987). The proximity of this area to a major metropolitan area (Norfolk and Virginia Beach, Virginia) makes it very attractive for outdoor recreation and development of second homes.

E. *Riparian/Alluvial Forested Wetlands*: North Carolina and other southern states have extensive forested wetlands. There are several types, including bottomland hardwood forests along rivers and streams, cypress strands, willow strands, and small headwater branches and drains. Functionally, however, they have many similarities. One is their capacity to act as water pollution filters. A very good synthesis of past research on this subject was made by Kuenzler (1989). He found that those along streams can remove large quantities of suspended sediments from cropland runoff as well as nitrogen and phosphorus from both point sources and nonpoint sources of pollution. For example, it was estimated that the systems removed 64% of the total nitrogen and 43% of the total phosphorus from upland sources in the Chowan River watershed (Kuenzler and Craig 1986).

These wetlands have been destroyed rapidly in recent decades. Turner et al. (1981) reported the combined loss of 30,000 acres of bottomland hardwood forests from about 1960 to 1975 in North Carolina and South Carolina. Such losses represent a small fraction of the total forest land so that they are not reflected by the statistics in total forest land acreage trends (*see* Chapter 3). Nevertheless, the decrease represents a substantially larger fraction of the total wetland area. Such reductions must be affecting water quality, given their high pollutant removal capacities. The National Wetlands Policy Forum is developing recommendations designed to stop, then reverse, wetland losses (Kuenzler 1989). Implementation of these and other policies developed by Federal and State authorities may turn out to be one of the most important estuarine water quality management actions in the near future.

Loss of Submerged Aquatic Vegetation

Reduction in submerged aquatic vegetation is of crucial environmental concern because a decline represents a reduction in fisheries and waterfowl habitats. In the mid-1970s and before, submerged aquatic vegetation (SAV) was common in the upper half of the Pamlico River estuary (Davis and Brinson 1976). By 1985, however, biomass had been reduced to about 1% of that of the 1970s and only widgeongrass was present (Davis and Brinson 1989). An after-the-fact analysis of the decline suggests that unusual weather conditions in 1978 contributed to the problem. Any tendency toward reestablishment of *Vallisneria americana* (wild celery), previously the most important species in the estuary, probably was negated by extremely high salinities prevalent in 1981 (Davis and Brinson 1989).

The decline of SAV in the Pamlico River has been mentioned frequently in discussions of the problems in the Albemarle-Pamlico, and it is usually compared to the SAV decline documented in the Chesapeake Bay (Orth and Moore 1982). There has been a tendency to extrapolate the Pamlico situation to other areas of the sounds. But actually, there is no historical evidence on SAV abundance for any other region except Currituck Sound (Adams et al. 1989). In terms of present conditions, Brinson and Davis (1989) carried out one of the most recent surveys and found great variability in SAV abundance from one area to another.

The marine SAV community in the Albemarle-Pamlico system appears relatively stable, according to Thayer et al. (1984). Eelgrass, a major component of this community, recovered substantially from the wasting disease of the 1930s. However, there is concern about future development activities that might affect SAV habitat, and about clam-kicking, a mechanical clam harvesting procedure which is thought to damage SAV (Peterson et al. 1983, 1987).

Declines in Fisheries

Declines in commercial fisheries have occurred in the Albemarle-Pamlico region following historic highs in the 1970s. For nearly 40 years, the total finfish catch remained relatively stable. But between 1968 and 1981, it rose dramatically to about three times what it had been previously. Since then, it has fallen back to about 1.5 times the 1930-1970 mean. It is this short-term decline in the past 8 years that has caught the attention of many people, and it has been widely publicized. Similarly, the total commercial shellfish harvest rose gradually until the late 1960s, fell back slightly in the early 1970s, then began a very steep increase in the late 1970s, reaching an all-time high in 1979 that was about twice the average for the preceding two decades. But again, it has been the decline since 1980 (down to about 1.5 times the 1950-1970 mean) that has been the focus of attention. Trends for individual fisheries are very mixed, with some commercial catches rising at the same time others were declining. For example, since 1950, blue crab landings have doubled, shrimp landings have shown little trend (but have displayed great interannual fluctuations), while oysters have declined. Flounder, croaker, and spot landings all skyrocketed in the early 1970s, and since 1980 have fallen back, but remain high in relation to the long-term means. Anadromous species generally have declined, either on a long-term, more-or-less continuous basis (alewives and American shad), or in recent years following an earlier increase (striped bass and catfish). The fishery declines are generally attributed to a combination of over-fishing declining water quality, and critical habitat loss or alteration (NCDNRCD 1987b). Reasons for the earlier increases in harvest are seldom discussed. Trends in commercial fisheries are covered in more detail in Chapter 7 of this report.

Fish Diseases and Kills

Episodes of infectious diseases that are associated with the presence of some microbes or parasites have been observed in the Albemarle-Pamlico system, as well as elsewhere along the U.S. east coast. A "red sore" disease reached epidemic proportions in some commercial species in Albemarle Sound during the 1970s (Esch and Hazen 1980). In the Pamlico River estuary, the most prevalent of these problems seems to be ulcerative mycosis (UM), a fungal infection (Noga et al. 1989). The perception that these diseases are more serious now than in the past is not strongly debated, despite the lack of any long-term systematic monitoring record. A recent, two-year monitoring effort (1985-1987) was conducted in the Pamlico River to assess the occurrence and species distribution of ulcerative mycosis. Overall, 16% of the menhaden sampled had UM lesions, but there was a strong seasonality in disease, with the highest incidences occurring in the Spring and Fall. At those times, up to 100% of the menhaden in individual trawl samples were infected. Less than 1% of other fish species examined during the study were infected (Noga et al. 1989).

No primary causes for the diseases have been established. The current working hypothesis is that environmental stress increases the susceptibility of the fishes to the diseases. Salinity, in particular, is one factor that is being examined, but to date there have been no controlled experiments performed to test a specific hypothesis.

Another widely publicized perception in North Carolina is that the number of fish kills in the estuaries has increased in recent years. Once again, unfortunately, there is no program to sample systematically; rather, the number of kills reported to authorities is the basis for this conclusion. Most reported kills occur in the Pamlico River, and menhaden are most often the species involved (*see* Chapter 5). The most frequent cause given by State agency scientists for the kills is low dissolved oxygen in the bottom waters of the estuary (Stanley 1985). Many feel that bottom water anoxia is more common in the Pamlico now than in the past, even though the available data for the past 20 years suggests otherwise (*see* Chapters 4 and 5).

Impairment of Nursery Area Function

Initial development of the post-larval stages of many fish and shellfish species occurs in primary nursery areas (PNAs) located in the uppermost areas of estuaries and their tributaries. The marshes and small embayments fringing Albemarle and Pamlico Sounds provide essential nursery functions for a majority of the commercial species in the North Carolina coastal area. Because of their location, PNAs are very sensitive to activities on adjacent uplands. Freshwater drainage, land-use changes and eutrophication can jeopardize the functional aspects of the primary nurseries. However, the exact extent of impairment apparently is difficult to estimate, even when historical data are present. For example, in North Carolina, the Wildlife Resources Commission, the Division of Marine Fisheries, and university researchers have collected information concerning abundance of juvenile fishes in PNAs of Pamlico Sound for some two decades, but there has never been a definitive analysis of environmental or fish population trends in the nursery areas (Adams et al. 1989).

The nursery areas are defined, for management purposes, on the basis of the numbers of juvenile fishes caught in a standardized sampling routine. Such designated areas are protected against damaging fishing practices through regulations of the Marine Fisheries Commission and enforced by the Division of Marine Fisheries. Trawling, as well as oyster and clam kicking (using propeller wash to excavate clams) are prohibited in such areas. Impacts from land use activities are less well-controlled, and there is suspicion that in the future, these activities will pose the most serious threats to the long-term health of the nursery areas. More specifically, the greatest weakness in existing regulatory programs is thought to lie in controlling non-point sources of water pollution and in regulating development landward of the nurseries (Adams et al. 1989).

Shellfish Closures

Closure due to pathogenic microbial contamination of shellfish waters in North Carolina has remained relatively constant over the past few years. About 50,000 acres of productive shellfish bottoms are currently closed on temporary or permanent basis. Often, after heavy rainfall, additional acreage is closed for several days to several weeks. Albemarle Sound is not a contributor to commercial shellfish, but Pamlico Sound has oysters, clams, and bay scallops in several areas. Most of the closure is to the south of the Pamlico Sound area, but Core Sound and Bogue Sounds are affected (See Chapter 7 for more details). New techniques to more accurately measure contamination and potential human impact are needed so that management can more effectively allocate shellfish resources. Relationships between contamination and land-use characteristics are poorly understood.

Toxicant Effects

Very little is known about the effects of toxicants on estuarine organisms or the distribution of toxic substances in the Albemarle-Pamlico Estuarine System. A preliminary report has just been issued on the first-ever systematic survey of Albemarle-Pamlico sediment heavy metals concentrations. This report deals with the Pamlico River estuary, the first of four subregions to be sampled over the next several years (Riggs et al. 1989). The results of the report are summarized in Table 2.1. The authors of the report concluded that the low metals concentrations within Chocowinity Bay surface sediments are similar to concentrations occurring in subsurface samples throughout the Pamlico (data not shown). The subsurface samples are interpreted to represent the natural background during preindustrial conditions. If this is the case, then the Chocowinity Bay sediments show little metals enrichment from man's activities. On the other hand, averages for all the Pamlico samples were about twice those for Chocowinity Bay, and in Kennedy Creek, a very small tributary in the upper estuary at Washington, NC, toxic metals may have been enriched by up to ten times the pre-man concentrations. One factor not considered by the report's authors is the effect of sediment composition on metals concentrations. The percent organic matter and the sand-clay ratio are known to affect the affinity of estuarine sediments exposed to (otherwise) equal loadings of metals (White et al. 1985). Riggs et al. (1989) did present data indicating that both of these factors varied considerably among their sampling locations, but their metals data apparently were not normalized with regard to these differences (J. Bray, personal communication). The Pamlico concentrations data, taken as a whole, appear to be typical of estuaries that are considered to be relatively unpolluted with the metals.

Table 2.1. *Heavy metal concentrations (µg/g) in the most and least polluted portions of the Pamlico River. "Pamlico average" is the trimmed mean for the whole system (i.e., all values more than 2 standard deviations from the mean were eliminated). Kennedy Creek is the most polluted and Chocowinity Bay is the least polluted portion of the system* (from Riggs et al. 1989).

Metal	Pamlico	Kennedy Creek			Chocowinity Bay		
	Average	Average	Min	Max	Average	Min	Max
Arsenic	12.80	21.20	5.80	35.40	7.80	3.60	12.60
Cadmium	0.36	0.85	0.30	1.70	0.18	0.00	0.40
Chromium	10.50	27.30	5.90	58.80	4.60	2.50	8.30
Copper	13.60	51.50	17.60	84.40	6.40	3.50	9.80
Nickel	2.70	8.40	1.50	13.30	1.00	0.10	2.10
Lead	35.90	68.50	29.80	86.90	21.70	11.90	40.90
Zinc	77.00	377.90	151.20	490.30	35.60	17.10	56.60
Mercury	0.09	0.44	0.16	1.30	0.06	0.03	0.08

Chapter 3

Trends in Nutrient Production: An Estimate Based on Changing Land Use and Population

The ultimate question is: Even if stringent point and nonpoint source nutrient controls are adopted, can [estuaries] survive in a desirable natural state in the face of continuing increases in nutrient sources resulting from population growth and changing land use? Only time will tell.
C.F. D'Elia (1987)

Of the wide variety of chemicals discharged into estuaries, two plant growth nutrients, nitrogen (N) and phosporus (P), have been identified again and again as among the most critical, with the potential for widespread impact on estuarine resources. Frequently, increases in population density, fertilizer use and conversion of forest land to agriculture are cited as the causes for increased nutrients leading to eutrophication in estuaries (e.g., Macknis 1985; North Carolina DNRCD 1987).

While it is intuitively obvious that increased estuarine nutrient loading ought to occur as the basin population grows, usually there are little or no historical data to clearly show the quantitative relationships between the anthropogenic changes and changes in nutrient loading. Scores of current N and P loading estimates have been made for various estuarine drainage basins, including the Neuse, Chowan, and Tar-Pamlico River estuaries in North Carolina (*see* Chapter 1), but studies of historical trends in nutrient loading have rarely been made. The objective of this study was to use historical population and agriculture statistics for estimating trends in annual N and P production within each of the major Albemarle-Pamlico sub-basins.

Actually, there is probably a large difference between nutrient *production* within a watershed and *loading* to an estuary. For purposes of this study, nutrient *production* refers to the sum of 1) the nutrients discharged from point sources, 2) that estimated to come from each non-point source (e.g. field, forest, or the atmosphere), and 3) the amount contained in the manure of farm animals. *Loading*, on the other hand, refers to the quantities of nutrient actually reaching the estuary. There is a difference between the two because of processing that occurs as nutrients are transported from the sources toward the estuary. The production rate normally exceeds the loading rate, because there are losses along the way, due to such processes as sedimentation (for P) and denitrification (for N).

The reader should keep in mind that the estimates made in this study are for production, not loading. Loading from the basin can be measured directly by multiplying stream discharges times nutrient concentrations. The data for the computations normally come from monitoring flows and concentrations at the head of the estuary. The advantage of this method is obvious; it gives a direct measure of the actual quantity of nutrient discharged from the watershed. However, the technique could not be used in this study because of a lack of long-term monitoring of N and P concentrations at the mouths of the streams and rivers emptying into the estuaries in North Carolina. In fact, there are very few estuaries for which such a data set is available. Another disadvantage is that this method gives no indication of the sources of the nutrients.

Methods

Trends in land use and nutrient production in the Albemarle-Pamlico basin were estimated for the period 1880 through 1987 by summing computed estimates of annual point and nonpoint source production for each county in the basin. The procedures were based on those of Thomas and Gilliam (1978), Craig and Kuenzler (1983), and Lowrance et al. (1985). For counties that are partly inside the basin, all data were weighted by the percentage of the county within the basin (Figure 3.1, Table 3.1, Appendix 3.1). Nonpoint sources considered included 1) eight categories of farm animals, 2) harvested agricultural cropland, 3) other non-forested farmland (mostly idle cropland), 4) forests, 5) pastureland, 6) urban land, and 7) all other land areas. Point sources included municipal wastewater treatment plant and industrial discharges. Atmospheric N deposition was also included in the estimates.

The primary sources for agricultural land use, crop and animal statistics were the censuses conducted by the U.S. Bureau of the Census and the North Carolina and Virginia Departments of Agriculture. Numbers of each type of farm animals, acreages and harvests of the major crop types, and acreages of the pastureland and "other farm land" categories came from the census reports (Table 3.2). Forest acreage statistics were compiled from U.S. Department of Agriculture Forest Service Resource Bulletins for North Carolina and Virginia (Table

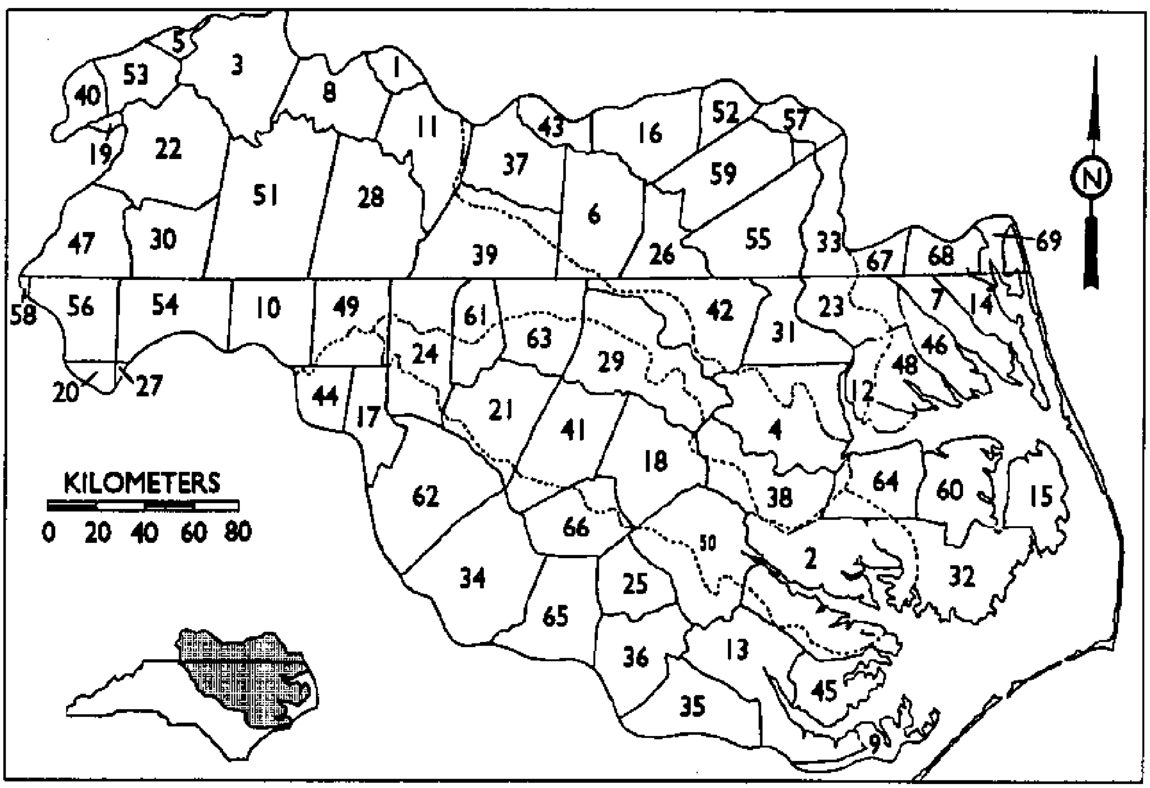


Figure 3.1. *Map showing counties in each of the Albemarle-Pamlico sub-basins. The counties are identified in Table 3.1.*

Table 3.1. *North Carolina and Virginia counties in the Albemarle-Pamlico basin (numbers correspond to those on map in Figure 3.1).*

Map No.	Name	Map No.	Name	Map No.	Name
1.	Appomattox	24.	Granville	47.	Patrick
2.	Beaufort	25.	Greene	48	Perquimans
3.	Bedford	26.	Greensville	49.	Person
4.	Bertie	27.	Guilford	50.	Pitt
5.	Botetourt	28.	Halifax (VA)	51.	Pittsylvania
6.	Brunswick	29.	Halifax (NC)	52.	Prince George
7.	Camden	30.	Henry	53.	Roanoke
8.	Campbell	31.	Hertford	54.	Rockingham
9.	Carteret	32.	Hyde	55.	Southampton
10.	Caswell	33.	Isle of Wight	56.	Stokes
11.	Charlotte	34.	Johnston	57.	Surry (VA)
12.	Chowan	35.	Jones	58.	Surry (NC)
13.	Craven	36.	Lenoir	59.	Sussex
14.	Currituck	37.	Lunenburg	60.	Tyrrell
15.	Dare	38.	Martin	61.	Vance
16.	Dinwiddie	39.	Mecklenberg	62.	Wake
17.	Durham	40.	Montgomery	63.	Warren
18.	Edgecombe	41.	Nash	64.	Washington
19.	Floyd	42.	Northampton	65.	Wayne
20.	Forsyth	43.	Nottoway	66.	Wilson
21.	Franklin (NC)	44.	Orange	67.	Suffolk
22.	Franklin (VA)	45.	Pamlico	68.	Chesapeake
23.	Gates	46.	Pasquotank	69.	Virginia Beach

Table 3.3. *Coefficients used to compute nitrogen and phosphorus production by five different land use categories and by different types of farm animals. Values for forest are from Loehr (1974); values for other land uses are from Beaulac and Reckhow (1980); values for animals are from Barker (1987).*

Land use category or animal type	Nitrogen (kg/year)	Phosphorus (kg/year)
Other Farmland	3.00/ha	0.40/ha
Other Land	3.00/ha	0.40/ha
Forest	1.50/ha	0.20/ha
Pastureland	4.00/ha	0.60/ha
Urban Land	6.00/ha	1.10/ha
Cattle		
Dairy	121.00/animal	22.00/animal
Beef	48.10/animal	13.10/animal
Swine	11.90/animal	4.20/animal
Horses	46.40/animal	11.00/animal
Sheep	6.80/animal	1.50/animal
Poultry		
Broilers	0.40/animal	0.10/animal
Layers	0.56/animal	0.20/animal
Turkeys	1.36/animal	0.52/animal

Table 3.2. *Sources of data on agricultural land use, crop harvests, farm animals, fertilizer sales, forest and urban land areas, population, and municipal and industrial discharges.*

Agricultural Land Use, Crop Harvests and Farm Animals Inventory

U.S. Bureau of the Census. 1880-1982. Primary source.

N.C. Department of Agriculture. 1923-1988. North Carolina Agricultural statistics. Annual Bulletins and Reports.

Virginia Department of Agriculture. 1920-1988. Virginia Agriculture Statistics (Annual Reports).

Forest Data

Virginia

U.S. Forest Service (1943); Cruikshank and Evans (1945); Larson and Bryan (1959); Sheffield (1976, 1977a, 1977b); Cost (1976); Brown (1985, 1986); Brown and Craver (1985).

North Carolina

U.S. Forest Service (1943); Cruikshank (1940); Cruikshank and Evans (1945); Larson (1957); Knight and McClure (1966); Welch and Knight (1974); Cost (1974); Welch (1975); Bechtold (1985).

Fertilizer Sales

Virginia Department of Agriculture. 1956-1988. Fertilizer used and results of inspection (annual reports). Richmond.

U.S. Bureau of the Census. 1954, 1959, 1964. County data on fertilizer materials applied to croplands.

Hargett and Berry (1985).

Mehring et al. (1985).

North Carolina Department of Agriculture. Various dates between 1956 and 1988. Data for some years contained in the N.C. agricultural statistics reports issued annually.

Population and Urban Land Areas

U.S. Bureau of the Census. 1880-1983. Census of Population.

U.S. Bureau of the Census. 1949-1988. County and City Data Book.

Municipal and Industrial Discharges

N.C. Stream Sanitation Committee (1946, 1957, 1959, 1961).

U.S. Public Health Service (1944, 1951, 1958, 1963).

U.S. Environmental Protection Agency (1971).

Hall (1970).

Virginia State Water Control Board (1975).

N.C. Division of Environmental Management (1986, 1989)

Virginia State Water Control Board: NPDES Self-Monitoring Data (1989).

North Carolina Division of Environmental Management: NPDES Self-Monitoring Data (1986-1989).

N.C. Board of Health. Various Dates. Annual reports.

3.2). Urban land areas were tallied from U.S. Bureau of Census data (Table 3.2). Here "urban" areas are defined as the land areas within the limits of towns and cities with populations greater than 2,500. The "other" land use category was calculated as the total basin land area minus the sum of all the other land use type acreages. This miscellaneous category consists primarily of non-forested, nonagricultural lands outside the boundaries of the towns and cities (i.e., business properties, house lots, roads, ponds, cleared power line right-of-ways, etc.).

Quantities of N and P released in the excreta of farm animals were estimated by multiplying numbers of animals times coefficients (Table 3.3). Mass balance models

Table 3.4. *Atmospheric deposition of (D) in kg/ha/year and mean concentration (C) in μg/l of nitrogen and phosphorus at several locations within, or near, the AP watershed.*

			NO3-N		NH4-N		Total-P		
Location	Year	Precip. (in.)	(D)	(C)	(D)	(C)	(D)	(C)	Ref.
North Carolina	1975		5.54 (NO_3+NH_4)		0.21				1
Duke Forest, NC	1972		1.46		0.74		0.28	21	2
Tar River Swamp, NC	1976						0.49	53	8
Rhode River Watershed, MD	1974	108.6	3.91	360			0.57	53	3
	1975	142.4	4.65	327			1.13	79	3
	1976	115	5.57	484			0.74	65	3
Creeping Swamp, NC	1977						0.70	54	7
Clinton, NC	1980	116.5	2.60	223	1.56	134	---		4
	1981	113	2.37	210	1.56	138	---		4
	1983	127.2	2.24	176	1.71	135	---		4
Lewiston, NC	1980	87.3	2.53	290	1.32	151	---		4
	1981	79.5	1.69	213	1.01	127	---		4
	1982	116.4	2.53	217	1.71	147	---		4
	1983	105.1	2.75	262	0.00		---		4
	1984	133.7	3.75	280	1.32	99	---		4
	1985	117.6	1.96	167	1.24	153	---		4
Raleigh, NC	1980	94.1	2.39	254	1.79	190	---		4
	1981	81.3	1.56	192	1.24	153	---		4
	1982	114.7	2.48	217	2.10	183	---		4
	1983	126.7	2.64	209	0.00		---		4
	1984	123.9	2.30	186	1.84	149	---		4
	1985	93.3	1.76	189	1.61	173	---		4
Greenville, NC	1958	119	8.00	672	1.30	109			5
Roanoke, VA	1958	127	8.90	701	2.40	189			5
Cape Hatteras, NC	1958	137	3.20	234	1.20	88			5

1. Wells and Jorgensen 1975; 2. Wells et al. 1972; 3. Miklas et al. 1977; 4. Olsen and Watson 1986; Olsen and Slavich 1986; 5. Junge 1958; 6. Galloway et al. 1984; 7. Kuenzler et al. 1980; 8. Holmes 1977.

for N and P were calculated for agricultural cropland, following the methods of Craig and Kuenzler (1983) and Lowrance et al. (1985). The annual cropland nutrient budgets for each AP sub-basin were estimated by:

(Precipitation + Fertilizer + Symbiotic N-Fixation) - (Harvest + Denitrification) = N Balance; and
(Precipitation + Fertilizer) - (Harvest) = P Balance.

The "balances", when positive, were assumed to represent the maximum "cropland pollution potential"; i.e., the quantity of nutrient that could leave the watershed through surface or subsurface flow. Of course, this assumes that nutrient storage in the soil system is not changing (Frissel 1978).

Wet precipitation inputs for each year were calculated by multiplying the total annual precipitation (average of several sites within the Albemarle-Pamlico (AP) basin, times the estimated N and P concentrations, times land areas. N and P concentrations in precipitation for the mid-1980s were based on measurements from National Atmospheric Deposition Program stations in the AP basin, and on other recent measurements (Table 3.4); but historical N concentrations had to be calculated indirectly. This was done by assuming that N deposition in 1880 was 20% of the rate today, and that the rate of change since 1880 has been exponential. These assumptions are, in turn, based on measured (present-day) atmospheric N deposition rates in remote areas (Table 3.4) and on estimated historical trends in N oxide production in the southeastern U.S. (*see* Discussion). The total atmospheric N deposition was twice the wet precipitation loading, based on the assumption that dry deposition equals wet deposition (*see* Discussion). No information on historical trends in atmospheric P production or deposition were available; therefore, a constant rate of deposition (0.5 kg/ha/yr) was assumed, based on measurements in the AP region (Table 3.4).

The amount of fertilizer applied annually to cropland was assumed to be equal to the amounts sold in, or shipped to, the counties. Historical data on fertilizer sales were taken from a number of sources (Table 3.2). Actually, most of the data are reported as tons of "mixed fertilizer" and "fertilizer materials" either received in the counties from manufacturers for retailers and consumers (North Carolina), or sold by each county (Virginia). To convert tons of mixed fertilizer and fertilizer materials into tons of elemental N and P, I multiplied by the percentages of N and P in each type of material sold. The N fixation rate used for soybeans was 105 kg/ha per year (93.5 lb/acre per year) (Frissel 1978), and for peanuts the rate was assumed to be 112 kg/ha per year (99.7 lb/acre per year) (Craig and Kuenzler 1983). The amounts of N and P harvested were determined by multiplying the nutrient content by the annual yields (e.g., bushels/acre) of the major crops (Gilbertson et al. 1978; Romaine 1965) (Table 3.5). Finally, denitrification rates were assumed to be 15% of the applied fertilizer N (Porter 1975; Thomas and

Table 3.5. *Nitrogen and phosphorus content in harvested crop materials (Gilbertson et al. 1978; Romaine 1965).*

Crop	Harvest Unit	Pounds/Harvest Unit	
		Nitrogen	Phosphorus
Corn (grain)	Bushel	0.900	0.153
Corn (silage)	Ton	4.0	0.45
Oats (grain)	Bushel	0.625	0.113
Wheat (grain)	Bushel	1.250	0.275
Hay			
Alfalfa	Ton	45.000	4.500
Bluegrass	Ton	30.000	4.500
Coastal Bermuda	Ton	23.125	3.875
Cowpea	Ton	60.000	5.500
Peanut	Ton	46.667	4.889
Red Clover	Ton	40.000	4.400
Soybean	Ton	45.000	4.500
Timothy	Ton	24.000	4.400
Cotton	Pound	0.018	0.002
Peanuts (nuts)	Pounds	0.036	0.002
Soybeans (grain)	Bushels	3.750	0.375
Tobacco (leaves)	Pounds	0.038	0.004

Gilliam 1978).

Nutrient production was not calculated by this mass balance approach for any land use category other than harvested cropland. Instead, export coefficients (kg N and P per ha per year) were multiplied times total sub-basin acreages to give the "expected" nutrient yields from pastureland, forests, urban, other farm lands, and "other" areas. N and P "yield" coefficients for each of these land-use categories were taken from the literature (Table 3.3).

Both municipal and industrial discharges were included in the point-source nutrient production estimates. For industrial sources the annual production was calculated by multiplying daily discharge times the total N or P effluent concentration times 365. Municipal production was computed as

kg N or P/year =

Sewered population * Per capita daily N or P production * Treatment factor * 365

where sewered population is the estimated number of persons served by the city's wastewater collection system. Information on industrial and municipal discharges was gleaned from several sources. The NPDES Compliance Monitoring data files were searched to provide lists of all current discharges within each AP sub-basin (>0.1 mgd), as well as information on N and P concentrations in the industrial discharges. The most difficult parameters to estimate were the treatment factors that would be applied to each discharge. Fortunately, there were periodic inventories of municipal wastewater facilities from 1942 through 1985 (Table 3.2) which included detailed information on the levels of treatment provided by each facility and the size of the "sewered" population. Another valuable source was the N.C. Department of Health annual reports, which yielded information on the early history of municipal wastewater treatment in North Carolina. For years before 1942, the sewered population was assumed to be equal to the city population (U.S. Census Bureau data), back to the time when the sewage collection system for the town was first constructed.

The per capita annual N and P production was taken as 4.6 kg N and 1.2 kg P (Gakstatter et al. 1978), and the N treatment factors ranged from 1 (untreated) to 0.47 (secondary treatment), depending on the type of wastewater treatment practiced by the municipal treatment plant. P treatment factors ranged from 1.0 to 0.74 (Table 3.6).

From 1880 through 1920 the nutrient production estimates were computed at 10-year intervals, corresponding to the U.S. Agricultural census dates. After 1920, more frequent agriculture census data were available so that I was able to make calculations at 4-to-5 year intervals. Many of the data were first compiled in the English units of measure (acres of land, pounds of crop harvest, tons of fertilizer sold, square miles of county land area, etc.) in which they were originally recorded (e.g., Appendix 3.3). But at some stage in the procedure, all these values were converted to metric units, and the summed nutrient production rates are expressed as kg/ha/year, or metric tons per year.

Results are presented for the whole

Table 3.6. *Per capita total nitrogen and total phosphorus loads (kg / year) in wastewater effluents as a function of treatment type (Gakstatter et al. 1978). Treatment factors are equal to the load for a given treatment type divided by the load for no treatment.*

Treatment type	Nitrogen kg/year	Nitrogen Factor	Phosphorus kg/year	Phosphorus Factor
None	4.6	1.00	1.2	1.00
Primary	4.2	0.90	1.1	0.90
Secondary				
Trickling filter	2.9	0.62	1.0	0.82
Activated sludge	2.2	0.47	1.0	0.82
Stabilization pond	1.9	0.42	0.9	0.74

Albemarle-Pamlico watershed, as well as for each of the major sub-basins: Chowan River, Roanoke River, Tar-Pamlico River, Neuse River, and "Coastal". The Coastal sub-basin includes all land area downstream from the mouths of the river estuaries, primarily parts of Camden, Currituck, Dare, Hyde, Pamlico, Pasquotank, Perquimans, Tyrrell and Washington Counties in North Carolina (Figure 3.1, Appendix 3.1). In some of the figures and tables (especially Appendix tables), the "Coastal" sub-basin is further sub-divided into the "Albemarle" and "Pamlico" sub-basins, in reference to the sound into which the land drains.

Results

Land Use

There have been relatively small changes in the amounts of land in each of the major land-use categories in the Albemarle-Pamlico basin use during the past century (Figures 3.2 and 3.3, Appendix 3.2). Forest has always been the most prevalent land use in the basin, ranging between 57.6% and 63.7% of the total basin land area. There was a peak in forest acreage in the 1960s. Harvested cropland, the second most prevalent land use, peaked at 3.55 million acres (1.4 million ha) in 1940 and has generally declined since, to 2.43 million (1.0 million ha) in 1987. Pastured land increased from about 0.8 million acres (0.32 million ha) in 1925 to a peak of 1.1 million acres (0.44 million ha) in the mid-1950s, and has since declined to around 0.85 million acres (0.34 million ha). In addition to the 1.1 million acre decline in harvested cropland since 1925, there must have been about 2 million acres of other land in farms "lost" during that time period, since the total "acres in farms" has declined from 11 million to around 8 million (4.45 million to 3.2 million ha) (Figure 3.3a). Finally, urban land areas (defined here as land in towns and cities >2,500 population) increased rapidly beginning about 1930, and today amounts to around 0.3 million acres (0.12 million ha), or about 2% of the total AP basin land area.

There are not good data on any of the major land use categories, except harvested cropland, before 1930, so that the 1880-1925 values used in the nutrient production calculations are only estimates, but probably are not far off. Judging from the number of cattle on farms, the known cropland acreages, and the total land in farms values, and assuming that urban land use was much less than 1% before 1930, the forested areas must have been about the same in the late 1800s as in 1925. That is the assumption I have made for purposes of the nutrient production calculations. Actually, the errors in this assumption are probably much less impor-

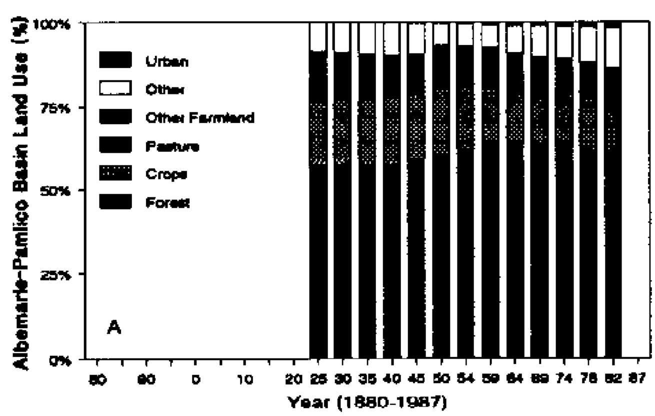


Figure 3.2. *Percentages of land use by six major categories for the Albemarle-Pamlico estuarine system drainage area, 1925-1982.*

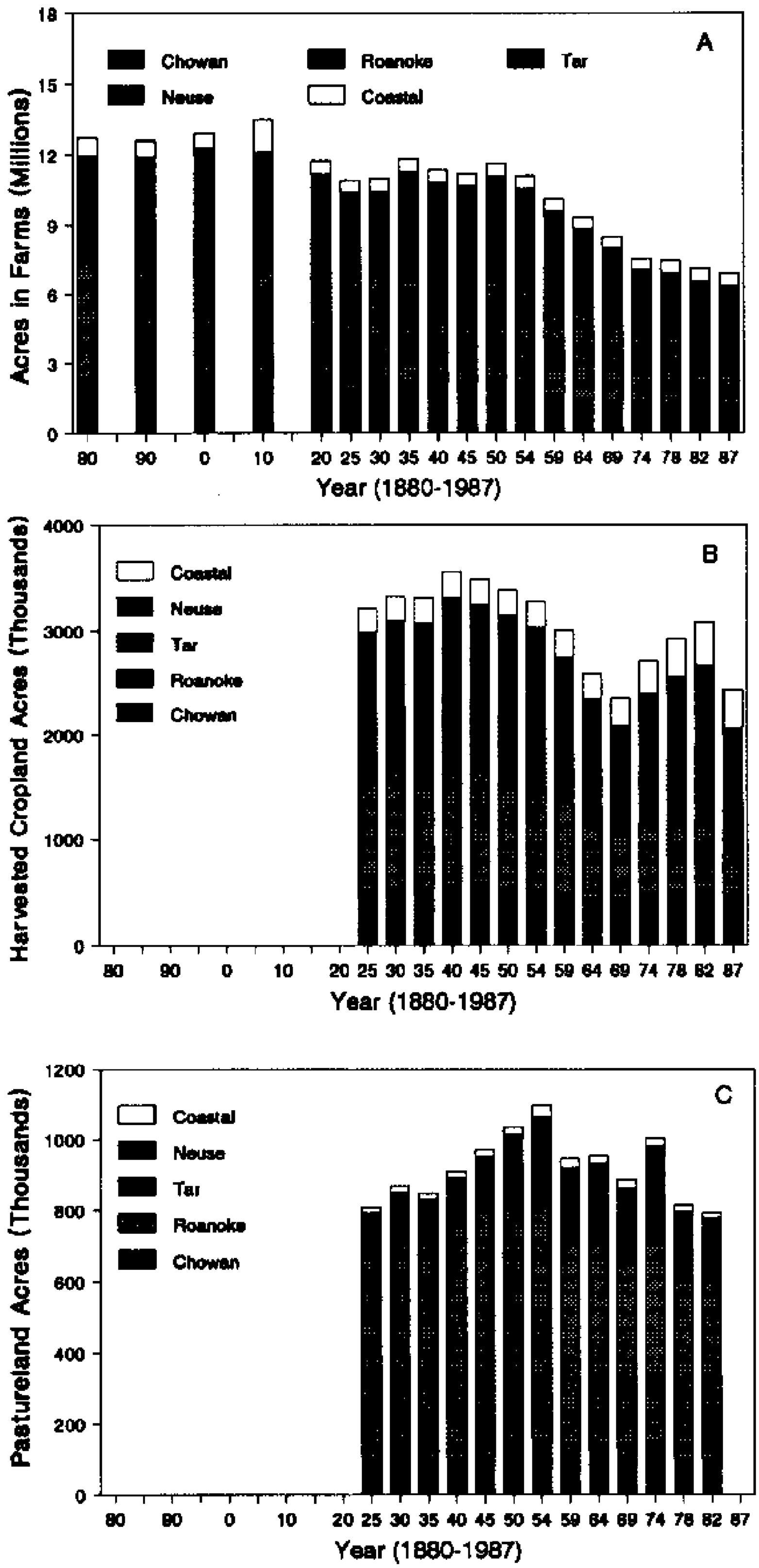
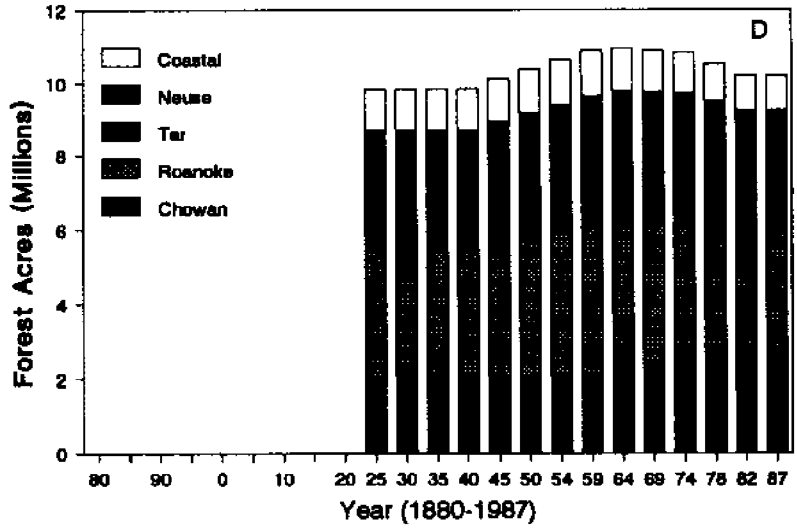
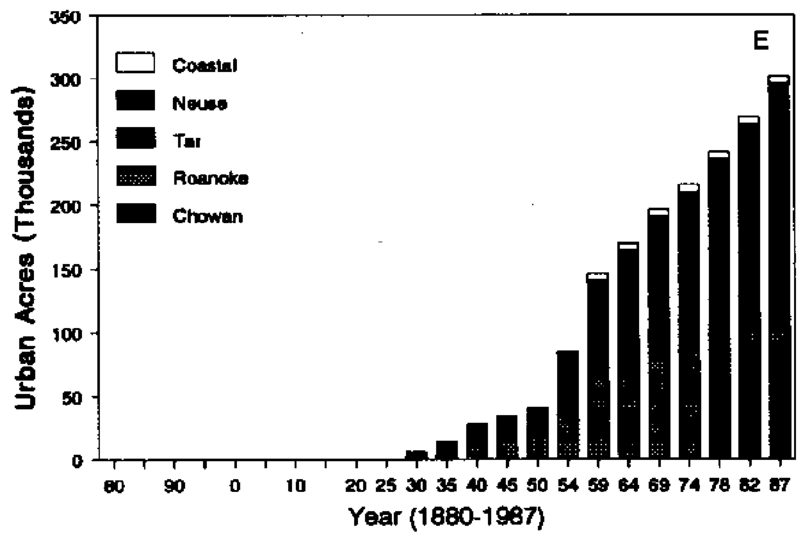


Figure 3.3. *Historical trends in land areas (land in farms, harvested cropland, pasture-land, forest, and urban) by sub-basin in the Albemarle-Pamlico drainage basin.*

Figure 3.3. *continued*

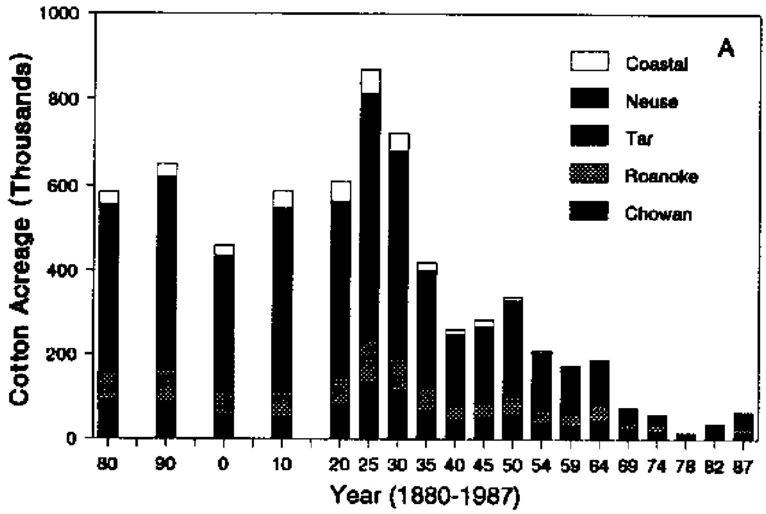


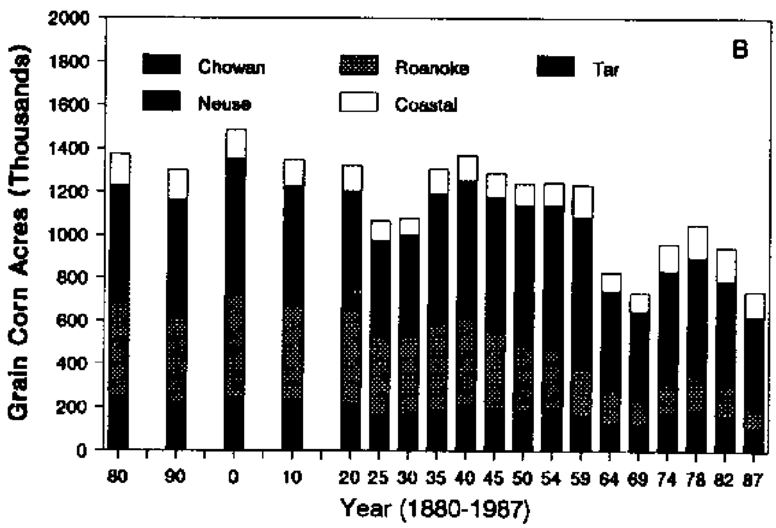


tant than those in choosing the export coefficients (*see* Discussion).

Some crops are much more important in the AP basin now than in the past, while others have become relatively unimportant over the years (Figure 3.4, Appendix 3.3). In terms of acres harvested, corn has been dominant throughout the past century, accounting for between 0.8 million acres and 1.5 million acres (0.32-0.61 million ha), or, on average, about 35% of the total harvested cropland. The second most widely planted crop today, soybeans, was first planted in significant acreages in the 1930s and 1940s, but up until about 1960 never made up more than 5-10% of the total. However, by 1987 there were 0.85 million acres (0.34 million ha) of soybeans, which was about one-third of the total harvested cropland.

In contrast, tobacco and, especially cotton, acreages have declined in the Albemarle-Pamlico basin (Figure 3.4). Annual tobacco plantings peaked in the 1930s and 1940s at around 0.6 million acres (0.24 million ha), but now are down





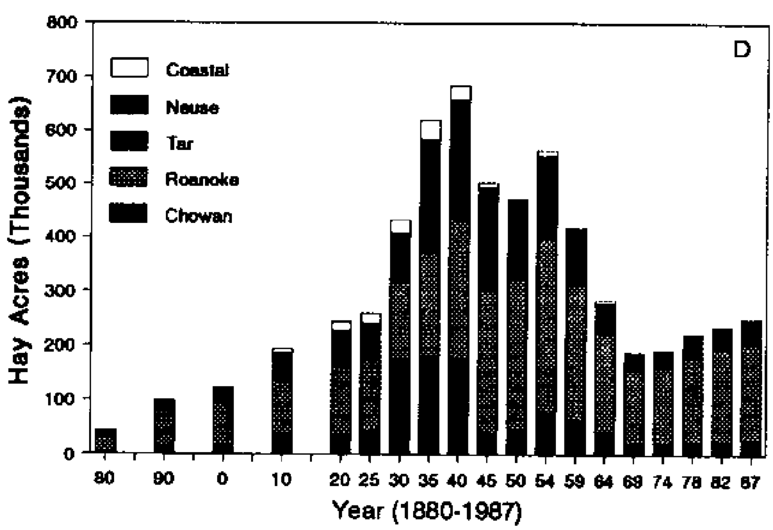
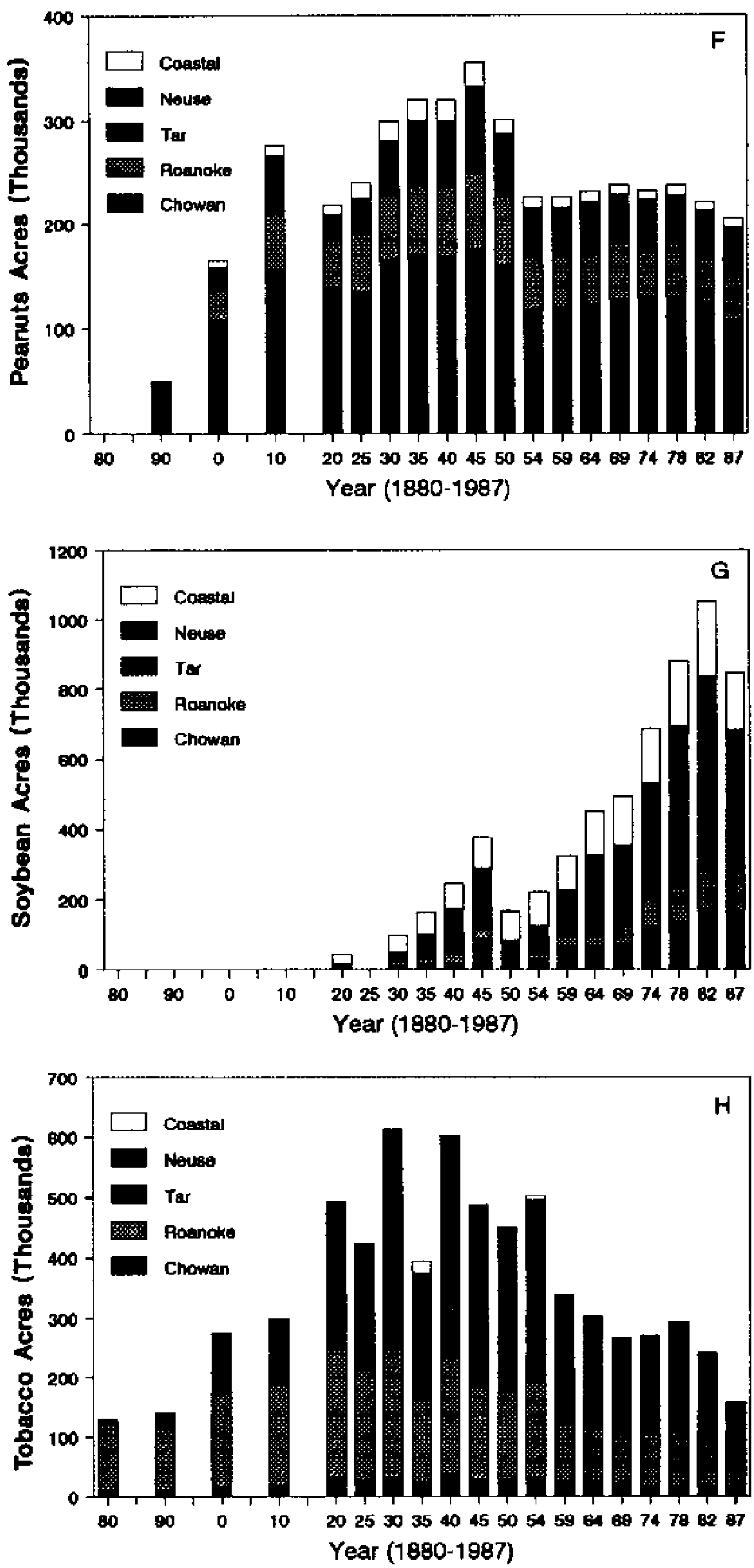


Figure 3.4. *Historical trends in amount of farm land used for six major crops, by subbasin, in the Albemarle-Pamlico basin, 1880-1987.*

Figure 3.4. *continued*



to around 0.2 million acres (0.08 million ha), or approximately 7% of total cropland acreage. 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 its 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 1987 only about 12% of AP basin cropland (0.3 million acres or 0.12 million ha) was devoted to wheat, and this was the second highest acreage planted in wheat, at least during a census year, over the past 100 years. Oats were widely grown in the late 1800s, (0.3 million acres or 0.12 million ha) but declined rapidly, then rose slightly in the 1950s, and have since fallen back to become insignificant in recent times in comparison to other crops. Peanut production in the AP basin increased rapidly in the early part of this century, and in terms of acres grown, peaked around 1945 at 0.35 million acres (0.14 million ha). Since 1954, the peanut acreage has remained nearly constant at about 0.23 million (0.09 million ha). Finally, hay crops are a relatively minor part of the total cropland use today (<10% of total). This crop was somewhat more important in the past, but was never dominant. The largest hay acreages were in the 1940s, when they peaked at around

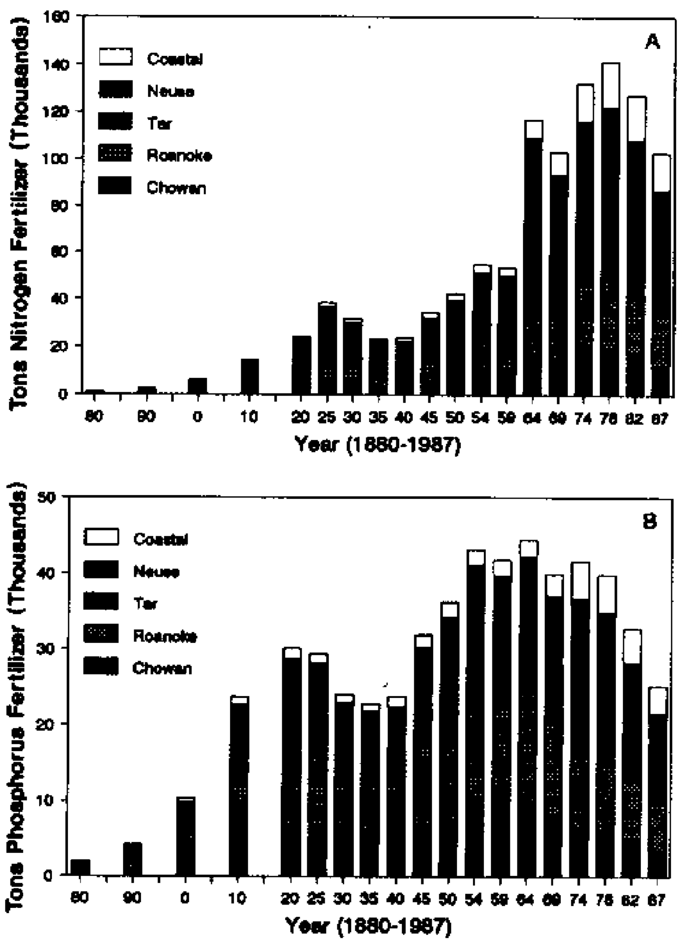


Figure 3.5. *Trends in nitrogen and phosphorus sold as commercial fertilizer, by sub-basin, in the Albemarle-Pamlico drainage basin, 1880-1987.*

0.7 million acres (0.28 million ha).

Harvested Cropland Nutrient Mass Balance

Since about 1900, the major nutrient inputs to croplands have been N and P fertilizer. Large increases in the use of fertilizers have occurred in the AP basin over the past 50 years (Figure 3.5, Appendix 3.4). Annual P sales peaked in the 1960s at around 45,000 tons P (40.9 million kg P), but have declined to 25,000-30,000 tons P (22.7-27.3 million kg P) in the 1980s (Figure 3.5b). Meanwhile, however, there has been a very rapid rise in the amount of N fertilizer sold. In fact, annual sales increased about 7-fold between 1940 and 1978, when a peak of 140,000 tons N (127.6 million kg N) was reached. N fertilizer sales, like P sales, have declined slightly in the 1980s, but some of the apparent decline may be attributable to low demand (i.e., poor weather) during the census years, rather than to a long-term downward trend. That was certainly the case in 1987, when acres planted, fertilizer use, and harvest were all lower than normal due to drought conditions in much of the region.

The other variable nutrient input on the cropland has been atmospheric deposition. As will be discussed below, there probably has been about a five-fold increase in the areal rate of atmospheric N deposition

Figure 3.6. *Trends in yield (pounds and bushels per acre) for seven major crops in the Albemarle-Pamlico basin, 1880-1987.*

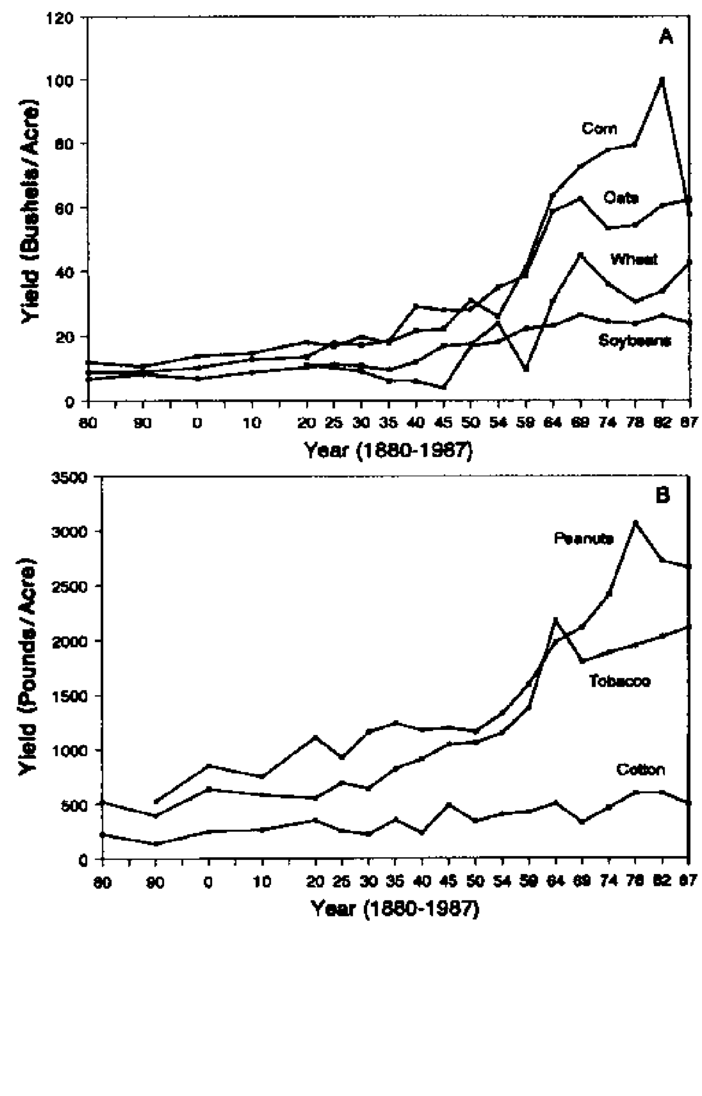


Table 3.7. *Croplands N and P mass balance, on a per hectare basis, for selected years.*

Input/Output	1880	1900	1920	1940	1959	1974	1987
(kg N/ha)							
N fertilizer	0.84	5.07	17.40	16.34	41.25	111.04	96.70
Harvest	-8.77	-12.78	-19.42	-29.73	-47.71	-80.41	-83.99
N fixation	0.00	6.26	9.01	17.31	19.79	36.17	46.02
Denitrification	-0.12	-0.76	-2.61	-2.45	-6.18	-16.65	-14.50
Precipitation	0.80	0.80	1.10	2.25	3.32	3.93	4.32
Balance	-7.25	-1.40	5.48	3.71	10.47	54.08	48.54
(kg P/ha)							
Fertilizer	1.69	8.45	22.41	16.70	32.68	36.05	24.96
Precipitation	0.27	0.29	0.31	0.36	0.55	0.54	0.59
Harvest	-1.48	-1.94	-2.70	-2.70	-6.03	-10.17	-10.24
Balance	0.48	6.81	20.02	14.36	27.19	26.42	15.30

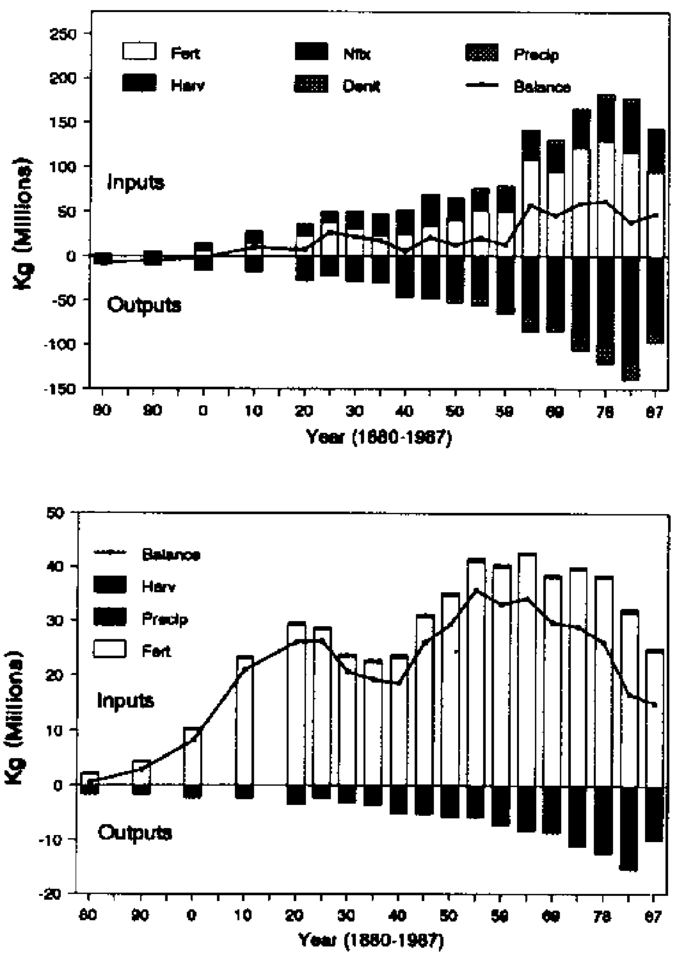


Figure 3.7. *Historical trends in cropland nitrogen and phosphorus mass balances in the Albemarle-Pamlico basin, 1880-1987.*

in the AP basin over the past century. However, the atmospheric N input to croplands today is still very small in comparison to fertilizer N and N fixation.

With increasing fertilizer and pesticides use, and more productive crop varieties, increases in yields (bushels or pounds per acre) for some crops has been very impressive (Figure 3.6, Appendices 3.5, 3.6). The greatest yield increases came between about 1940 and the 1970s. For example, corn yield increased about 5-fold, from around 20 bushels/acre to over 100 bushels/acre. Wheat yields improved about 4-fold, oats by a factor of about 2.5, and soybean yield approximately doubled over the past 40 years or so. There have been impressive increases in the tobacco and peanut yields also (Figure 3.6).

Cropland nutrient mass balances for all of the AP basin

Figure 3.8. *Historial trends in numbers of eight major categories of farm animals, by sub-basin, in the Albemarle-Pamlico basin, 1880-1987.*

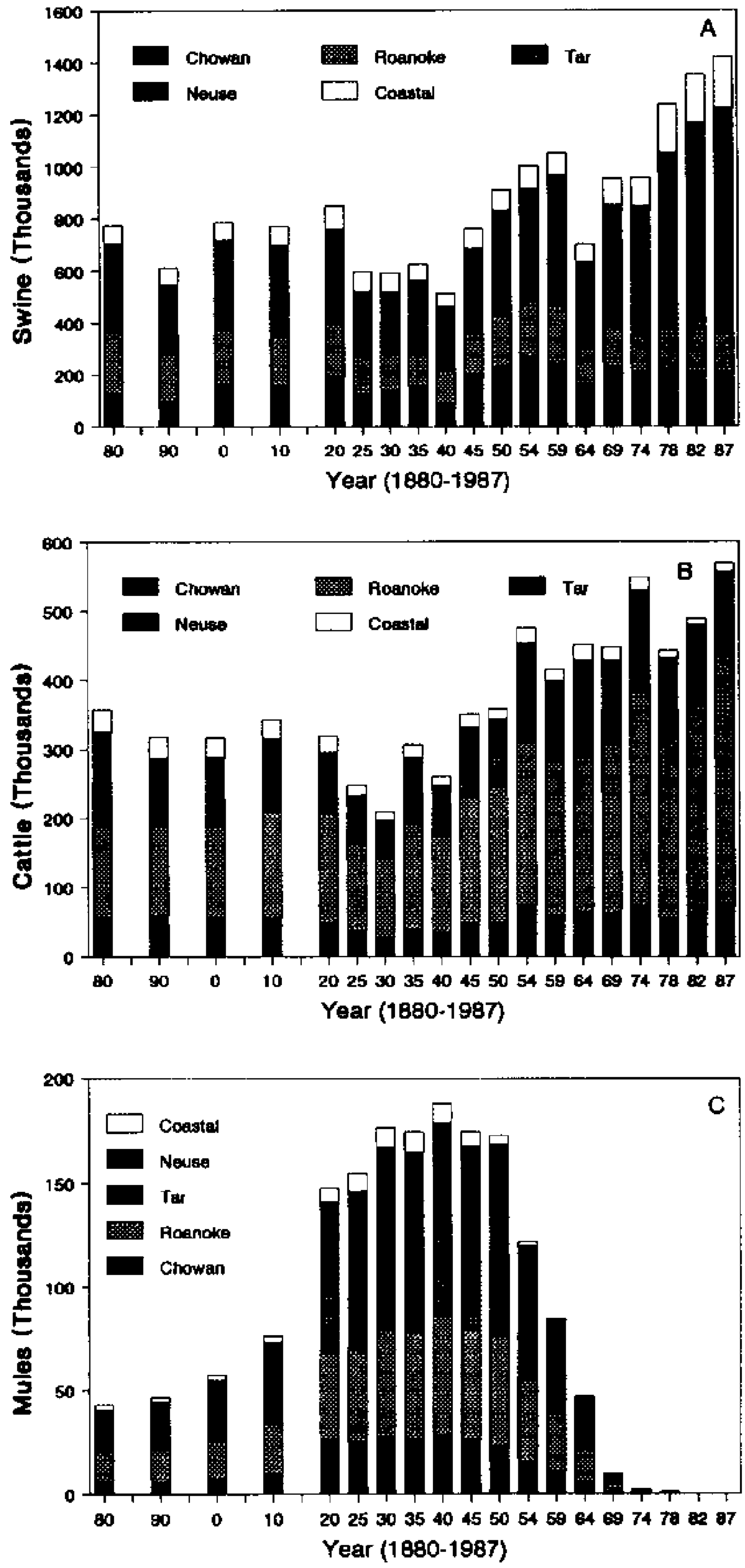
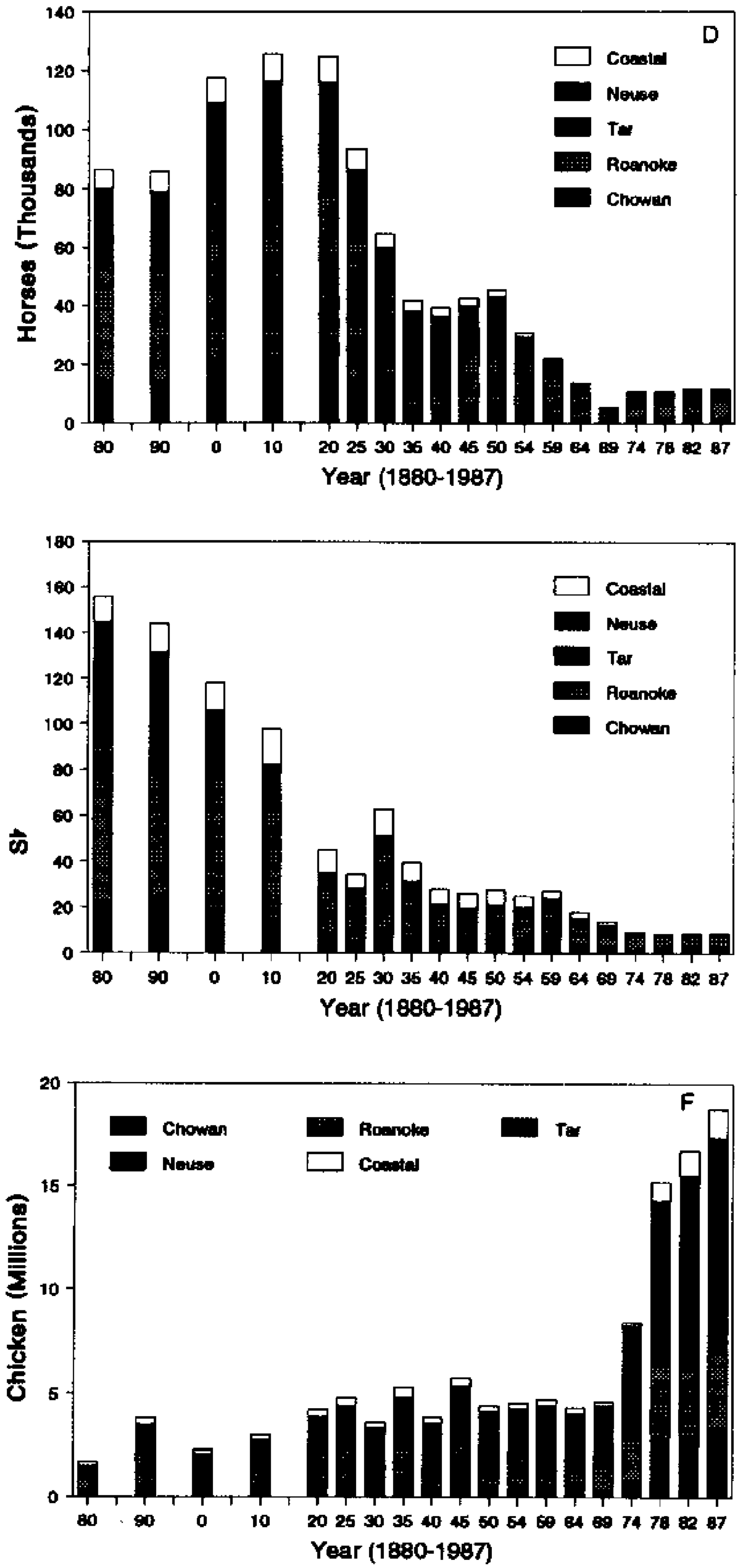


Figure 3.8. *continued*



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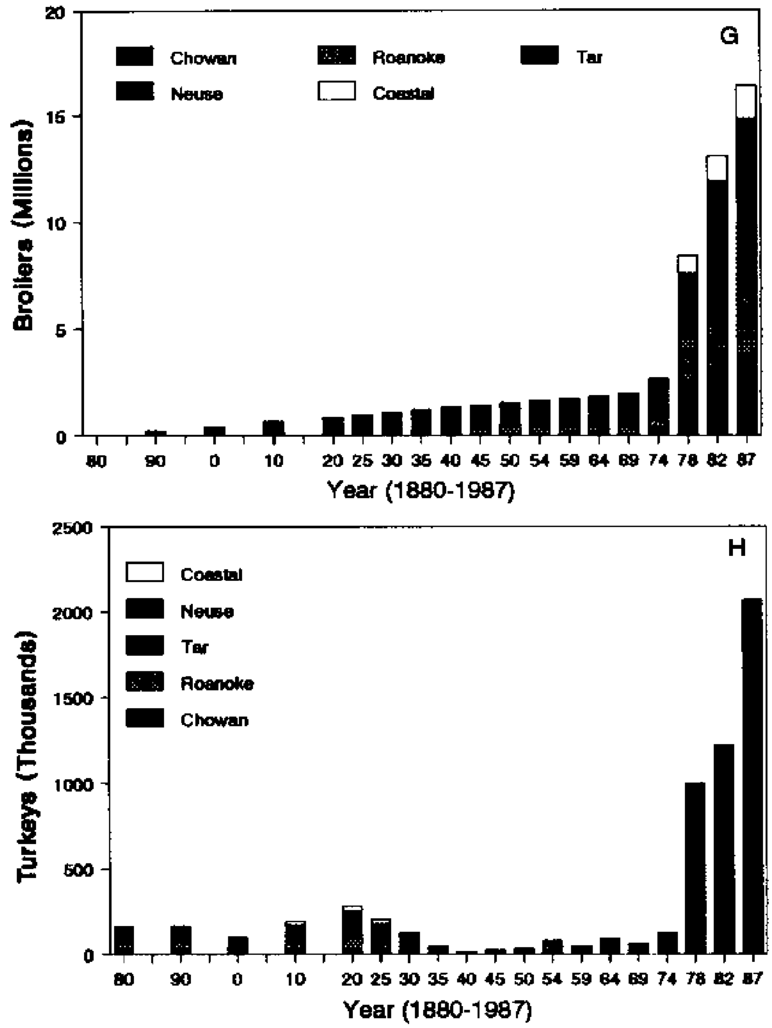

are shown in Figure 3.7. The N "balance", which represents the difference between inputs and outputs, has increased gradually from near zero, or less than zero, in the late 1800s, to around 50 million kg N per year by 1964, but appears to not have changed greatly since then. The P "balance", on the other hand, increased most rapidly in the early 1900s, reaching a peak of about 36 million kg P in the 1950s. Since, then, the P balance has declined to about 20 million kg P, or about the same amount as in the period 1910-1940.

The annual excess cropland N has ranged from -7.2 kg/ha in the late 1880 to as high as 54.1 kg/ha in 1974. The trend is about the same as that described above for the whole AP basin; what differences there are due simply to differences in the amount of harvested cropland. There was a rapid increase in the 1950-1970 period, with a leveling off since then (Table 3.7). Excess cropland P also followed about the same pattern described above for the whole basin, and the per hectare values have ranged from 0.5 kg in 1880 to as high as 31.3 kg in 1969. In recent years the excess P has been around 15 kg/ha.

Farm Animal Inventories and Nutrient Production

In every census since 1880, swine have been the most numerous large farm animal in the Albemarle-Pamlico basin (Figure 3.8, Appendix 3.7). Between 1880 and 1940, the swine inventory fluctuated between 500,000 and 850,000 head, but after 1945 it rose steadily, and by 1959 there were over 1 million head. A decline in the early 1960s was followed by another period of increase, so that now there are more than ever (1.4 million) of these animals. The increases in swine since 1959 have taken place in the Tar, Neuse, and Coastal sub-basins, while inventories in the Roanoke and Chowan basins have fallen slightly. Swine production is concentrated in the central coastal plain in North Carolina; thus the Tar River Basin has 23% of all the hogs in the AP system, and 38% are in the Neuse River basin.

Cattle, on the other hand, have always been most numerous in the northwestern

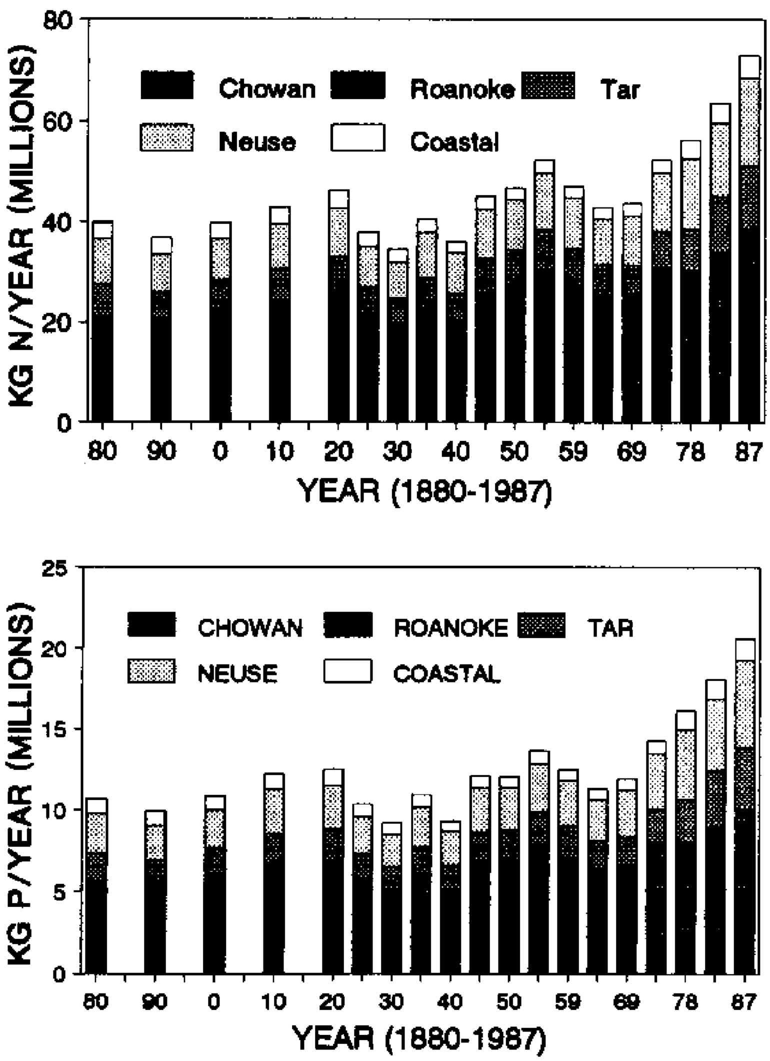

Figure 3.9. *Historical trends in annual nitrogen and phosphorus produced in excreta of farm animals (millions of kg) in each sub-basin of the Albemarle-Pamlico drainage area, 1880-1987.*

part of the AP basin. Total numbers ranged between 250,000 and 350,000 up until the 1940s, but showed no particular trend. Since then, there has been a general increase, to around 570,000 today (Figure 3.8). Most of the increase has been in the Roanoke River basin, probably in the western Piedmont and Appalachian foothills sections. Since 1930, the number of cattle in that basin has nearly tripled, and there has been nearly a doubling in the Chowan basin. But in the more southerly Tar, Neuse, and Coastal basins, the increases have been much smaller.

Numbers of mules peaked in the 1940s at around 180,000, but they, along with horses and sheep, have become an insignificant part of the total farm animals inventory in the past two decades (Figure 3.8). Mules could not compete with tractors, which rapidly began to take the place of human and animal power in southern agriculture in the late 1940s. In just two decades, between 1950 and 1970, the mule had practically disappeared from farms in the AP region. Likewise, inventories of horses had shown a steep decline earlier in the 1920s, as automobiles and trucks became the more common method of transportation for farm families. Finally, sheep raising in the AP basin declined rapidly during the first quarter of this century, as reflected in the inventories, which went from 155,000 animals in 1880 to only 30,000 by 1925 (Figure 3.8).

Poultry production in some areas of the AP basin has increased dramatically in the

Table 3.8. *Major nutrient point sources in the Albemarle-Pamlico basin. Numbers correspond to ranks in Figure 3.10. M = Municipal; I = Industrial.*

Number	Facility	Type	Sub-basin
1	Raleigh, NC	M	Neuse
2	Weyerhaeuser	I	Roanoke
3	Union Camp	I	Chowan
4	Weyerhaeuser	I	Neuse
5	Roanoke, VA	M	Roanoke
6	Durham, NC (Northside)	M	Neuse
7	Rocky Mount, NC	M	Tar
8	Danville, VA	M	Roanoke
9	Greenville, NC	M	Tar
10	Cary, NC	M	Neuse
11	Wilson, NC	M	Neuse
12	Goldsboro, NC	M	Neuse
13	Martinsville, VA	M	Roanoke
14	Kinston, NC	M	Neuse
15	Texasgulf Chemicals	I	Tar
16	Havelock, NC	M	Neuse
17	New Bern, NC	M	Neuse
18	Reidsville, NC	M	Roanoke
19	Salem, VA	M	Roanoke
20	Eden, NC	M	Roanoke

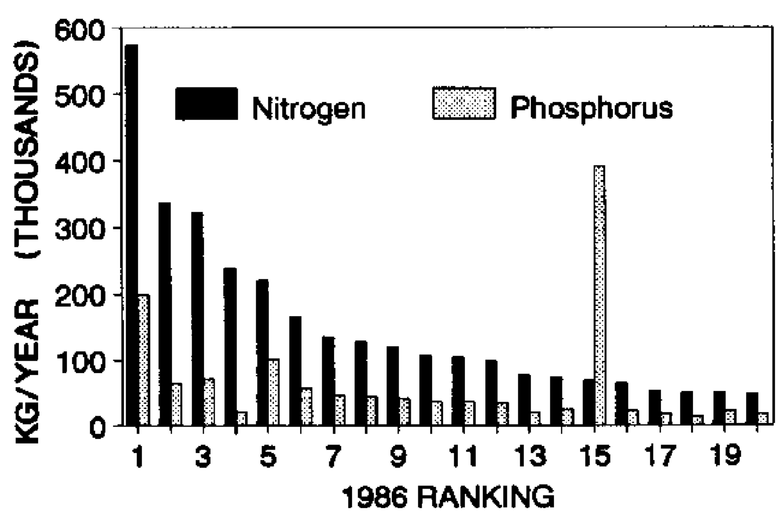

Figure 3.10. *Ranking of point sources in the Albemarle-Pamlico basin, in terms of kg N produced per year in 1986.*

past two decades. Growth of the poultry industry has been one of the most notable developments in southern agriculture since World War II. Historically, poultry on most southern farms had been a barnyard business to provide eggs for the table and to earn a little "egg money" for groceries and other things. Chicken was not eaten regularly but was something families ate on Sunday and on special occasions. Chickens were kept mainly for the eggs. But by the mid-1940's, there had developed "businessmen-farmer teams" for the commercial production of "eating chickens", or "broilers." The businessman hatched the eggs, contracted with farmers to raise the chicks on feed that he supplied from his mill to growers on credit, and finally processed and marketed the birds. Farmers provided the housing, labor, and management in return for an assured market (Fite 1984).

This "vertical integration" of the industry, along with increased efficiency of feed utilization, led to lower prices (relative to other meats). This, in turn, helped increase consumer demand, producing a boom in broiler and egg production that continues today. Some Piedmont and coastal areas in North Carolina have become areas of intense poultry production. The industry tends to be locally concentrated. For example, in 1987 about one half the total number of chickens in North Carolina were in only 6 of the State's 100 counties (N.C. Department of Agriculture 1988). One such area is in the central coastal plain, within the Tar and Neuse River watersheds. Thus nearly half of the total broilers and chickens inventoried in the AP region in 1987 were in those two sub-basins (Figure 3.8). Turkey farming is even more focused; in 1987, 80% of the total inventory was in the Neuse basin (Figure 3.8). Total AP poultry inventories (broilers, chickens, and turkeys) grew slowly from around 2 million in 1880 to approximately 6 million in 1959. Since then, however, poultry inventories have increased at an amazing rate, so that by 1987 there were over 37 million of these animals in the Albemarle-Pamlico Basin.

N production from farm animals increased slowly between 1880 and 1969, but has increased rapidly since 1969, so that over the past century this N source has almost doubled (Figure 3.9, Appendix

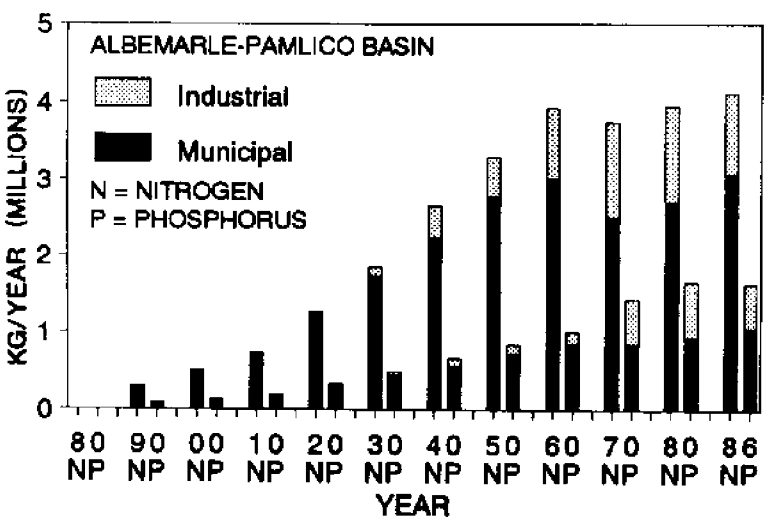

Figure 3.11. *Trends in point source loadings of nitrogen (N) and phosphorus (P) from point sources in the Albemarle-Pamlico watershed, 1880-1887.*

3.8). In 1880 animal produced about 40 million kg N, compared to 45 million kg in 1969. But the 1987 value was almost 75 million kg/year. Cattle have contributed 40%-60% of the total animal N in most census years, and swine have usually made the second largest contribution (15%-25%). In the past, horses, mules, and poultry also made significant contributions to the animal excreta N. But in recent years, just three animal types — cattle, swine, and poultry — have been responsible for more than 95% of the total. Since 1978, the percentages have been about 50% from cattle, 20% from swine, and 30% from poultry.

Animal excreta P amounted to about 11 million kg in 1880, and was only slightly higher (12 million kg) in 1969. By 1987 the animal P had increased to over 21 million kg/year. The pattern has been similar to that for N, both in terms of the changes in production rate, and the percentages contributed by each animal type. In recent years about 40% of the P has come from cattle, about 30% from swine, and about 30% from poultry.

Point-Source Nutrient Production

The urban population, and hence the estimated sewered population, in the Albemarle-Pamlico, has risen rapidly in recent years, and today the largest urban centers are in the western areas of the sub-basins, primarily in the Raleigh-Durham area in North Carolina (Neuse River basin) and in the Roanoke, Virginia area (Roanoke River basin). A high percentage of the total municipal loading comes from a small number of the largest cities (Figure 3.10 and Table 3.8). Tracking this population increase, point source loading in the AP basin rose rapidly during the first half of this century (Figure 3.11, Appendix 3.9), and the geographical distribution of the municipal loading has corresponded closely to the population patterns, suggesting that there is little variation in the level of treatment (i.e., percent N and P removal) within the region. However, the rate of increase slowed, at least temporarily, about mid-century as secondary treatment became more widespread (Figure 3.11).

In 1986 the estimated total municipal N and P loadings were 3.07 million kg and 1.06 million kg, respectively. About half the total N came from cities and towns in the Neuse basin, 28% from the Roanoke basin, 16% from the Tar basin, 5% from the Chowan basin, and only about 3% from the coastal areas (Figure 3.11). Municipal P loading was distributed among the basins in about the same proportions.

Although the AP basin is relatively unindustrialized, there are a few major industries that contribute large quantities of N and P; in some cases much more than the municipal sources. In 1986 the industrial sources contributed about 1.04 million kg N and 0.56 million kg P. This amounts to about one-fourth and one-third the total AP basin point source N and P, respectively. Two types of industries — pulp and paper mills and phosphate mining — predominate, in terms of N and P production. Most of these have come to the region since World War II. There are pulp/paper mills on the lower Roanoke River, tributaries of the Chowan river, and the lower Neuse River. Point source loading in the Chowan River basin is especially dominated by the industrial sources, which produce about twice as much N and P as the municipal plants in this relatively unurbanized basin (Figure 3.11). The Tar-Pamlico River presents an unusual situation also. There, the Texasgulf phosphate mine discharge dominates the point source P loading. Since it was built in 1964, this single source has accounted for two-thirds to three-fourths of the total annual point source P produced in the Tar-Pamlico basin.

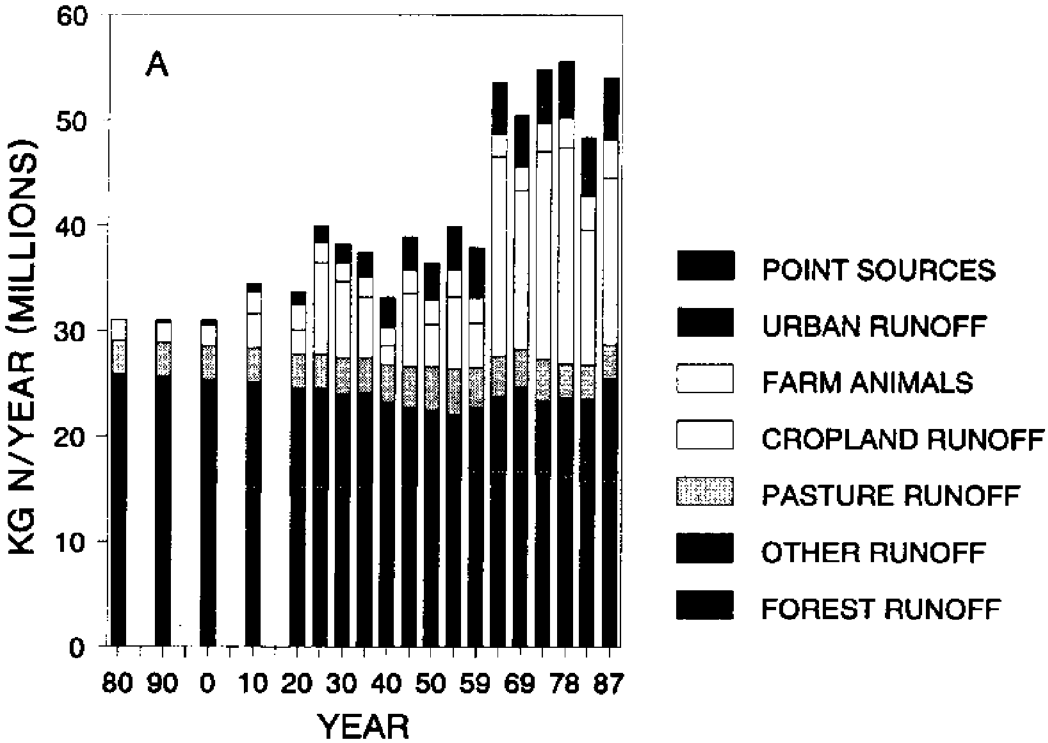

Figure 3.12. *Trends in estimated total nitrogen production, from all point and non-point sources, in the Albemarle-Pamlico watershed and from each major sub-basin, 1880-1987.*

Trends in Total Nutrient Production by All Sources

Time series plots for trends in estimated total N production from all sources, both nonpoint and point, are given in Figure 3.12. Several important assumptions have been made regarding these estimates:

1. The production by forests, other land (here the sum of two land use types described above: "other farmland" and "other land"), pasture, and urban lands was calculated by multiplying acreages times constant yield coefficients.

2. The cropland N production was assumed to be equal to one-third of the cropland N balance calculated above.

3. Animal N production was assumed to be equal to 5% of the animal N in excreta.

Similar assumptions were made for P, with one difference; the cropland P production was assumed to be one-fifth of the computed P balance.

For the whole Albemarle-Pamlico basin, the total annual N production from all sources is estimated to have nearly doubled over the past century, from around 30 million kg in 1880 to 55 million kg in 1987. Between 1880 and 1959, the increase was only about 5 million kg (18%). Then, primarily because of the rapid increase in the cropland balance in the 1960s, the total N production rose rapidly, but appears to have remained nearly constant in the 1970s and 1980s.

The percentage contributions by each N source have changed greatly over the past century. In 1880, the most important

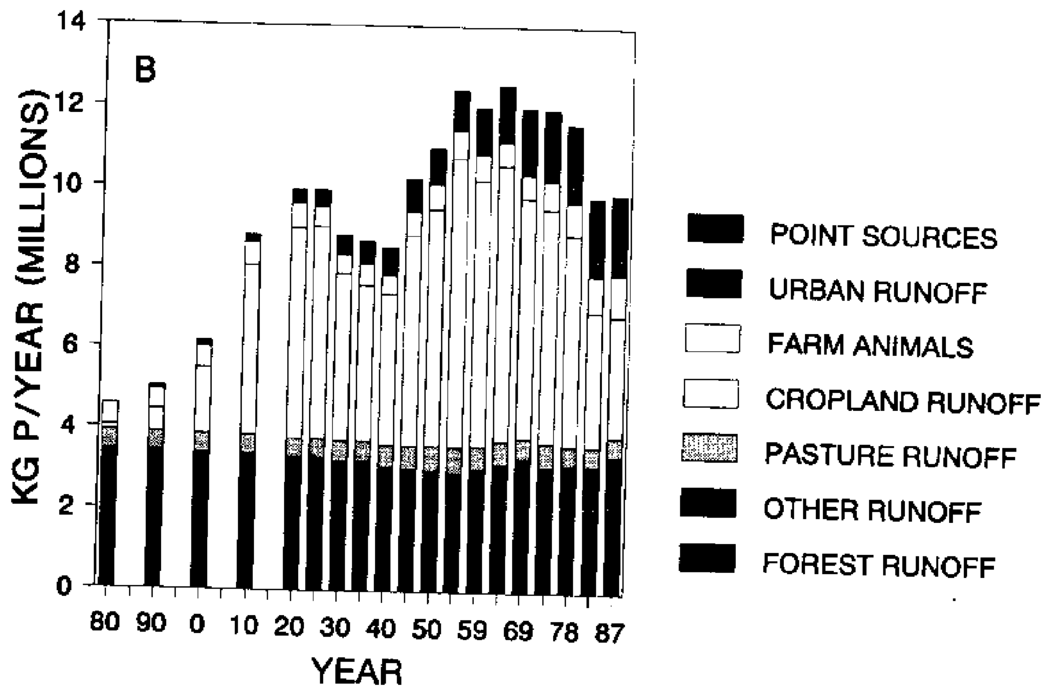

Figure 3.13. *Trends in estimated phosphorus production, from all point and non-point sources, in the Albemarle-Pamlico watershed, and from each major sub-basin.*

sources were forest (45%) and "other" lands (35%). Pasture and farm animals contributed almost all the remainder (Figure 3.12). Today, according to these estimates, the forest, other lands, and pasture N production is about the same, in terms of kg/year, but new sources have diminished the relative importance of these three. The most important new N source is cropland excess N, which now makes up about 30% of the total. Animals, urban runoff, and point sources together contribute about 17% of the total.

Two of the sub-basins, the Tar and the Neuse, appear to have experienced larger relative increases in N production than the Chowan, Roanoke, or Coastal sub-basins (Figure 3.12). In the Chowan basin, N production rose gradually in the early 1900s, but is no greater today than in 1930, although there have been relatively large short-term fluctuations. The Coastal basin N production also rose fairly gradually, from around 3 million kg in 1880 to about 5.3 million kg in 1978. In this area, the increases from cropland have been offset, to some extent, by decreases from forest and "other" land. The Roanoke basin followed a pattern similar to that for the Tar and Neuse; i.e., a gradual increase up until the 1950s, followed by a rapid rise in N production in the 1960s. But in the Roanoke, the overall increase has not been as great as in the other two sub-basins. In other words, the Roanoke N production has increased by about 50% over the past century, whereas in the Tar and the Neuse basins, the increases have been 80% and

115%, respectively. Most of this difference appears to be due to much greater increases in cropland N balance in the Tar and Neuse than in the less agricultural Roanoke basin.

The most notable difference between total N production and total P production in the AP basin is that P production appears to have declined in recent years, particularly in the Chowan and Roanoke sub-basins (Figure 3.13). For the whole AP watershed, total P production rose rapidly from around 4.5 million kg in 1880 to nearly 10 million kg by 1920. Following a decline in the 1930s, the P production rates began to increase again, reaching an all-time high of about 12.5 million kg/year around 1960. Since then, P production has fallen back to about 10 million kg/year. So, overall the increase during the past century has been about 110%, but during the past quarter century there may have actually been a 20% decrease. As in the case of N production, much of the change in P production has been caused by changes in the cropland balance. In recent years, this source has accounted for about 30% of the total P; in some years in the 1960s it was as much as 60% of the total. The other new P sources, point and urban runoff, make up about 10% and 3%, respectively, of the total today.

There are quite large differences in the trends for each of the sub-basins. In the Chowan and Roanoke, the decreases in recent years are most noticeable, particularly in the Chowan. There, the cropland P mass balance has declined by almost 75% since 1954, causing about a 50% decrease in the estimated total P production. The same pattern in the Roanoke has led to about a 30% decrease. P production in the Tar and Neuse basins appears not to have changed greatly in recent times, although there are substantial year-to-year changes. The coastal sub-basin is the area in the AP watershed where the P production trend has been the least variable. The long-term, gradual increase in P production appears to be continuing, although there was less P produced in 1982 and 1987 than in the two previous census years.

Discussion

Likely sources of error associated with the municipal loading estimates include the sewered population values and the treatment factors used in the calculations. As noted above (*see* Methods) the sewered population for years before the first municipal treatment plant inventory in 1942 was assumed to be equal to the populations of the cities and towns. This caused some overestimation of the nutrient loading. However, this error would make little difference in the overall loading estimates since the "potential" sewered population then was so small. The problem with using "treatment factors" is that the facilities in a given city often have not performed at the expected efficiencies, for a number of reasons, including storm-related bypassing of raw sewage in combined systems, wastewater flows exceeding the design capacity of the systems, and poor maintenance of the equipment. The latter was reported to be a serious problem in many cities and towns in the AP basin during the 1950s (N.C. Stream Sanitation Committee 1959). Thus, the actual nutrient loading would be greater than I estimated if this type of error became serious.

Nevertheless, comparison of my estimates with those made by others using different techniques shows that, for recent times at least, the "treatment factors" method gives reasonably accurate estimates. The data I used for comparison come primarily from calculations made by multiplying average effluent discharges (MGD) times average N and P concentrations in the effluent (mg/l). The products for all municipal plants in the basin are then summed to give the total expected

Table 3.9. *Comparison of point source loadings estimated by two different techniques. "Flow x Con." refers to multiplication of effluent discharge rates (MGD) times nutrient concentrations (mg/l). "T. Factors" refers to the use of treatment factors, used in combination with estimates of sewered population. Numbers in parentheses (beside kg/year values) refer to data sources given at bottom of table.*

	Nitrogen (kg/yr)		Phosphorus (kg/yr)	
Basin/Year	"Flow x Con." Method	"T. Factors" Method	"Flow x Con." Method	"T. Factors" Method
Tar-Pamlico (1986-88)				
Municipal	545,496 (1)	490,542	95,598 (1)	165,046
Texasgulf	71,373 (1)	70,000	346,647 (1)	391,000
Chowan (1980)	881,000 (2)	722,798	165,300 (2)	136,531
Neuse (1980-82)	1,510,000 (3)	1,470,626	430,000 (3)	437,911

[1]N.C. Division of Environmental Management (1989)
[2]N.C. Division of Environmental Management (1982)
[3]N.C. Division of Environmental Management (1983)

loading. The results (Table 3.9) agree reasonably well with my calculations. Note that the 1988 Tar River values reflect a reduction in P loading that resulted from a 1987 ban of phosphate detergents in North Carolina. Thus, this value is approximately 40% lower than my estimate for 1987 (before the ban), which is about the same as the percentage reduction attributed to the P detergent ban by state officials (N.C. DNRCD 1989). I had to use the less direct "treatment factors" approach because monitoring of treatment plant effluent N and P concentrations in North Carolina and Virginia did not begin until about 1980; thus, the "flow times concentration" method commonly used today could not be used for estimating historical loadings.

Gakstatter et al. (1978) surveyed median P and N concentrations in the effluents from over 800 municipal wastewater plant using various treatment processes. Their data show that conventional secondary treatment removes little P and only about 25-45% of the N. Tertiary treatment considerably increases the N and P removal, but this advanced treatment is not yet used in enough plants to make a difference in the overall loading. For example, in 1985 the median Neuse River basin N and P effluent levels were 13 mg N/liter and 6 mg P/liter (data provided by NC Division of Environmental Management), which is typical for secondary treatment processes such as trickling filters and activated sludge.

Before 1950 there was no significant N or P removal from wastewater discharged into the rivers of the AP basin. Although sewage collection systems had been constructed for most of the larger cities in the early 1900s, as late as 1945 about two thirds of the sewered population was using systems that provided no treatment (N.C. Stream Sanitation Committee 1946). Rather, the raw sewage was simply discharged into nearby streams and rivers. About half of the sewage that was treated received only primary treatment, which removes, at best, only about 10% of the N and P. Thus, N and P loading was growing at about the same rate as the sewered population. As secondary treatment came into widespread use in the 1950s and 1960s, the overall nutrient removal efficiencies increased, causing a slowing in the rate of increase in municipal nutrient loading. But there has been little additional improvement since then because further increases in treatment efficiencies have not occurred, or have occurred more slowly to keep up with increases in urban population.

The greatest source of error in the nonpoint nutrient production estimates undoubtedly comes from uncertainties in the areal export coefficients, rather than from the acreages. Measured export coefficients were compiled by Beaulac (1980) from scores of studies and presented in tabular and graphical form in Beaulac and Reckhow (1980). They discussed factors that affect the coefficients for each land-use type and urged that for application to a particular geographic area, only those coefficients from studies in similar areas be considered. However, there are two potential problems in using this simple, obvious criterion. First, there may be no data available that seems suitable for a given area, or secondly, there may be so much variability in the area to be modeled that choosing a truly representative coefficient value is very difficult. Unfortunately, most of the studies have been made for watersheds with mixed land uses rather than just one. Nevertheless, I tried to choose coefficients as carefully as possible, considering those presented in Beaulac and Reckhow (1980), and in other sources (e.g., Loehr 1974).

Soil scientists are much more certain about what factors affect rates of denitrification than they are about the actual rates in the field. Studies in North Carolina and elsewhere have shown that the rate is inversely related to drainage and directly related to the presence of soil horizons which restrict water movement. Gambrell et al. (1975) measured essentially no denitrification on one moderately well drained soil and as much as 60 kg/ha on a poorly drained soil; both sites were within the AP basin. The figure of 15% loss of applied N lost by denitrification that I used is very frequently used in computations of N balances. Apparently it originated from denitrification experiments conducted under laboratory or greenhouse conditions. Thomas and Gilliam (1978) concluded that it is generally accepted as being as accurate as any.

The very large increase in the cropland N balance (inputs minus outputs) between 1959 and 1964 is probably somewhat misleading, since N (and P) fertilizer sales in 1964 seem to have been unusually large, especially in comparison to the relatively small (for that time) harvest. Nevertheless, there was apparently a rather steep increase in the "excess N" during the period 1954-1964. Apparently, yields were not increasing as rapidly as was the rate of application of N to the croplands. Later, in the 1970s and 1980s, the fertilization rate seemed to level off, or perhaps decline slightly. This appears to be the main reason for the stabilization in the N balance. It is interesting to note however, that since the early 1960s, there appears to have been no increase in the amount of excess N on croplands. The trend in cropland P balance in recent years is even more surprising, in that there seems to have been about a 50% reduction in the cropland "excess" P since 1954.

Estimating historical trends in atmospheric N oxide concentrations is difficult, because of the weak historical data base for precipitation chemistry. Before 1955 there were only sporadic measurements (apparently none in the AP basin) and Stansland et al. (1986) have concluded that their reliability is so questionable that they should not be used for trend analysis. C.E. Junge (1958) published results of the first large scale study of rain water chemistry in the U.S., for the period July 1955-July 1956. His set of 60 stations included one at Cape Hatteras, NC, where NO_3 concentrations ranged generally between 0.15 and 0.30 mg/liter. Ammonia was also measured; it fluctuated seasonally but averaged about 0.04 mg/liter. A more thorough study was made in the AP basin area about ten years later, and the results were reported in Fisher (1968). A trend of increasing nitrate northwest from the coast was found; from 0.17 to 0.40 mg NO_3/liter (average annual) in the Pamlico Sound area to 1.00 mg/liter in the western end of the Roanoke River basin. Ammonium concentrations were considerably lower, averaging about 0.1 mg NH_3/liter over the whole AP basin. Calculated annual nitrate and ammonium loadings for the AP basin were about 2 tons/square mile and 0.35 tons/square mile, respectively (Fisher 1968).

The most recent data are from stations that was established in 1978, as a part of the National Atmospheric Deposition Program (NADP). Data from several NADP stations in the AP basin (most in the Piedmont and Central Coastal Plain areas) indicate that between 1981 and 1985 the precipitation weighted mean NO_3 concentrations (mg/liter) averaged about 0.9; whereas the NH_3 averaged around 0.2 (Olsen and Watson 1984; Olsen and Slavich 1985, 1986; Sweeney and Olsen 1987). Thus, for purposes of the loading calculations, I assumed that total atmospheric N concentrations in precipitation (NO_3 + NH_3 + other combined forms) was approximately 0.36 mg/liter (as N) in the mid-1980s. Over eastern North America the total wet and total dry deposition are thought to be of approximately equal magnitude (Stansland et al. 1986); therefore I doubled the calculated precipitation loading to give the total atmospheric N loads.

Another problem in estimating historical trends in atmospheric N oxides is that they are formed primarily by the fixation of atmospheric N at high temperatures of combustion rather than by oxidation of the N contained in the fuels. Thus the "emission factors" (i.e., the rate of N oxide emission per unit of fuel N) have to be taken into account, as well as the quantities of fuel burned. It is the uncertainty about changes in the emission factors that is most problematic. Based on estimates of emission factors and data on fuel consumption, Husar (1986) estimated that in the southeastern U.S., N oxides production increased in an exponential fashion from less than 1 million ton/year in 1900 to around 6 million tons/year by the mid-1970s. Husar showed that his results were similar to those of Gschwandtner et al. (1985) who also estimated trends in atmospheric N oxide emissions since 1900.

Since there are no reliable measurements of AP basin atmospheric N levels before 1950, I was forced to make historical estimates by combining data on present-day concentrations from remote areas, current concentration data for the AP basin, and the suspected exponential rate of increase described above. The remote areas values are assumed to represent conditions in the AP area in the late 1800s. The values came from NADP data summarized by Galloway et al. (1984). They showed that in the remote areas, the (presumably) "background" nitrate levels are around 4 μM N (0.23 mg NO_3/liter). Assuming that the nitrate:ammonia ratio has not changed, I estimated the atmospheric precipitation N for 1880 to have been 0.07 mg/liter (as N). If this estimate is close to the real 1880 concentration, then the current (mid 1980s) levels would represent about a 5-fold increase over the past century.

Yet another problem concerning atmospheric N deposition effects on nutrient production in the AP basin has to do with the uncertainty about the percentage of the increased deposition that actually leaves the forest, pasture, or other land. Recently, a controversial report on the role of acid rain in polluting coastal waters with N was prepared by the Environmental Defense Fund (Fisher et al. 1988). This EDF report contended that one-fourth of all N contributed by human activity to the

Chesapeake Bay originates in acid rain and associated dry deposition falling directly on the bay or onto its watershed. Atmospheric N, it was concluded, exceeds sewage outfalls and runoff of animal waste as a N source to the bay. These results were based on an assumption that forests retain 80% of the atmospheric N, pasture and croplands retain 70%, and urban lands 35%. Given that atmospheric N deposition is so large in comparison to other present-day inputs, it is no surprise that even if 0%-30% (from forests and croplands) of the atmospheric N is assumed to leave the and, then this becomes an important contribution to the streams and estuaries — especially when it is assumed (as both EDF and I did) that only 5% of animal N leaves the pastures and other sites of production.

But as the report noted, there is considerable variability in measures losses of atmospheric N from various land use categories; in some studies in areas similar to those drained by the rivers in the AP basin, the retention of atmospheric N has been found to be very high. Weller et al. (1986), for example, found that a coastal plain watershed in Virginia retained 97% of the atmospheric N deposited on it, and in a recently-published book on forest nutrition management it was stated that "with some notable exceptions (such as high elevation spruce/fir forests in the northeastern United States), the majority of forest ecosystems are N limited, so most nitrate deposited in acid rain is retained — indeed, nitric acid may fertilize forest ecosystems" (Binkley 1986, p. 208). Thus, forests appear to "buffer" a large part of the atmospheric N they intercept. For example, Lowrance et al. (1985) showed that for several agricultural-forested watersheds in Georgia, the N output via streamflow was always considerably less than the atmospheric N input, despite considerable additional N input from fertilization. Fisher (1968) came to a similar conclusion after comparing precipitation nitrate loading and stream nitrate transport for several areas within the AP basin.

The relatively low values and small geographical variability in forest may also give some indirect indication that historical increases in atmospheric N deposition have not made such a large impact on the total AP basin nutrient export as might be expected. Forest N yield estimates available in the literature are nearly all from studies carried out during the past two decades; i.e., recent enough to reflect effects of the relatively high atmospheric N deposition rates that developed by the middle of this century.

The N and P loading estimates made by others for the Chowan, Neuse and Tar River basins are roughly one-third to one-half the 1987 estimated total N and P production calculated above (*compare* Table 1.3, Chapter 1 with Figures 3.12 and 3.13). But those other estimates were also made using — in most cases — some combination of land use yield coefficients, instream flow times nutrient concentration calculations, and summed point source loading. It would probably be futile to try to determine the reasons for the differences in each case, but I suspect that the major difference has to do with the use of their instream concentration times flow calculations vs. my reliance on cropland mass balances, and land use coefficients. In general, the actual instream nutrient loads, and the loading to the estuaries, is considerably less than the quantities of nutrients produced at the sources, as was mentioned in the introduction to this chapter.

Of course, there is no long-term historical instream data for any part of the AP basin that could be used for comparison with the nutrient production estimates presented here, but there are at least some recent instream data for comparison. Christian et al. (1987) have monitored N and P concentrations in the lower Neuse River above New Bern. They multiplied N and P concentrations in grab samples times mean daily river flows to give total annual in-stream loading estimates. Their results, 3.5 million kg N per year and 0.8 million kg P/year, are 1/4 as large as my N estimate and 1/3 as large as my P estimate for nutrient production in the Neuse Basin. 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 sinks for nutrients, removing 83% of the total N and 51% of the total P from water draining into the lower Chowan. Such losses, Kuenzler (1989) noted, are within the range of values derived from detailed input-output studies of swamp forests within the Southeast.

It is clear from the historical trend data presented above that the rapidly increasing farm animal numbers, particularly swine and poultry, in the Neuse and Tar-Pamlico basins, has lead to greatly increased N and P loading in recent years. I have assumed that only 5% of the N and P produced by farm animals leaves the pastures, feedlots, and barns. However, if the loss were increased to 10% or 15%, then there would be a substantial impact on the total nutrient production. 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 become essentially 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, however, the animal waste treatment facilities are not nearly as strongly regulated as municipal point sources, but North Carolina State officials are becoming increasingly wary of the potential problems (North Carolina DNRCD 1986).

Chapter 4

Pamlico River Estuary Water Quality Trends

History of Water Quality Studies in the Albemarle-Pamlico System

Very little hydrographic and water quality data have been collected for the open waters of the Pamlico Sound. The North Carolina Division of Environmental Management has never included the sound proper in its water quality monitoring program, and university researchers also have shied away from the sound as a site for their studies. Before 1963, temperature and salinity were the only hydrographic variables that had been monitored there. The data were from surveys published by Winslow (1889), Grave (1904), Coker (1907), and Roelofs and Bumpus (1953). Woods (1967) collected temperature, salinity, dissolved oxygen, chlorophyll *a*, and total phosphorus data from June 1963 to October 1966. His stations were located in southwestern Pamlico Sound and in the lower Tar-Pamlico and Neuse River estuaries, and they were sampled monthly. Apparently, these are the only DO and nutrient data ever collected in the Sound. Data for the open waters of Albemarle Sound are also sparse, except for a two-year period of intensive sampling during the early 1970s (Bowden and Hobbie 1977).

Probably the most important reason for this lack of attention to the sounds is the perception that the most serious water quality problems are confined to the tributary river estuaries along their western shores. Another factor is that the sounds are too shallow for even small oceanographic research vessels, and too large for the small boats that are often used to sample in the river estuaries.

> *"In reality, nutrients are choking us. There's no doubt about it. That river out there is dying because of its nutrient load. That's my opinion and many other fishermen's opinion on this river."*
>
> W. Phillips (1987)

Also, there are no major permanent university or government research laboratories on the shores of either the Albemarle or Pamlico Sounds. Researchers from the Duke University and University of North Carolina labs in the Morehead City-Beaufort, NC, area seldom venture northward into Pamlico Sound. Rather, most of the research on water quality in the Pamlico and Albemarle Sound region has been carried out by scientists from three State university campuses farther inland: North Carolina State University in Raleigh, the University of North Carolina at Chapel Hill, and East Carolina University at Greenville.

Since the early 1960s, researchers from these institutions have, for the most part, focused their attention in three areas: 1) the Pamlico River Estuary, 2) the Neuse River Estuary, and 3) western Albemarle Sound (Chowan River and the lower Roanoke River). These are also the sites where the North Carolina state agencies, principally the Division of Environmental Management and the Division of Marine Fisheries, have made most of their studies.

The Pamlico River is one of the few areas in the Albemarle-Pamlico system for which there is enough water quality data to permit a time series analysis of trends.

It is, in fact, one of the most thoroughly monitored estuaries in the Southeast region. Since the mid-1960s, there have been numerous ecological research and monitoring projects, funded by both the phosphate mining industry (Texasgulf, Inc. and North Carolina Phosphate Corporation) and government agencies (principally the University of North Carolina Water Resources Research Institute and the UNC Sea Grant College Program).

Research topics have included basic hydrography and water-column nutrient dynamics (Hobbie 1970a, 1970b, 1974; Hobbie et al. 1972; Copeland and Hobbie 1972; Harrison and Hobbie 1974; Hobbie et al. 1975; Lauria and O'Melia 1980; Kuenzler et al. 1979; Stanley 1984b, 1986a, 1986b, 1987, 1988a, 1989), sediment biogeochemistry and benthic nutrient cycling (Matson et al. 1983; Kuenzler et al. 1984), organic carbon and deoxygenation (Sick 1967; Davis et al. 1978), bacteria heterotrophy (Crawford et al. 1974), phytoplankton ecology (Sherk 1969, Hobbie 1971; Carpenter 1971a, 1971b; Stanley 1983, 1984a; Stanley and Daniel 1985a, 1985b, 1986), submerged macrophytes (Davis and Brinson 1976, 1989), distribution and biomass of ctenophores (Miller 1974), zooplankton abundance (Peters 1968), meiobenthos (Reid 1970, 1978), macrobenthos (Tenore 1968, 1970, 1972), fish (Miller and Dunn 1980; Currin et al. 1984); and fish disease (Noga et al. 1989). Much of this work has been summarized in an estuarine profile prepared for the U.S. Fish and Wildlife Service by Copeland et al. (1984). In addition, several studies of the tributaries of South Creek were presented in the *Journal of the Elisha Mitchell Scientific Society* (Volume 101, No. 2, 1985).

Nitrogen and phosphorus dynamics have continued to receive a great deal of attention by Pamlico investigators since the late 1960s. Consequently, there is much more nutrient data for the river than for most other estuaries in the region. Routine monitoring of nutrients began in 1967 and was continued through 1973. Various hydrographic variables (salinity, dissolved oxygen, temperature, pH, and chlorophyll *a*) were also measured. Since 1975, the sampling for N and P nutrients and related hydrography has continued uninterrupted, thanks to a co-operative agreement between Texasgulf, Inc. and the Institute for Coastal and Marine Resources at East Carolina University. In addition to these monitoring efforts, two Pamlico research projects (Davis et al. 1978; Kuenzler et al. 1979) collected significant amounts of nutrient and hydrography data between 1975 and 1977. Despite the accumulation of a large quantity of data, it has never been analyzed in the kind of thorough, systematic fashion that would be needed to address some of the growing environmental issues for the estuary.

Methods

Data Sources

The nutrient and hydrographic data used in this study were produced by two long-term monitoring studies and two shorter-term research projects. The first monitoring study ran from 1967 to 1973 and was led by John Hobbie of North Carolina State University. It was supported by funds from two sources: 1) the Office of Water Resources Research, U.S. Department of the Interior, through the University of North Carolina Water Resources Research Institute, and 2) Texas Gulf Sulfur Company (now Texasgulf, Inc.). The initial objective was to study the effects of phosphorus from the phosphate mining operation (Copeland and Hobbie 1972). Later the scope of the project was broadened to include nitrogen.

After the NC State University sampling ended, there was an 18-month lapse until East Carolina University began a new program in January 1975. This study was made possible by funds provided by Texasgulf to the University's Institute for Coastal and Marine Resources (ICMR). This program has run continuously since 1975.

In addition to these two long-term monitoring programs, there were two research projects in the mid-1970s which produced significant amounts of nutrient and hydrographic data. One was an investigation of nitrogen and phosphorus cycling in the estuary that was headed by Ed Kuenzler of the University of North Carolina at Chapel Hill. The other research project, under the direction of Graham Davis and Mark Brinson from the Biology Department at East Carolina University, dealt primarily with organic carbon and deoxygenation in the Pamlico River. Both of these projects were funded by the UNC Water Resources Research Institute.

Nutrient and hydrographic data from these studies are contained in 18 project completion reports and technical reports (Appendix 4.1). Rather than cite each of these, I will often refer to the four projects as: 1) "Hobbie," 2) "ICMR," 3) "Davis et al.," and 4) "Kuenzler et al." "Hobbie" refers to all the data collected between 1967 and 1973, and "ICMR" to the East Carolina University monitoring program (1975-1990).

In 1967, only surface water temperature, salinity and phosphorus concentrations were monitored. Bottom water temperature and salinity were added in mid-1968, and surface and bottom water oxygen in late 1968. Then in mid-1969, Hobbie expanded the program again to include surface water pH, and two surface nitrogen fractions (ammonia and nitrate). Finally, in 1970, surface water total nitrogen, total dissolved nitrogen and chlorophyll *a* were added to the suite of parameters analyzed. Fortunately, all these parameters except two have continued to be measured up until the present. In 1985 surface water particulate nitrogen and particulate phosphorus measurements were substituted for the total N and P analyses, but the totals can still be computed by summation of the dissolved and particulate fractions.

Texasgulf has maintained weather instruments at their plant on the south shore of the Pamlico River since before 1969. The company provided data on wind (total miles per day), precipitation, and air temperature for the trend analyses. The U.S. Geological Survey maintains a flow gauging station on the Tar River near Tarboro, NC. Their data (daily average cfs) are published each year in the "Water Resources Data" series (e.g., USGS 1987).

I have also compiled information on station locations and identification numbers used by the four studies (Appendix 4.2). The exact locations of the ICMR stations (1975-1986) are known. However, I had to estimate the latitude and longitude for each of the stations used in the three other studies, because the reports show them on maps, but give no precise locations. Notice that in some cases, stations from different projects were located at the same position. For example, stations 22 and 1 used by Davis et al. were at the same position as ICMR station 11 sampled between January and June 1975, and ICMR station 12 sampled since July 1975.

Changes in Analytical Methods

A potentially serious problem in a study of this kind is that sampling and analytical methodologies may have varied so much over the years that comparison of the data is impossible. Therefore, I have reviewed and compiled notes on the methods used by the four projects. These notes are in Appendix 4.3 and are summarized in Table 4.1.

Trend Analysis Techniques

It soon became apparent that the time series analyses would be impossible unless I grouped the stations, because in the early

Table 4.1. *Methods used for Pamlico nutrient and hydrographic measurements.*

Parameter	Study	Instrument or Method	Reference
1. Water temperature	Hobbie	Thermistor	A
	Kuenzler	Thermistor	A
	Davis	Thermistor	B
	ICMR	Thermistor	B
2. Salinity	Hobbie	Induction salinometer	A
	Kuenzler	Induction salinometer	A
	Davis	Conductivity probe	B
	ICMR	Conductivity probe	B
3. Dissolved oxygen	Hobbie	Winkler titration	C
	Kuenzler	Winkler titration	D
	Davis	Oxygen electrode	E
	ICMR	Oxygen electrode	E
4. pH	Hobbie	Electrode (?)	F
	Kuenzler	Electrode	F
	Davis	Electrode	G
	ICMR	Electrode	H
5. Total phosphorus	Hobbie	Persulfate digestion/mixed color reagent	I,J,K
	Kuenzler	Persulfate digestion/automated mixed color reagent	L
	Davis	Persulfate digestion/mixed color reagent	M
	ICMR	Persulfate digestion/mixed color reagent (automated in 1985)	L,M,N
6. Total dissolved phosphorus	Hobbie	Persulfate digestion/mixed color reagent	I,J,K
	Kuenzler	Persulfate digestion/automated mixed colore reagent	L
	Davis	Persulfate digestion/mixed color reagent	M
	ICMR	Persulfate digestion/mixed color reagent (automated in 1985)	L,M,N
7. Orthophosphate phosphorus	Hobbie	Mixed color reagent	I,K
	Kuenzler	Mixed color reagent (automated)	L
	Davis	Mixed color reagent	M
	ICMR	Mixed color reagent (automated in 1985)	N
8. Ammonia nitrogen	Hobbie	Alkaline hypochlorite/nitrite diazotization	O,K
	Kuenzler	Indophenol	L
	Davis	Indophenol	P,Q
	ICMR (1975-79)	Ion selective electrode	R
	(1980-86)	Indophenol	P
9. Nitrate nitrogen	Hobbie	Cadmium reduction/nitrite diazotization	S,K
	Kuenzler	Cadmium reduction (automated)/nitrate diazotization	L
	Davis	UV spectrophotometric	T
	ICMR (1975)	Brucine	T
	(1975-86)	Cadmium reduction/nitrite diazotization (automated 1985)	U
10. Total dissolved nitrogen	Hobbie	UV oxidation/nitrite diazotization	V,K
	Kuenzler	Kjeldahl (automated)	L
	Davis	Kjeldahl	M
	ICMR (1975-79)	Kjeldahl/ammonia electrode	L
	(1980-85)	Kjeldahl/indophenol	L,P
	(1985-86)	Persulfate digestion/indophenol	N
11. Total nitrogen	Hobbie	UV oxidation/nitrite diazotization	V,K
	Davis	Kjeldahl	M
	ICMR (1975-79)	Kjeldahl/ammonia electrode	L
	(1980-85)	Kjeldahl/indophenol	L,P
	(1985-86)	Persulfate digestion/indophenol	N

Table 4.1. *continued*

Parameter	Study	Instrument or Method	Reference
12. Particulate N and P	ICMR (1985-86)	Persulfate digestion/indophenol	N
13. Chlorophyll *a*	Hobbie	Acetone extraction/spectrophotometric	K,U
	Kuenzler	Acetone extraction/spectrophotometric	W
	Davis	Acetone extraction/spectrophotometric	U
	ICMR	Acetone extraction/spectrophotometric	U
14. Phytoplankton	Hobbie	Utermohl concentration/light microscopy	X
	ICMR	Membrane filtration concentration/light microscopy	D

A. Beckman induction Salinometer Model RS5-3 meter and probe
B. Yellow Springs Instrument Co. Model 33 S-C-T meter and probe
C. Carpenter (1965)
D. American Public Health Association (1975)
E. Yellow Springs Instrument Co. Model 51A meter and probe
F. Unknown
G. Corning Model 10
H. Various instruments used
I. Menzel and Corwin (1965)
J. Murphy and Riley (1962)
K. Strickland and Parsons (1968)
L. U.S. Environmental Protection Agency (1974)
M. U.S. Environmental Protection Agency (1976)
N. U.S. Environmental Protection Agency (1979)
O. Richards and Kletch (1961)
P. Solorzano (1969)
Q. Scheiner (1976)
R. Orion Model ?
S. Morris and Riley (1963)
T. American Public Health Association (1971)
U. Strickland and Parsons (1972)
V. Armstrong et al. (1966)
W. Lorenzen (1967)
X. Utermohl (1958)

years many of them were sampled for relatively short periods. Also there have been only a few locations sampled during all of the 20-year study period. Therefore, I partitioned the river into ten segments, A-J, with boundaries as shown in Figure 4.1. Appendix 4.2 indicates which sampling stations fall into each of the segments.

The Seasonal Kendall-Tau test indicated there were no long-term trends in flow, salinity, delta Sigma-t, or DO in the Pamlico between 1975 and 1989. For each of the four stations, none of the test results were significant at the 90% level ($\alpha<0.1$)

Results and Discussion

It is very important that the reader keep in mind the purpose and limitations of trend analysis. First, one wishes to know whether or not there has been a statistically significant change in the parameter under examination. This is the one question which is directly addressed by the Seasonal Kendall test. If a trend is determined to be significant, the next question is: "How large is the change?" Remember that "significant change," as used in a statistical context, does not necessarily mean large. The Kendall slope gives an estimate of the average rate of change over the whole test period. But even though the slope estimate might be large, it is meaningless unless the trend is determined to be statistically significant. On the other hand, some statistically significant trends might have very small slopes.

Also, keep in mind that the Kendall test measures monotonic changes over the whole test period; it cannot detect short-term ups and downs during that period. Therefore, the outcome of the test naturally will be influenced somewhat by the time interval chosen. Even in instances where there are no reversals in the trend, the rate of increase or decrease might vary, but the slope estimator will give no information about these rate changes.

Obviously, the trend analysis results cannot explain the causes for significant trends in the variables. Nevertheless, it is tempting to assume a cause and effect relationship between two parameters when the trend in one could logically explain a trend in the other. This is a dangerous trap which one must constantly be aware of during the course of a study like this. On the other hand, it is certainly possible that there is a functional relationship between the variables. As long as one remembers that the statistical results cannot prove or disprove the connection, there is nothing wrong with considering them to be evidence of a possible relationship.

Climatic Factors and River Flow

Three climatic variables (air temperature, wind, precipitation) and river flow were included in the Pamlico trend analysis because changes in these variables, especially river flow, might help explain trends in some of the other variables of more direct concern. However, as will be shown below, only one of these four factors has changed significantly over the past twenty years.

Air temperatures at the Texasgulf plant on the south side of the river are usually lowest in January, averaging around 42°F (5.5°C), while July temperatures average higher than any other month, around 80°F

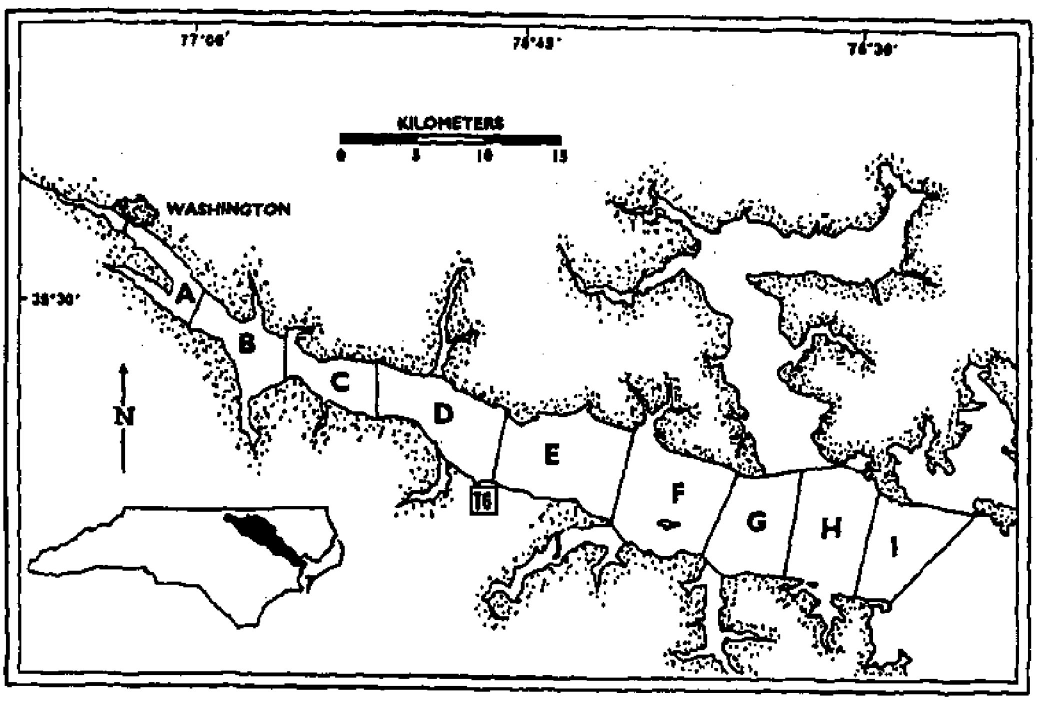

Figure 4.1. *Map showing division of the Pamlico River estuary into ten segments used in the trend analyses.*

Table 4.2. Seasonal Kendall Test results for air temperature, wind, precipitation and Tar River flow.

		Time Interval	
Parameter		**1967-1986**	**1975-1986**
Monthly Mean Air Temperature	Z	0.307	1.821
	Slope	0.017	0.129
	P	0.719	0.069*
Total Wind Miles	Z	0.831	1.128
	Slope	0.192	0.409
	P	0.407	0.358
Total Monthly Precipitation	Z	0.447	
	Slope	0.000	
	P	0.653	
Monthly Mean Tar River Flow	Z	0.253	
	Slope	1.750	
	P	0.803	

P<0.1 = * (Significant)
P<0.01 = ** (Highly Significant)

(26.6°C) (Figure 4.2). Over the past 20 years, the variation in the monthly means has been greater in the winter (up to 12°F above normal for January) than in the summer. This difference is also clearly shown in Figure 4.2, which shows that there has been little variability in the summers, while the winters were relatively warm in the 1971-1975 period, very cold in 1976 and 1977, and have tended to be warmer each year since the late 1970s.

Despite these fluctuations in the winter and summer maxima temperatures, the Seasonal Kendall test results were that there was no statistically significant trend in the mean monthly air temperature between 1967 and 1986 (Table 4.2). However, since 1975, there has been a significant (p = .069) upward trend, averaging 0.13°F per year.

For any given month there can be great year-to-year variability in the average daily wind (Figure 4.3) but the overall pattern is that average velocities are highest in late winter and lowest in late summer. The difference between the March and August wind velocities averages around 30 percent

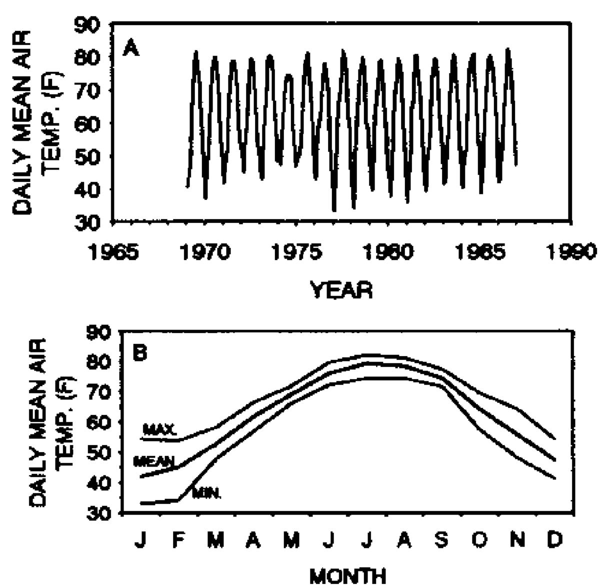

Figure 4.2. *Daily mean air temperature (°F), averaged by month, at the Texasgulf Chemicals Co. plant on the south shore of the Pamlico River estuary. (A) monthly averages, January 1969-December 1986. (B) maximum, minimum and median of averages for each month.*

(115 total miles vs. 78 total miles per day). Again, however, the interannual variability is great, so that some summer months have had higher winds than the average for the winter months. Overall, there was no trend toward increasing or decreasing winds during the 1967-1986 period (Table 4.2).

Monthly precipitation at the Texasgulf plant has ranged from less than 0.5 inches to over 17 inches during the study period (Figure 4.4), but normally it peaks at around 6 inches in July and is lowest in November, about 2.5 inches. The Seasonal Kendall test showed no significant trend in the monthly precipitation totals between 1967 and 1986 (Table 4.2).

Even though precipitation onto the watershed is highest in the summer, Tar River flow is usually highest in the late winter months, a pattern that is typical for eastern North Carolina (Giese et al. 1979) and the region (Nixon 1983). This seasonal pattern is caused by the increased evapotranspiration that occurs during the summer. Daily mean flows at Tarboro, averaged by month, normally vary from about 800 cfs in September to around 4000 cfs in March (Figure 4.5b). Changes in flow can be very sudden and of great magnitude (Figure 4.5a).

There have been some short-term trends in Tar River flow, but no overall, long-term change since 1967. Figure 4.5a shows, for example, that between 1984 and 1986, there was a decrease in the late winter and early spring flows. A decline in winter flows also occurred between 1979 and 1981. Overall, 1981 was the lowest flow year in the study period. Other low flow years were 1967, 1974, and 1986. However, the Seasonal Kendall test for the two decades between 1967 and 1986 gave no significant upward or downward trend in the mean monthly flow (Table 4.2).

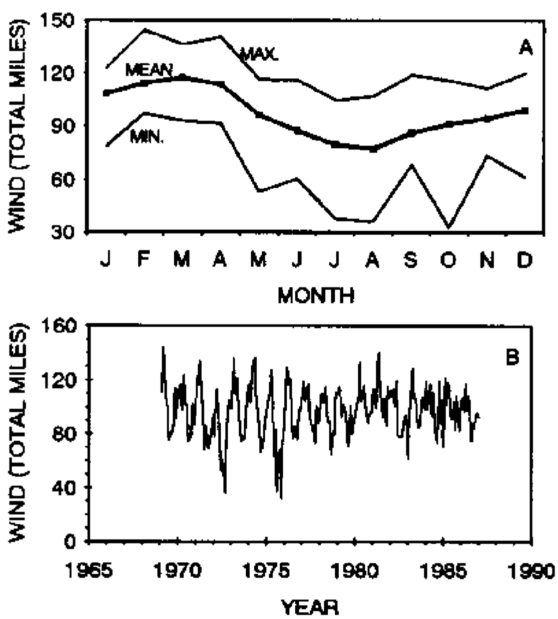

Figure 4.3. *Wind (total miles per day), averaged by month, at the Texasgulf Chemicals Co. plant on the south shore of the Pamlico River estuary. (A) Monthly averages, January 1969-December 1986. (B) Maximum, minimum, and median of monthly averages.*

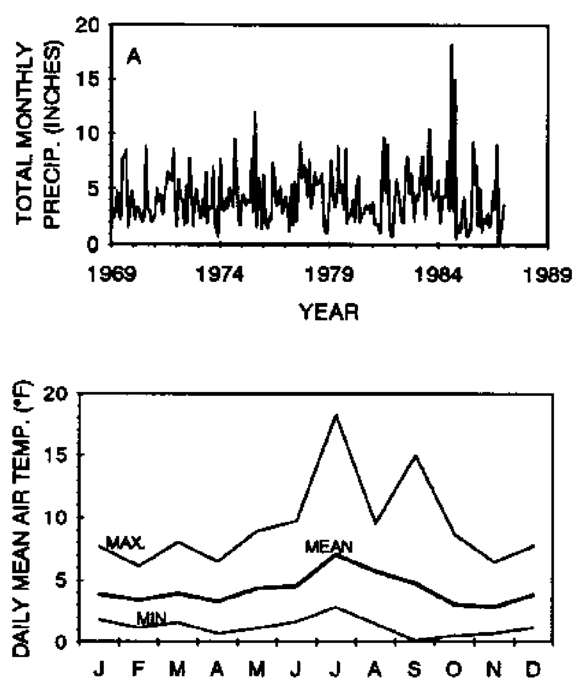

Figure 4.4. *Total monthly precipitation (inches) at the Texasgulf Chemicals Co. plant on the south shore of the Pamlico River estuary. (A) Monthly totals, January 1969-December 1986. (B) Maximum, minimum, and median of totals for each month.*

Water Temperature, Salinity and pH

Water temperature is the most predictable of all the parameters that have been monitored in the Pamlico studies. Surface temperatures in the estuary typically range from around 4°C to about 30°C over the course of the year (Figure 4.6). The lowest temperatures occur in January in most years, and the peak temperatures come in July and August. On some sampling dates, there is as much as 5°C variation in temperatures, but much of this difference probably results from the samples being taken at different times of the day. It takes 4-6 hours to visit all the stations in the estuary. Bottom water temperatures exhibit the same seasonal pattern and range as the surface temperatures. Occasionally there is strong thermal stratification in the water column, but this is rare. Normally the difference between surface and bottom temperatures is less than 2°C (e.g., Stanley 1988a). The Seasonal Kendall test indicated no significant trend in surface water temperature (Table 4.3) for the three river segments examined. Likewise, no trends were found in the bottom water temperature data (Table 4.3).

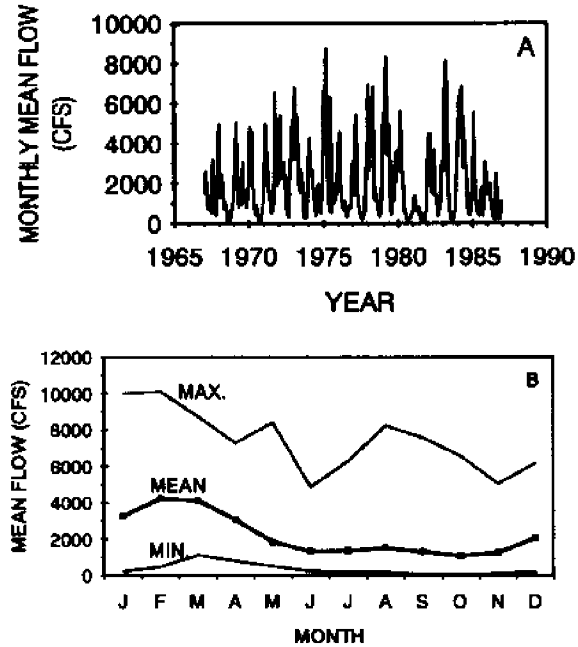

Figure 4.5. *Daily mean flow (cfs), averaged by month, of the Tar River at Tarboro, NC. (A) Monthly averages, January 1967-December 1986. (B) Maximum, minimum, and median of averages for each month.*

Figure 4.6. *Surface water temperature (°C) in the Pamlico River estuary during 1984, as a function of time (x-axis) and distance (y-axis). Top of plot is station 12 upriver (see Methods for explanation of distance scale).*

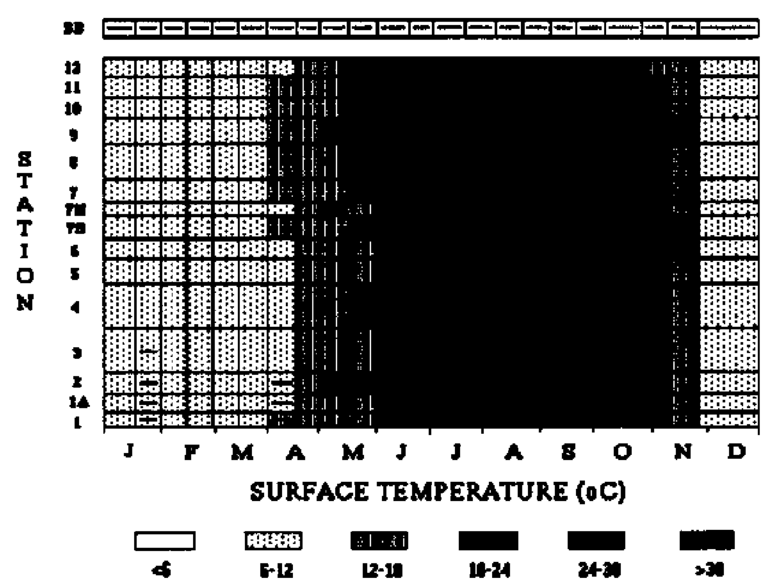

Table 4.3. *Seasonal Kendall Test results. Segment B = Upriver; Segment E = Midriver; Segment H = Downriver. P<0.1 = * (Significant); P<0.01 = ** (Highly Significant).*

		River Segments and Time Intervals					
		1967-1986			1975-1986		
Parameter		B	E	H	B	E	H
Surface Dissolved Oxygen	Z	3.745	3.292	4.301	1.172	3.089	2.268
	Slope	0.060	0.050	0.080	0.030	0.090	0.090
	P	0.002 **	0.002 **	<0.002 **	0.242	<0.002 **	0.023 *
Bottom Dissolved Oxygen	Z	-1.560	1.310	-1.830	-0.930	-0.880	-0.180
	Slope	0.040	0.030	-0.060	-0.040	-0.040	-0.020
	P	0.120	0.190	0.067	0.352	0.384	0.857
Bottom Dissolved Oxygen % Saturation	Z	-1.624	1.593	-2.217	-1.696	-0.376	-0.721
	Slope	-0.406	0.400	-0.523	-1.100	-0.130	-0.446
	P	0.103	0.112	0.027 *	0.091	0.704	0.472
Surface Salinity	Z	2.220	0.600	-1.530	0.690	0.930	-1.070
	Slope	0.050	0.030	-0.100	0.030	0.090	-0.130
	P	0.026 *	0.555	0.124	0.490	0.352	0.285
Bottom Salinity	Z	1.930	-1.090	-2.830	-1.280	0.930	-0.100
	Slope	0.070	-0.060	-0.130	0.110	0.090	-0.010
	P	0.054 *	0.276	0.005 **	0.201	0.352	0.920
Surface Temperature	Z	-0.240	-0.100	-0.430	0.420	0.890	0.870
	Slope	-0.025	-0.019	-0.060	0.144	0.231	0.317
	P	0.810	0.920	0.667	0.674	0.373	0.384
Bottom Temperature	Z	0.103	0.270	1.456	0.409	1.067	0.830
	Slope	0.003	0.006	0.046	0.022	0.033	0.050
	P	0.912	0.787	0.147	0.682	0.285	0.412
pH	Z	-0.716	-3.543	-3.752	0.397	2.158	0.070
	Slope	-0.006	-0.039	-0.037	0.012	0.042	0.021
	P	0.478	<0.002 **	<0.002 **	0.697	0.032 *	0.484
Orthophosphate P	Z	1.390	2.070	2.880	1.489	-1.136	3.141
	Slope	0.025	0.080	0.040	0.051	-0.077	0.086
	P	0.165	0.040 *	0.004 **	0.136	0.254	0.003 **
Total Phosphorus	Z	4.453	4.699	5.547	1.546	0.085	4.882
	Slope	0.149	0.234	0.146	0.142	0.013	0.255
	P	<0.002 **	<0.002 **	<0.002 **	0.124	0.940	<0.002 **

Table 4.3. *continued*

		River Segments and Time Intervals					
		1967-1986			1975-1986		
Parameter		B	E	H	B	E	H
Total Dissolved P	Z	5.723	4.644	5.156	2.487	0.327	2.917
	Slope	0.115	0.222	0.112	0.198	0.061	0.213
	P	<0.002	<0.002	<0.002	0.013	0.741	0.004
		**	**	**	*		**
Ammonia Nitrogen	Z	-5.512	-5.357	-6.131	-1.642	-1.073	-2.003
	Slope	-0.303	-0.250	-0.228	-0.179	-0.100	-0.233
	P	<0.002	<0.002	<0.002	0.101	0.285	0.046
Nitrate Nitrogen	Z	-2.813	1.327	3.010	0.062	0.838	-0.333
	Slope	-0.280	-0.019	0.026	0.005	0.015	-0.017
	P	0.005	0.187	0.003	0.522	0.407	0.741
		**		**			
Total Nitrogen	Z	4.721	4.536	2.871	2.618	2.923	0.238
	Slope	1.547	1.356	0.845	1.664	1.807	0.150
	P	<0.002	<0.002	0.004	0.009	0.004	0.818
		**	**	**	**	**	
Total Dissolved N	Z	1.169	1.467	0.183	1.385	1.488	-1.059
	Slope	0.260	0.292	0.040	0.450	0.619	-0.709
	P	0.242	0.142	0.857	0.168	0.136	0.289
Chlorophyll *A*	Z	2.648	-1.398	-1.293	3.218	2.937	-0.034
	Slope	0.294	-0.156	-0.140	0.635	0.451	-0.004
	P	0.008	0.165	0.197	<0.002	0.003	0.976
		**			**	**	

Seasonal salinity patterns in the Pamlico are affected mainly by variation in freshwater runoff (Copeland and Hobbie 1972; Stanley 1986). Typically, salinity is lowest during the late winter and early spring when freshwater inflow is highest (Figure 4.7). The salinity increases to maximum values during the summer and fall, coincident with lowest river flow. In some years this seasonal pattern may be upset by unusually high or low freshwater inflow associated with hurricanes or periods of drought. Examples of such events are given in descriptions of data from individual years by Hobbie (1974) and Stanley (1986a, 1986b, 1987).

There are also interannual variations in salinity which become obvious only when data from a number of years are compared (Figure 4.8). For example, 1967-1970, 1976-1977, 1981, 1985 and 1986 were relatively high salinity years, while 1978-1979 and 1983-1984 were low salinity years. In some periods, the salinity gradually trended downward (1968-1971) or upward (1983-1986), but in other instances, the change was more abrupt. For example, between the 1979-1980 winter and the 1980-1981 winter, the mean salinity appears to have increased about 8 ppt.

The Seasonal Kendall test indicated that surface salinity has increased upriver in segment B since 1967. The trend was statistically significant (p = 0.026) with a slope of 0.05 ppt per year, or 0.9 ppt during the 18-year sampling period. In the downriver segment, H, the trend was downward but the significance level (p = .124) was not quite low enough to be classified as statistically significant. Salinity has not changed in the middle segment (Table 4.3).

Bottom water salinity upriver in segment B has also trended upward slightly during the past two decades. The change detected by the Kendall test was statistically significant (p = 0.054) at a rate of 0.07 ppt per year, or about 1.25 ppt during the sampling period. Farther downriver, no significant trend was detected in segment E (mid-river), but a highly significant (p = 0.005) downward trend was detected in segment H near the mouth of the estuary. The rate of decrease was -0.13 ppt per year, which amounts to 2.3 ppt, or about 15%, during the 18 year sampling interval.

It is difficult to explain the salinity trend results, or to see a pattern in them. The fact that there were significant trends for the 1968-1986 period, but none for the 1975-1986 period, suggests that most of the change occurred between 1968 and 1975. The trend upriver was positive, but downriver it was negative, and I can think of no explanation for this contradiction. Also, there was no significant downward trend in river flow which would be expected if the upriver salinity is trending upward. On the other hand, trends in pH and nitrate nitrogen described below could be explained by these salinity trends. In short, no definitive conclusions can be drawn from these data regarding a salinity trend in the river since 1968.

The Pamlico report prepared by North Carolina DNRCD (1987a) cited an analysis by Sholar (1980), and included a time-series salinity plot from his report, which showed a decrease in the mean annual salinity for the "Pamlico Sound area" (stations not given) over the period 1948-1980. Comparison of Sholar's trend plot with the "Mean of All Stations" plot in Figure 4.8 suggests to me that if Sholar's analyses were extended to include the higher salinity years following 1980, it is likely that no overall (1948-1986) trend would be seen.

The pH in estuaries is influenced by the mixing of seawater and freshwater and by the rates of microbial (algal and bacterial) respiration and algal photosynthesis in the water. Freshwater typically has pH's lower than seawater, and the situation can be complicated in estuaries like the Pamlico by the inflow of water flushed from swamps that is often quite acid (low pH) (Hobbie et al. 1972). When algal photosynthesis is high, the pH is also high because the algae

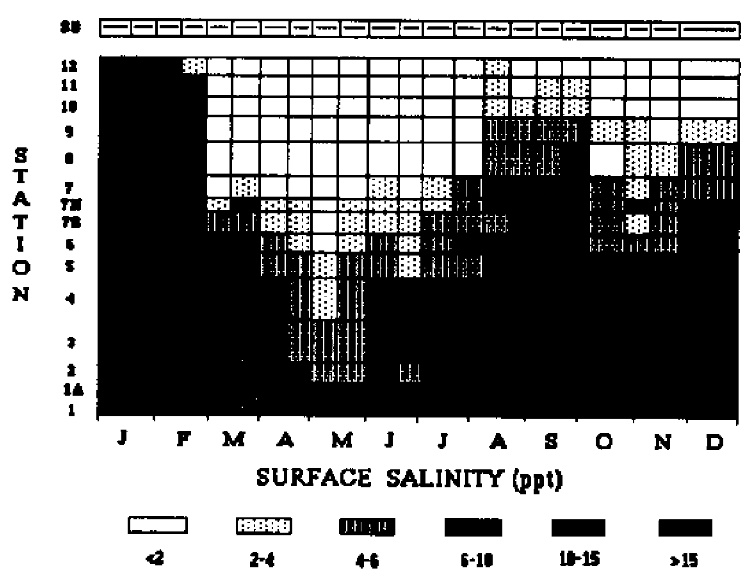

Figure 4.7. *Surface salinity (ppt) in the Pamlico River estuary during 1984, as a function of time (x-axis) and distance (y-axis). Top of plot is station 12 upriver (see Methods for explanation of distance scale).*

have removed most of the carbon dioxide and made the water basic. Respiration, on the other hand, adds carbon dioxide to the water, thus increasing the acidity and lowering the pH.

The pH in the Pamlico usually ranges from around 6.5 to over 8.5, but because it is influenced by several variables, there are not very clear spatial or temporal patterns. About all that can be said is that it tends to be lower upriver than downriver, and it sometimes goes up during the algal blooms that occur in the river in the late winter and early spring.

Highly significant downward trends in pH ($p < 0.002$) were detected by the Seasonal Kendall trend test for segments H and E between 1975 and 1986 (Table 4.3). The slopes were about 0.04 pH units per year, which amounts to a change of 0.68 units over the sampling period. The lower pH could be related to declining salinity, at least in segment H. As explained above, lower salinity (i.e., increased freshwater inflow) should lead to lower pH.

Nitrogen

Nitrate Nitrogen: Nitrate nitrogen is one of the most variable nutrients in the Pamlico, but there is a seasonal pattern in this variability. In most years, highest concentrations occur upriver during winter, coincident with peak Tar River flows, and lowest concentrations occur downriver during the summer. The primary cause of this pattern is that freshwater from the Tar River has much higher nitrate concentrations than does Pamlico Sound water at the other end of the estuary. But a secondary cause is that nitrate often behaves nonconservatively in the estuary. That is to say, the decline in nitrate concentration in the estuary is caused by more than simple dilution by seawater. Nitrate is used up (assimilated) by phytoplankton, which are scarce in the Tar River but abundant in the upper estuary, and there is apparently little replacement of the assimilated nitrate. Consequently, nitrate concentrations usually exhibit a temporal-spatial pattern in the estuary that is the inverse of the salinity pattern, but nitrate levels decrease more rapidly than salinity increases, especially in the upper end of the estuary. This accounts for the nonlinear relationship between salinity and nitrate (Figure 4.9).

The most significant change in nitrate nitrogen in the Pamlico during the past 20 years occurred upriver, where there apparently has been a decline. The Seasonal Kendall test results indicated a highly significant ($p = 0.005$) decrease in nitrate for river segment B (upriver) during the period between 1967 and 1986. But there was no significant change for the 1975-1986 period, suggesting that the decline occurred during the early 1970s. The average rate of change was about 0.3 μM/year, or 5.1 μM during the 17-year sampling

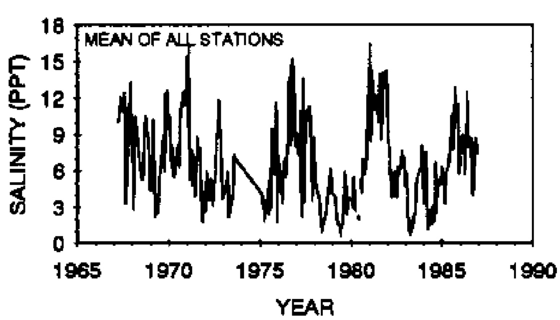

Figure 4.8. *Surface salinity (ppt) in the Pamlico River estuary, 1967-1986. Values plotted are averages of all stations sampled.*

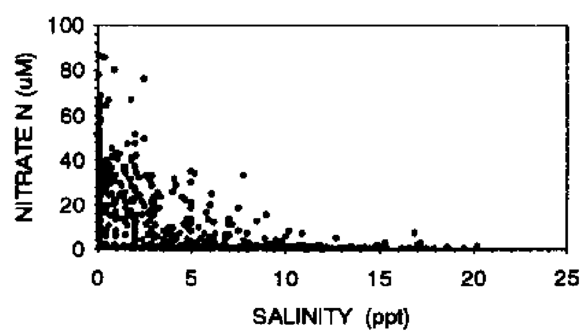

Figure 4.9. *Nitrate nitrogen (μM) versus salinity (ppt). Data are from stations 1, 5, 8, 10 and 12 (1975-1986).*

period. This change represents approximately a 25% decrease from the 1970 median nitrate level. Based on the relationship between nitrate and salinity described above, it would be reasonable to conclude that this decrease was due, at least in part, to the salinity increase detected in this segment.

The Seasonal Kendall test indicated a highly significant ($p = 0.003$), but small (0.4 μM), nitrate increase downriver (segment H) over the 1967-1986 period. Again, this change could be explained by salinity, which was shown above to have decreased in this segment. But this could also be simply an artifact resulting from changes in analytical sensitivities. Before 1975, nitrate levels lower than 0.1 μM were reported frequently, but after 1980, the values less than 0.71 μM were reported as 0.71 μM, the lower limit of detection (Appendix 4.3). This change in data reporting probably had little effect on the upriver trend results, because the nitrates there were usually higher than 0.71 μM, but it may have contributed to the apparent upward trend in the downriver segment, H, where nitrate is much less abundant. The nitrate data from 1975 through 1979 were omitted from the Kendall test because of the very high (3.57 μM) lower detection limit reported during that period. In any case, there has been no significant change in nitrate levels downriver since 1975.

Ammonia Nitrogen: Ammonia nitrogen is also more abundant in Tar River water than in Pamlico Sound water, but in the Pamlico River estuary, concentrations do not range as widely as nitrate concentrations. In general, they are between 1 and 8 μM upriver (segment B), <0.71 μM to 6 μM downriver (segment H) and intermediate in the middle segments. This relatively constant pattern probably results from ammonia production in the sediments and water associated with organic matter decomposition. This production tends to offset losses from assimilation and dilution, and at some times of the year it is a more important source of ammonia than inflowing Tar River water (Kuenzler et al. 1979).

Ammonia abundance in the estuary appears to be trending downward at a rapid rate. During the period 1967-1986, the decline was highly significant ($p < 0.002$) for all three river segments examined (Table 4.3). The average rate of decrease was quite rapid — about 0.3 μM/year upriver (segment B) and around 0.23 μM/year farther downriver (segment H). For segment B, this is equivalent to about a 60% decline over the 17-year period of record. The decline is especially noticeable when one compares values from the early 1970s with those for 1984-1986. Once again, it should be remembered that data from the period 1975 through the end of 1979 had to be eliminated from consideration in the trend test because of the high minimum detection limit associated with the method used for the analyses in those years.

Total Nitrogen: Total nitrogen (TN), which consists of total dissolved nitrogen plus particulate nitrogen, is the most difficult nitrogen fraction to measure accurately. The problem has to do with uncertainties about the completeness of the digestion used to break down the organic constituents. There have been several changes in the methodology used to analyze Pamlico TN, and there is much uncertainty about the efficiency of some of the methods used (see Appendix 4.3).

TN concentrations have fluctuated widely, and sometimes abruptly, during the 17-year period of record (see Figure 31 in Stanley 1988). However, I strongly suspect that much of this variability can be traced to methodological problems. For example, I doubt that the abrupt decline in 1977 and the sudden rise in 1980 are real. There were changes in the methodologies at each of these times. Also, the apparent wide fluctuations during 1975-1977 probably are due in part to the fact that data from this period are from three different sampling programs (Kuenzler et al., Davis et al., and ICMR), each of which used a different method for the TN analyses. Of course, this is only speculation and unfortunately there is no way to determine whether or not this is the correct explanation. The methods used to measure TN have been less variable since 1980, and during this period there have not been such abrupt fluctuations as in the earlier years.

The trend test indicated highly significant increases in TN in all three segments between 1967 and 1986 and in segments B and E between 1975 and 1986. But, as indicated above, there are reasons to doubt the validity of these results. I think the most likely explanation for the apparent trends is that the digestion method used in the early analyses (ultraviolet radiation), gave less complete breakdown of the organic nitrogen than the more rigorous wet chemical digestions used later (*see* Appendix 4.3 for more details). This would explain the apparent increase in the TN concentrations. Once again, however, this is only speculation, and I cannot be sure that had the methodology remained constant, there would not have been an upward trend in the concentrations.

Total Dissolved Nitrogen: Total dissolved nitrogen is not a particular chemical form of nitrogen, but rather includes a large number of compounds, including ammonia and nitrate, that passed through the glass fiber filter when the dissolved and particulate fractions are separated. Hobbie (1974) subtracted the inorganic forms (nitrate and ammonia) from TDN to obtain estimates of dissolved organic nitrogen (DON), but could not explain changes in the DON data:

> "... The yearly cycle of the dissolved organic nitrogen concentration is also difficult to interpret in terms of known changes in biology and hydrography of the river. The very high values for dissolved organic nitrogen in 1970-1971 (August through December) correlate well with the very low stream flow. On the other hand, when the streams started to flow again in mid-January there was a reduction in dissolved organic nitrogen concentration followed by an eventual increase which may well correlate with the increased biological productivity at that time. During 1971-1972, the dissolved organic nitrogen concentrations were very low during the heavy rains of October and November. On the other hand, the high rates of flow in May seem to contain quite high amounts of dissolved organic nitrogen. A number of hypotheses can be put forth as to the reason for abrupt changes, such as there is a flushing effect of high waters on swamps that increases the dissolved organic nitrogen in the rivers and streams. Also it is possible that DON is being produced during algal blooms. At this time, however, we do not have enough information as to the source and fates of these compounds that are lumped under the name dissolved organic nitrogen. Certainly the biologically active part is very small... Yet, these compounds are still potentially important as they contain a great deal of nitrogen and their total concentrations are always greater than the total concentrations of the dissolved inorganic nitrogen" (Hobbie 1974, pages 73-75).

The Seasonal Kendall test showed that there has been no significant change in total dissolved nitrogen in the Pamlico (Table 4.3). However, as noted above, the methods used to measure TN and TDN have changed several times over the study period, so this result may not be valid.

Phosphorus

Concentrations of all three forms of phosphorus measured in the Pamlico samples (total phosphorus [TP], total dissolved phosphorus [TDP], and orthophosphate phosphorus [OP]) are generally higher in the summer than in the winter. For example, in 1984, dissolved orthophosphate concentrations were often >2 μM during the summer and fall, and less than 2 μM during the winter. Both TDP and TP followed the same temporal pattern as OP. TDP ranged from around 2-10 μM in winter samples to 10-20 μM in summer samples. TP was only slightly higher, indicating that particulate phosphorus makes up a relatively small fraction of the total P in the estuary.

Nixon (1983) noted that this summer increase in phosphorus is a feature common to many estuaries, and he discussed several possible explanations, but concluded that no single factor can explain the pattern in all the estuaries. Judging from the information presented in Nixon's discussion, and other available information, I suspect that two factors are important in the Pamlico. The first is increased bottom water hypoxia in the summer. As shown by Kuenzler et al. (1984) for the Pamlico River, and by similar studies for many other estuaries (e.g., Taft and Taylor [1976] for Chesapeake Bay), this hypoxia increases the release of phosphate from the sediments. Second, Tar River flow decreases in the summer, so that there is less dilution of the phosphorus-rich Texasgulf effluent and slower flushing of the discharge from the estuary.

There is also spatial variability in the phosphorus levels that usually follows a pattern. Highest concentrations are found in the middle section of the river, especially adjacent to the Texasgulf discharge, with intermediate concentrations upriver and lowest concentrations at the outer end of the estuary near Pamlico Sound.

For obvious reasons, there has always been a great deal of interest in trends in phosphorus in the Pamlico, so it is not surprising that Hobbie wrote about this topic in every Pamlico report he prepared. In a 1971 report, he made these comments:

> "... Early studies centered around the possible effects that the establishment of a phosphate mine on the south side of the river (Texas Gulf Sulfur Corp.) would have on the water chemistry and biology. It is now apparent (Hobbie 1970a) that there is enough phosphorus naturally present in the river and that the phosphorus added from the phosphate mine operations has no added effect on the biology."
>
> "The natural levels of P in the estuary are in the 1-2 μg-at P/liter range (1 μg-at P equals 31 μg) for [orthophosphate phosphorus]. As a result of the mining activities, levels as high as 93 μg-at/liter have been measured. However, the release is intermittent and the higher phosphorus water is found as patches that move seaward along the south shore of the estuary. Because of removal of phosphorus by the sediments, removal by microorganisms, and dispersion dilution, the patches of high phosphorus water do not reach Pamlico Sound. There does appear to be, however, an increase over the past three or four years in the concentration of phosphorus entering the estuary in the river water. This may be the result of increased sewage treatment and of increased use of detergents" (Hobbie 1971, pages 5-8).

In another report (Copeland and Hobbie 1972) summarizing the 1967-1969 sampling, three conclusions were given regarding phosphorus in the estuary: 1) there had been a tripling of total phosphorus levels in the upper river, 2) the middle river was greatly affected by the high concentrations of total phosphorus entering from Texas Gulf Sulfur, and 3) the lower section of the river also seemed to be strongly affected by Texas Gulf Sulphur's activities.

Finally, after his monitoring program ended in 1973, Hobbie had this to say about the 1971-1973 phosphorus data:

> ". . . It is interesting to remember the increase of phosphorus in the upper stations and the entire river that were seen over the first four or five years of phosphorus measurements. Although high amounts of phosphorus are still seen in the upper parts of the river, the increase does not appear to have continued past 1970 or so" (Hobbie 1974, page 50).

Results of the Seasonal Kendall tests seem to confirm Hobbie's observation that phosphorus was increasing in the river in the late 1960s. The increase in TP was shown to be highly significant ($p<0.002$) in all three river segments examined for the time period 1967-1986 (Table 4.3). The average rate of increase at the middle segment, E, was 0.23 μM/year, or about 4.4 μM over the 19-year sampling period. This amounts to approximately a doubling of the 1967 TP levels. In the upriver and downriver segments, B and H, the TP levels trended upward at about half this rate. However, when only the period 1975-1986 was examined, it was found that there was a significant increase in TP only downriver in segment H ($p<0.002$). But the average annual rate of increase in this segment since 1975 has been 0.25 μM/year, nearly twice the rate over the longer period.

Total dissolved phosphorus and orthophosphate phosphorus have also increased significantly, particularly in the lower estuary. The trend test results are about the same as for TP, which is not surprising since OP and TDP are the major fractions comprising TP. For TDP, the increases between 1967 and 1986 were highly significant ($p<0.002$ for all three segments), and the rate of increase was highest in the middle segment (Table 4.3). During the more recent sampling period, 1975-1986, there were also increases in TDP in segments H and B, but not in the middle river segment, E. Orthophosphate increased in segments H and E between 1967 and 1986, but only in the downriver segment, H, since 1975. The average annual rate of increase varied from 0.04 μM/year to about 0.086 μM/year. For the downriver segment, H, these rates translate to an overall increase of about 0.7 μM since 1967.

The fact that phosphorus abundance has not changed in the mid-river segment since 1975 probably is a reflection of declining P loading from Texasgulf, counterbalanced, to some extent, by increased loading from the Tar River. Monthly loading of P (in tonnes) from the plant site has decreased by about two-thirds since the mid-1970s (Figure 4.10). It would seem that this large reduction 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 P loading to the river (North Carolina DNRCD 1987). But, the decreased TG load probably has been offset to some 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.

Nutrient Limitation in the Pamlico

Nitrogen-to-phosphorus ratios are often computed for aquatic ecosystems to indicate which of the two nutrients is most likely to be limiting to phytoplankton growth. The ratios can be calculated several ways, but most often they are made by dividing the water-column concentrations of total dissolved inorganic nitrogen (DIN) by the concentration of orthophosphate phosphorus (OP). The significance of this ratio stems from the fact that algal production is determined in part by the need for nitrogen and phosphorus in proportions (atomic) of 16:1, respectively (Redfield 1934). Water-column DIN:OP ratios less than the "Redfield Ratio" indicate that nitrogen is less abundant than phosphorus relative to the phytoplankton's need. On the other hand, values higher than 16:1 indicate that phosphorus is less abundant. Thus, if the phytoplankton continue to grow and there is no N or P replenishment in the water, one nutrient will be exhausted (i.e., become "limiting") before the other, depending on the ratio. Studies by Parsons et al. (1961) and Rhee (1978) indicated that there is some variability in algal composition ratios, and hence it is probably more realistic to view composition ratios as ranging from around 10:1 to 20:1 (Boynton et al. 1982).

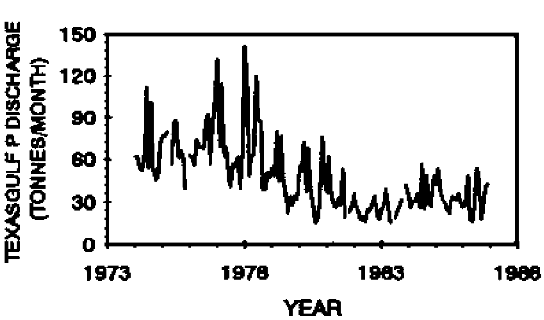

Figure 4.10. *Texasgulf phosphorus discharge (tonnes), by month, 1974-1986.*

Calculated ratios of water column DIN:OP suggest that nitrogen is more likely than phosphorus to be limiting upriver in the Pamlico during the summer and downriver at all times of the year. Figures 4.11-4.13 give the ratios at five stations along the salinity gradient between 1979 and 1986. In the lower half of the estuary (stations 1 and 5), DIN:OP ratios are almost always less than the ideal Redfield ratio (16:1), or the 10:1-20:1 range of N:P ratios normally found in algal cells. Upriver, the ratios increase, more because of increasing DIN (principally nitrate), rather than decreasing phosphate. There is also a strong seasonal pattern in the ratios at all stations. This pattern is determined primarily by the nitrate levels, which vary more than either ammonia or nitrate over the course of the year. Figure 4.14 more clearly

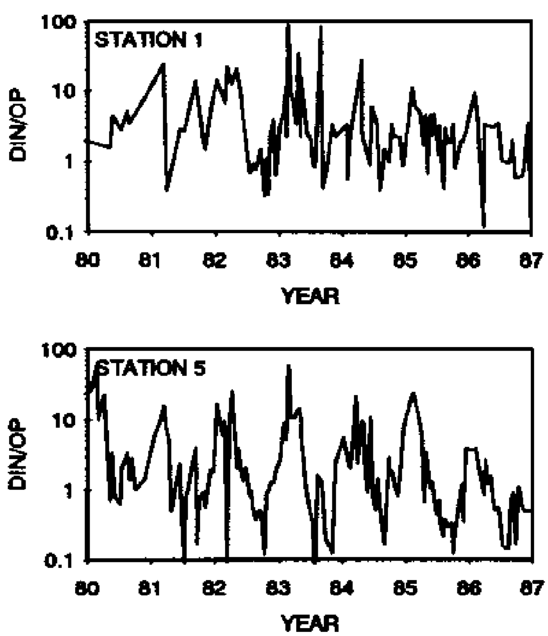

Figure 4.11. *Ratio of total dissolved inorganic nitrogen (DIN) to orthophosphate phosphorus (OP) in the Pamlico River estuary, 1979-1986. (A) station 1, (B) station 5.*

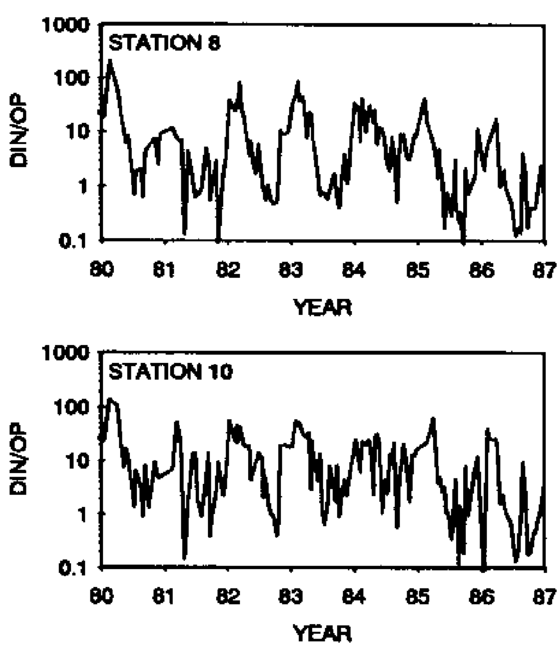

Figure 4.12. *Ratio of total dissolved inorganic nitrogen (DIN) to orthophosphate phosphorus (OP) in the Pamlico River estuary, 1979-1986. (A) station 8, (B) station 10.*

shows the decline in the N:P ratio with increasing salinity. Most instances of N:P higher than 16:1 occur upriver in the winter months when river flows, and hence nitrate levels, are highest. Similar results for other estuaries are discussed later in this report.

It is very important to realize that these N:P ratios are only evidence for possible N or P limitation, not proof that such limitation exists. Phytoplankton must consume the nutrients faster than they are resupplied, from either internal recycling or outside input, in order for one or the other to become limiting. In fact, other factors, such as light or temperature, often control algal growth to such an extent that the nutrients are not exhausted. In these circumstances, the N:P ratio has no influence on the growth. In other words, both the absolute and the relative N and P concentrations must be considered (along with the resupply rate!) when one speculates on algal nutrient limitation. The importance of limitation by factors other than nutrients is often overlooked in the heat of debate associated with the long-running N vs. P limitation controversy. But given the high turbidity, particularly upriver in winter (Kuenzler et al. 1979), and the wide temperature fluctuations that characterize estuaries like the Pamlico, these factors probably override nutrient influences, at least during some parts of the year.

Dissolved Oxygen

The trend test (Table 4.3) showed a highly significant ($p<0.002$) upward trend in surface water dissolved oxygen for all three river segments tested. The estimated slopes were 0.05-0.08 mg/liter per year, which amounts to an increase of 0.9-1.4 mg O_2/liter, or approximately 10%, over the 18-year period of record. The reasons for this apparent increase are unknown.

For bottom water dissolved oxygen, there were no statistically significant trends in the concentrations, but the percent saturation data did show a significant downward trend in segment H (Table 4.3). The annual average percent saturation declined from about 70% to 60% over 18 years. There was no significant trend in the segment B and segment E data. Dissolved oxygen dynamics in the Pamlico River are described in more detail in Chapter 5.

Chlorophyll a

Chlorophyll *a* is a reliable indicator of algal biomass that has been monitored in the Pamlico since 1970. The most important findings from this sampling are that blooms of algae occur each late winter or early spring, but the median chlorophyll *a* levels peak in the summer months. The winter blooms occur in the middle reaches

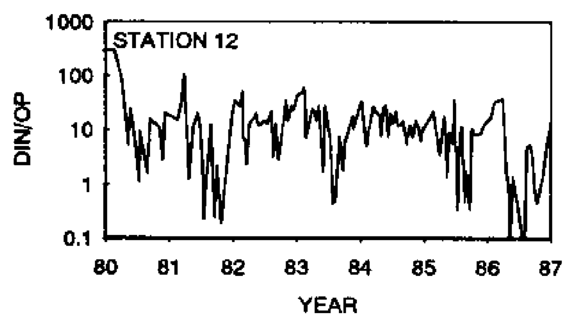

Figure 4.13. *Ratio of total dissolved inorganic nitrogen (DIN) to orthophosphate phosphorus (OP) in the Pamlico River estuary, 1979-1986, at station 12.*

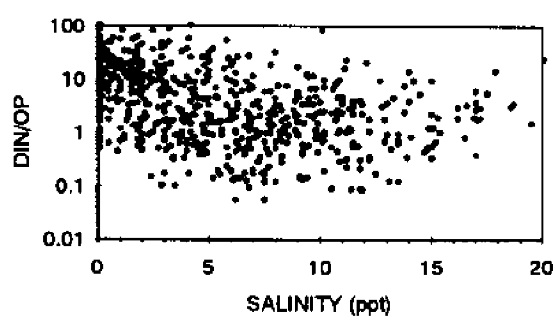

Figure 4.14. *DIN:OP ratio versus salinity in the Pamlico River estuary, 1979-1986. Data from stations 1, 5, 8, 10 and 12.*

of the estuary (Stanley 1987; Hobbie 1974). Two other features of the blooms are that they are short-lived, and they usually occur at only one or two sampling stations. Also, river flow can play an important role in the timing and location of the winter blooms. In some years, high water inflow from the Tar flushes out much of the algal population from the river.

The trend test results indicate that chlorophyll *a* concentrations have increased in the middle and upper segments, B and E, of the Pamlico, but not in the downriver segment, H. Upriver in segment B, the increase was highly significant ($p<0.01$), during both time intervals tested. The average annual rates of increase were 0.29 μg/liter per year and 0.64 μg/liter per year for 1967-1986 and 1975-1986, respectively. This is equivalent to about a 50 percent increase during the 16-year period of record.

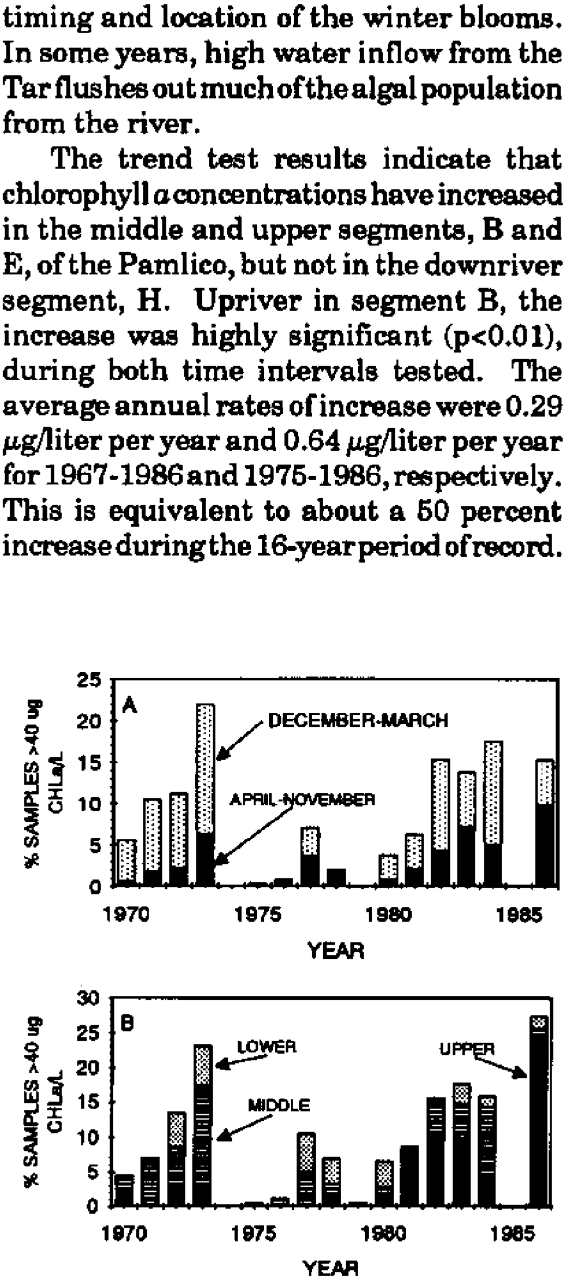

Figure 4.15. *Pamlico River estuary chlorophyll a. Percentage of sample values greater than 40 μg/liter for each year (1970-1986). (A) Data grouped by two periods (April-November and December-March). (B) Data grouped by river segment: "upper" = segments A, B and C; "middle" = segments D, E and F; "lower" = segments G, H and I.*

For the mid-river segment, E, there was no significant change in chlorophyll *a* over the whole sampling period, 1970-1986. But when the shorter period 1975-1986 was tested, a significant increase ($p = 0.003$) was detected. In other words, chlorophyll apparently declined in this river segment during the 1970s, and then increased again in the 1980s. The time-series plot (Figure 51 in Stanley 1988) for this segment clearly shows the decrease from concentrations typically between 10 and 20 μg/liter in the early 1970s to often <10 μg/liter in the mid-1970s. Of course, these data are from different sampling programs, but I could find no evidence of changes in the analytical techniques that could explain the differences. Therefore, I must assume that the decline was real.

A very noticeable feature of the chlorophyll time-series plots is that in recent years the bloom peaks appear to be more frequent and higher, particularly upriver in segment B. But closer examination showed no clear long-term trend in the frequency of high values. I made a plot of the percentage of values over 40 μg/liter for each year since the sampling began in 1970 (Figure 4.15). Note that there were no data for 1974, and the 1985 data were not used because some of them are suspect. In 1979, the North Carolina Environmental Management Commission adopted a chlorophyll *a* quality standard of 40 μg/liter for "... all lakes, sounds, estuaries, reservoirs and other slow-moving waters not designated as trout waters" (North Carolina Department of Natural Resources and Community Development 1987, page 38). This standard applies during the months April through November. In most years, the highest number of Pamlico samples exceeding 40 μg/liter occurred in the winter months of December through March, when the standard is not applicable (Figure 4.15a). The percentage of April-November samples violating the standard has ranged from

<1% in 1970, 1975-1976 and 1980, to around 10% in 1986. There has been no clear trend in these percentages. Overall the early 1970s values are about the same as those for the early-to-mid 1980s. The dip in the mid-1970s may be real, or may be an artifact associated with the relatively infrequent late winter sampling between 1975 and 1979.

In most years, high chlorophyll *a* values were more frequent in the upper and middle river areas than in the lower estuary (Figure 4.15b). In the upper area—encompassing river segments A, B and C—up to 24% of the values were >40 μg/liter (1986). More typically, the percentage was around 5-10. Farther downriver in the middle reach (segments D, E and F), the percentages were about the same, but in the lower river (segments G-I), no more than 6% of the samples had over 40 μg chlorophyll *a*/liter in any year. Again, there has been no obvious change in this pattern since the sampling was begun in 1970.

Phytoplankton Species Composition and Biomass

Phytoplankton have not been monitored regularly for a long period in the Pamlico River. Therefore, there are not sufficient data to permit analysis of trends by the Seasonal Kendall procedure. How-

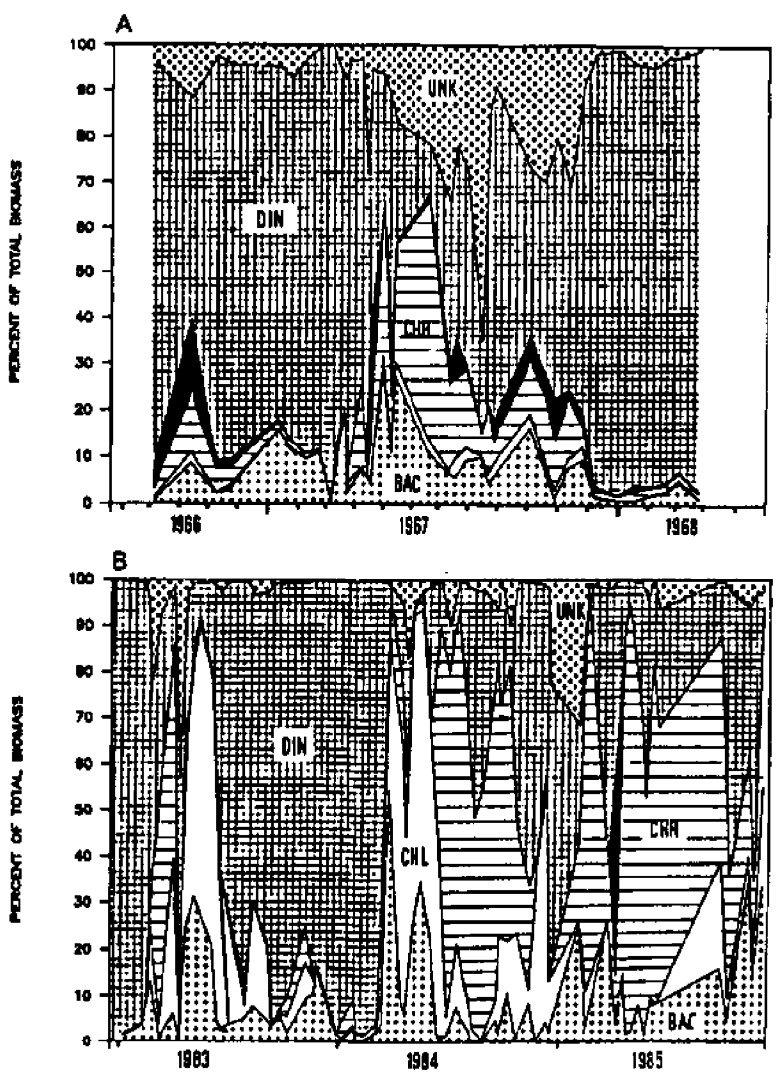

Figure 4.16. *Phytoplankton biomass (averaged by sampling date) in the Pamlico River for (A) 1966-1968 and (B) 1983-1985. Wet weight (mg/liter) for each class expressed as percent of total biomass. BAC = Bacillariophyceae; CHL = Chlorophyceae; CHR = Chrysophyceae; black = Cyanophyceae; DIN = Dinophyceae; UNK = Unknown.*

ever, there have been two major studies of phytoplankton species, numbers and biomass in the Pamlico. Since these studies were separated by a time interval of approximately 15 years, I thought it might be useful to compare the results, which might at least give clues about the presence or absence of long-term changes in the estuary's phytoplankton. The first study was by Hobbie (1971) for the time period August 1966 through April 1968. Samples came from the same stations used for nutrient and hydrographic monitoring. The second phytoplankton study, sponsored by North Carolina Phosphate Corporation, was made during the period April 1982 through December 1985 (Stanley 1983, 1984a; Stanley and Daniel 1985a, 1985b, 1986). Samples were collected approximately every other week from stations in the river and in South Creek. River stations were the same ones used for the nutrient and hydrography study.

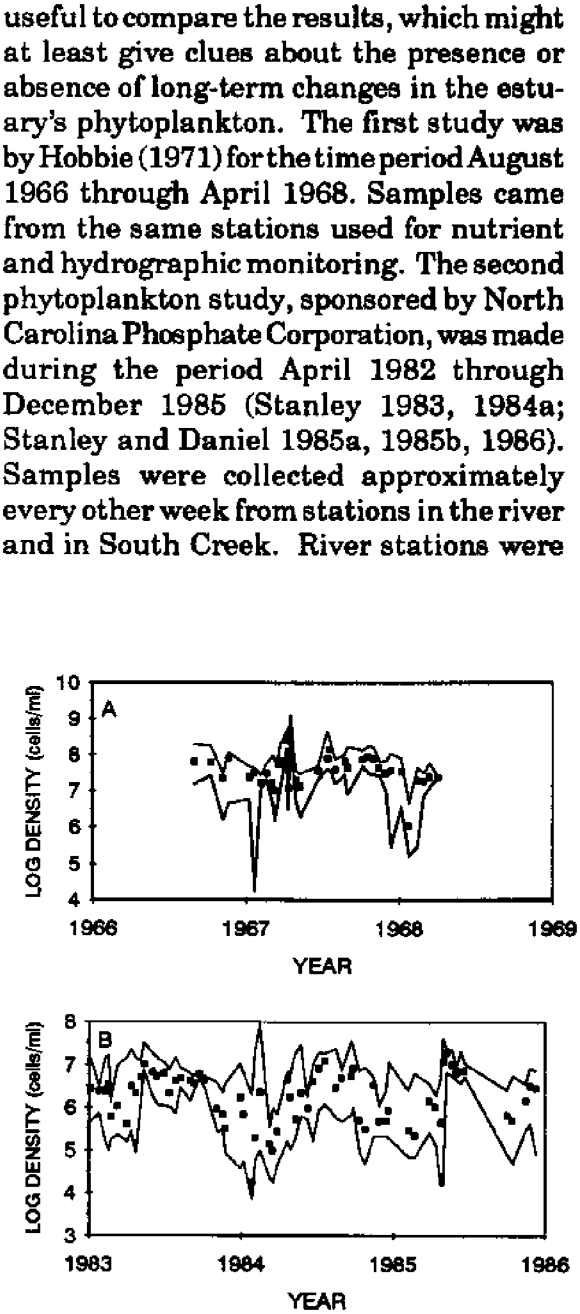

Figure 4.17. *Average phytoplankton cell density (log cells / liter) in the Pamlico River estuary during two sampling periods: (A) 1966-1968 and (B) 1983-1985.*

The data suggest that phytoplankton species composition in the Pamlico has not changed substantially during the past two decades. Figure 4.16 shows phytoplankton biomass broken down by class, for both the 1966-1968 samples and the 1983-1983 samples. The plotted data are means of all stations sampled on each date. In both sample periods, four classes made up the bulk of the total biomass. These were diatoms (Class Bacillariophyceae), green algae (Class Chlorophyceae), chrysophytes (Class Chrysophyceae), and dinoflagellates (Class Dinophyceae). Diatoms usually comprised around 10-20% of the total biomass, although there is considerable scatter, as there also is for each of the other algal classes. Diatoms were most important in the winter and spring. The green algae were also relatively important in the spring, comprising, on average, 58% and 17% of the total biomass in 1983 and 1984, respectively (Stanley and Daniel 1985b). At other times of the year in 1983 and 1984, and in all of 1966-1968, they were an insignificant part of the total. The seasonal pattern for the chrysophytes is clearer; they definitely were more abundant in the summer than at other times, both during the 1966-1968 and 1983-1985 sampling periods. In some instances, they averaged 70-90% of the total biomass. Overall, the most abundant algal class was the dinoflagellates, which made up 80% or more of the total on many dates, particularly in the fall and winter.

From the data presented in Figure 4.17, it would appear that algal cell density and biomass (data not shown) were substantially higher in the late 1960s than now. Between 1966 and 1968, the cell densities (averaged on each sample date for all stations) were mostly between 10^7 and 10^8 cells/liter, which was 10-100 times higher than the typical 1983-1985 cell density. Similarly, biomass in the 1966-1968 period appears to have been about ten times higher than in the 1983-1985 sampling period. There is considerable scatter in the data from both periods.

However, there are four reasons to suspect that these apparent declines in cell density and biomass are not real. First, about three-quarters of the samples collected during the 1966-1968 study were from the winter when dinoflagellate blooms (*Heterocapsa triquetra*) are greatest. Consequently, there were a few samples with very high densities and biomasses which greatly affected the means. If there had been more (presumably low biomass) samples from other seasons, the average would have been considerably lower. Second, in several samples, Hobbie found extremely high numbers of a very small unidentified alga that was less than 2 μm^3 in volume. This species contributed nothing to the biomass but considerably increased the average cell density. Third, a check of the cell volumes assigned to some of the most abundant species showed that Hobbie's estimates were, in some cases, higher than those used in the more recent study. For example, Hobbie estimated the volume for *Heterocapsa triquetra* as 3360 μm^3, compared to 2011 μm^3 by Stanley and Daniel (1985a). And finally, the trend in chlorophyll *a* in the river over the past two decades contradicts these phytoplankton biomass results.

It is unfortunate that the algal biomass data are not comparable, but perhaps there is a lesson to be learned from this attempt. It would seem that estimating algal cell density and biomass is an "art" as much as a "science," because of the difficulty associated with identifying the extremely small forms that make up so much of the phytoplankton. Perhaps the only solution is to have one person commit himself or herself to making counts for an estuary over a long period of time. This would at least insure internal consistency in the time series so that data from different periods would be comparable. Unfortunately, turnover in technical personnel and the tendency to conduct short-term studies make this an unlikely solution.

In his report on the 1966-1968 data, Hobbie made some interesting comments regarding phytoplankton and eutrophication in the Pamlico:

> ". . . Overall, the algae indicate that the Pamlico River estuary is a highly eutrophic body of water. Whether or not it should be called polluted depends upon the definition of pollution chosen and also upon someone's opinion as to the state of the river before man's activities began in the drainage basin. Because the algae are not a menace or hindrance to fishing or recreation, I do not believe the estuary is polluted. The natural fauna are still present and so far the algae are the only indicator showing pollution. Of course, any more nutrient enrichment should be avoided as the next step may be deoxygenation of the water. This deoxygenation would undoubtedly kill many fish and shellfish. Although it is just speculation at this point, it is very likely that if the algae bloom occurred during the summer months, the increased respiration associated with the higher water temperature might well reduce the oxygen to a low level. For this reason, it is important to understand how the phytoplankton are operating and to avoid any changes to the estuary regime that would create an algal bloom in summer" (Hobbie 1971, page 35).

Some comments should also be made regarding blue-green algae in the Pamlico, since blooms of these nuisance algae have become common in some areas of coastal North Carolina in recent years. In particular, the lower Chowan River and the lower Neuse River experience severe blue-green algae blooms during some, but not all, summers (North Carolina Department of Natural Resources and Community Development 1982; Christian et al. 1988). First, it should be noted that the blooms in these two systems have been restricted to fresh waters, or waters of very low salinity. The comparable region in the Tar-Pamlico would be upstream of Washington (i.e., upriver from station 12 used for the Texasgulf monitoring program). Although no sampling for algae has been done in that area, it is probably safe to assume that no blooms have occurred there of the magnitude and spatial extent comparable to those in the Chowan and Neuse. Hobbie (1971) apparently found blue-greens to be numerically abundant at some times in the Pamlico River estuary, but Stanley and Daniel (1985b) did not find them in large numbers in the more recent study. It is possible that this discrepancy represents a change in the river's algal species composition, but I suspect that the more likely explanation lies in the difficulty, alluded to above, of correctly identifying these tiny algae. Most are less than 2 μm in diameter, so that they appear as tiny dots under the 400X magnification used to make the cell counts. One person may count these as algae, while another might disregard them as pollen grains or other non-algal items. This is certainly possible, but there is no way to know if this actually happened.

Whether or not blue-green algae are present in the Pamlico estuary, it is clear from both the 1966-1968 and 1983-1983 studies that they do not contribute significantly to the total algal biomass. Using Hobbie's raw data, I calculated that the blue-greens usually made up less than 10% of the total biomass in the late 1960s. Similarly, during the more recent sampling period (1983-1985), there were only a few species of blue-green algae and they accounted for less than 1% of the algal density and biomass in the river (Stanley and Daniel 1985).

CHAPTER 5

Stratification and Bottom Water Hypoxia in the Pamlico River Estuary*

> *"One of the things we can do is to look at places like the Chesapeake Bay, the Hudson River and the San Francisco Bay. They were showing the same signs of stress about 10 years ago that the Pamlico is showing now . . . the signals are there."*
>
> B.J. Copeland (1987)

Introduction

The severity of dissolved oxygen (DO) depletion in the bottom waters of estuaries appears to range widely, depending on a combination of factors including morphometry, vertical density stratification, and perhaps nutrient and organic matter inputs. Persistent bottom-water hypoxia is common in stratified estuaries that have deep channels. Examples include Chesapeake Bay and some of its tributaries (Taft et al. 1980; Officer et al. 1984; Kuo and Neilson 1987; Kuo et al. 1991) and parts of the Puget Sound System (Christensen and Packard 1976). Coastal ocean areas such as the Atlantic inner continental shelf south of Long Island, NY (Swanson and Sindermann 1979; Falkowski et al. 1980) and the northern Gulf of Mexico (Boesch 1983; Harper et al. 1981) also have experienced severe hypoxia. Fortnightly mixing related to spring-neap tidal cycles has been observed in some estuaries, including the James, Rappahannock, and York rivers (Haas 1977; D'Elia et al. 1981; Ruzecki and Evans 1986). In shallow estuaries wind mixing tends to decrease water column stratification more frequently, so that bottom water hypoxia is generally of short duration and limited in spatial extent. In Mobile Bay, for example, periods of stratification and mixing occur as frequently as daily (Turner et al. 1987; Schroeder et al. 1990).

Given that stratification is a key factor in the establishment of hypoxia, there is an obvious need for better description and quantification of the roles of freshwater discharge, lunar tides, and winds as physical energy inputs influencing vertical mixing. But so far, only a few such studies have been made. In Chesapeake Bay, multi-year observations and mathematical modeling have shown that wind is responsible for breakup of the summer stratification in the early fall and that wind-induced destratification continues through mid-spring (Goodrich et al. 1987; Blumberg and Goodrich 1990). It has been determined that for Mobile Bay — a shallow, bar-built estuary — the tide is less important than river flow and wind-driven circulation (Schroeder and Wiseman 1986; Schroeder et al. 1990). It seems reasonable that wind and river flow may strongly influence stratification and bottom oxygen conditions in many of our nation's estuaries, given that over half have mean depths <5 m (Nixon 1988), and that many of those along the southern Atlantic and Gulf coasts are isolated from strong lunar tides by chains of barrier islands.

In this paper we examine the relationships among bottom water oxygen, vertical stratification, and the factors responsible

**coauthored by S.W. Nixon, Graduate School of Oceanography, University of Rhode Island, Narragansett, Rhode Island* for stratification-destratification in the Pamlico River Estuary in North Carolina. The study is based primarily on a 15-year set of biweekly oxygen, salinity, temperature, and nutrient concentration measurements, but we also have incorporated some recent continuous monitoring results.

The Pamlico is a shallow (2.7 m mean depth), oligohaline-mesohaline estuary extending 65 km from Washington, NC, to the western edge of Pamlico Sound (Figure 5.1). The estuary varies in width from about 0.5 km near Washington to about 6.5 km at its mouth. The Pamlico "River" is actually the estuary of the Tar River, which drains most of the 14,000 km² basin area. Total freshwater flow into the Pamlico typically ranges between 28 m^3s^{-1} in October and 112 m^3s^{-1} in February (Giese et al. 1979). Freshwater flushing times corresponding to this flow range are estimated to be between 80 and 28 days. Lunar tides in the estuary are almost negligible (7 cm), due to restrictions imposed by the Outer Banks, a chain of barrier islands separating Pamlico Sound from the Atlantic Ocean. However, "wind tides" of 0.5-1.0 m are not uncommon, and are most likely following several days of sustained winds from directions approximately parallel to the estuarine axis (Giese et al. 1979). Prevailing summertime winds in the Pamlico region are from the SW and NE.

Seasonal salinity patterns in the estuary are set primarily by variation in Tar River flow. Typically, surface salinity is <8 ppt during the late winter and early spring. The salinity increases to maximum values (10-15 ppt) during fall. However, there is considerable interannual variability. During drought years the salinity may approach that of Pamlico Sound (20-24 ppt). Temperatures in the estuary typically range from 4°C in January to 30°C in August. Details of the hydrography and ecology of the estuary are given in Giese et al. (1979) and Copeland et al. (1984).

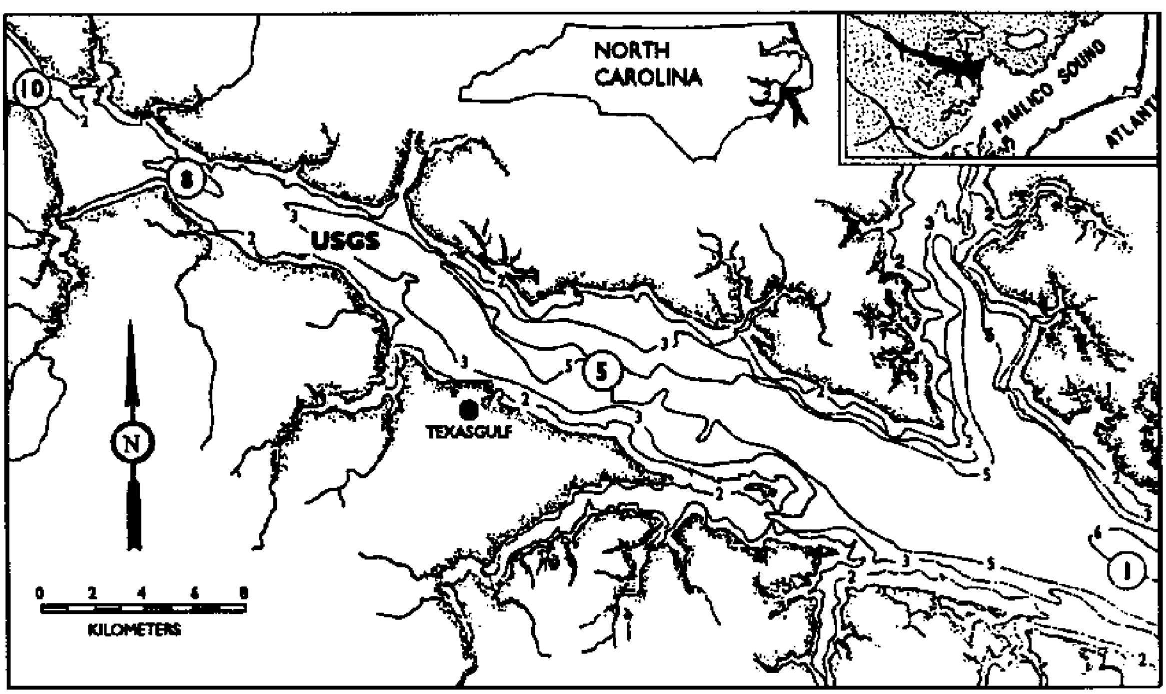

Figure 5.1. *Location of water quality sampling stations (10,8,5, and 1) and the U.S. Geological Survey continuous monitoring station (USGS) in the Pamlico River Estuary. Depth contours in m.*

Hypoxia, or "dead water" as it is known locally, has become one of the most important environmental issues for the Pamlico. Hypoxia in the estuary was first documented in the late 1960s (Hobbie et al. 1975), and was investigated more thoroughly in the mid-1970s (Davis et al. 1978), but knowledge about it seems to have become widespread only in more recent times. A recurring theme in many newspaper articles, regulatory agency documents, and some of the scientific literature written during the late 1980s is that nutrient inputs promote large blooms of phytoplankton that eventually die, decompose, and contribute in a major way to low oxygen conditions during summer. In addition, most fish kills in the estuary in recent years have been attributed to hypoxia in the bottom waters. Many citizens, and some scientists, suspect that bottom water anoxia and fish kills are more common in the estuary now than in the past.

Methods

Most of the data used in this study are from an ongoing water quality monitoring program sponsored by Texasgulf Chemicals, Inc. and carried out by East Carolina University since 1975. Salinity, temperature, dissolved oxygen, NO_3-N, NH_4-N, PO_4-P, and chlorophyll *a* are among the suite of variables measured approximately every other week at 20 sampling stations in the Pamlico. For this study we chose to use data from four of these stations; they are all located near mid-channel along the axis of the estuary. Station 1 is near the mouth at Pamlico Sound, and Stations 5, 8, and 10 are progressively farther toward the head of the estuary (Figure 5.1). Mean low tide water depths are approximately 5.0 m, 4.5 m, 4.5 m, and 3.5 m, respectively. Temperature and salinity were measured with a YSI Model 33 S-C-T meter, and dissolved oxygen was measured with a YSI Model 51 oxygen meter and electrode. Oxygen concentrations read from the air-calibrated meter were corrected to ambient water temperature and salinity. Measurements were made at two depths: approximately one-half meter below the surface and one-half meter above the bottom. These will be referred to as "surface" and "bottom" readings. Samples for chlorophyll *a*, and N and P were collected only at the surface. Chlorophyll *a* was measured by the method of Strickland and Parsons (1972), and the N and P analyses were by methods given in USEPA (1979) and APHA (1985).

In addition, we will present excerpts from a time-series (3-hr measurement interval) of near-surface and near-bottom DO, temperature, and salinity (determined from temperature and specific conductance measurements). The data are from a study carried out by the U.S. Geological Survey, using a Minimonitor, a U.S.G.S. designed instrument controlled by a CR10 micrologger with data storage in an SM-192, which has permanent memory. The monitor was mounted on the piling supporting Pamlico River Light 5 (a U.S. Coast Guard navigation channel marker) about halfway between our stations 5 and 8 (Figure 5.1). The near-bottom and near-surface probes were 1.2 m and 3.6 m above streambed, respectively. Mean low water depth at this marker is estimated to be 4.5 m. The Minimonitor was serviced at 2-week intervals. Vertical profiles of temperature, specific conductance, and DO were measured and compared to monitor readings. After the probes were cleaned, monitor and field readings were again compared. If the field and monitor readings differed only by a relatively small amount, the monitor was adjusted to agree with field readings. If the difference between the monitor and field readings was large, probes or the entire monitor were replaced with a laboratory-calibrated unit. The monitor was returned to the laboratory for routine recalibration at 3-month intervals (Bales 1990).

Wind velocity data, provided by Texasgulf Chemicals, Inc., were recorded at their plant site about midway down the estuary on the south shore (Figure 5.1). Wind speeds were converted to stress using the quadratic law with a drag coefficient of 1.5 x 10^{-3} (Garratt 1977). Daily mean Tar River discharge data are from the U.S. Geological Survey gage at Tarboro, NC, which is 80 km upstream from the estuary; consequently there can be substantial travel time lags between it and the estuarine sampling stations. About one-half of the drainage basin is ungauged, but precipitation rates and runoff rates are similar to those in the gauged areas, so that total freshwater drainage into the estuary is proportional to the gauged flow (Giese et al. 1979).

We used the Spearman Rank Correlation procedure to investigate relationships among the hydrographic variables. This is a nonparametric test of the presence or absence of association between two variables. It can also estimate the strength of the relationship, if one exists (Conover 1980; Daniel 1978). The computed coefficient (R) will range between -1 (perfect inverse relationship) and +1 (perfect direct relationship). The Spearman test is in-

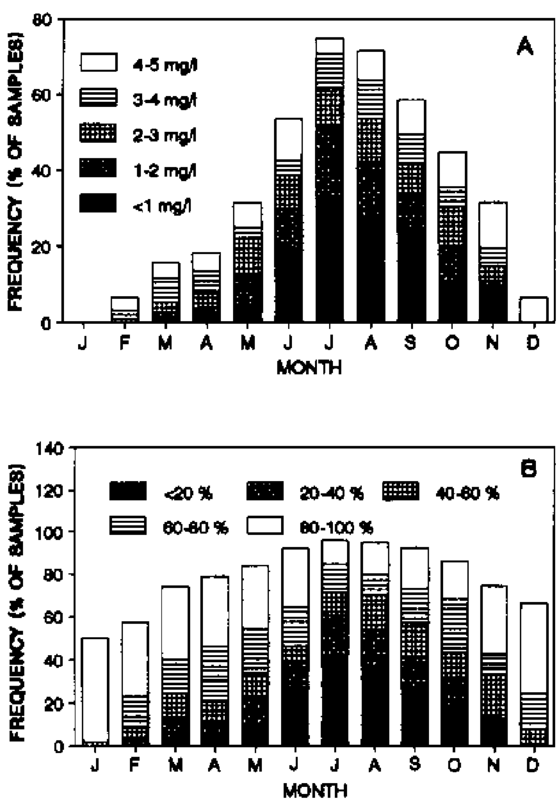

Figure 5.2. *Frequency of five DO concentration ranges (A) and percent saturation ranges (B) for each month. All data from four monitoring stations for the period 1975-89 included.*

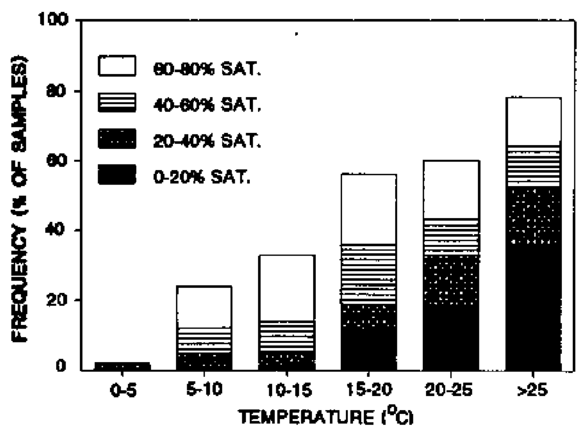

Figure 5.3. *Frequency of four DO percent saturation ranges for six temperature ranges. Includes all data from four monitoring stations for the period 1975-89.*

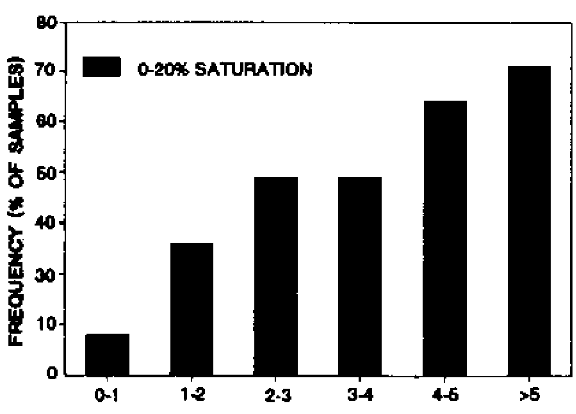

Figure 5.4. *Frequency of samples with <20% DO saturation for six delta Sigma-t ranges. Includes only measurements made when water temperature was >15°C.*

cluded in SYSTAT, a statistics package available for microcomputers. We implemented Version 4.0 of SYSTAT, which is documented in the user's manual by Wilkinson (1988), on a microcomputer.

The Seasonal Kendall-Tau test was used to examine the flow, salinity, delta sigma-t, and bottom DO data for long-term trends. The test, which was developed by Hirsch et al. (1982) is a nonparametric procedure suitable for application to water-quality parameters which are often skewed, serially correlated, and affected by seasonality. The test compares all possible combinations of pairs of values over time, assigning a plus if an increase occurs from one value to the next, or a minus if a decrease occurs. If more pluses occur than minuses, then an increasing trend is indicated; conversely, more minuses than pluses indicate a decreasing trend. The pairs of values compared are from the same "seasonal" period — in this case, months. In other words, only January values were compared with other January values, only June values were compared with June values, etc. The data within each month were summarized as means, and the test was run on the monthly means. A significance level (alpha) of 0.10 or less was considered to show statistical significance.

Results and Discussion

Seasonal and Spatial Variability

Frequency distribution plots of all measurements made between 1975 and 1989 show a distinct seasonal pattern in Pamlico bottom water oxygen (Figure 5.2a). Concentrations <5 mg l^{-1} are least common in the winter months (0-15%) and most common in July (75%). About one-third of the July measurements are <1 mg l^{-1}. This pattern is in part a reflection of the effect that annual water temperature and salinity cycles in the estuary have on oxygen solubility. But other factors must be involved, since the percent saturation frequency plot shows the same pattern (Figure 5.2b).

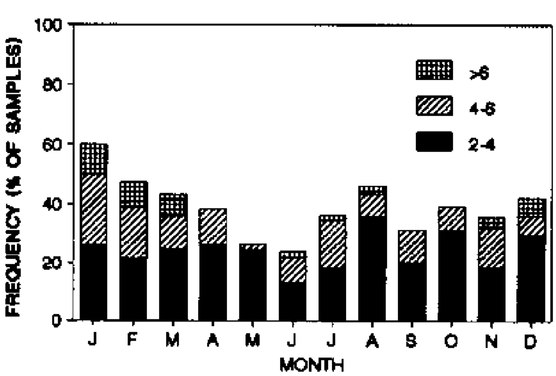

Figure 5.5. *Frequency of three delta Sigma-t ranges (bottom water - surface water) for each month. Includes all data from four monitoring stations for the period 1975-89.*

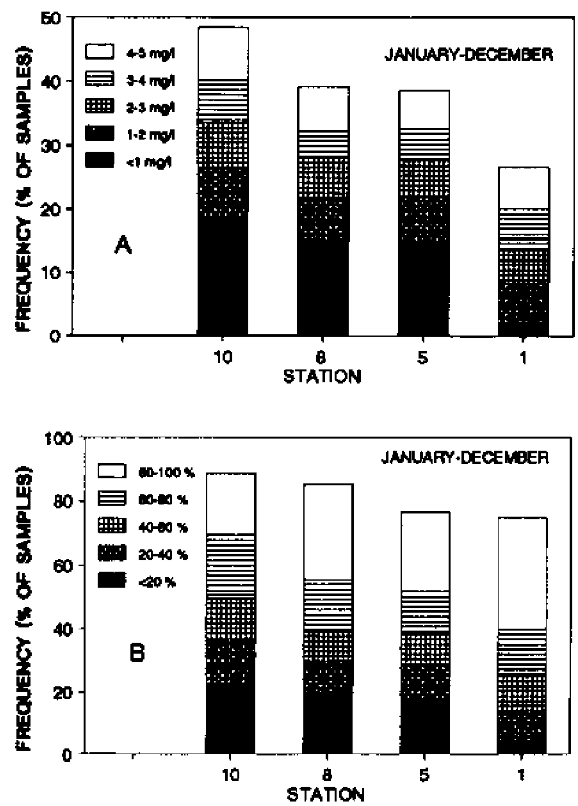

Figure 5.6. *Frequency of five DO concentration ranges (A) and percent saturation ranges (B) for each monitoring station. Includes all data for the period 1975-89.*

Instances of strong undersaturation (<40%) are rare in the winter but frequent in the summer months (39-61%).

A plot of all bottom water DO percent saturations, grouped into six water temperature ranges (Figure 5.3), reveals a sharp increase in the probability of moderate hypoxia at temperatures >15°C. Below this temperature, only 4% of the DO measurements were less than 40% saturation, but above 15°C, 38% were <40% saturation, and above 25°C over half the measurements (52%) were <40% saturation. Severe hypoxia (<20% saturation) is also most prevalent at the higher water temperatures. In addition, Figure 5.4 shows that for temperatures above 15°C the frequency of severe hypoxia increases with increasing strength of water-column stratification, as measured by delta Sigma-t. On the other hand, the scarcity of hypoxia during winter (<15°C) cannot be due to a lack of water-column stratification because a frequency plot of delta Sigma-t indicates that stratification is even more common in the winter than in the summer (Figure 5.5). Thus, it appears that the combination of stratification and warm water temperature is most conducive to the development of bottom water hypoxia in the Pamlico.

Severe hypoxia occurs more frequently in the upper half of the estuary than near the mouth (Figures 5.6 and 5.7). When data for all months are considered, around

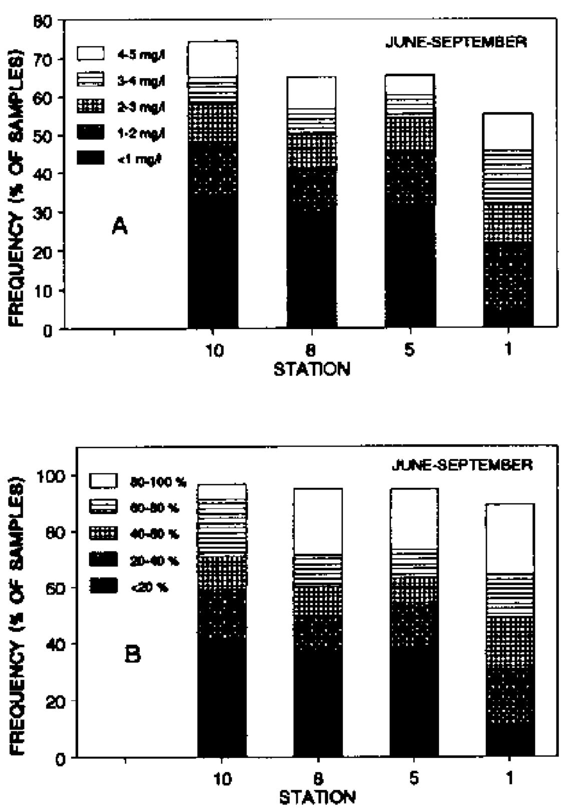

Figure 5.7. *Frequency of five DO concentration ranges (A) and percent saturation ranges (B) for each monitoring station. Includes only June-September data for the period 1975-89.*

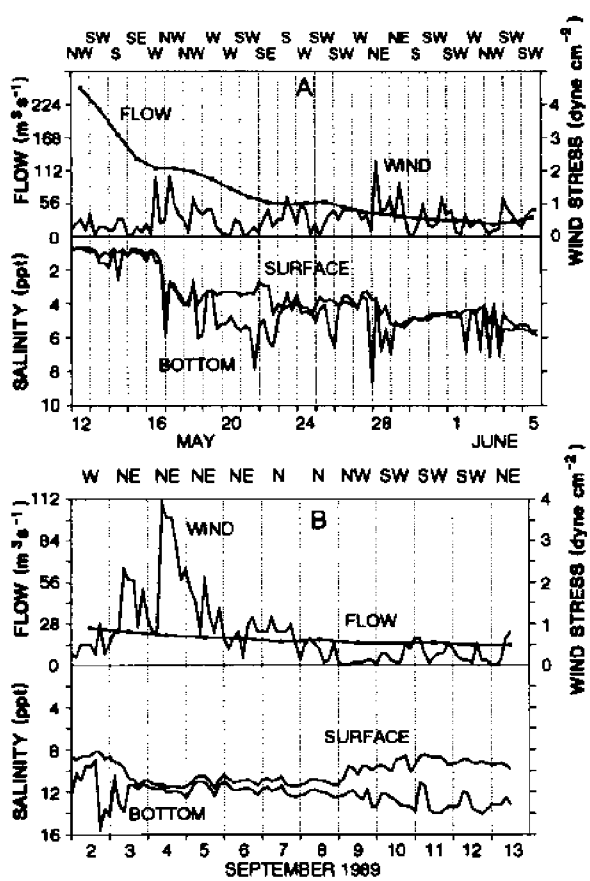

Figure 5.8. *Surface and bottom salinity, Tar River flow, and wind stress and direction for two periods during 1989. Salinity and wind data are plotted at 3-hr intervals, and flow is the daily mean.*

15% of the upper- and mid-estuary measurements (Stations 10, 8, and 5) give oxygen concentrations <1 mg l^{-1}, while at Station 1 near the mouth only 2% of the values are below 1 mg l^{-1} (Figure 5.6a). However, there is less spatial variation in the frequency of oxygen concentrations in the 1-5 mg l^{-1} range. About 30% of Station 10 values fall in this range, compared to 25% at stations farther down the estuary. The percent saturations also show a greater spatial difference in the lowest range than in the higher ranges (Figure 5.6b). From 18 to 23% of samples from the upper- and mid-estuary stations are less than 20% saturated, compared to only 4% at Station 1. A similar analysis of data from the summer months (June - September) shows that even though the frequency of low oxygen increases during warm weather, the spatial pattern does not change; i.e., low oxygen is still most common in the upper regions of the estuary (Figure 5.7). Concentrations less than 1 mg l^{-1} occur in one-third of the samples from the upper estuary, but in only 4% of the samples from near the mouth. The percent saturation data show the same pattern. One possible explanation for these spatial patterns is that because of its orientation in relation to the directions of the prevailing winds, the upper estuary is not as well mixed as the lower estuary. Correlation analysis evidence that supports this conclusion will be presented below.

Short-Term Variability

Unfortunately, the long-term monitoring data provide little insight into the short-term dynamics of stratification and hypoxia in the Pamlico, due to the relatively long sampling interval (two-three weeks). But data from the 1989 continuous monitoring study show that stratification/hypoxia events can develop and break down very rapidly. These data also strongly suggest that wind and freshwater flow into the estuary are important factors influencing the timing of these events. Three sequences, representing a variety of wind and flow conditions between May and November, will be summarized.

The first time-series covers a period characterized by rapidly declining Tar River discharge (Figure 5.8a). On May 12 the discharge at Tarboro was 250 m^{3}s^{-1} — about three times the long-term average for that time of year. By late May flow had fallen to more typical rates, around 40 m^{3}s^{-1}, and it changed little from then until the end of the interval on June 5. Surface salinity responded to the declining freshwater input by rising from 1 ppt early in the period to 5 ppt at the end. Despite relatively low wind stress (<0.5 dyne cm^{-2}) early in the period, there was little stratification, as evidenced by the small differences between surface and bottom salinities. Thus, river flow appeared to be the

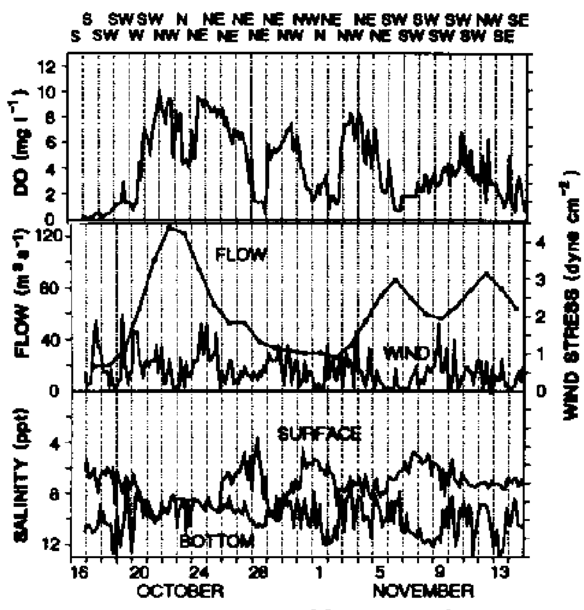

Figure 5.9. *Surface and bottom salinity, Tar River flow, wind stress and direction, and bottom water DO concentration for the period October 16-November 14, 1989. Salinity, wind, and DO data are plotted at 3-hr intervals; flow is the daily mean.*

dominant control then. But as flow decreased, wind became more important, as demonstrated by the development of weak stratification (2 ppt) on 19 May after wind stress subsided below 1 dyne cm^{-2}. This stratification was broken up three days later as the winds increased. From then until the end of the period, wind velocities were variable, with only brief periods of calm. Consequently, there were no sustained stratification events.

The second sequence (2-13 September) was highlighted by below normal freshwater discharge and a strong wind event associated with the passage of a storm front. The period began with weak westerly winds, high surface salinity (9 ppt), and weak stratification (Figure 5.8b). A lens of saltier water in the vicinity appears to have intruded twice for brief periods on 2 and 3 September. This movement may have been related to tidal forcing or internal seiching within the estuary. As the storm approached, wind stress increased and shifted to the NE. This mixed the water column and began to drive saltier water in from the eastern end of the estuary, so that by the time the storm had passed on 6 September, salinities throughout the water column had risen to about 11 ppt. Gradually, over the next 4-5 days, the wind shifted back to the SW, and surface salinities decreased slowly to 8-9 ppt. Also, the wind velocities declined, allowing a vertical salinity gradient of about 5 ppt to develop. After 9 September both increasing bottom salinity and decreasing surface salinity contributed to the widening vertical salinity gradient.

No oxygen data are available for these first two sequences, but there are DO data for the final sequence, spanning the period mid-October to mid-November, 1989 (Figure 5.9). This sequence is also interesting

Table 5.1. *Spearman Rank Correlations between bottom water DO and selected variables. F=flow on day of DO measurement; F-5, F-10, and F-15=5, 10, and 15-day lagged flows; WS=wind stress on day of DO measurement; WS-1 and WS-2=1 and 2-day lagged wind stress; BSAL=bottom water salinity; CHLA=chlorophyll a; and DSIGMAT =delta Sigma-t. Surface samples were analyzed for N and P concentrations.*

Variable	Station			
	10	8	5	1
F	0.149	-0.030	0.030	-0.167
F-5	0.139	0.034	0.026	-0.351**
F-10	0.112	-0.150	-0.012	-0.201
F-15	0.166	-0.087	-0.045	-0.108
WS	0.072	0.279**	0.184*	0.062
WS-1	0.199*	0.293**	0.279**	0.344**
WS-2	0.140	0.305***	0.134	0.178
BSAL	-0.477***	-0.446***	-0.400***	-0.145
NO_3-N	0.284**	0.298**	0.146	0.357**
NH_4-N	0.104	0.241*	0.134	0.366**
PO_4-P	0.113	-0.066	-0.113	-0.067
CHLA	-0.175	-0.155	0.035	-0.023
DSIGMAT	-0.655***	-0.674***	-0.742***	-0.432***

*p<.05
**p<.01
***p<.001

Table 5.2. *Spearman Rank Correlations between D Sigma-t and selected variables. F=flow on day of DO measurement; F-5, F-10, and F-15=5, 10, and 15-day lagged flows; WS=wind stress on day of DO measurement; WS-1 and WS-2=1 and 2-day lagged wind stress; BSAL=bottom water salinity. Surface samples were analyzed for N and P concentrations.*

Variable	Station			
	10	8	5	1
F	-0.210*	-0.081	0.009	0.111
F-5	-0.204*	-0.085	0.027	0.128
F-10	-0.173	0.110	0.114	0.205
F-15	-0.199*	0.030	0.159	0.231*
WS	-0.184*	-0.257*	-0.197*	-0.221*
WS-1	-0.202*	-0.319**	-0.234*	-0.300**
WS-2	-0.108	-0.178	0.028	-0.127
BSAL	0.732***	0.550***	0.452***	0.265*
NO_3-N	-0.262**	0.203*	-0.109	-0.484***
NH_4-N	-0.225*	-0.288**	-0.160	-0.377**
PO_4-P	-0.066	-0.060	-0.160	-0.377**

*p<.05
**p<.01
***p<.001

because it includes large, short-term fluctuations in Tar River discharge and wind stress, which interacted to produce four distinct episodes of stratification. The first was in progress at the beginning of the sequence on 16 October. Tar River flow had declined from a previous peak to 20 m^3s^{-1}, winds were blowing slowly from the south, and there was a 6 ppt difference between surface and bottom salinities. Also, bottom water DO was extremely low — well below 1 mg l^{-1}. The next day, a strong afternoon wind from the south eroded the salinity gradient, but was not sufficient to destroy it. Even stronger winds on the 19th temporarily broke up the gradient, and finally on the 20th it was destroyed following a third day of strong afternoon wind. At this time, the bottom water DO rose dramatically, reaching saturation concentration (9 mg l^{-1}) by 21 October. Subsiding winds on the 22nd and 23rd led to brief periods of stratification and lowered DO. Again, these very sharp fluctuations may have been caused by short-term tidal or seiching effects.

Meanwhile, in response to widespread precipitation over the Tar basin, a flow pulse had been building steadily for about 4 days, reaching a peak of 125 m^3s^{-1} at Tarboro on 22 October. That pulse reached the estuary station three days layer, quickly reducing the surface salinity to 5 ppt, and setting up the second stratification event, which eventually amounted to a 5 ppt vertical gradient. Bottom water DO fell rapidly from 6 mg l^{-1} on 27 October to around 1 mg l^{-1} the following day. This seems to be a clear example of stratification caused by a moderate pulse of freshwater spreading out over the estuary surface under low wind stress conditions. In addition, encroachment of saline Sound water, as evidenced by the slowly increasing bottom salinity, strengthened the density gradient even more. On the 28th, both the passing of the Tar River pulse and increasing wind stress combined to turn the water column over in a matter of a few hours during the evening.

Within 48 hours, another stratification event had begun to develop (30 October). This time, winds switched from the NE to the NW, and decreased in velocity. This event lasted about 4 days, with a vertical salinity gradient of about 4-6 ppt and bottom water DO reduced to around 2 mg l^{-1}. It ended late on 2 October following increased wind stress the previous night. The fourth episode began almost immediately, and for the next three days (4-6 November), there was weak stratification that was nearly broken on several occasions, but apparently did not completely disappear, since the bottom water DO continued to fall, reaching 1 mg l^{-1} on the 6th. The vertical salinity gradient strengthened on the next day, weakened on the 9th following stronger winds, and fluctuated between 2 and 6 ppt for the remainder of the sampling period. Bottom DO also fluctuated, mostly between 2 and 4 mg l^{-1}.

In summary, these time series data suggest that, at least in the mid-estuary, stratification events and bottom water oxygen levels are tightly coupled with variations in freshwater discharge and wind stress. Stratification can change in a matter of hours, and episodes lasting from one to several days seem to be common.

Spearman Correlation Results

Results of the Spearman Rank Correlation analyses tended to corroborate conclusions drawn from the frequency plots and the continuous monitoring data. Several variables were tested for correlation with bottom water DO concentration at each of the four long-term monitoring stations. Only data from 1975-89 samplings when the water temperature was >15°C were used (Table 5.1). Delta Sigma-t (bottom - surface), gave the highest correlation coefficient. The oxygen vs. delta Sigma-t relationship was inverse and was strongest at the three stations farthest up the estuary. The only physical variable showing a significant positive correlation to bottom water DO was wind stress lagged by one day, another indication of the rapidity with which stratification events are established and broken up. Tar River discharge, lagged 5, 10, or 15 days, seemed to be less important, as the only significant combination was the 5-day lagged flow at Station 1. The significant positive correlations between bottom oxygen and surface NO_3-N are interpreted to result from the presence of larger fractions of high NO_3 river water during mixing periods when there is no hypoxia. Note that there was a strong negative correlation between DO and bottom salinity. The positive correlation between bottom oxygen and surface NH_4, and the negative correlation between delta Sigma-t and surface NH_4 (*see* Table 5.2) are interesting in that they suggest that stratification in the Pamlico may lead to depletion of this nutrient in the surface layer.

Additional Spearman analyses were made to test for associations between delta Sigma-t, and two factors that could influence the strength of the stratification — Tar River flow and wind stress (Table 5.2). Flows were lagged 0, 5, 10, and 15 days, and wind stress was lagged 0, 1 and 2 days. The computed correlation coefficients between flow and delta Sigma-t were significant ($p<.05$) for only Station 10 at the upper end of the estuary. As would be expected, time lags of 0 and 5 days gave the strongest correlation for the upper stations, whereas 10 and 15-day lags gave the highest coefficients for the outer end of the estuary. There is a curious trend in the flow vs. delta Sigma-t coefficients, from negative in the upper estuary to increasingly positive at the lower station. This result could be interpreted to be a result of the salt wedge moving up and down the estuary in response to the strength of the flushing exerted by freshwater inflow.

Wind stress was significantly correlated with stratification (Table 5.2) at all stations when the previous day's wind was considered, but only at one station when a 2-day lag was used. In addition, the strength of these correlations trended upward toward the lower end of the estuary. This seems logical, since the shape and orientation of the Pamlico is such that fetch over which the prevailing SW and NE winds blow increases toward the mouth.

Interannual Trends

Seasonal and interannual variability of salinity in the Pamlico is determined primarily by freshwater runoff. Typically, salinity is lowest during the late winter and early spring when freshwater inflow is highes. The salinity increases to maximum values in the summer and fall, coincident with lowest Tar River flow. In some years this seasonal pattern may be upset by extended periods of precipitation or drought. For example, 1978, 1979, and 1987 were relatively high flow and low salinity years, while droughts in 1981 and 1988 resulted in unusually high salinities (*see* Chapter 4).

Water column stratification in the estuary is much more variable than bottom salinity on a short-term basis. The only apparent long-term pattern in stratification is that its strength and variability are reduced during years when bottom salinity is relatively low, such as 1978-79 and 1987. This is to be expected, since delta sigma-t is influenced primarily by differences between bottom and surface salinities.

The Seasonal Kendall-Tau test indicated there were no long-term trends in flow, salinity, delta Sigma-t, or DO in the Pamlico between 1975 and 1989. For each of the four stations, none of the test results were significant at the 90% level (alpha <0.1).

Event Frequency

Using hourly wind measurements collected by Texasgulf during the summers of 1980-1985, we calculated the resultant daily vectors of the axial (along the channel, 295°NW or 115°SE) and coaxial (cross-channel, 25°NE or 205°SW) components of the relative wind stress on the Pamlico. At this level of analysis, the definition of a "strong" wind is somewhat arbitrary, but the choice of a cross-channel vector equal or greater than 100,000 km^2d^{-2} or an axial vector equal or greater than 50,000 km^2d^{-2} (0.24 and 0.12 dyne cm^{-2}) seemed reasonable based on the frequency with which such winds occur and a consideration that the generally weaker axial winds may produce vertical mixing at lower speeds because of their longer fetches. It would be useful in subsequent work to consider this problem in more detail.

If the preliminary definition is accepted, strong cross-channel and axial wind events occurred, on average, with the frequencies given in Table 5.3 during the summers of 1980-1985. Thus, there might be, on average, a vertical mixing and reoxygenation of the bottom water approximately every 8.6 days during June, every 11.5 days during July, every 12.4 days during August, and every 6.5 days during September.

Table 5.3. *Frequency of occurrence (number per month) of strong cross-channel and axial wind events during the summers of 1980-1985. Assuming that only one day of strong wind is needed to destratify the estuary, we have considered two or more sequential days of strong wind as one event. Events are separated by two or more days of weaker wind.*

Month	Cross-Channel	Axial	Total
June	1.8	1.7	3.5
July	2.0	0.7	2.7
August	2.2	0.3	2.5
September	3.0	1.6	4.6

There is evidence that, at this frequency of reoxygenation, oxygen demand by the sediments and water column is sufficient to lead to hypoxia or anoxia. If the average summer Pamlico benthic oxygen uptake rate of 378 $\mu mol\ m^{-2}h^{-1}$ measured by Kuenzler et al. (1984) is applied to the area of sediment in the upper and mid sections of the estuary where hypoxia is most frequent (142.4 km^2, see Nixon 1989, Appendix A), it appears that the total benthic oxygen uptake might amount to about 41,339 kg d^{-1}. If we assume that one-half of the total volume of 322.2 x $10^6 m^3$ of water contained in this part of the estuary is below the pycnocline, then the sediments could lower the oxygen content of the bottom water only by some 0.26 mg l^{-1} d^{-1}. At this rate, the total oxygen consumed by the sediments during the longest average interval between strong wind events (12.4 days in August) would lower the concentration by about 3.2 mg l^{-1}.

Respiration by plankton and bacteria in the water appears to be somewhat greater. Data presented by Davis et al. (1978, their Figure 4) show concentrations of 2-3 mg l^{-1} of particulate organic carbon in the waters of the Pamlico during summer. At this concentration, their oxygen uptake regressions (see their Figure 52) indicate that 8-14 mg l^{-1} of oxygen were consumed during five days in July and 3-5 mg l^{-1} were consumed during five days in August. These rates of water column respiration are 2.3 to 10.8 times greater that the five-day oxygen uptake by the sediments and are sufficiently great that hypoxia and anoxia could easily result if the water were only mixed every 6.5 to 12.4 days. The sum of these estimated benthic and water column respiration rates (0.82-2.95 mg $l^{-1}d^{-1}$) compares reasonably well with the observed oxygen loss rates during periods of stratification in the fall of 1989 (Figure 5.9). It seems clear that it is the balance between oxygen uptake and the frequency of strong wind events that largely determines the spatial extent and duration of the low oxygen problem in the bottom waters of the Pamlico.

Effects of Hypoxia on Pamlico Biota

Anoxia or hypoxia in estuarine bottom waters obviously has the potential to seriously impact benthic organisms, either acutely via kills or chronically via physiological stress. The short-term effects were documented in the Pamlico during the late 1960s by Tenore (1972), who found that 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. There have been no follow-up studies to determine whether the benthos density and distributions have changed in the Pamlico over the past two decades. It would be helpful to be able to correlate the degree of impact on the benthos with changes in the areal extent, frequency, and persistence of hypoxia events. But the data base to allow such an analysis is not available.

"Flounder walk" is the local term describing movements of large numbers of the fish into shallow waters along the Pamlico. The phenomenon typically occurs in the summer during extended periods of hot weather and calm winds, and is usually interpreted as evidence of an hypoxic event in the estuary. Data obtained from the North Carolina Division of Environmental Management show that low DO was suspected to be the cause of most fish kills investigated in the Pamlico during the past two decades (NCDNRCD, unpublished data). Most of the reported kills were not in the main stem of the estuary, but rather near the heads of relatively small tributary creeks. Menhaden were the species involved in most episodes, and the great majority of the kills were reported during the summer. In some cases, dissolved oxygen was measured and found to be low in the kill vicinity; in other instances low DO was inferred from circumstantial evidence (e.g., "sulfide-like odors"). Unfortunately, most of these investigations took place several days after the kills, so that precise determination of circumstances at the time of the kill was very difficult. It should also be noted that hypoxia-related kills of fish, particularly menhaden, occur frequently in many other estuaries along the mid-Atlantic and Gulf coasts of the U.S. (e.g., Turner et al. 1987), under circumstances similar to those surrounding the Pamlico episodes.

Conclusions

While hypoxia is not the only environmental issue of concern in the Pamlico, it is certainly one of the most important. Because there are documented and potential links between low oxygen and kills of fish and commercially valuable shellfish, the public has been more attentive to this issue than to most others. As noted above, many believe that increasing nutrient inputs are promoting larger blooms of phytoplankton that eventually lead to more "dead water" and fish kills than in the past.

However, the results of our analysis of the historical data do not support such a view. There has been no trend toward lower bottom water DO over the past 15 years. In addition, the Spearman Correlation results detected no cause-and-effect relationship between nutrients or algal abundance and bottom water DO. Of course, it could be argued that lag effects are involved which would not be detected by comparing contemporaneous measurements. However, one of us (Nixon 1989) has searched — without success — for evidence of a link between either: 1) the size of the winter-spring blooms of phytoplankton in the estuary and the frequency and extent of hypoxic conditions in the bottom waters of the estuary the following summer, or 2) the summer bloom and the severity of hypoxia.

The North Carolina Division of Environmental Management has recently designated the Tar-Pamlico as "Nutrient Sensitive Water," with the goal of reducing nitrogen loading to improve water quality in the estuary. We would not argue that success in reducing the rate of increase in nutrient loading may be beneficial in the future. But reduction in N loading, at least within any practical constraint, may not result in an increase in the oxygen content of the stratified bottom water of the estuary during summer. At that time of year, the waters of the Pamlico are "wind sensitive," and we will have to accept the intermittent hypoxia and anoxia as natural features of the system.

Chapter 6

The Pamlico River: Comparisons with Other Estuaries

Introduction

In the past, relatively few comparative studies of estuarine water quality have been made. It has been speculated that the reasons for this include: 1) the widespread belief among ecologists that estuaries are so variable that attempts to generalize from one to another are bound to fail; and 2) the great difficulty of organizing, funding, and executing studies of more than one system (Nixon 1983). During the 1990s, the U.S. Environmental Protection Agency plans to carry out a major, national comparative study of estuaries as part of its Environmental Monitoring and Assessment Program (EMAP).

In addition, few comparative analyses of existing data for different estuaries have been published. S.W. Nixon, an estuarine ecologist experienced in comparative syntheses, points out that attempts at such reviews are hampered by the relatively small number of estuaries that have been thoroughly studied, by differences in methodology used to produce the data, and by the problems that arise from spatial and temporal variability within each system (Nixon 1983).

Nixon (1983) used previously published and unpublished information for his comparative study of fourteen estuaries on the Atlantic, Gulf, and Pacific Coasts of the United States. Fortunately, the Pamlico River was one of the estuaries included in the study. Topics covered include physical characteristics, nutrients, phytoplankton and primary production, zooplankton, icthyoplankton, benthos, and fish. In this chapter, I have relied heavily on information contained in the Nixon report. Anyone interested in comparative estuarine ecology should consult this source; it is one of the most comprehensive reports on the subject available at this time.

> *"One of the things we can do is to look at places like the Chesapeake Bay, the Hudson River and the San Francisco Bay. They were showing the same signs of stress about 10 years ago that the Pamlico is showing now . . . the signals are there."*
> B.J. Copeland (1987)

Another comparative study that provided useful data was authored by Boynton et al. (1982). They reviewed data concerning nutrients, phytoplankton production, and chlorophyll *a* from 63 different estuarine systems. Finally, I have attempted to make some comparisons between the Pamlico River and the nearby Neuse River estuary. Unpublished 1985 and 1986 nutrient and hydrographic data from the Neuse study were used to illustrate similarities and differences between it and the Pamlico River.

Nutrients

Comparing cycles of orthophosphate phosphorus in 14 estuaries, Nixon (1983) found that annual mean concentrations were less than 1 μM in Chesapeake Bay, in the mid and lower regions of the Potomac River Estuary, in Apalachicola Bay, Florida, and in Kaneohe Bay, Hawaii. Highest mean concentrations were found in the Pamlico River (approximately 4 μM) and in South San Francisco Bay (about 25 μM). All the other systems had mean annual phosphate levels of 1-3 μM. One feature common to most of the estuaries, including the Pamlico River, is the summer increase in phosphate, particularly at their lower reaches. Presumably, the high Pamlico phosphate is due to the large discharge from the Texasgulf phosphate mine on the south shore of the estuary (*see* Chapter 3).

The relationship between phosphate input and concentrations that Nixon developed may provide a clue as to whether or not the Pamlico phosphate levels would decrease if loading from Texasgulf, or other sources, were decreased. From a plot of phosphate input versus mean annual phosphate concentration for all the estuaries surveyed (Figure 6.1a), Nixon concluded that indeed there is a correlation between the two. There was considerable scatter in the data, but this was reduced when the

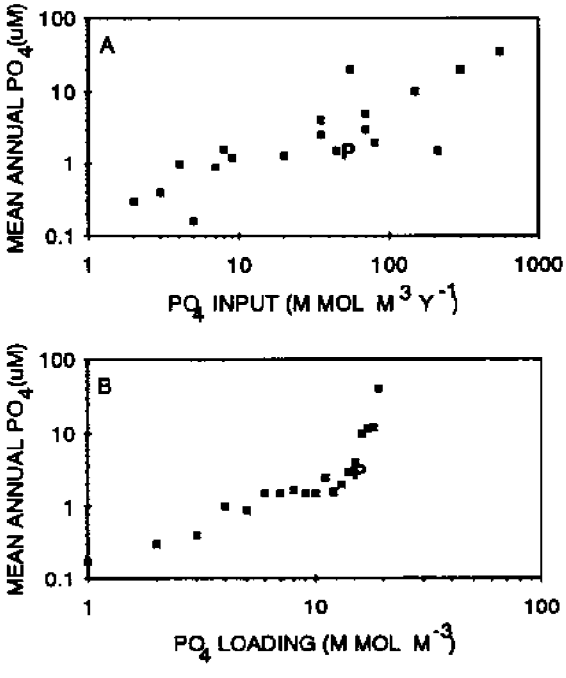

Figure 6.1. *A. Mean annual concentrations of inorganic phosphorus (μM) in several estuaries as a function of the estimated annual inputs of phosphorus. P = Pamlico River estuary. B. Same as above except that inputs have been corrected for differences in flushing times (Redrawn from Figure 14 in Nixon 1983).*

effects of different flushing rates were taken into account (Figure 6.1b). This correction was made by multiplying the annual input by the approximate mean annual freshwater replacement time. The estuarine data appeared to follow the same relationship found for lakes by Schindler (1978).

A comparison of salinity and nutrients in the Pamlico River and the Neuse River showed that except for orthophosphate phosphorus, there was little difference between the two estuaries. Volume-weighted monthly medians for the period January 1985 to December 1986 were calculated and are plotted in Figure 6.2. This method of presenting the data eliminates bias arising from different sampling station locations in each estuary relative to the salinity gradients. The problem is most severe for factors that vary greatly along the salinity gradient. The weighted monthly median salinities ranged from 8 ppt to about 13 ppt in the Neuse and from 8-12 ppt in the Pamlico. Both estuaries had highest salinities in the fall and lowest salinities in the late winter. Nitrate nitrogen was around 1 μM in both the Neuse and Pamlico during the summer, and 5-12 μM in the winter (Figure 6.2b). February and March median values were higher in the Pamlico, but November and December values were higher in the Neuse. Overall, there seems to be no significant difference in the nitrate between the two estuaries. Similarly, ammonia nitrogen was higher in the Neuse some months and in the Pamlico during other months (Figure 6.2c), but there appears to be no substantial difference overall.

Both estuaries had highest orthophosphate phosphorus in the summer months (Figure 6.2d), and lowest values in the winter. The winter values were similar for both — around 1 μM — but the Pamlico had higher summer phosphate than the Neuse. The difference was nearly two-fold for most months between June and December. This difference probably reflects the influence of P loading from the Texasgulf (TG) facility into the Pamlico. The more-or-less constant TG loading ought to be most noticeable in the low-flow periods (i.e., summer and fall) when Tar River P loading is reduced.

Nixon (1983) also compiled data on annual cycles of inorganic nitrogen (DIN) for a number of estuaries, including the Pamlico River. Two of his general conclusions about DIN cycles apply to the Pamlico: 1) nitrate is often more abundant than ammonia during spring and fall in the lower salinity systems, and 2) concentrations of nitrate appear highest in the upper portion of the estuaries. However, the range in annual mean concentrations was very large; from about 1 μM in Kaneohe Bay, Hawaii, to over 100 μM in Delaware Bay. The Pamlico average was 18 μM, about the same as the Patuxent River Estuary, Chesapeake Bay, Potomac River, and North San Francisco Bay (Nixon 1983). Nixon's plots of mean annual DIN concentration versus DIN input and loading (Figure 6.3), prepared in the same manner as the DIP loading versus concentration plots described above, led him to conclude that there is a linear relationship between nitrogen loading and the average concentrations observed in the estuaries. But the slope of a line drawn through this data would be less than one, indicating that DIN concentrations do not rise or fall in estuaries in 1:1 proportion to changing loading. It appears that a doubling in the loading rate ought to produce about a 50% increase in mean concentration.

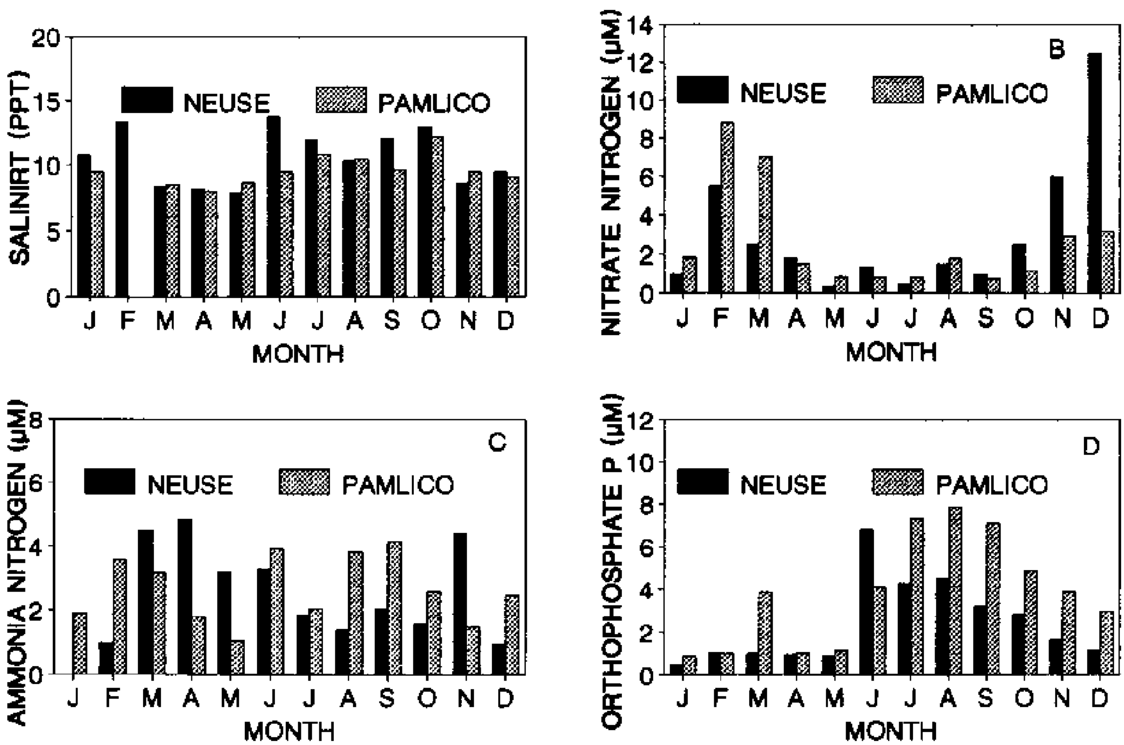

Figure 6.2. *Salinity, nitrogen and phosphorus in the Pamlico River and Neuse River estuaries, 1985-1986. Values are volume-weighted monthly medians. (A) Salinity (ppt), (B) Nitrate nitrogen (μM), (C) Ammonia nitrogen (μM), (D) orthophosphate phosphorus (μM).*

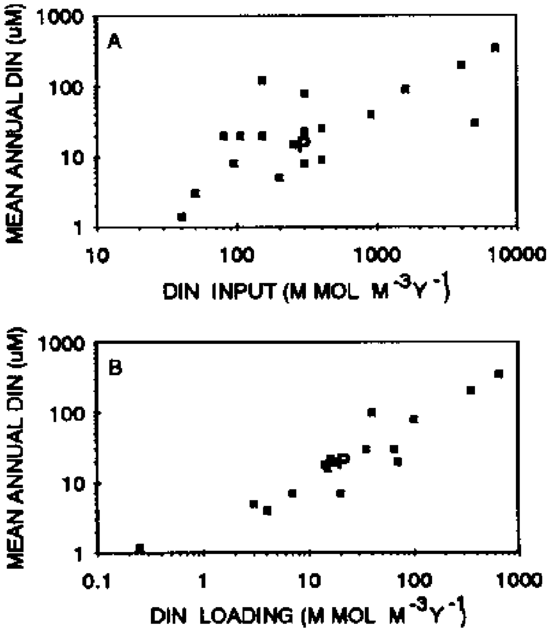

Figure 6.3. *A. Mean annual concentrations of inorganic nitrogen (µM) in several estuaries as a function of the estimated annual inputs of nitrogen. P = Pamlico River estuary. B. same as above except that inputs have been corrected for differences in flushing times (Redrawn from Figure 17 in Nixon 1983).*

There continues to be much controversy and uncertainty surrounding the issue of nutrient limitation in estuaries. Over the past two decades, the general consensus has been that nitrogen is more likely than phosphorus to limit algal growth. Boynton et al. (1982) compiled data on N:P concentrations and ratios from nearly 30 estuaries, including the Pamlico River (Figure 6.4). Here are their conclusions:

> "The data . . . support the notion that nitrogen is consistently less abundant than phosphorus during periods of peak [algal] productivity in a wide variety of estuarine ecosystems. In most cases, those those that do not follow this pattern are heavily enriched by point and diffuse nutrient sources throughout the year (e.g., High Venice Lagoon, Hudson River). On the right side of [Figure 6.4], actual concentrations of DIN and DIP [orthophosphate phosphorus] at the time of peak produc-

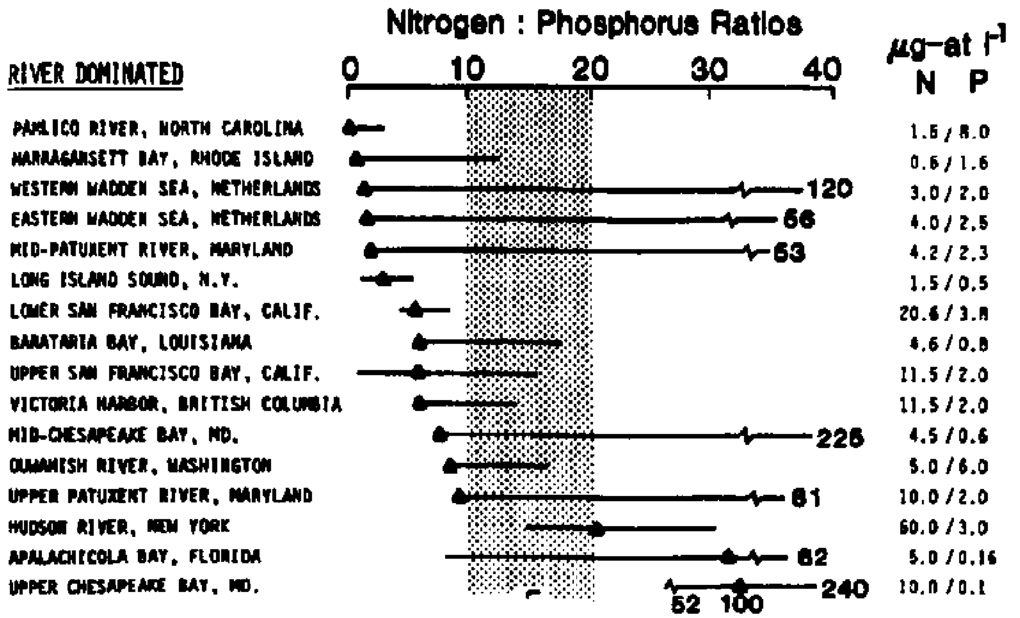

Figure 6.4. *Seasonal mean DIN:DIP ratios from 16 river-dominated estuarine ecosystems. Horizontal bars indicate the annual ranges in DIN:DIP ratios; solid triangles represent ratio at time of maximum productivity. Absolute concentrations (µM) at time of peak productivity are on the right. Vertical band represents the typical range of algal composition ratios (part of Figure 5 in Boynton et al. 1982).*

> tion are shown. Clearly, actual concentrations vary considerably between various estuaries and it is an open question whether these concentrations are limiting. However, nitrogen enrichment in estuarine areas often stimulates algal growth, indicating that despite relatively high ambient concentrations, nitrogen limitation of phytoplanktonic production can occur (Ryther and Dunstan 1971; Williams 1972; Goldman et al. 1983; Thayer 1974)"
>
> (Boynton et al. 1982, page 78).

Some ecologists, after making detailed studies of individual estuaries, have come to the conclusion that phytoplankton growth limitation shifts from N to P at different times of the year. There seems to be a seasonal pattern in the shifts. For example, Webb and Eldridge (1988) conducted experiments in the lower York River that showed the phytoplankton were P limited in the late fall and winter, and N limited in the late spring and summer. They speculated that seasonal shifts in P and N inputs to the estuary were the most likely cause of the shift. In the York River, P shows maximum concentrations in summer and the minimum in winter; the major input of N is nitrate from wintertime runoff. Recall that this is the same as the pattern for the Pamlico River (*see* Chapter 4).

These results parallel those from studies in a low salinity portion of the Chesapeake Bay system (D'Elia et al. 1986), and in other areas of the bay (Fisher et al. 1988; Malone 1988; Love et al. 1988). Despite extreme nutrient enrichment in the headwaters of the Delaware estuary, phytoplankton productivity in the middle and lower estuary alternates between light, phosphorus and nitrogen limitation over the seasonal cycle, according to (Pennock and Sharp 1988). It is also their view that these factors vary spatially over the salinity gradient. In general, Delaware Bay P limitation is most prominent in the mid-estuary during the late spring, while N limitation is more significant at the mouth of the estuary during the summer.

Dissolved oxygen

Chesapeake Bay was one of only two estuaries found to have serious low DO problems in a review of 14 systems by Nixon (1983) (the other was Mobile Bay). The low oxygen phenomenon has been experienced for many years in the Chesapeake, he noted, and may be, in part at least, a natural feature of the system. The Bay's deep channel, lying between broad, shallow, very productive waters, may collect and concentrate much of the organic matter fixed in the shallows. Nixon speculated that this enrichment, combined with a well-stratified water column, may cause the anomalous low oxygen feature. In Mobile Bay, the deep channel (Mobile Ship Channel) is well oxygenated and the low oxygen water is spread out over shallows that have been isolated from much of the tidal circulation by shoals and dredge spoil (Nixon 1983).

I recently attempted an assessment of dissolved oxygen conditions in the twenty-three estuaries in North Carolina, South Carolina, and Georgia for which some data were available (Stanley 1985). One conclusion from this review was that none of these estuaries suffer 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 oxygen conditions.

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 speeds. More than 80% of the variation in DO content 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 has been widely publicized (e.g., Officer et al. 1984), but the study conclusions have been questioned by other bay-area scientists (Seliger and Boggs 1988) who have re-examined the data. They summarized their new findings as follows:

> "Analysis of the complete data base on measurements of dissolved oxygen in the Chesapeake Bay for the period 1950-1985 results in two conclusions: a) there has been no statistically significant pattern of increase in summer anoxia of bay waters over the past 36 years, and b) annual streamflow-induced stratification is the controlling factor in the annual volume of summer anoxic waters in the bay, at greater than the 99.99% confidence level. These conclusions are in sharp contrast with those of an EPA-funded 5-year study of the bay and with those

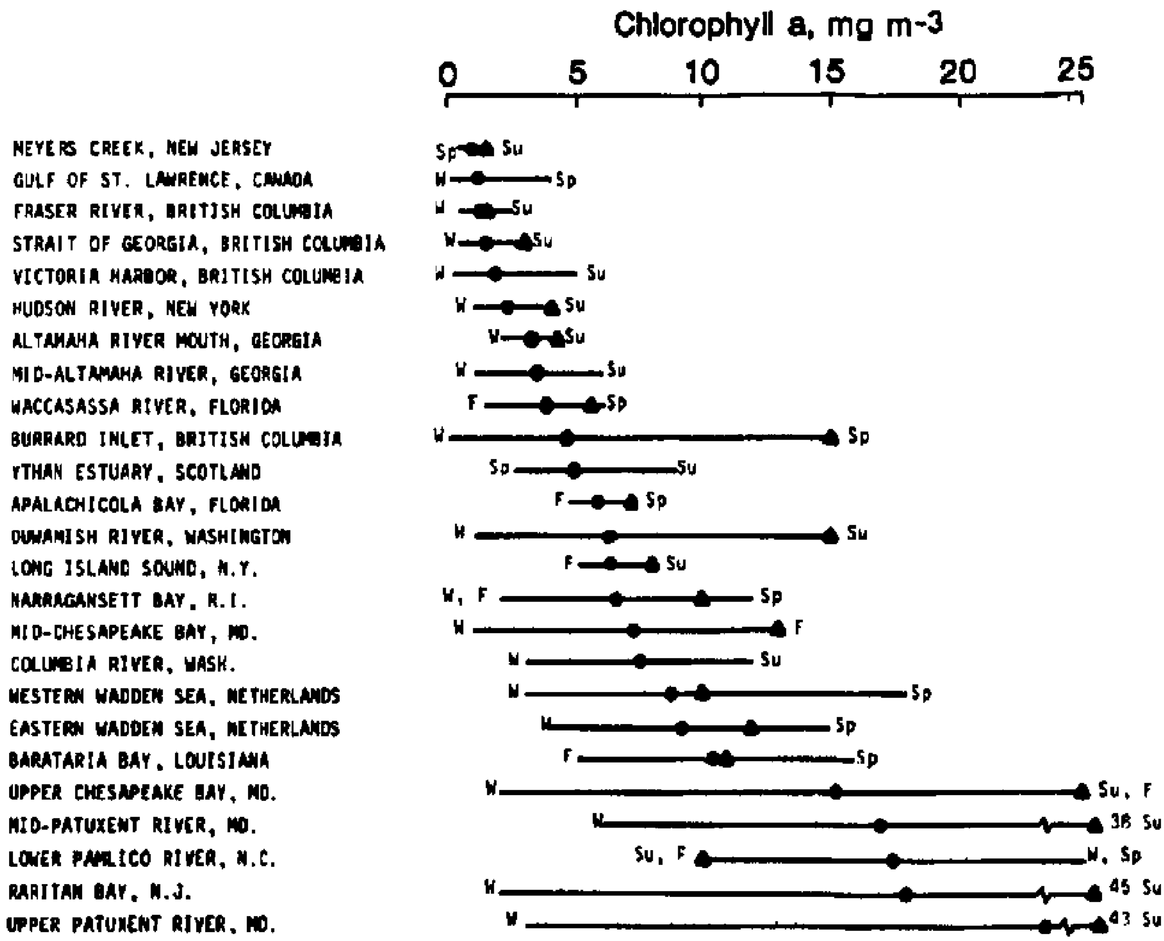

Figure 6.5. *Summary of chlorophyll a concentrations in 25 estuaries. Annual ranges and seasons in which maximum and minimum concentrations occurred are indicated. Solid triangle indicates chlorophyll a concentration at time of maximum productivity (part of Figure 4 in Boynton et al. 1982).*

of a major review of anoxia published in Science [Officer et al. 1984], namely that anoxia in the bay has increased by a factor of 15 since 1950 and that benthic respiration, rather than stratification, has been the controlling factor in this 15-fold increase in anoxia. This apparent increase in anoxia has been attributed to increased nutrients and has been assumed to be a major factor in the decline of fish and shellfish species in the bay. A federal and multi-state program for restoring the bay biota is based on reversing this 15-fold increase in anoxia by reducing nutrients in the bay. In the absence of any evidence for increased summer anoxia since the 1950s, the scientific basis of this program should be re-evaluated"

(Seliger and Boggs 1988).

Chlorophyll a and Phytoplankton Biomass

In his comparative estuarine study, Nixon (1983) also presented data on the standing crop of phytoplankton, as estimated by chlorophyll *a*. The estimated annual mean for the Pamlico River was about 16 μg/liter. For all the estuaries, the range was from about 2 μg/liter in Kaneohe

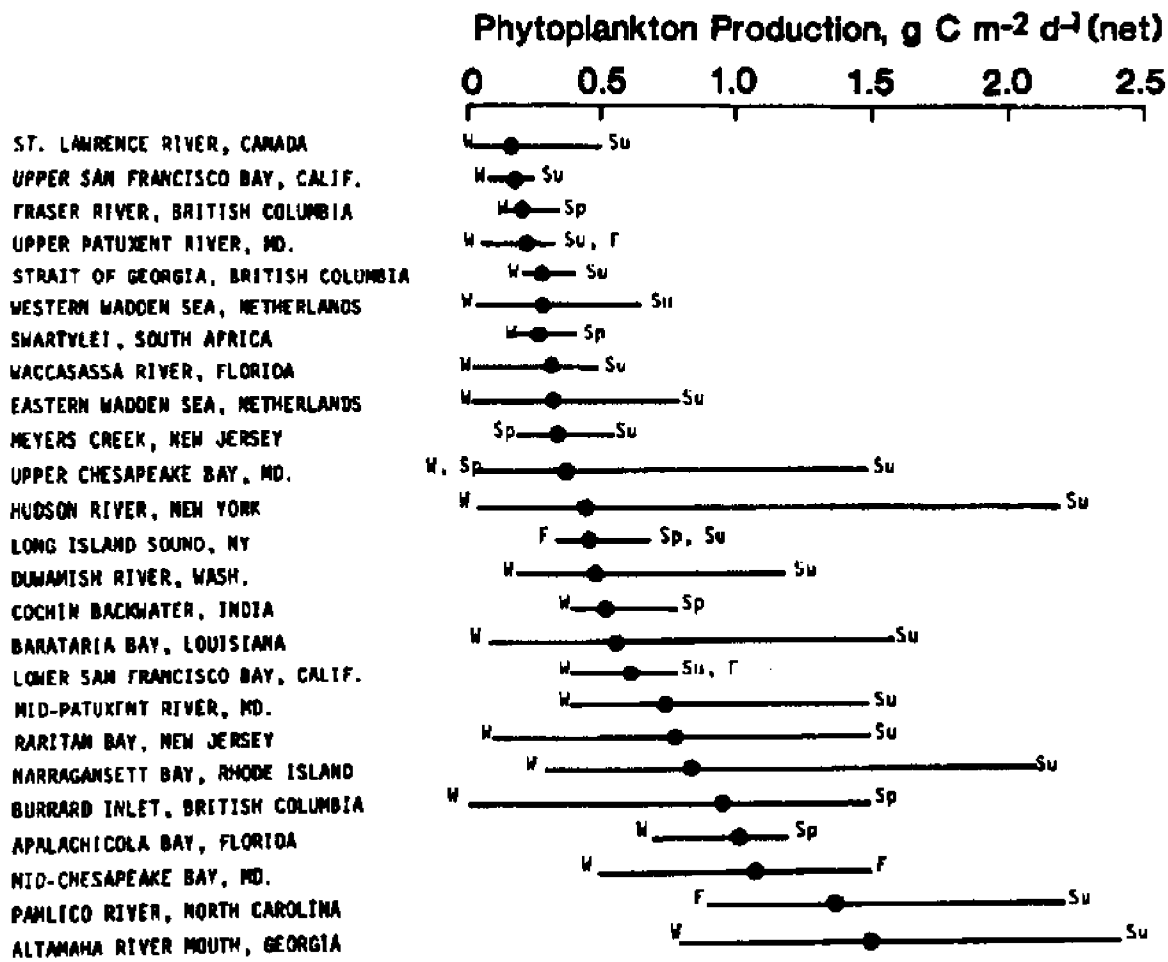

Figure 6.6. *Summary of average daily phytoplankton production rates (solid dot) in 25 estuarine systems. Horizontal bars indicate annual ranges. Season in which maximum and minimum rates occurred is also indicated. (W, winter; Sp, spring; Su, summer; F, fall) (part of Figure 3 in Boynton et al. 1982).*

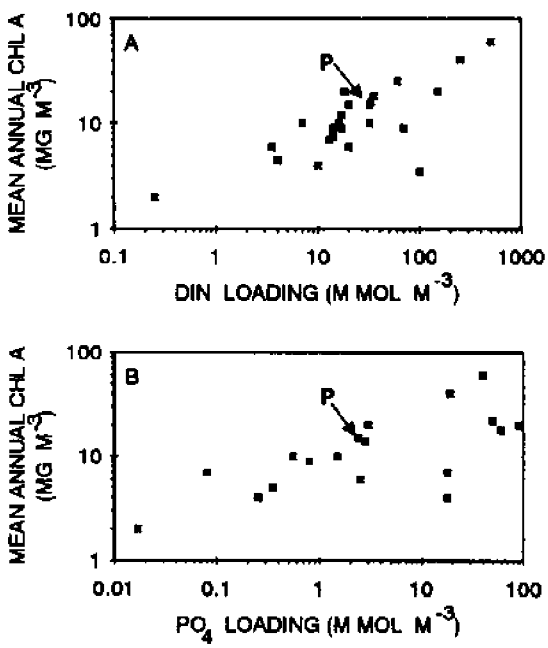

Figure 6.7. *Mean annual chlorophyll a as a function of the estimated annual loading of dissolved inorganic nitrogen (top) and dissolved inorganic phosphorus (bottom). P = Pamlico River. The regression line relating mean annual chl a in lakes to P loading is from Schindler (1978) (redrawn from Figure 20 in Nixon 1983).*

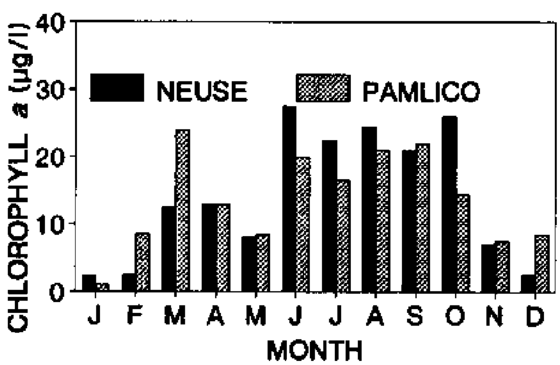

Figure 6.8. *Chlorophyll a in the Pamlico River and Neuse River estuaries, 1986. Values plotted are volume-weighted monthly medians.*

Bay, Hawaii, to almost 20 µg/liter for the Patuxent River estuary. A winter-spring bloom was found to occur in a number of the estuaries, including the Pamlico, of course, but was inconspicuous or absent in others. Some estuaries had strong mid-summer blooms.

Boynton et al. (1982) also presented comparative data on chlorophyll *a* and average daily primary production rates in the Pamlico River and in 44 other estuarine systems (Figures 6.5 and 6.6). The Pamlico data used in this comparison were from the early-to-mid 1970s. In terms of both chlorophyll *a* and primary productivity, the Pamlico ranked as one of the highest of the river-dominated estuaries included in the comparison. However, there is so much overlap among the top third of the systems, that real differences, if they exist, are obscured. These plots also cannot take into account the considerable year-to-year variability in algal biomass and productivity within each estuary, so that individual rankings are impossible. The authors of this paper drew no conclusions regarding the order of the rankings, such as effects of nutrient loading, hydrography, or climate.

One of the most interesting of all the comparisons in the Nixon study described above was between nutrient loading and chlorophyll *a* (Figure 6.7). The results were described as follows:

> ". . . I have made a preliminary attempt to relate the annual mean chl a averaged over each estuary to the input of inorganic nitrogen and phosphorus. . . The results are not without scatter, but as a beginning I think they are impressive enough to merit attention and further effort. . . . The response of estuarine phytoplankton may not be as dramatic as that of lakes. While nitrogen and phosphorus loadings increased 2000 times from Kaneohe Bay to the most heavily enriched MERL microcosm, the annual standing crop of chl *a* only increased

Table 6.1. *Summary of phytoplankton data from several east coast estuaries. BAC = Bacillariophyceae (diatoms), CHL Chlorophyceae, CYA = Cyanophyceae, CHR = Chrysophyceae, and DIN = Dinophyceae. S = total number of species found; D = average cell density (cells l^{-1}); and B = average biomass (mg wet mass l^{-1}).*

South Creek,	S: 146	47	17	2	7	10	21	0-10
This Study	D: 3.9×10^6	14	11	6	61	6	2	
	B: 1.60	14	14	<1	16	51	4	
South Creek,	D: 52.7×10^6						<15	
Hobbie (1971)	B: 9.11							
Pamlico River,	S: 173	50	18	3	6	8	15	0-20
Stanley and Daniel (1985)	D: 4.2×10^6	3	14	<1	59	20	3	
	B: 3.37	3	7	<1	8	80	1	
Gales Creek, NC,	S: 339	55	7	—	5	22	11	
Campbell (1973)								
Cape Fear River, NC	S: 203	66	12	4	1	7	10	11-15
Carpenter (1971)								
Chowan River, NC	B: 5.61	20	11	22	1	29	17	0
Stanley and Hobbie (1981)								
Neuse River, NC	S: 297	23	37	14	9	4	13	0-10
Stanley (unpublished)	D: 12.5×10^6	12	16	63	3	<1	5	
	B: 3.48	15	34	2	6	17	26	
Currituck Sound, NC,	S: 204							
Tyndall (1980)	D: 6.6×10^6							
	B: 0.48	13	20	22	5	17	22	
Chesapeake Bay,	S: 149	49	13	2	6	17	13	5-20
Van Valkenburg et al. (1978)	D: 10×10^6	21	21	10	18	10	20	
	B: 3.97	28	<1	<1	6	56	8	
Chesapeake Bay,	S: 219	59	1	4	4	19	13	>20
Old Plantation Creek,								
Marshall (1980)								
James River Estuary,	S: 74	70	9	1	0	11	9	>15
Marshall (1967)	D: 1.3×10^6							
Narragansett Bay,	S: 75	57	2	0	3	19	19	28-30
Smayda (1957)	D: 6.7×10^6	94				6		

> about 30-fold. The consequences of such an increase may still be profound, of course, and evidence of an apparently linear response to nutrient input confirms the importance of eutrophication as a concern in estuarine management. Since maximum chl *a* levels increase with increasing average values ... it follows that more intense blooms are part of the response to increased nutrient input. These blooms, more than the average standing crops, may have the greatest impact on estuarine water quality"
> (Nixon 1983, page 25-26).

Of course, individual estuaries like the Pamlico are unlikely to experience changes in nutrient loading as great as the range among these estuaries. Figure 6.7 shows that the rates of change of chlorophyll *a* with increasing N and P loading are actually quite small. This suggests that if N or P loading in the Pamlico were to decrease by 50%, the chlorophyll might be expected to decline by only about 10%.

Chlorophyll *a* concentrations in the Pamlico were similar to those in the Neuse River estuary in 1985 and 1986, despite the higher phosphorus levels in the Pamlico (Figure 6.8). The volume-weighted monthly median chlorophyll *a*'s were highest in both estuaries in the summer months and lowest in the winter months. Fifteen to twenty-five μg/liter values were typical during the summer, while the winter concentrations were generally 8 μg/liter or less. Summer chlorophyll *a* values seemed to be slightly higher in the Neuse, although the difference is probably not statistically significant. It should be noted that data from the lower Neuse River, where blue-green algal blooms occur, were not used in these comparisons.

At the time of Hobbie's 1971 Pamlico study, there had been very few studies published of phytoplankton species composition and biomass along the southeastern U.S. coast. Most of the earlier studies were nonquantitative, emphasizing systematics, rather than cell counts, or had used preservation techniques (e.g., formalin solutions) that destroy the microflagellates which make up so much of the total phytoplankton biomass in estuaries. Hobbie was able to compare his results with those from a study by Patten et al. (1963) of the phytoplankton in the York River estuary, and he concluded that the yearly cycles in these two systems were similar. Both rivers had mostly flagellates upriver and more diatoms toward the mouth. Also, both had blooms of the dinoflagellate *Heterocapsa triquetra* (called *Peridinium triquetrum* in the Hobbie [1971] report) in late winter and early spring. Although he gave no details, Hobbie commented that "the rest of the algae species found in the Pamlico River estuary are also found in Chesapeake Bay and farther north" (Hobbie 1971, page 30).

By 1985, quantitative phytoplankton studies had been made for several east coast estuaries. Stanley and Daniel (1985b) compiled the results from these for comparison with their more recent Pamlico survey (Table 6.1). They discussed several similarities between the Pamlico phytoplankton pattern and those from the other estuaries. First, the Pamlico species composition, as reflected in the percentages of species in each algal class, was similar to those for most other estuaries included in the comparison. Generally, diatoms (class Bacillariophyceae) was the most diverse group, followed by the Chlorophyceae (green algae) and Dinophyceae (dinoflagellates). Together, these three groups usually comprised 75% or more of the total species.

Another similarity was that chrysophytes and dinoflagellates appear to be predominant in terms of average cell density and biomass. In addition, the average wet weight biomass and density did not range widely among those estuaries for which estimates were available. Biomass averaged 3.37 mg/liter in the Pamlico, 5.61 mg/liter in the lower Chowan River, 3.48 mg/liter in the lower Neuse River, 3.97 mg/liter in Chesapeake Bay, and 0.48 mg/liter in Currituck Sound.

Finally, the microflagellates have been found to contribute heavily to the total algal biomass in the Pamlico (Stanley and Daniel 1985), in Chesapeake Bay (Van Valkenburg et al. 1978), and probably in most other estuaries. The overall similarities in patterns of algal abundance in estuaries of this region are striking, given the great seasonal and spatial variability within each of the estuaries. In fact, it appears from this comparison that average algal abundance in the estuaries of this region is much less variable than the seasonal and spatial variation within any one of the systems.

CHAPTER 7

Trends in the Sounds' Fisheries

The fish, oyster and game problem of North Carolina demands serious attention and vigorous remedies for their restoration. We hang our heads in shame when Wilmington restauranteurs advertise Norfolk oysters, while the once famous New River oyster has practically disappeared from the market. Instead of robbing our rivers and bays and sounds of their fish and oysters, we should be conserving them, taking plenty and leaving plenty to increase the supply. But like many other matters that have to be solved by our law-making bodies, it is hard to get an application of common sense.

Wilmington Star (1911)

The Albemarle-Pamlico system has supported commercial fisheries for over a century, but as the newspaper editorial excerpt (*at right*) suggests, there were problems for the industry almost from its beginning. This editorial was prompted by a fisheries convention held at Wilmington, NC in December 1911 "to take some action in regard to the great depletion of the fishing industries in the State" (Pratt 1912). Politicians, fisheries "experts" and local fishermen participated in the convention. Many hypotheses were raised to explain the demise of the fisheries, and the discussion was intense — at times heated; but little concrete evidence was available to substantiate most of the claims and counterclaims. However, the convention was followed by some new state regulations intended to "protect and perpetuate" the fishing industry.

This scenario has, of course, been repeated many times since, as North Carolina and other coastal states have struggled to balance diverse, often competing, interests in various schemes to manage the commercial and recreational fisheries in our nations estuaries.

Commercial Fisheries

The Database

The first comprehensive statistical survey for North Carolina was made in 1880, and partial or complete surveys have been made at varying intervals since then. Complete statistics are available for the years: 1880, 1887-1890, 1897, 1902, 1908, 1918, 1923, 1927-1932, 1934, 1936-1940, 1945, and 1950 to date. Monthly landings of each commercial species are reported by county, and annual totals are published in the *North Carolina Landings* series. Chestnut and Davis (1975) compiled the data from the annual reports for the 1880-1973 period in their *Synopsis of Marine Fisheries in North Carolina.* I used the data in that synopsis, along with statistics for more recent years in the *Annual Summary* (1974-1979) or monthly reports (1980-1987) of North Carolina landings published jointly by the North Carolina Division of Marine Fisheries and the U.S. National Marine Fisheries Service (National Marine Fisheries Service 1974-1979; North Carolina Division of Marine Fisheries 1980-1987). Only the data from counties in the N.C. Division of Marine Fisheries Central and Northern Districts were tallied to give the totals reported in this study. These districts include all the coastal counties from Carteret northward (Chestnut and Davis

1975).

The usual limitations of commercial landings statistics should be kept in mind. First, and most important, they measure the quantity of fish landed, which is not necessarily a good indicator of the abundance of the species. One reason for this discrepancy is that fishing "effort" is generally not taken into account. Effort fluctuates in response to changes in demand (i.e., price per pound) for the species, fishery technology, the cost of fishing (e.g., fuel prices), weather, and restrictions imposed by state and federal agencies. Second, the fact that fish are landed in a particular county does not necessarily mean that they were caught in nearby waters. Even worse, no distinction is made in the summary landings reports between fish caught in the sounds and those caught offshore in the Atlantic Ocean. Finally, the older data are somewhat suspect because there probably was underreporting and because different species in the same group were not always tallied separately (Chestnut and Davis 1975).

A good description of the biology of each of the major commercial species and some analyses of trends in the North Carolina commercial landings up through the mid-1940s were made by the following contributors to the *Study of Marine Fisheries in North Carolina* (Taylor 1951): E.W. Roelofs (for edible finfishes), A.F. Chestnut (oysters), C. Broad (shrimp), J.C. Pearson (blue crabs), and W.A. Ellison, Jr. (menhaden). Later reviews of the catch data can be found in reports by Godwin et al. (1971) and the North Carolina Division of Marine Fisheries (1984). David Stick's (1958) book, entitled *The Outer Banks of North Carolina*, contains a chapter on the history of fisheries along the North Carolina coast, with interesting details gleaned from a review of the late nineteenth century printed material and from interviews with residents of the area. The most recent analysis of the status and trends of the Albemarle-Pamlico commercial and recreational fisheries was made by Hogarth et al. (1989).

Edible Finfish

The development of commercial fisheries in the Albemarle-Pamlico region, especially along the Outer Banks, was retarded in the 1800s by the difficulty of delivering seafoods, while they were fresh, from these remote areas to the inland consumers. Consequently, the earliest fisheries were engaged in catching those types of fish which could be preserved for later sale. Thus, the first commercial fisheries up the rivers and sounds concentrated on such species as alewives (herring) and shad, which could be smoked or salted without losing their flavor. These anadromous species were caught in large numbers during their annual spawning migrations with seines operated from the mainland along the shores of Albemarle Sound and the Chowan River. These fisheries, along with whaling, were the limit of commercial fishing along the North Carolina coast until the mid-1800s (Stick 1958; Godwin et al. 1971).

Commercial fishing really began on a large scale in North Carolina following the Civil War, as coastal residents came to recognize the potential income represented by the seafood in the nearby waters. Seine fishing spread, and by the 1870s, shad fisheries were operating around Roanoke Island and in Pamlico Sound. An important mullet fishery developed in Core Sound at about the same time. The catch was salted and taken to Morehead City where it could be shipped out by train (Stick 1958). Pound nets were introduced about 1869 and, along with gill nets, proved so efficient that most of the Albemarle haul-seines gradually went out of business. During the late 1800s and early 1900s, extensive fisheries developed for sturgeon near some of the inlets. But this lasted only a few years before sturgeon became scarce (Stick 1958; Godwin et al. 1971).

Improvements in transportation were very slow in coming to this area, so that around the turn of the century, when statistics began to be kept on the commercial fisheries, the most important ones were still alewives and shad, along with the sound and beach mullet fishery. Between 1887 and 1900, these three accounted for about two-thirds of the total edible finfish harvest (Figures 7.1-7.3). It was not until after World War II that extensive ocean trawling began for species such as flounder (Godwin et al. 1971).

Up until the early 1970s, alewives, or "river herring," continued to be the single most important component of the Albemarle-Pamlico edible finfish harvest, but the fishery has been characterized by tremendous year-to-year variations. For example, the highest landings on record occurred in 1969, but a sharp drop (about

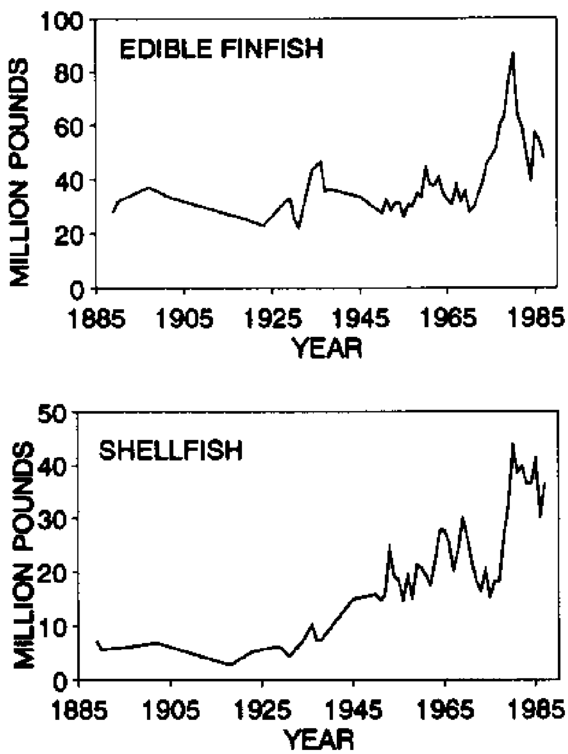

Figure 7.1. *Trends in total edible finfish and shellfish commercial landings in the Albemarle-Pamlico Sound system. Data sources are given in text.*

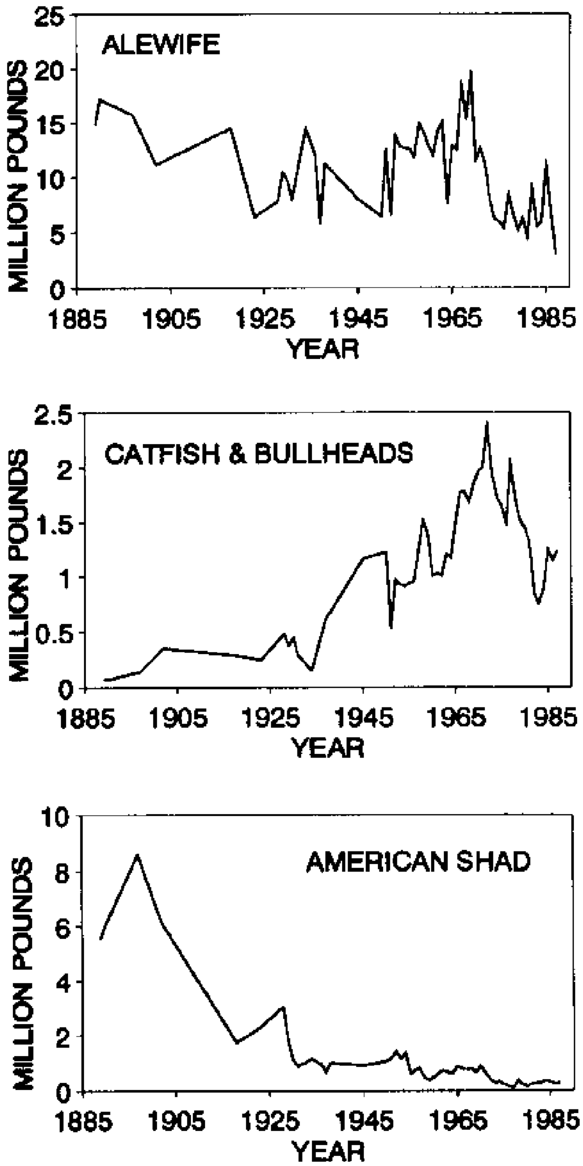

Figure 7.2. *Trends in anadromous species landings in the Albemarle-Pamlico Sound system. "Alewife" includes alewives (Alosa pseudoharengus) and blueback herring (Alosa aestivalis). Another common name for the group is "river herring." Data are from sources given in text.*

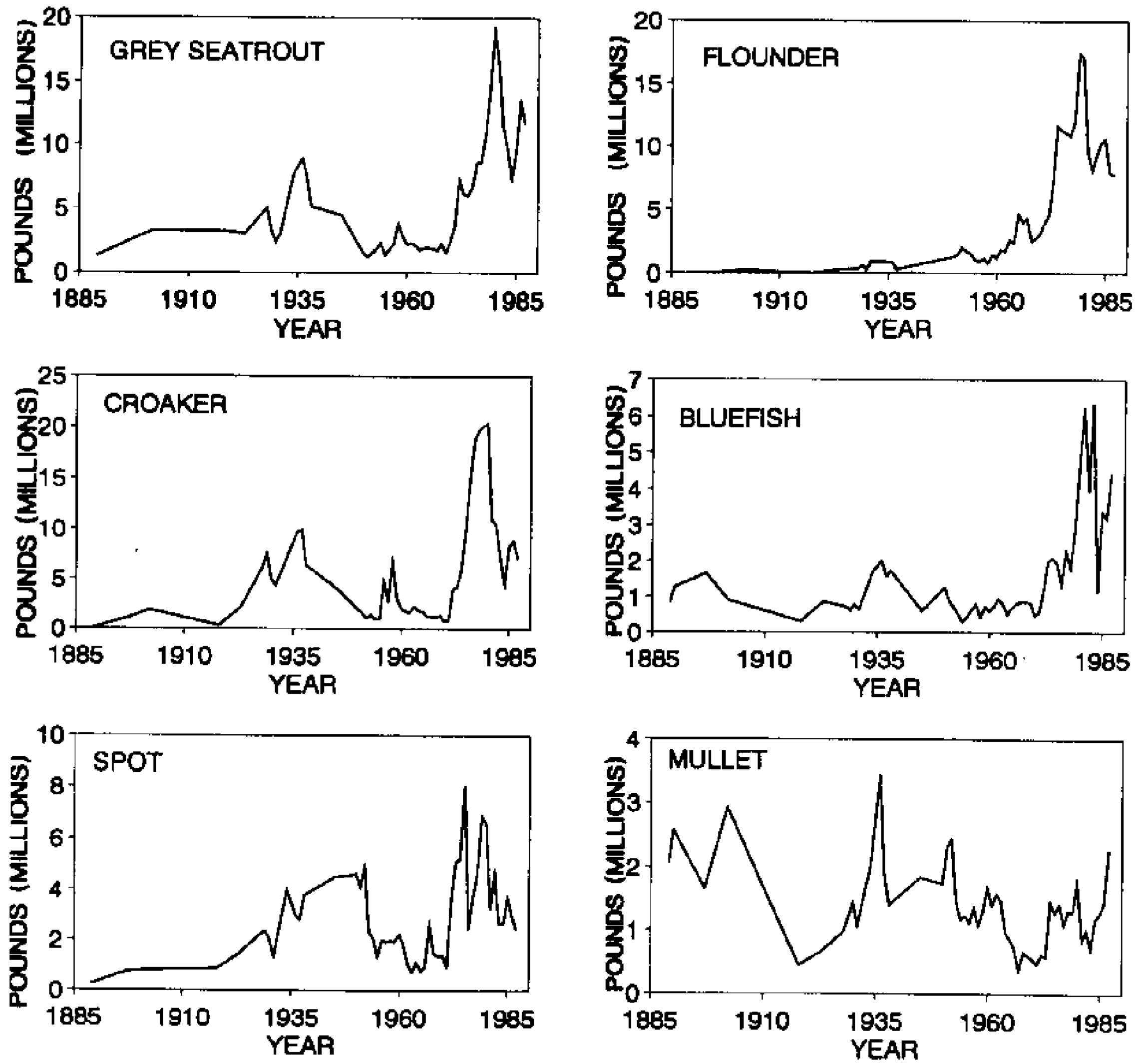

Figure 7.3. *Trends in annual landings of the major types of edible finfishes in the Albemarle-Pamlico Sound system. Data are from sources given in text.*

50%) occurred the following year (Figure 7.2). The fishery declined to around 7 million pounds per year in the mid-1970s and has fluctuated around that level since, although an all-time low was reached in 1987. A Division of Marine Fisheries report in 1984 attributed at least the initial decline to increases in offshore landings by foreign vessels, which apparently led to later agreements with the foreign governments involved to reduce their offshore herring catch (Godwin et al. 1971). However, the report went on to say that "the failure of the fishery to recover since the reduction of foreign fishing is probably related to poor water quality in the Chowan River and Albemarle Sound." No specific hypotheses linking water quality to the fishery were mentioned.

Around 1900, six-to-eight million pounds of shad (primarily American shad) were caught in the Albemarle region each year, but during the first half of this century, the fishery declined precipitously in North Carolina, and in other states along the Atlantic seaboard. Since that time, the fishery has not recovered, and during the last decade has lingered around 0.2 to 0.5 million pounds per year (Figure 7.2). Due to the drastic decline of this species, it was studied extensively in the 1950s and 1960s. Walburg and Nichols (1967) cited the three factors which are so frequently mentioned in discussions of fishery declines: 1) habitat destruction, 2) pollution, and 3) overfishing. Dams on some of the rivers have prevented the shad from reaching their natural spawning grounds and eliminated many miles of nursery areas. Pollution, particularly that which lowers dissolved oxygen levels in the water, are thought to be harmful, particularly for juvenile shad. Paper mills located on the lower reaches of the Chowan, Roanoke and Neuse rivers in North Carolina produce high oxygen-demanding organic wastes (i.e., BOD) which may have contributed significantly to this problem, particularly in the past when there was little treatment to remove the BOD. Finally, Walburg and Nichols (1967) concluded that fishing pressure has been an important factor in shad abundance, but up until at least 1971, there were no laws or regulations in North Carolina which specifically applied to the management of the shad fishery (Godwin et al. 1971).

After an apparent decline in the early 1900s, catches of striped bass rose gradually between 1920 and the mid 1960s (Figure 7.4). Then, beginning in 1967, striped bass were caught by ocean trawlers fishing off the northern Outer Banks. The landings quadrupled, from one-half million pounds to 2 million pounds, and remained high for several years. Then, after a record catch of 2.3 million pounds in 1970, the landings began a decline that was not halted until the early 1980s, but by then the catches were at historic lows of 100-200 thousand pounds.

Besides the increased fishing pressure, there may be other factors involved in the striped bass decline. Manooch and Rulifson (1989) used results from long-term studies of striped bass reproduction in the Roanoke River to develop a hypothesis linking river flow and the survival of young striped bass. Their analyses are based primarily on data collected each year since 1956 by a North Carolina State University researcher, W.W. Hassler. The following description of trends in those data is excerpted from the Manooch and Rulifson report:

> "Although no apparent trends were detected in the total striped bass egg production in the river, the viability rate of those eggs declined drastically beginning in the mid-1970s. Egg viability ranged from 80% to 96% from 1960 through 1974, but declined to 56% in 1975 and ranged from 23% to 74% in the succeeding years through 1987 (Figure 7.5). In the past, the Roanoke/Albemarle striped bass population has been supported by dominant year classes produced at approximately 5-year intervals. A dominant year class, indicated by a juvenile abundance index of at least 10 young-of-year fish per trawl tow, has not been produced since 1976 (Figure 7.5). The estimated number of striped bass in the spawning migration remained within historical levels through the mid-1970s, but in 1980, that number also declined. Since 1981, the estimated spawning population has remained below 100 thousand fish."

The authors of this report go on to discuss several aspects of the life cycle of striped bass which are affected by river flow. They conclude that the construction of six upstream dams on the Roanoke River in the 1950s and 1960s, and the resulting water flow regulation, has had a negative impact on the striped bass. Finally, the report makes recommendations to the U.S. Army Corps of Engineers and the electric

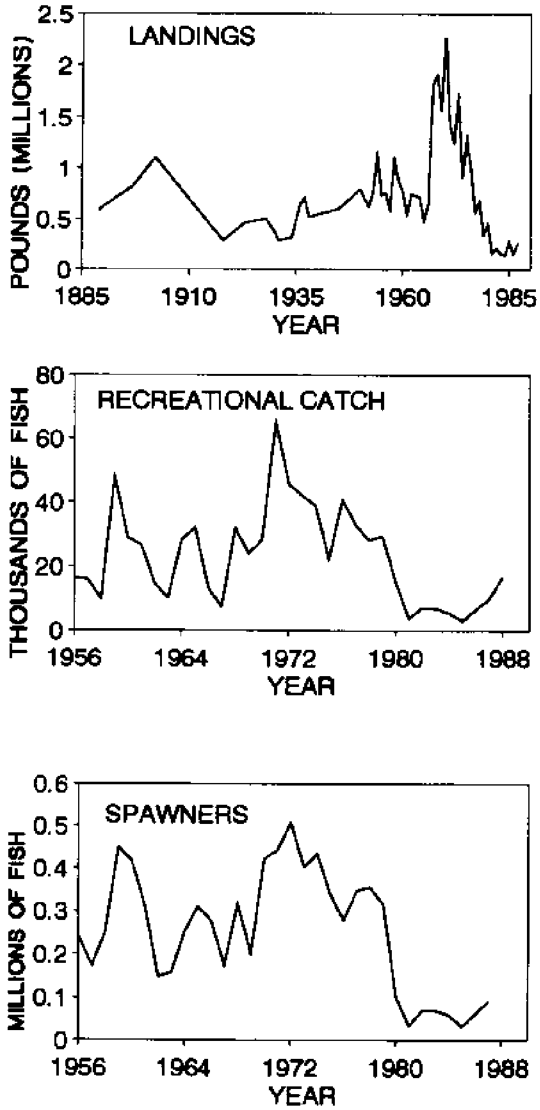

Figure 7.4. *Trends in Albemarle-Pamlico region commercial catch of striped bass, and Roanoke River recreational catch, and numbers of spawning striped bass. Commercial catch data are from sources given in text. Recreational catch and spawning population data are from Mannoch and Rulifson (1989).*

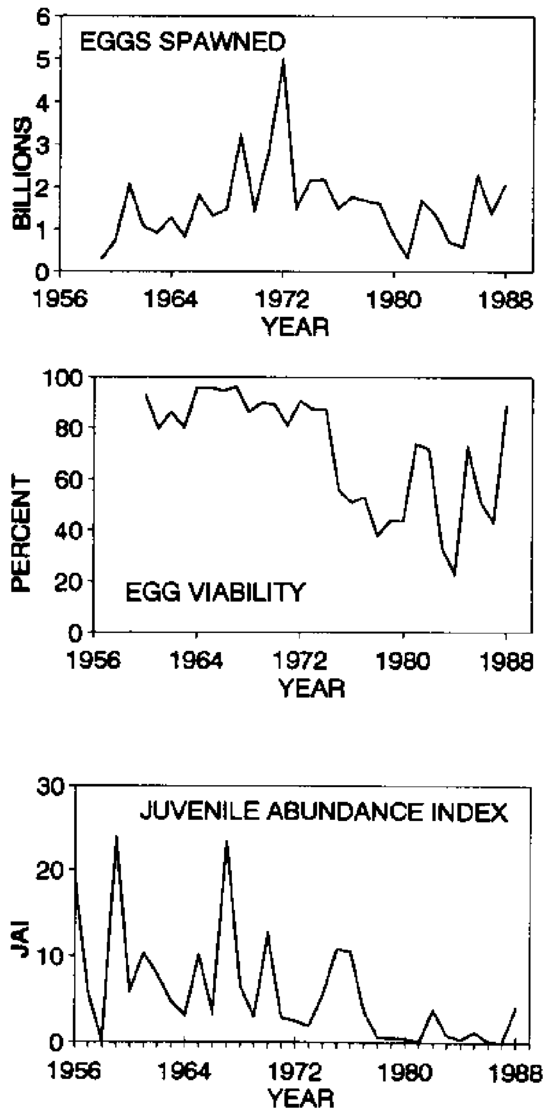

Figure 7.5. *Trends in eggs spawned, egg viability, and juvenile abundance index for the Roanoke River striped bass population. Data are from Mannoch and Rulifson (1989).*

power company, who operate the dams. In order to increase striped bass reproductive success, discharges from the reservoirs should be regulated during the spawning period so that flow in the lower Roanoke is kept as close as possible to the average rate, for that time of year, that existed before the dams were built (Manooch and Rulifson 1989).

The declines in anadromous species landings have been more than offset since 1960 by dramatic increases in catches of five edible marine finfishes: grey seatrout, flounder, croaker, bluefish and spot. Trends in landings of these five have been very similar. They all increased rapidly in the 1970s, peaked around 1980, and have fallen back somewhat since then (Figure 7.3).

The North Carolina Division of Marine Fisheries has monitored juvenile fish abundance within the Albemarle-Pamlico system since 1979. The data are used to generate year-class strengths for four finfish species: Atlantic croaker, spot, southern flounder, and weakfish (grey sea trout). No significant trends for any of these spcies are indicated between 1979 and 1988. Years of relatively high abundance were 1982 and 1986 for southern flounder, 1981 and 1986 for weakfish, and 1983 for Atlantic croaker. The absence of downward trends indicates that any stress on these species (such as overfishing) is not great enough to cause a decline in relative juvenile production. Fluctuations are most likely due to yearly variations in environmental parameters, such as temperature, salinity, weather patterns, and/or currents. These factors all affect larval transport and survival (Hogarth, et al. 1989).

Blue Crabs

There was a minor blue crab fishery in North Carolina as early as the 1880s and 1890s, but the demand was apparently much smaller than the catch, as indicated in this 1887 report by Rathbun:

> "Blue crabs are very abundant on this coast, but they are not much in demand as food. Above Morehead City and Beaufort, the fishermen take them in immense numbers in their drag-nets while fishing for sea-trout, mullet and other fish, and consider them a great annoyance, as it is difficult to remove them from the nets. They kill nearly all that are captured in this way by a blow from a stick carried along for the purpose, and then throw them away, or use them as manure. A few are kept for food, but none are sold, beyond an occasional barrel-full, mostly soft-shelled, which are sent to some of the larger inland towns."

In the 1930s, the crab industry began to grow, partly because of new crabbing methods, but mainly because of an increasing demand for imported crabmeat in northern markets. Pearson (1951) described the close inverse relationship that existed in the 1930s and 1940s between crab harvests in North Carolina and the Chesapeake Bay. In years when the abundance of crabs in Chesapeake Bay was insufficient to satisfy the markets, more North Carolina crabs were harvested and exported to markets in the Chesapeake region. This led to the belief by some North Carolina fishermen that a high natural abundance of crabs in one region was accompanied by a low abundance in the other and vice versa.

The rapid increase in North Carolina crab landings after 1950 (Figure 7.6) was undoubtedly due in part to decreased dependence on the Chesapeake markets. At the same time, more and more processing factories were being built in North Carolina. Prior to 1930, there were no more than half a dozen crab-picking plants in the state. Although a crab meat canning industry had been established in Beaufort in 1943, by 1946, there were still only 16 crab houses in the state, compared to over 100 on Chesapeake Bay (Pearson 1951). However, in the late 1960s, several factories, each employing hundreds of workers, were built along the western shores of Pamlico Sound (Godwin et al. 1971), and by 1984, there were more than 25 processing plants in the area (North Carolina Division of Marine Fisheries 1984).

After reaching historic highs of around 20 million pounds in 1964 the landings declined nearly 50% by 1968, presumably due to mass mortalities of blue crabs that occurred from North Carolina to Florida. An emergency investigation was authorized to find the cause, but by the time the study finally began, the mortalities were over and landings had returned to their former levels. The study showed the presence of several pesticides and disease organisms in blue crabs, but failed to make any conclusions concerning possible causes for the mortalities (Godwin et al. 1971).

After 1969, the crab harvest again declined for several years, to a low of 11 million pounds in 1975. Brief notes included in the *Annual Summaries* of landings during that period included suggestions that since demand was good and prices were high, "only a general scarcity of crabs could account for the decline in landings" (National Marine Fisheries Service 1974). But in a few years, the annual catches began a steep rise again, so that by 1980, they were higher than ever — nearly 35 million pounds. Landings for all years in this decade except one have been above 25 million pounds (Figure 7.6), making crabs the single most important component of the North Carolina commercial fishery, in terms of pounds harvested.

Shrimp

Shrimp, like blue crabs, have shown a remarkable growth in popularity as a choice seafood since the early part of this century. In the 1880s, shrimp were also regarded as "trash," and thrown away by haul-seiners who fished for spot, croaker and butterfish in Pamlico Sound (Earll 1887). But later the demand began to increase gradually. Between 1912 and 1915, Federal Bureau of Fisheries personnel at Beaufort used an otter trawl to collect specimens for their research. North Carolina fishermen adapted and modified this gear and the shrimp fishery began to grow rapidly (Figure 7.6). The landings increased to an all-time peak of 13 million pounds in 1953 (Godwin et al. 1971).

"Destruction of the estuarine habitat of young shrimp" was mentioned by Godwin et al. (1971) as the probable cause of the decline in shrimp harvests after 1953, but no details were given. There has been no obvious trend in the shrimp landings since 1960, but often they have fluctuated widely from one year to the next (Figure 7.6). Such variations are to be expected in a fishery based on an annual crop which is greatly dependent on environmental conditions during the critical growth period (North Carolina Division of Marine Fisheries 1984). Salinity and temperature are two variables widely thought to have great influence on the annual harvests. Although no statistical analysis appears to have been made between these factors and the shrimp landings, they are frequently mentioned in discussions of fluctuations in the annual catches. For example, the low catches in 1978, 1981 and 1984 were attributed to unusually cold winters and heavy spring rains (North Carolina Division of Marine Fisheries 1984; National Marine Fisheries Service 1978, 1981).

Oysters

Before the Civil War, shellfish such as the oyster were more important as an industry in the northeastern states than in the southern states primarily because of better railroad systems, but in the late 1800s, it became an even bigger industry in the north due to a new steam canning

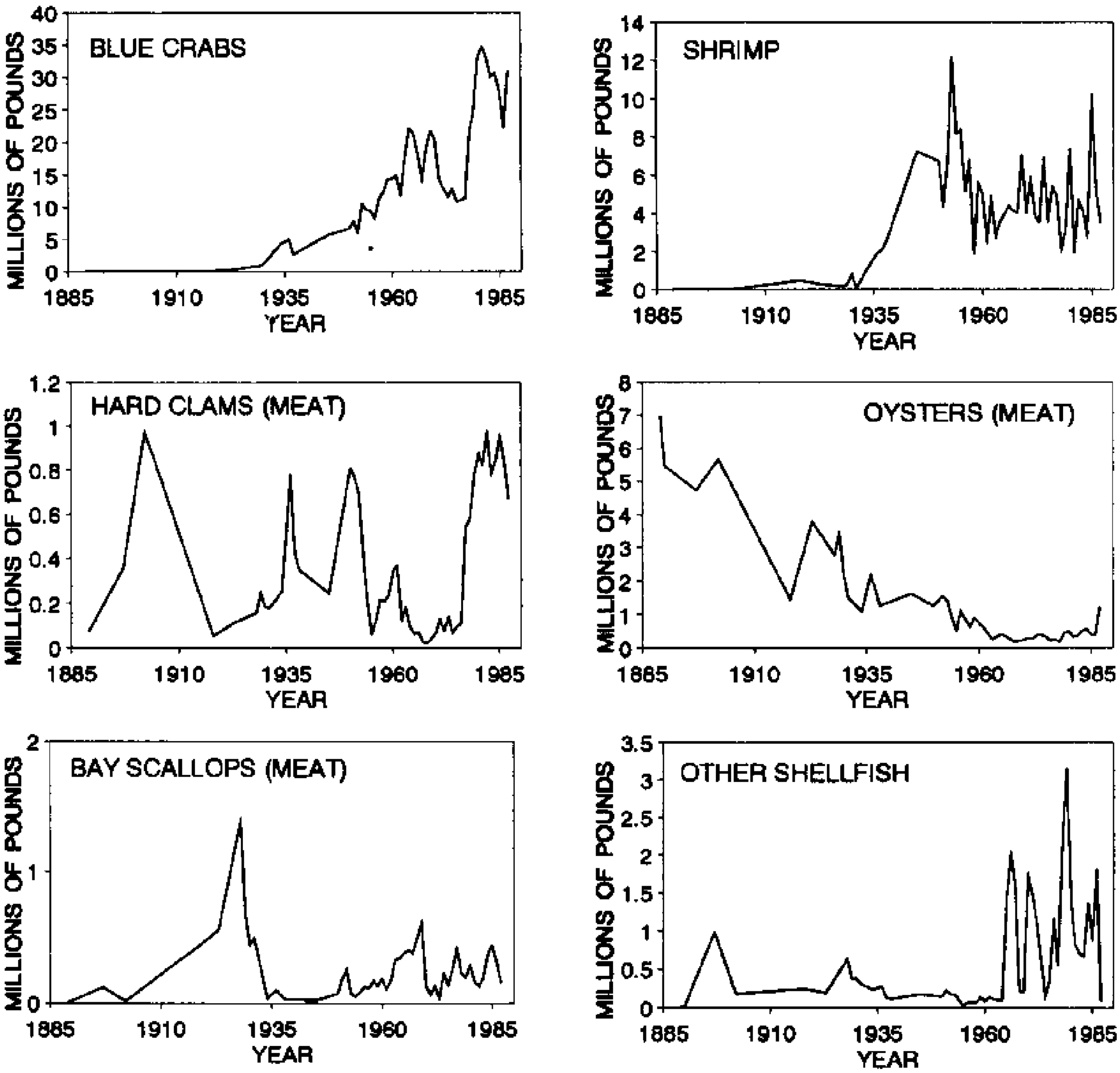

Figure 7.6. *Trends in annual landings of the major types of shellfish in the Albemarle-Pamlico Sound region (N.C. Dividion of Marine Fisheries "Central and Northern Districts"). Shrimp landing pounds are "heads on." Data sources are given in text.*

process for oysters, the expanded railroad systems to carry them to markets, and a booming postwar economy which allowed more people to buy products like oysters. It was not long before the supply was exhausted in estuaries such as the Chesapeake Bay, and new sources of oysters were needed.

Before about 1890, oysters were harvested in North Carolina only to supply local markets. In the 1880s, these markets were located in New Bern, Beaufort, Washington, and other small cities in the region. The most important beds were in the vicinity of Ocracoke Inlet (Winslow 1889). The late 1880s scarcity of oysters in the Chesapeake Bay region had an important impact on oyster production in North Carolina; experienced Chesapeake oystermen and their dredging fleet moved into North Carolina waters. The influx of these oystermen, with their more efficient dredging and tonging methods used in Maryland and Virginia, led to sudden increased production for North Carolina, coinciding with the decline in Maryland (Chestnut 1951). North Carolina oystermen complained bitterly:

> "The people here are poor and depend entirely upon the waters for support. But the Virginia men are down here and have taken entire possession of all the oyster grounds; their boats are much larger than those here, and when these are at work the Virginians will run down upon them and tear them up; and when they try to retaliate it is useless, for they are armed to the teeth with Winchester rifles and some have 36 lb. guns. Unless something is done to stop their dredging, these people will be in a starving condition in twelve months" (Whitehurst 1891).

The exploitation of Pamlico Sound by the northern fleet was brief, for laws were immediately passed shortening the season and prohibiting non-residents from dredging in the State (Thorson 1982). Meanwhile, the local residents adopted the dredging methods that had been introduced, so that when the season was lengthened in 1897, production of oysters greatly increased. The following year new and extensive beds were discovered two miles or more offshore in Pamlico Sound. More oysters were harvested that year (1898) than ever before or since in the history of the industry. The supply seemed inexhaustible, and increased preparations were made for the next year. But when the season opened in 1899, oysters were scarce. What followed was typical of the debates, and uncertainties, that have persisted ever since about the reasons for fluctuations in annual harvests of oysters and other commercial fish and shellfish. Some attributed the scarcity to overfishing, others to severe storms that had occurred in August and October of 1899. Grave (1904) concluded that the reason for the decline was "close and indiscriminate dredging in the past two seasons."

In the 1880s, conservation groups, scientists and concerned citizens were becoming aware that certain fisheries were declining. The American Fisheries Society, founded in 1870, was one of the first groups to call for government action, and in 1872, the federal government created the United States Fish Commission to investigate fishery problems. North Carolina, like other states, was prompted to follow the federal government's example, and in 1887, formed its first shell-fish commission to examine local fishery problems much of the early efforts of the commission were directed at oysters.

Through a series of laws and regulations enacted particularly in the period from 1891 to 1925, the Fisheries Commission attempted to control the growth and development of the shellfish industry in North Carolina. But the agency had only marginal success early on, for at least three reasons, according to Thorson (1982): 1) commercial fisheries are difficult to manage because they are affected by so many variables; 2) there was little known about the ecology of the fishes and shellfishes, and the Fisheries Commission carried out very little scientific research of its own; and 3) the agency was underfunded and understaffed.

Oyster landings in the Albemarle-Pamlico system have trended downward almost continuously since the late 1890s (Figure 7.6), a pattern similar to that for most other oyster producing areas. With one exception, annual catches since 1953 have all been less than 1 million pounds, generally fluctuating between 200 thousand and 500 thousand pounds. The catch in 1987 was 1.2 million pounds, the highest in 34 years.

Trends in the North Carolina oyster harvests up until 1945 were discussed by

Chestnut (1951), who attributed the ups and downs to a variety of causes. These included varying intensity of harvesting effort, changes in laws and regulations, planting of oysters and shells, the Great Depression, and fears about disease outbreaks in other parts of the country which presumably were caused by eating oysters.

Chestnut's discussion is most notable for the one variable not mentioned as a factor in the NC oyster harvest: water quality. In a companion paper summarizing the hydrography of the sounds, by Nelson Marshal, it was surmised that at the time (the late 1940s) "pollution of North Carolina's marine waters is restricted to a few local situations mostly in the vicinity of towns and cities where toilet sewage, and, in a few instances, industrial sewage, is either untreated or inadequately handled" (Marshall 1951, p 58). He cited as evidence for this conclusion the State Board of Health statistics on areas closed to the harvesting of oysters. As of April, 1949, about 27,000 acres were closed. In fact, this is one of only two references to pollution in the volume containing this paper. The other concerns the effect of poor water quality on the shad fishery farther inland in some of the coastal rivers. This lack of emphasis on water quality as an issue affecting the NC fisheries in the 1940s is significant, in light of the fact that this was probably the most thorough synthesis of available knowledge of the estuaries of North Carolina up until that time.

Shellfish Sanitation Programs designed to monitor and regulate oyster and clam harvesting in North Carolina and other producer states have been in existence for about 65 years. During 1924 and 1925, outbreaks of typhoid fever in Chicago, New York, Washington and several other cities were determined to have been caused by sewage-polluted oysters. The resulting publicity paralyzed the oyster industry and threatened the economy of shellfish producing states. Consequently, the industry, along with various state and federal health agencies, began to formulate a plan for sanitary control of the shellfish industry (N.C. State Board of Health 1956). One of the responsibilities of the Shellfish Sanitation Program in each state is to monitor shellfish growing areas for the purpose of determining which areas shall be open to shellfish harvesting. In North Carolina, the first survey was made sometime between 1925 and 1930, and additional surveys have been made periodically since then. In recent years, the most thorough surveys of all the State's shellfishing grounds are made about every three years. Data collected during these surveys provides some information about trends in sewage pollution in various regions. Today, waters are closed to oystermen when tests show there are more than 14 fecal coliform organisms per 100 ml of water, a standard established by the U.S. Food and Drug Administration and the Public Health Service. The original measures set up in the 1920s were 70 fecal coliform bacteria per 100 ml of water (Peters 1989).

North Carolina has about 2 million acres of coastal waters, but portions of these waters are low-salinity and freshwater areas that do not support shellfish. Waters suitable for shellfish comprise 1.42 million acres of this total, according to N.C. Shellfish Sanitation Program estimates. In 1988, 51.7 thousand acres (3.6%) of these waters were closed to shellfishing (North Carolina Division of Health Services 1988). Only about 30% (15 thousand acres) of the total closed area was in the Pamlico-Albemarle region north of Core Sound. Most of the prohibited areas were south of Pamlico Sound, in the Morehead City/Beaufort area and in Brunswick County south of Wilmington.

The data collected since 1971 indicate

that in the Albemarle-Pamlico region closures in some areas are increasing much more rapidly than in others. Figure 7.7 shows that, since 1971, the total amount of prohibited area in the Pamlico-Albemarle area has not changed a great deal. However, the lack of a trend is somewhat misleading, as was pointed out in a recent Shellfish Sanitation Program report. Improvements in some areas have been offset by increases in closures in a few areas with the most rapid population growth, such as Dare County, where the permanent population increased 40% between 1980 and 1986. Dare County increased 65% in prohibited shellfishing acreage during the same period. In Hyde County, the population growth was negligible, but there were agricultural activities that led to an increase of 818 acres closed since 1980 (North Carolina Division of Health Services 1988). Naturally, state officials are worried that such rapid growth in some of these coastal areas could greatly increase the shellfish closures in the future.

In addition to sewage pollution, other factors such as weather, diseases, economics, and management activities play important roles in setting the annual harvest of oysters and clams in the Albemarle-Pamlico region. In some years, the conditionally-approved areas may be closed for several days or weeks following heavy rains, which lead to temporary increases in the fecal coliform counts. Also, parasitic organisms that kill oysters are a serious threat to the fishery. "Dermo" (the infectious protozoan *Dermocystidium marinum = Perkinsus marinus*) is the most prevalent disease, but another, named MSX, showed up in 1988 in some beds (Davis 1989). In the same year, red tides came to North Carolina for the first time in memory, causing all oystering to cease just one week after the season had opened. Finally, like other fisheries, the oyster industry in North Carolina is heavily influenced by economic factors, some originating outside the state. For example, clams are normally more important in the Albemarle-Pamlico region than oysters, but fluctuations in clam prices can have an effect on the oyster harvest. Most North Carolina clams are exported to the northern states. But in years when the supply there is plentiful, clam prices may decline so much that N.C. fishermen go after the oysters with more effort than at other times when clam prices are higher.

Early attempts at oyster rehabilitation by the state began in the 1920s and 1930s, but were later judged to have been unsuccessful due to a lack of knowledge of oyster biology and selection of unsuitable planting areas. In 1947, the state enacted legislation to begin a new program of planting seed oysters and shells by the Division of Commercial Fisheries, which was augmented by University of North Carolina Institute of Fisheries Research studies. An analysis of the oyster program in 1970 showed that despite the efforts to improve the fishery, the landings had continued to decline. In 1970, the return of commercial production to the fishery was

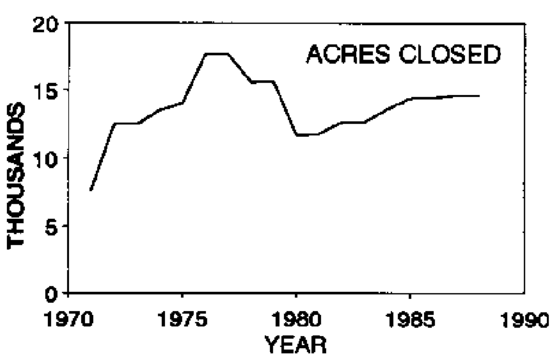

Figure 7.7. *Trends in saline waters closed to shellfishing in the Albemarle-Pamlico region (Pamlico, Craven, Beaufort, Hyde, Dare, and part of Carteret Counties). Data provided by N.C. Division of Health Services, Shellfish Sanitation Program.*

only three-tenths of a bushel of oysters for each bushel of seed oysters and shell planted. Thus, it was concluded that "the present oyster rehabilitation program cannot improve oyster production and probably cannot even prevent further decline in the industry" (Godwin et al. 1971).

Nevertheless, the Oyster Rehabilitation Program has been continued. The quantities of shell planted increased from around 100 thousand bushels in the late 1970s to an average of about 300 thousand bushels per year by the mid-1980s. A 1984 report predicted that the outlook for the oyster fishery was good, based on the Division's strong commitment to a large scale cultch planting and relaying program (North Carolina Division of Marine Fisheries 1984). One Division official recently estimated that this activity increases the oyster harvest by 50% in North Carolina.

Recreational Fisheries

By the mid-1800s, recreational fishing had attained the status of a recognized sport in coastal North Carolina. Most of the fishing was in the rivers, creeks and lakes, but sound waters, and even the ocean, were becoming increasingly attractive. In 1838, the first hotel at Nags Head on the Outer Banks was completed, and by the 1850s, there were cottages belonging to non-residents on the banks. By the Civil War, it was popular for planters and businessmen from eastern North Carolina to take their families to the Outer Banks during the summer months (Johnson et al. 1986; Stick 1958).

But the growth of sport fishing in the region — particularly on the Outer Banks — was slow in the early 20th century, because the area was so isolated and inaccessible. Until well into the century, water transportation was the only way to reach the Outer Banks. And even on the mainland, there were few roads near the sounds. It was 1919 before the first automobile reached the Outer Banks. In the late 1920s, a hard-surfaced road was built on Roanoke Island and a toll bridge was built to connect the island with Nags Head, on Bodie Island. However, there was no bridge linking Roanoke Island with the mainland. About 1930, the state began a road and bridge program that would gradually link the entire region. By 1940, the Albemarle Sound area was crisscrossed with paved roads and linked by bridges, but the Banks remained inaccessible to automobile traffic. After World War II, the state built a paved road between Oregon Inlet and Hatteras Village. Roanoke Island was finally linked to the mainland by a bridge completed in 1963 (Johnson et al. 1986), and later another bridge was opened to traffic between Kitty Hawk and the mainland. Since then, a fourth bridge link has been built, connecting Bodie Island (Nags Head, Kitty Hawk, and Kill Devil Hills) with Hatteras Island to the south. Today, the barrier islands south of Hatteras still have no bridge links to the mainland, but the state operates a regular (car-carrying) ferry schedule between Hatteras and Ocracoke and between Ocracoke and Swan Quarter and Cedar Island.

Accessibility by automobile spurred rapid growth of recreation on the Outer Banks. By 1957, tourism had replaced commercial fishing as the number one industry in Dare County. In 1940, there were no motels in Hatteras Village or on Roanoke Island and only two at Nag's Head. By 1955, there were 15 hotels, 60 motels, and approximately 500 rental cottages in Dare County. During the 1970s, Dare County's growth rate exceeded the state average rate by almost 6 times, and between 1971 and 1986, travel and tourism revenues in the county increased from $11 million to over $340 million, making Dare the states' leader in the tourism industry

(Brower et al. 1989).

Obviously then, there is indirect evidence that recreational fishing in the Albemarle-Pamlico system has grown, especially since World War II. Today, the recreational fisheries are an important component of the overall fishery harvest. In fact, for a number of important species, the recreational harvest probably exceeds the commercial harvest. Some of these species are bluefish, spotted scatroot, red drum, and Spanish mackerel. The North Carolina Division of Marine Fisheries (DMF) began collecting data on recreational landings in 1987.

Unfortunately, however, there is no long-term record of catch, or any direct measure of effort, for the important recreational fish species, with one exception. Beginning in 1956, W.W. Hassler and his colleagues conducted studies to provide long-term information on the status and abundance of striped bass in the Roanoke River and Albemarle Sound. Sport catch and effort data for striped bass in the Roanoke River were tabulated over a 140-mile area from the mouth of the river to the Roanoke Rapids dam. Most years, about 75% of the total striped bass catch was made in the area just below the dam, and about 25% in downstream locations.

The recreational striped bass catch, like the commercial catch, had generally declined in the Roanoke since the early 1970s. The estimated harvest has ranged from a high of 65,399 fish in 1971 to only 3,131 fish in 1985 (Figure 7.4). The catch per unit effort for 1981, 1982 and 1983 were the lowest on record for the 28-year period of record. However, as Hassler and Taylor (1984) noted in their analysis of these data, it should be noted that striped bass size limits and creel limits were changed in 1981. Also, bow netting and fight netting were eliminated in that year. The new and more restrictive regulations were responsible for some part of the decreased catches and catches per unit effort.

In fact, since 1980, the regulations on both commercial and sport harvesting of striped bass have become more and more restrictive, in an effort by the North Carolina Division of Marine Fisheries and the Wildlife Resources Commission to preserve the Roanoke striped bass stock. Manooch and Rulifson (1989) presented a summary table showing a total of 42 regulation changes between 1979 and 1988 concerning striped bass fishing. Included were many new regulations that would tend to decrease the recreational catch, such as increased minimum size limits, creel limits, shortened seasons and the elimination of some gear types. Environmental factors that may be affecting the Roanoke striped bass have been discussed above.

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Appendices

Appendix 1.1. Population of North Carolina and Virginia counties in the Albemarle-Pamlico basin. The total population figures given for the individual sub-basins have been adjusted (i.e., reduced) according to the percentage of the county land areas within the A/P watershed.

County	State	1790	1800	1810	1820	1830	1840	1850
Beaufort	NC	5,462	6,242	7,203	9,850	10,969	12,225	13,816
Bertie	NC	12,606	11,249	11,218	10,805	12,262	12,175	12,851
Camden	NC	4,033	4,191	5,347	6,347	6,733	5,663	6,049
Carteret	NC	3,732	4,399	4,823	5,609	6,597	6,591	6,939
Caswell	NC	10,096	8,701	11,757	13,253	15,185	14,693	15,269
Chowan	NC	5,011	5,132	5,297	6,464	6,697	6,690	6,721
Craven	NC	10,469	10,245	12,676	13,394	13,734	13,438	14,709
Currituck	NC	5,219	6,928	6,985	8,098	7,655	6,073	7,236
Dare	NC							
Durham	NC							
Edgecombe	NC	10,255	10,421	12,423	13,276	14,935	15,708	17,189
Forsyth	NC							11,168
Franklin	NC	7,559	8,529	10,166	9,741	10,665	10,980	11,713
Gates	NC	5,392	5,881	5,965	6,837	7,866	8,161	8,426
Granville	NC	10,982	14,015	15,476	18,222	19,355	18,187	21,249
Greene	NC	6,893	4,128	4,867	4,533	6,413	6,595	6,169
Guilford	NC	7,191	9,442	11,420	14,511	18,737	19,175	19,754
Halifax	NC	13,965	13,945	13,620	17,237	17,739	16,865	16,589
Hertford	NC	5,828	6,701	6,052	7,712	8,537	7,484	8,142
Hyde	NC	4,120	4,829	6,029	4,967	6,184	6,458	7,636
Johnston	NC	5,634	6,301	6,867	9,607	10,938	10,599	13,726
Jones	NC	4,822	4,339	4,968	5,216	5,608	4,945	5,038
Lenoir	NC		4,005	5,572	6,799	7,723	7,605	7,828
Martin	NC	6,080	5,629	5,987	6,320	8,539	7,637	8,307
Nash	NC	7,393	6,975	7,268	8,185	8,490	9,047	10,657
Northampton	NC	9,981	12,353	13,082	13,242	13,391	13,369	13,335
Onslow	NC	5,387	5,623	6,669	7,016	7,814	7,527	8,283
Orange	NC	12,216	16,362	20,135	23,492	23,908	24,356	17,055
Pamlico	NC							
Pasquotank	NC	5,497	5,379	7,674	8,008	8,641	8,514	8,950
Perquimans	NC	5,440	5,708	6,052	6,587	7,419	7,346	7,332
Person	NC		6,402	6,642	9,029	10,027	9,790	10,781

Appendix 1.1. Continued

County	State	1790	1800	1810	1820	1830	1840	1850
Pitt	NC	8,275	9,084	9,169	10,001	12,093	11,806	13,397
Rockingham	NC	6,187	8,277	10,316	11,474	12,935	13,442	14,495
Stokes	NC	8,528	11,026	11,645	14,033	16,196	16,265	9,206
Surry	NC	7,191	9,805	10,366	12,320	14,504	15,079	18,443
Tyrrell	NC	4,744	3,395	3,364	4,319	4,732	4,657	5,113
Vance	NC							
Wake	NC	10,192	13,437	17,086	20,102	20,398	21,118	24,888
Warren	NC	9,297	11,284	11,004	11,158	11,887	12,919	13,912
Washington	NC		2,422	3,464	3,986	4,552	4,525	5,664
Wayne	NC	6,133	6,772	8,687	9,040	10,331	10,891	13,486
Wilson	NC							
Appomattox	VA							9,193
Bedford	VA	10,531	14,125	16,148	19,305	20,246	20,203	24,080
Botetourt	VA	10,524	10,427	13,301	13,589	16,354	11,679	14,908
Brunswick	VA	12,827	16,339	15,411	16,687	15,767	14,346	13,894
Campbell	VA	7,685	9,866	11,001	16,569	20,350	21,030	23,245
Charlotte	VA	10,078	11,912	13,161	13,290	15,252	14,595	13,955
Dinwiddie	VA	13,934	15,374	18,190	20,482	21,901	22,558	25,118
Floyd	VA						4,453	6,458
Franklin	VA	6,842	9,302	10,724	12,017	14,911	15,832	17,430
Greensville	VA	6,362	6,727	6,853	6,858	7,117	6,366	5,639
Halifax	VA	14,722	19,377	22,133	19,060	28,034	25,936	25,962
Henry	VA	8,479	5,259	5,611	5,624	7,100	7,335	8,872
Isle of Wight	VA	9,028	9,342	9,186	10,139	10,517	9,972	9,353
Lunenburg	VA	8,959	10,381	12,265	10,662	11,957	11,055	11,692
Mecklenberg	VA	14,733	17,008	18,453	19,786	20,477	20,724	20,630
Montgomery	VA	13,228	9,044	8,409	8,733	12,306	7,405	8,359
Nottoway	VA		9,401	9,278	9,658	10,130	9,719	8,437
Patrick	VA		4,331	4,695	5,089	7,395	8,032	9,609
Pittsylvania	VA	11,579	12,697	17,172	21,232	26,034	26,398	28,796
Prince George	VA	8,173	7,425	8,050	8,030	8,367	7,175	7,596
Roanoke	VA						5,499	8,477
Southampton	VA	12,864	13,925	13,497	14,170	16,074	14,525	13,521
Surry	VA	6,227	6,535	6,885	6,594	7,109	6,480	5,679
Sussex	VA	10,549	11,062	11,362	11,884	12,720	11,229	9,820
Total		449,134	519,415	579,126	640,248	720,507	711,144	772,244
Chowan River		100,869	116,649	120,885	127,550	135,533	127,832	127,015
Roanoke River		139,952	164,236	184,885	204,916	242,690	244,086	263,537
Albemarle Sound		29,127	31,495	36,252	40,902	43,668	40,853	44,275
Tar-Pamlico R.		53,033	58,541	64,036	71,628	78,866	80,797	89,025
Neuse River		56,851	66,869	80,183	91,520	99,888	99,937	108,301
Pamlico Sound		2,296	2,691	3,340	2,801	3,475	3,620	4,255

Appendix 1.1. Continued

County	State	1860	1870	1880	1890	1900
Beaufort	NC	14,766	13,011	17,474	21,072	26,404
Bertie	NC	14,310	12,950	16,399	19,176	20,538
Camden	NC	5,343	5,361	6,274	5,667	5,474
Carteret	NC	8,186	9,010	9,784	10,825	11,811
Caswell	NC	16,215	16,081	17,825	16,028	15,028
Chowan	NC	6,842	6,450	7,900	9,167	10,258
Craven	NC	16,268	20,516	19,729	20,533	24,160
Currituck	NC	7,415	5,131	6,476	6,747	6,529
Dare	NC		2,778	3,243	3,768	4,757
Durham	NC				18,041	26,233
Edgecombe	NC	17,376	22,970	26,181	24,113	26,591
Forsyth	NC	12,692	13,050	18,070	28,434	35,261
Franklin	NC	14,107	14,134	29,829	21,090	25,116
Gates	NC	8,443	7,724	8,897	10,254	10,413
Granville	NC	23,396	24,831	31,286	24,484	23,263
Greene	NC	7,925	8,687	10,037	10,039	12,038
Guilford	NC	29,056	21,736	23,585	28,052	39,074
Halifax	NC	19,442	29,408	30,300	28,908	30,793
Hertford	NC	9,504	9,273	11,843	13,851	14,294
Hyde	NC	7,732	6,445	7,765	8,903	9,278
Johnston	NC	15,656	16,897	23,461	27,239	32,250
Jones	NC	5,730	5,002	7,491	7,403	8,226
Lenoir	NC	10,220	10,434	15,344	14,879	18,639
Martin	NC	10,195	9,647	13,140	15,221	15,383
Nash	NC	11,687	11,077	17,731	20,707	25,478
Northampton	NC	13,372	14,749	20,032	21,242	21,150
Onslow	NC	8,856	7,569	9,829	10,303	11,940
Orange	NC	16,947	17,507	23,689	14,948	14,690
Pamlico	NC			6,323	7,146	8,045
Pasquotank	NC	8,940	8,131	10,369	10,748	13,660
Perquimans	NC	7,238	7,945	9,466	9,293	10,091
Person	NC	11,221	11,170	13,719	15,151	16,685
Pitt	NC	16,080	17,376	21,794	25,519	30,889
Rockingham	NC	16,746	15,708	21,744	25,363	33,163
Stokes	NC	10,402	11,208	15,353	17,199	19,866
Surry	NC	10,380	11,252	15,302	19,282	25,515
Tyrrell	NC	4,944	4,173	4,545	4,225	4,980
Vance	NC				17,581	16,684
Wake	NC	28,627	35,617	47,939	49,207	54,626
Warren	NC	15,726	17,768	22,619	19,360	19,151
Washington	NC	6,357	6,516	8,928	10,200	10,608
Wayne	NC	14,905	18,144	24,951	26,100	31,356
Wilson	NC	9,720	12,258	16,064	18,644	23,596
Appomattox	VA	8,889	8,950	10,080	9,589	9,662
Bedford	VA	25,068	25,327	31,205	31,213	30,356
Botetourt	VA	11,516	11,329	14,809	14,854	17,161

Appendix 1.1. Continued

County	State	1860	1870	1880	1890	1900
Brunswick	VA	14,809	13,427	16,707	17,245	18,217
Campbell	VA	26,197	28,384	36,250	41,087	23,256
Charlotte	VA	14,471	14,513	16,653	15,077	15,343
Dinwiddie	VA	30,198	30,702	32,870	13,515	15,374
Floyd	VA	8,236	9,824	13,255	14,405	15,388
Franklin	VA	20,098	18,364	25,084	24,985	25,953
Greensville	VA	6,374	6,362	8,407	8,230	9,758
Halifax	VA	26,520	27,828	23,588	34,424	37,197
Henry	VA	12,105	12,303	16,009	18,208	19,265
Isle of Wight	VA	9,977	8,320	10,572	11,313	13,102
Lunenburg	VA	11,983	10,403	11,535	11,372	11,705
Mecklenberg	VA	20,096	21,318	24,610	25,359	26,551
Montgomery	VA	10,617	12,556	16,693	17,742	15,852
Nottoway	VA	8,836	9,291	11,156	11,582	12,366
Patrick	VA	9,359	10,161	12,833	14,147	15,403
Pittsylvania	VA	32,104	31,343	52,589	50,941	46,894
Prince George	VA	8,411	7,820	10,054	7,872	7,752
Roanoke	VA	8,048	9,350	13,105	30,101	15,837
Southampton	VA	12,915	12,285	18,012	20,078	22,848
Surry	VA	6,133	5,585	7,391	8,256	8,469
Sussex	VA	10,175	7,885	10,062	11,100	12,082
Total		846,102	873,324	1,116,259	1,198,807	1,289,775
Chowan River		136,252	129,470	159,100	149,971	161,296
Roanoke River		286,223	295,286	373,454	421,261	407,307
Albemarle Sound		43,965	41,908	51,105	52,768	58,159
Tar-Pamlico R.		100,488	112,434	150,083	152,551	171,460
Neuse River		131,542	149,205	197,858	215,333	254,546
Pamlico Sound		4,344	4,853	8,490	9,699	10,729

Appendix 1.1. Continued

County	State	1910	1920	1930	1940
Beaufort	NC	30,877	31,024	35,026	36,431
Bertie	NC	23,039	23,993	25,844	26,201
Camden	NC	5,640	5,382	5,461	5,440
Carteret	NC	13,776	15,384	16,900	18,284
Caswell	NC	14,858	15,759	18,214	20,032
Chowan	NC	11,303	10,649	11,282	11,572
Craven	NC	25,594	29,048	30,685	31,298
Currituck	NC	7,693	7,268	6,710	6,709
Dare	NC	4,841	5,115	5,202	6,041
Durham	NC	35,276	42,219	67,196	80,244
Edgecombe	NC	32,101	37,995	47,894	49,162
Forsyth	NC	47,311	77,269	111,681	126,475
Franklin	NC	24,692	26,667	29,456	30,382
Gates	NC	10,455	10,537	10,551	10,060
Granville	NC	25,102	26,846	28,723	29,344
Greene	NC	13,083	16,212	18,656	18,548
Guilford	NC	60,497	79,272	133,010	153,916
Halifax	NC	37,646	43,766	53,246	56,512
Hertford	NC	15,436	16,294	17,542	19,352
Hyde	NC	8,840	8,386	8,550	7,860
Johnston	NC	41,401	48,998	57,621	63,798
Jones	NC	8,721	9,912	10,428	10,926
Lenoir	NC	22,769	29,555	35,716	41,211
Martin	NC	17,797	20,838	23,400	26,111
Nash	NC	33,727	41,061	52,782	55,608
Northampton	NC	22,232	23,184	27,161	28,299
Onslow	NC	14,125	14,703	15,289	17,939
Orange	NC	15,064	17,895	21,171	23,072
Pamlico	NC	9,966	9,060	9,299	9,706
Pasquotank	NC	16,693	17,670	19,143	20,568
Perquimans	NC	11,054	11,137	10,668	9,773
Person	NC	17,356	18,973	22,039	25,029
Pitt	NC	36,340	45,569	54,466	61,244
Rockingham	NC	36,442	44,149	51,083	57,898
Stokes	NC	20,151	20,575	22,290	22,656
Surry	NC	29,705	32,464	39,749	41,783
Tyrrell	NC	5,219	4,849	5,164	5,556
Vance	NC	19,425	22,799	27,294	29,961
Wake	NC	63,229	75,155	94,757	109,544
Warren	NC	20,266	21,593	23,364	23,145
Washington	NC	11,062	11,429	11,603	12,323
Wayne	NC	35,698	43,640	53,013	58,328
Wilson	NC	28,269	36,813	44,914	50,219
Appomattox	VA	8,904	9,255	8,402	9,020
Bedford	VA	29,549	30,669	29,091	29,687
Botetourt	VA	17,727	16,557	15,457	16,447

Appendix 1.1. Continued

County	State	1910	1920	1930	1940
Brunswick	VA	19,244	21,025	20,486	19,575
Campbell	VA	23,043	26,716	22,885	26,048
Charlotte	VA	15,785	17,540	16,061	15,861
Dinwiddie	VA	15,442	17,949	18,492	18,166
Floyd	VA	14,092	13,115	11,698	11,967
Franklin	VA	26,480	26,283	24,337	25,864
Greensville	VA	11,890	11,606	13,388	14,866
Halifax	VA	40,044	41,374	41,283	41,271
Henry	VA	18,459	29,238	20,088	26,481
Isle of Wight	VA	14,929	14,433	13,409	13,381
Lunenburg	VA	12,780	15,260	14,058	13,844
Mecklenberg	VA	28,956	31,208	32,622	31,933
Montgomery	VA	17,268	18,595	19,605	21,206
Nottoway	VA	13,462	14,161	14,866	15,556
Patrick	VA	17,195	16,850	15,787	16,613
Pittsylvania	VA	50,709	56,493	61,424	61,697
Prince George	VA	7,848	12,915	10,311	12,226
Roanoke	VA	19,623	22,395	35,289	42,897
Southampton	VA	26,302	27,555	26,870	26,442
Surry	VA	9,715	9,305	7,096	6,193
Sussex	VA	13,664	12,834	12,100	12,485
Total		1,457,881	1,664,437	1,919,348	2,078,286
Chowan River		176,392	187,148	188,454	191,659
Roanoke River		437,061	491,723	525,304	564,084
Albemarle Sound		64,365	64,446	65,729	67,371
Tar-Pamlico R.		198,375	225,741	267,433	281,927
Neuse River		299,103	358,655	438,650	488,704
Pamlico Sound		11,417	10,950	11,222	11,425

Appendix 1.1. Continued

County	State	1950	1960	1970	1980	1987
Beaufort	NC	37,134	36,014	35,980	40,355	45,000
Bertie	NC	26,439	24,350	20,528	21,024	22,000
Camden	NC	5,223	5,598	5,453	5,829	6,000
Carteret	NC	23,059	30,940	31,603	41,092	52,000
Caswell	NC	20,870	19,912	19,055	20,705	22,000
Chowan	NC	12,540	11,729	10,764	12,558	13,000
Craven	NC	48,823	58,733	62,554	71,043	83,000
Currituck	NC	6,201	6,601	6,976	11,089	13,000
Dare	NC	5,405	5,935	6,995	13,377	18,000
Durham	NC	101,639	111,995	132,681	152,785	166,000
Edgecombe	NC	51,634	54,226	54,226	55,988	59,000
Forsyth	NC	146,135	189,428	215,118	243,683	262,000
Franklin	NC	31,341	28,755	26,820	30,055	33,000
Gates	NC	9,555	9,254	8,524	8,875	9,000
Granville	NC	31,793	33,110	32,762	34,043	37,000
Greene	NC	18,024	16,741	14,967	16,117	17,000
Guilford	NC	191,057	246,520	288,645	317,154	328,000
Halifax	NC	58,377	58,956	53,884	55,286	56,000
Hertford	NC	21,453	22,718	23,529	23,368	24,000
Hyde	NC	6,479	5,765	5,571	5,873	8,900
Johnston	NC	65,906	62,936	61,737	70,599	79,000
Jones	NC	11,004	11,005	9,779	9,705	10,000
Lenoir	NC	45,953	55,276	55,204	59,819	60,000
Martin	NC	27,938	27,139	24,730	25,948	26,000
Nash	NC	59,919	61,002	59,122	67,153	72,000
Northampton	NC	28,432	26,811	23,099	22,584	22,000
Onslow	NC	42,047	82,706	103,126	112,784	129,000
Orange	NC	34,435	42,970	57,567	77,055	84,000
Pamlico	NC	9,993	9,850	9,467	10,398	11,000
Pasquotank	NC	24,347	25,630	26,824	28,462	29,000
Perquimans	NC	9,602	9,178	8,351	9,486	11,000
Person	NC	24,361	26,394	25,914	29,164	31,000
Pitt	NC	63,789	69,942	73,900	90,146	99,000
Rockingham	NC	64,816	69,629	72,402	83,426	86,000
Stokes	NC	21,520	22,314	23,782	33,086	36,000
Surry	NC	45,593	48,205	51,415	59,449	62,000
Tyrrell	NC	5,048	4,520	3,806	3,975	4,000
Vance	NC	32,101	32,002	32,691	36,748	39,000
Wake	NC	136,450	169,082	229,006	301,327	371,000
Warren	NC	23,539	19,652	15,810	16,232	17,000
Washington	NC	13,180	13,488	14,038	14,801	14,000
Wayne	NC	64,267	82,059	85,408	97,054	100,000
Wilson	NC	54,506	57,716	57,486	63,132	65,000
Appomattox	VA	8,764	9,148	9,784	11,971	13,000
Bedford	VA	29,627	31,028	26,728	34,927	40,000
Botetourt	VA	15,766	16,715	18,193	23,270	25,000

Appendix 1.1. Continued

County	State	1950	1960	1970	1980	1987
Brunswick	VA	20,136	17,779	16,172	15,632	16,000
Campbell	VA	28,877	32,958	34,248	45,424	49,000
Charlotte	VA	14,057	13,368	12,366	12,266	12,000
Dinwiddie	VA	18,839	22,183	21,668	22,602	22,000
Floyd	VA	11,251	10,462	9,775	11,563	12,000
Franklin	VA	24,560	25,925	28,163	35,740	38,000
Greensville	VA	16,319	16,155	9,604	10,903	11,000
Halifax	VA	41,442	33,637	30,076	30,599	30,000
Henry	VA	31,219	40,335	50,901	57,654	58,000
Isle of Wight	VA	14,906	17,164	18,285	21,603	24,000
Lunenburg	VA	14,116	12,523	11,687	12,124	12,000
Mecklenberg	VA	33,497	31,428	29,426	29,444	30,000
Montgomery	VA	29,780	32,923	47,157	63,516	69,000
Nottoway	VA	15,479	15,141	14,260	14,666	14,000
Patrick	VA	15,642	15,282	15,282	17,647	18,000
Pittsylvania	VA	66,096	58,296	58,789	66,147	68,000
Prince George	VA	19,697	20,270	24,371	25,733	27,000
Roanoke	VA	41,486	61,693	53,817	72,945	78,000
Southampton	VA	26,522	27,195	18,582	18,731	19,000
Surry	VA	6,220	6,220	5,882	6,046	6,000
Sussex	VA	12,785	12,411	11,464	10,874	10,000
Total		2,319,010	2,587,025	2,757,979	3,174,859	3,431,900
Chowan River		202,199	201,504	180,563	185,925	187,500
Roanoke River		591,367	622,439	627,608	728,357	763,470
Albemarle Sound		69,813	70,856	71,045	83,398	90,595
Tar-Pamlico R.		294,867	297,327	290,695	319,906	342,664
Neuse River		568,141	645,904	721,831	858,542	964,740
Pamlico Sound		10,693	10,712	10,909	14,435	18,567

Appendix 3.1. County land areas in five major sub-basins of the Albemarle/Pamlico Estuarine system watershed. "Percent of County Area" is the value used to adjust county totals (for population, agricultural acreages and yields, and all other non-point source variables) to give estimates of the county's contribution to the basin

		County Area (sq. m.)			Land Area in Basin	
County	State	Land	Water	Sum	Square Miles	Percent of C. Area
CHOWAN RIVER						
Bertie	NC	698	33	731	170	24.4
Brunswick	VA	563			518	92.0
Chowan	NC	172	57	230	110	63.9
Dinwiddie	VA	507			466	92.0
Gates	NC	337	7	344	252	74.8
Greensville	VA	300			300	100.0
Hertford	NC	353	6	359	353	100.0
Isle of Wight	VA	319			160	50.0
Lunenburg	VA	432			432	100.0
Mecklenberg	VA	616			105	17.0
Northampton	NC	547		547	357	65.3
Nottoway	VA	316			167	53.0
Prince George	VA	266			136	51.0
Southampton	VA	603			603	100.0
Suffolk City	VA	409			123	30.0
Surry	VA	281			169	60.0
Sussex	VA	491			491	100.0
TOTAL		7,210			4,911	
ROANOKE RIVER						
Appomattox	VA	336			95	28.4
Beaufort	NC	826	135	961	8	1.0
Bedford	VA	747			641	85.8
Bertie	NC	698	33	731	518	74.2
Botetourt	VA	545			71	13.1
Brunswick	VA	563			45	8.0
Campbell	VA	505			427	84.6
Caswell	NC	428		428	383	89.5
Charlotte	VA	477			477	100.0
Floyd	VA	381			31	8.2
Forsyth	NC	419		419	124	29.6
Franklin	VA	683			683	100.0
Granville	NC	544		544	186	34.2
Guilford	NC	657		657	12	1.8
Halifax	NC	742		742	302	40.7
Halifax	VA	816			816	100.0
Henry	VA	382			382	100.0
Martin	NC	462		462	342	74.0
Mecklenburg	VA	616			511	83.0
Montgomery	VA	390			168	43.0

Appendix 3.1. Continued

County	State	County Area (sq. m.) Land	Water	Sum	Land Area in Basin Square Miles	Percent of C. Area
Northampton	NC	547		547	190	34.7
Orange	NC	400		400	7	1.8
Patrick	VA	481			425	88.3
Person	NC	401		401	250	62.3
Pittsylvania	VA	995			995	100.0
Roanoke	VA	251			228	90.8
Rockingham	NC	569		569	476	83.7
Stokes	NC	457		457	386	84.5
Surry	NC	536		536	15	2.8
Vance	NC	269		269	145	53.9
Warren	NC	441		441	171	38.8
Washington	NC	343	85	428	56	16.3
TOTAL		16,907			9,567	
TAR-PAMLICO						
Beaufort	NC	826	135	961	776	93.9
Edgecombe	NC	511		511	511	100.0
Franklin	NC	494		494	426	86.2
Granville	NC	544		544	220	40.4
Halifax	NC	742		742	440	59.3
Hyde	NC	613	736	1,349	159	25.9
Martin	NC	462		462	120	26.0
Nash	NC	544		544	402	73.9
Pamlico	NC	338	228	566	27	8.0
Person	NC	401		401	32	8.0
Pitt	NC	655		655	372	56.8
Vance	NC	269		269	124	46.1
Warren	NC	441		441	270	61.2
Washington	NC	343	85	428	89	25.9
Wilson	NC	375		375	63	16.8
TOTAL		7,558			4,031	
NEUSE RIVER						
Beaufort	NC	826	135	961	43	5.2
Carteret	NC	536	532	1,068	111	20.7
Craven	NC	699	60	759	643	92.0
Durham	NC	299		299	216	72.2
Franklin	NC	494		494	65	13.2
Granville	NC	544		544	138	25.4
Greene	NC	269		269	269	100.0
Johnston	NC	793		793	793	100.0
Jones	NC	468		468	369	78.8
Lenoir	NC	400		400	400	100.0
Nash	NC	544		544	142	26.1
Orange	NC	400		400	209	52.3

Appendix 3.1. Continued

		County Area (sq. m.)			Land Area in Basin	
County	State	Land	Water	Sum	Square Miles	Percent of C. Area
Pamlico	NC	338	228	566	165	48.9
Person	NC	401		401	119	29.7
Pitt	NC	655		655	283	43.2
Wake	NC	859		859	723	84.2
Wayne	NC	557		557	520	93.4
Wilson	NC	375		375	312	83.2
TOTAL		9,457			5,520	
COASTAL						
Albemarle Sound						
Bertie	NC	698	33	731	10	1.4
Camden	NC	239	77	316	239	100.0
Chowan	NC	172	57	230	62	36.1
Currituck	NC	246	177	423	246	100.0
Dare	NC	391	880	1,271	225	57.6
Gates	NC	337	7	344	85	25.2
Hyde	NC	613	736	1,349	128	20.9
Pasquotank	NC	228	65	293	228	100.0
Perquimans	NC	246	89	335	246	100.0
Tyrrell	NC	390	169	559	390	100.0
Washington	NC	343	85	428	198	57.8
TOTAL		3,903			2,057	
Pamlico Sound						
Carteret	NC	536	532	1,068	15	2.8
Dare	NC	391	880	1,271	167	42.4
Hyde	NC	613	736	1,349	326	53.2
Pamlico	NC	338	228	566	145	42.9
TOTAL		1,877			653	

Notes:

a. Area south of 35° latitude (i.e., Core and Bogue Sounds) excluded from Coastal sub-basin

b. Pamlico-Albemarle boundary is a line running east-west through Manteo, N.C.

c. Tar-Pamlico River estuary basin includes all coastal drainage west of the mouth of the estuary. The boundary between Tar-Pamlico and Pamlico Sound (Coastal) corresponds to the eastern edge of USGS cataloging unit 03020104 (see maps in NOAA National Estuarine Atlas for identification of these units (NOAA 1985)).

d. The southern boundary of Pamlico Sound is a line between Hog Island and Swash Inlet (southwest of this line is Core Sound) - Note that NOAA National Estuarine Atlas has this boundary farther southwest, at a line between Marshallberg and Core Banks.

e. The boundary between Chowan River Basin and Albemarle Sound is mouth of Chowan River near Edenton, corresponding to boundary between USGS cataloging units 03010203 and 03010205.

Appendix 3.1 Continued

f. Albemarle Sound corresponds to USGS cataloging unit 03010205.
g. Pamlico Sound corresponds to USGS cataloging unit 03020105.
h. Eastern boundary of Neuse River basin = boundary between USGS cataloging units 03020204 and 03020106.
i. Eastern boundary of Roanoke River basin = boundary between USGS cataloging units 03010107 and 03010205.

Appendix 3.2a. Acres of Land in Farms

	1880	1890	1900	1910	1920
Chowan River	2464949	2365240	2456909	2313583	2097147
Roanoke River	4967022	5068506	5283595	5315135	5076096
Albemarle Sound	666732	600988	549003	1269179	492413
Tar-Pamlico R.	1859608	1824614	1878555	1836714	1650105
Neuse River	2684615	2679392	2677646	2671131	2359364
Pamlico Sound	100326	93821	91390	89467	83981
Total Coastal	767058	694810	640393	1358646	576394
Total	12743253	12632562	12937098	13495209	11759107

	1925	1930	1935	1940	1945
Chowan River	1938618	1928197	2058922	2002257	1945566
Roanoke River	4785518	4901548	5037644	4823633	4678175
Albemarle Sound	431990	446340	445547	457963	448986
Tar-Pamlico R.	1518034	1531564	1800901	1723753	1738125
Neuse River	2153428	2113459	2424232	2282723	2325327
Pamlico Sound	76134	69267	77256	70737	59460
Total Coastal	508124	515607	522803	528700	508447
Total	10903722	10990375	11844502	11361065	11195640

	1950	1954	1959	1964	1969
Chowan River	2036286	1964801	1678576	1505628	1435360
Roanoke River	4741180	4470567	4094046	3787973	3303075
Albemarle Sound	476410	456960	446638	430965	406375
Tar-Pamlico R.	1851346	1775610	1685385	1565672	1497199
Neuse River	2459176	2351979	2133319	1974766	1775826
Pamlico Sound	67413	69741	70407	66588	62602
Total Coastal	543823	526702	517045	497554	468977
Total	11631811	11089659	10108371	9331593	8480437

	1974	1978	1982	1987
Chowan River	1346248	1295363	1214301	1177872
Roanoke River	2841138	2752780	2655110	2575457
Albemarle Sound	405070	447050	469384	455303
Tar-Pamlico R.	1257590	1285257	1202536	1166460
Neuse River	1597807	1592321	1473881	1429665
Pamlico Sound	69163	69634	80138	77734
Total Coastal	474233	516684	549523	533037
Total	7517017	7442404	7095350	6882489

Appendix 3.2b. Acres of Harvested Cropland

	1880	1890	1900	1910	1920
Chowan River	428302		477991		529202
Roanoke River	1045276		1096797		1114829
Albemarle Sound	174349		156921		192890
Tar-Pamlico R.	472982		485395		551255
Neuse River	628622		715262		806725
Pamlico Sound	19829		17983		30145
Total Coastal	194178		174904		223035
Total	2769360		2950347		3225045

	1925	1930	1935	1940	1945
Chowan River	514563	553523	536273	563039	578564
Roanoke River	1068344	1113728	1063036	1156245	1102232
Albemarle Sound	203374	205196	212333	214223	217026
Tar-Pamlico R.	589380	623476	623346	672674	646010
Neuse River	812425	801286	853217	919896	915909
Pamlico Sound	30104	28884	29498	30645	29944
Total Coastal	233478	234080	241831	244868	246970
Total	3218190	3326093	3317703	3556722	3489685

	1950	1954	1959	1964	1969
Chowan River	550976	525518	500087	444313	442954
Roanoke River	1009016	964181	846882	707756	592530
Albemarle Sound	209160	216972	221581	213997	228732
Tar-Pamlico R.	668130	642814	607239	518450	454082
Neuse River	919543	897536	797235	673052	599697
Pamlico Sound	28070	28798	29862	29798	32049
Total Coastal	237231	245770	251442	243795	260781
Total	3384895	3275818	3002886	2587367	2350043

	1974	1978	1982	1987
Chowan River	507897	521092	552496	458237
Roanoke River	638962	658832	693834	412340
Albemarle Sound	271252	320775	348359	313078
Tar-Pamlico R.	537258	592236	618788	529547
Neuse River	715831	782523	808933	665532
Pamlico Sound	38967	44916	55826	49081
Total Coastal	310219	365691	404185	362159
Total	2710167	2920374	3078236	2427815

Appendix 3.2c. Acres of Pastureland. "E" Indicates interpolated (i.e., estimated values)

	1880E	1890E	1900E	1910E	1920E
Chowan River	102597	102597	10259	710259	7102597
Roanoke River	577820	577820	577820	577820	577820
Albemarle Sound	11624	11624	11624	11624	11624
Tar-Pamlico R.	54387	54387	54387	54387	54387
Neuse River	59654	59654	59654	59654	59654
Pamlico Sound	1772	1772	1772	1772	1772
Total Coastal	13397	13397	13397	13397	13397
Total	807855	807855	807855	807855	807855

	1925	1930	1935	1940	1945
Chowan River	102597	119365	99317	105373	111430
Roanoke River	577820	604630	604854	644213	683571
Albemarle Sound	11624	16380	14292	14651	15010
Tar-Pamlico R.	54387	52271	57147	63361	69574
Neuse River	59654	73687	70303	79901	89500
Pamlico Sound	1772	2380	2918	2528	2138
Total Coastal	13397	18760	17210	17179	17148
Total	807855	868713	848831	910027	971223

	1950	1954	1959	1964	1969
Chowan River	134737	158095	125814	122233	114944
Roanoke River	677105	649190	573672	585665	533586
Albemarle Sound	18742	30597	21423	17969	18789
Tar-Pamlico R.	87827	118383	101139	105367	104417
Neuse River	115986	137943	120729	121578	110111
Pamlico Sound	2136	3883	4798	3087	4885
Total Coastal	20878	34480	26221	21056	23674
Total	1036534	1098091	947576	955899	886733

	1974	1978	1982	1987E
Chowan River	154561	102693	103336	103336
Roanoke River	566171	496487	505091	505091
Albemarle Sound	18420	14590	10336	10336
Tar-Pamlico R.	122847	91387	78804	78804
Neuse River	137980	106237	93067	93067
Pamlico Sound	5187	4294	2459	2459
Total Coastal	23607	18884	12794	12794
Total	1005165	815688	793092	793092

Appendix 3.2d. Acres of "other land" in farms; generally the sum of two land categories in the agriculre census reports: 1) Other Cropland (Idle, Crop Failure, etc.) and 2) Other Land - Not Pasture and Range (i.e., house lots, ponds, roads, etc.). Harvested cropland, non-forested pastureland, and forested lands are not included in this landuse category. "E" indicates values estimated by interpolation

	1880E	1890E	1900E	1910E	1920E
Chowan River	300461	300461	300461	300461	300461
Roanoke River	951039	951039	951039	951039	951039
Albemarle Sound	43533	43533	43533	43533	43533
Tar-Pamlico R.	196642	196642	196642	196642	196642
Neuse River	285889	285889	285889	285889	285889
Pamlico Sound	18491	18491	18491	18491	18491
Total	1796054	1796054	1796054	1796054	1796054
Coastal	62024	62024	62024	62024	62024

	1925	1930	1935	1940	1945
Chowan River	300461	255712	247368	170800	137025
Roanoke River	951039	854695	815374	638900	523509
Albemarle Sound	43533	41655	35929	29707	16847
Tar-Pamlico R.	196642	156457	182137	119154	123019
Neuse River	285889	232745	212408	171269	142240
Pamlico Sound	18491	5198	8845	6327	4789
Total	1796054	1546462	1502061	1136157	947429
Coastal	62024	46853	44774	36034	21636

	1950	1954	1959	1964	1969
Chowan River	156098	107639	111867	124987	156938
Roanoke River	622008	475913	508789	492693	465201
Albemarle Sound	36012	18343	23795	42397	44102
Tar-Pamlico R.	146107	113000	139261	173697	226112
Neuse River	194216	156896	189233	216248	301567
Pamlico Sound	7288	5421	6874	7548	5310
Total	1161729	877212	979819	1057569	1199231
Coastal	43299	23764	30669	49945	49413

	1974	1978	1982	1987E
Chowan River	98802	109107	91147	91147
Roanoke River	323489	376364	317112	317112
Albemarle Sound	27570	29476	29325	29325
Tar-Pamlico R.	120576	151130	107819	107819
Neuse River	172335	181918	132203	132203
Pamlico Sound	2751	4866	5013	5013
Total	745523	852860	682619	682619
Coastal	30322	34342	34338	34338

Appendix 3.2e. Acres of Forest. "E" Indicates interpolated (i.e., estimated) values

	1880E	1890E	1900E	1910E	1920E
Chowan River	2063556	2063556	2063556	2063556	2063556
Roanoke River	3375191	3375191	3375191	3375191	3375191
Albemarle Sound	857692	857692	857692	857692	857692
Tar-Pamlico R.	1342457	1342457	1342457	1342457	1342457
Neuse River	1914105	1914105	1914105	1914105	1914105
Pamlico Sound	298843	298843	298843	298843	298843
Total Coastal	1156535	1156535	1156535	1156535	1156535
Total	9851844	9851844	9851844	9851844	9851844
	1925E	**1930E**	**1935E**	**1940**	**1945E**
Chowan River	2063556	2063556	2063556	2063556	2082702
Roanoke River	3375191	3375191	3375191	3375191	3506594
Albemarle Sound	857692	857692	857692	857692	882699
Tar-Pamlico R.	1342457	1342457	1342457	1342457	1389694
Neuse River	1914105	1914105	1914105	1914105	1949371
Pamlico Sound	298843	298843	298843	298843	302491
Total Coastal	1156535	1156535	1156535	1156535	1185190
Total	9851844	9851844	9851844	9851844	10113551
	1950E	**1954E**	**1959**	**1964**	**1969E**
Chowan River	2101848	2120994	2140140	2178594	2208389
Roanoke River	3637997	3769399	3900802	4021611	4008157
Albemarle Sound	907706	932713	957720	890980	865470
Tar-Pamlico R.	1436932	1484169	1531406	1527421	1508630
Neuse River	1984637	2019902	2055168	2060987	2032545
Pamlico Sound	306139	309787	313435	281047	277998
Total Coastal	1213845	1242500	1271155	1172027	1143468
Total	10375258	10636964	10898671	10960640	10901189
	1974	**1978E**	**1982**	**1987**	
Chowan River	2238184	2166571	2094957	2094957	
Roanoke River	3994704	3929931	3865158	3865158	
Albemarle Sound	839960	773923	707887	707887	
Tar-Pamlico R.	1489839	1444911	1399982	1399982	
Neuse River	2004102	1952878	1901654	1901654	
Pamlico Sound	274949	260658	246366	246366	
Total Coastal	1114909	1034581	954253	954253	
Total	10841738	10528871	10216003	10216003	

Appendix 3.2f. Acres of Urban Land. "E" Indicates interpolated (i.e., estimated) values

	1880E	1890E	1900E	1910E	1920E
Chowan River	0	0	0	0	0
Roanoke River	0	0	0	0	0
Albemarle Sound	0	0	0	0	0
Tar-Pamlico R.	0	0	0	0	0
Neuse River	0	0	0	0	0
Pamlico Sound	0	0	0	0	0
Total Coastal	0	0	0	0	0
Total	0	0	0	0	0

	1925E	1930E	1935E	1940	1945E
Chowan River	0	0	0	0	0
Roanoke River	0	2000	5000	10240	16000
Albemarle Sound	0	0	0	0	0
Tar-Pamlico R.	0	1000	2000	3840	3840
Neuse River	0	3000	7000	13440	14000
Pamlico Sound	0	0	0	0	0
Total Coastal	0	0	0	0	0
Total	0	6000	14000	27520	33840

	1949	1954E	1959	1964E	1969
Chowan River	0	960	1920	1920	1920
Roanoke River	21120	40000	62720	70000	76160
Albemarle Sound	0	2000	4480	5000	5760
Tar-Pamlico R.	3840	12000	18560	23000	27520
Neuse River	15360	30000	58880	70000	85120
Pamlico Sound	0	0	0	0	0
Total Coastal	0	2000	4480	5000	5760
Total	40320	84960	146560	169920	196480

	1974E	1978E	1982	1987
Chowan River	3100	4400	5760	7000
Roanoke River	82000	89000	95360	100000
Albemarle Sound	5400	5200	5120	5000
Tar-Pamlico R.	30000	33000	36480	39000
Neuse River	95000	110000	126080	150000
Pamlico Sound	0	0	0	0
Total Coastal	5400	5200	5120	5000
Total	215500	241600	268800	301000

Appendix 3.2g. Acres "Other Land", calculated by subtracting sum of harvested cropland, pasture, other farmland, forested land and urban land from total land area

	1880	1890	1900	1910	1920
Chowan River	248189	245361	198499	167122	147289
Roanoke River	172914	206666	121394	166274	103361
Albemarle Soun	229281	237954	246709	246919	210741
Tar-Pamlico R.	513051	485735	500640	454492	434779
Neuse River	643890	571417	557250	536196	465787
Pamlico Sound	78985	80715	80831	73724	68668
Total	1886310	1827848	1705323	1644727	1430625
Coastal	308266	318669	327540	320643	279409

	1925	1930	1935	1940	1945
Chowan River	161928	150947	196590	240336	233383
Roanoke River	149846	171997	258784	297452	290334
Albemarle Soun	200256	195557	196233	200206	184898
Tar-Pamlico R.	396653	403859	372433	378034	347382
Neuse River	460087	507336	475128	433548	421141
Pamlico Sound	68710	82615	77816	79577	78558
Total	1437481	1512311	1576984	1629153	1555697
Coastal	268966	278172	274049	279783	263456

	1950	1954	1959	1964	1969
Chowan River	199445	229897	263276	271057	217959
Roanoke River	154995	223557	229375	244515	446606
Albemarle Soun	144860	115854	87482	146137	153627
Tar-Pamlico R.	236684	209155	181915	231585	258758
Neuse River	302418	289883	310915	390294	403120
Pamlico Sound	74287	70032	62951	96441	97678
Total	1112689	1138378	1135913	1380029	1577748
Coastal	219147	185886	150433	242578	251305

	1974	1978	1982	1987
Chowan River	140560	239241	295407	479574
Roanoke River	516915	571626	645686	1239652
Albemarle Soun	153877	172516	215454	280180
Tar-Pamlico R.	279001	266857	337647	532188
Neuse River	406912	398604	470223	721907
Pamlico Sound	96065	103186	108256	120014
Total	1593330	1752030	2072673	3373513
Coastal	249942	275702	323709	400194

Appendix 3.3a. Acres of Cotton

	1880	1890	1900	1910	1920
Chowan River	88793	82613	53869	49240	78840
Roanoke River	70835	79539	55479	61555	65597
Albemarle Sound	26617	28447	20792	32705	36445
Tar-Pamlico R.	177765	198983	125439	188211	173018
Neuse River	218561	258981	201940	250561	248026
Pamlico Sound	3398	3313	2682	7096	8029
Total Coastal	30015	31760	23475	39801	44474
Total	585970	651877	460202	589368	609954
	1925	1930	1935	1940	1945
Chowan River	131248	114726	67794	44336	47847
Roanoke River	109380	93829	58149	36765	37771
Albemarle Sound	47896	36180	17723	9772	13366
Tar-Pamlico R.	255884	209202	120769	78933	83691
Neuse River	318540	263494	155061	88517	99389
Pamlico Sound	5413	4925	2281	1925	2505
Total Coastal	53309	41105	20004	11697	15871
Total	868361	722355	421776	260248	284568
	1950	1954	1959	1964	1969
Chowan River	58204	37028	32360	43949	23589
Roanoke River	49128	33119	27138	39170	19172
Albemarle Sound	8633	5018	3523	2666	743
Tar-Pamlico R.	104717	65138	54174	62812	24843
Neuse River	117427	69780	57240	40509	6045
Pamlico Sound	1090	188	166	53	2
Total Coastal	9723	5206	3688	2719	746
Total	339198	210270	174601	189159	74395
	1974	1978	1982	1987	
Chowan River	18717	4085	10861	16782	
Roanoke River	16475	3586	8781	15192	
Albemarle Sound	561	145	2055	5010	
Tar-Pamlico R.	21246	6847	16010	23540	
Neuse River	2018	379	813	3243	
Pamlico Sound	0	0	0	0	
Total Coastal	561	145	2055	5010	
Total	59017	15041	38521	63767	

Appendix 3.3b. Acres of Corn

	1880	1890	1900	1910	1920
Chowan River	250538	223285	247696	227704	218000
Roanoke River	438406	405352	469645	439683	435434
Albemarle Sound	130990	123063	123291	106009	105400
Tar-Pamlico R.	227416	215942	251102	218008	210797
Neuse River	310732	320067	382387	342766	338137
Pamlico Sound	14765	12787	13630	14905	15727
Total Coastal	145755	135850	136921	120914	121126
Total	1372847	1300496	1487751	1349075	1323494

	1925	1930	1935	1940	1945
Chowan River	167531	168164	189603	206713	196529
Roanoke River	360268	369001	397501	406418	356745
Albemarle Sound	82458	63821	96254	99345	96222
Tar-Pamlico R.	174197	180371	243641	263587	238970
Neuse River	270262	284565	364595	375396	383849
Pamlico Sound	12832	13560	17364	17439	14095
Total Coastal	95290	77381	113618	116784	110317
Total	1067548	1079483	1308958	1368898	1286410

	1950	1954	1959	1964	1969
Chowan River	187997	196799	163185	122244	122487
Roanoke River	306596	270905	220661	159497	110830
Albemarle Sound	87304	90849	98910	78459	71830
Tar-Pamlico R.	240621	244216	253064	161115	140425
Neuse River	407992	428207	448365	298669	274622
Pamlico Sound	10146	10953	49696	9166	9139
Total Coastal	97451	101802	148606	87625	80968
Total	1240657	1241929	1233881	829150	729333

	1974	1978	1982	1987
Chowan River	170285	192011	163193	107545
Roanoke River	143423	156428	139871	93580
Albemarle Sound	109513	138304	136877	101746
Tar-Pamlico R.	198971	223166	187257	162888
Neuse River	321874	322969	294461	256582
Pamlico Sound	15845	16373	21956	15731
Total Coastal	125358	154677	158833	117477
Total	959911	1049251	943615	738071

Appendix 3.3d. Acres of Hay

	1880	1890	1900	1910	1920
Chowan River	2833	13146	15560	35712	36812
Roanoke River	35658	67925	77205	98942	125720
Albemarle Sound	1195	2239	2959	5199	14069
Tar-Pamlico R.	1692	6046	9913	19061	27175
Neuse River	1803	9173	14818	32196	37473
Pamlico Sound	50	243	570	1922	2005
Total Coastal	1245	2482	3529	7121	16074
Total	43232	98773	121026	193032	243253

	1925	1930	1935	1940	1945
Chowan River	42355	174382	180169	173971	39437
Roanoke River	131498	144099	191857	258985	264423
Albemarle Sound	15795	21764	31302	23926	7039
Tar-Pamlico R.	31118	48939	103188	104084	64779
Neuse River	36540	41341	108717	120655	124524
Pamlico Sound	1858	1285	4698	1829	1553
Total Coastal	17653	23049	36000	25755	8593
Total	259163	431811	619931	683450	501756

	1950	1954	1959	1964	1969
Chowan River	44746	77269	62507	43164	20645
Roanoke River	276568	322427	251549	177750	136053
Albemarle Sound	2314	9800	3883	4166	1339
Tar-Pamlico R.	59615	81630	60094	33795	13534
Neuse River	88847	71991	41947	23911	15364
Pamlico Sound	614	521	335	254	335
Total Coastal	2928	10321	4218	4421	1674
Total	472704	563638	420315	283040	187270

	1974	1978	1982	1987
Chowan River	20377	23008	25020	26951
Roanoke River	139586	157796	169578	176775
Albemarle Sound	1563	672	532	1158
Tar-Pamlico R.	12603	14954	15743	21013
Neuse River	16947	22813	23082	23218
Pamlico Sound	315	291	126	224
Total Coastal	1877	963	658	1382
Total	191391	219534	234081	249339

Appendix 3.3e. Acres of Oats

	1880	1890	1900	1910	1920
Chowan River	50531	41540	16339	10074	2890
Roanoke River	211057	175138	110177	57683	25164
Albemarle Sound	6741	9866	3047	2568	1075
Tar-Pamlico R.	34304	47167	18338	10882	4061
Neuse River	37656	53483	26171	18823	7683
Pamlico Sound	891	1692	975	1040	849
Total Coastal	7631	11558	4022	3608	1925
Total	341180	328887	175048	101071	41721
	1925	1930	1935	1940	1945
Chowan River	692	972	927	1051	2741
Roanoke River	7004	5936	6253	7785	9634
Albemarle Sound	287	261	333	617	1845
Tar-Pamlico R.	489	621	1375	3903	9228
Neuse River	905	999	1088	2750	8314
Pamlico Sound	586	512	326	498	1705
Total Coastal	873	773	659	1115	3550
Total	9963	9301	10302	16604	33467
	1950	1954	1959	1964	1969
Chowan River	4387	16739	7491	2992	2640
Roanoke River	14892	27036	24038	11205	9715
Albemarle Sound	1433	2269	2260	4219	4951
Tar-Pamlico R.	8873	17977	15659	7068	5974
Neuse River	11921	24547	21480	10790	9673
Pamlico Sound	1592	1508	806	494	917
Total Coastal	3025	3777	3066	4712	5868
Total	43096	90075	71733	36767	33870
	1974	1978	1982	1987	
Chowan River	1176	1168	1016	141	
Roanoke River	6334	8582	4931	2745	
Albemarle Sound	1874	1494	820	1481	
Tar-Pamlico R.	3658	4452	6263	5603	
Neuse River	5270	10582	7812	9408	
Pamlico Sound	161	98	221	52	
Total Coastal	2035	1591	1042	1533	
Total	18474	26376	21063	19430	

Appendix 3.3f. Acres of Peanuts

	1880	1890	1900	1910	1920
Chowan River		43593	107910	156465	139240
Roanoke River		1833	26947	54044	45511
Albemarle Sound		1393	6640	10173	8821
Tar-Pamlico R.		2040	20352	46721	23425
Neuse River		1035	3350	8448	1330
Pamlico Sound		14	36	86	7
Total Coastal		1407	6677	10259	8827
Total		49908	165236	275936	218334

	1925	1930	1935	1940	1945
Chowan River	135647	166071	170454	168057	176011
Roanoke River	55275	61234	67678	68230	75478
Albemarle Sound	15412	19636	19696	19494	23358
Tar-Pamlico R.	31045	45324	53889	56417	69992
Neuse River	2371	7365	8119	6885	10096
Pamlico Sound	40	62	127	63	25
Total Coastal	15452	19699	19823	19557	23383
Total	239789	299693	319964	319145	354959

	1950	1954	1959	1964	1969
Chowan River	160008	119086	120134	121017	127649
Roanoke River	65477	48899	47984	50255	53498
Albemarle Sound	13807	10125	10057	10180	9806
Tar-Pamlico R.	56024	43081	42957	45031	42063
Neuse River	5547	4481	4514	4581	4620
Pamlico Sound	7	5	1	1	1
Total Coastal	13815	10129	10058	10181	9807
Total	300871	225676	225646	231065	237636

	1974	1978	1982	1987
Chowan River	129255	129644	123493	108993
Roanoke River	48493	50655	47186	46577
Albemarle Sound	9378	9523	8610	8817
Tar-Pamlico R.	40863	42655	37836	37615
Neuse River	3826	4363	3794	3265
Pamlico Sound	0	0	0	0
Total Coastal	9378	9523	8610	8817
Total	231816	236840	220919	205267

Appendix 3.3c. Acres of Corn for Silage

	1880	1890	1900	1910	1920
Chowan River					
Roanoke River					
Albemarle Sound					
Tar-Pamlico R.					
Neuse River					
Pamlico Sound					
Total Coastal					
Total					
	1925	**1930**	**1935**	**1940**	**1945**
Chowan River	846	1375		1134	
Roanoke River	3727	4252		3849	
Albemarle Sound	78	113		212	
Tar-Pamlico R.	313	554		494	
Neuse River	763	1524		1557	
Pamlico Sound	0	0		1	
Total Coastal	78	114		213	
Total	5728	7819		7246	
	1950	**1954**	**1959**	**1964**	**1969**
Chowan River	1619	4037	2992	5317	9503
Roanoke River	5462	11634	14497	29016	47205
Albemarle Sound	335	249	359	763	821
Tar-Pamlico R.	746	2264	3130	3962	5999
Neuse River	1252	3911	4270	6951	10717
Pamlico Sound	1	27	239	241	445
Total Coastal	336	276	597	1004	1266
Total	9416	22121	25486	46250	74689
	1974	**1978**	**1982**	**1987**	
Chowan River	7397	6812	5759	5499	
Roanoke River	39163	46626	40682	38316	
Albemarle Sound	908	298	1252	440	
Tar-Pamlico R.	5449	6051	9833	5020	
Neuse River	7822	10292	9743	6200	
Pamlico Sound	538	341	427	161	
Total Coastal	1446	639	1679	600	
Total	61277	70419	67695	55636	

Appendix 3.3g. Acres of Soybeans

	1880	1890	1900	1910	1920
Chowan River					2949
Roanoke River					1397
Albemarle Sound					26374
Tar-Pamlico R.					5339
Neuse River					5120
Pamlico Sound					3169
Total Coastal					29544
Total					44349
	1925	**1930**	**1935**	**1940**	**1945**
Chowan River		8933	12513	18790	90183
Roanoke River		14777	19338	26125	27507
Albemarle Sound		42193	57143	65478	78317
Tar-Pamlico R.		11168	29198	57222	61972
Neuse River		14941	39769	71296	109879
Pamlico Sound		6310	6696	7726	8101
Total Coastal		48503	63840	73205	86418
Total		98322	164657	246637	375958
	1950	**1954**	**1959**	**1964**	**1969**
Chowan River	13709	31156	66400	69531	76568
Roanoke River	6473	12498	26025	31957	49190
Albemarle Sound	73605	85081	84354	104840	118302
Tar-Pamlico R.	41547	56355	81861	111900	121313
Neuse River	23013	26223	52555	114592	109261
Pamlico Sound	10451	12262	14732	18020	18601
Total Coastal	84056	97343	99086	122860	136903
Total	168797	223575	325928	450840	493234
	1974	**1978**	**1982**	**1987**	
Chowan River	123513	136243	174778	167038	
Roanoke River	82613	100538	127257	108167	
Albemarle Sound	136261	157918	182765	138418	
Tar-Pamlico R.	163577	208060	238801	180141	
Neuse River	161536	252510	297729	228632	
Pamlico Sound	20014	24329	30638	24009	
Total Coastal	156275	182247	213403	162427	
Total	687514	879598	1051967	846405	

Appendix 3.3h. Acres of Tobacco

	1880	1890	1900	1910	1920
Chowan River	11165	10042	18886	18399	32064
Roanoke River	108719	106789	156046	170347	216137
Albemarle Sound	5	0	32	19	388
Tar-Pamlico R.	5280	12343	47566	41952	98919
Neuse River	5721	11570	53540	67735	145568
Pamlico Sound	7	0	24	9	239
Total Coastal	13	0	56	27	627
Total	130897	140744	276094	298460	493315

	1925	1930	1935	1940	1945
Chowan River	28068	31943	23787	37470	29090
Roanoke River	186729	216422	140627	196871	155236
Albemarle Sound	366	1429	5683	1143	1070
Tar-Pamlico R.	79407	141815	83896	136672	112652
Neuse River	128633	220503	127651	229675	189140
Pamlico Sound	233	451	12942	798	586
Total Coastal	600	1880	18624	1941	1656
Total	423437	612563	394586	602630	487774

	1950	1954	1959	1964	1969
Chowan River	27470	30982	23479	19120	16168
Roanoke River	146410	160193	109731	98666	86564
Albemarle Sound	1096	5791	842	772	634
Tar-Pamlico R.	103466	115046	77909	69810	63185
Neuse River	171673	190239	126790	114722	98907
Pamlico Sound	580	764	466	423	330
Total Coastal	1676	6555	1307	1194	964
Total	450695	503015	339215	303513	265788

	1974	1978	1982	1987
Chowan River	17403	16973	14782	9613
Roanoke River	86936	92758	73742	47323
Albemarle Sound	469	509	567	344
Tar-Pamlico R.	62357	67683	55613	36753
Neuse River	102543	115434	97329	63606
Pamlico Sound	355	486	281	214
Total Coastal	824	995	849	558
Total	270062	293844	242316	157853

Appendix 3.3i. Acres of Wheat

	1880	1890	1900	1910	1920
Chowan River	24441	16910	17730	11775	18408
Roanoke River	180601	174947	201298	169663	199870
Albemarle Sound	8801	669	159	39	318
Tar-Pamlico R.	26525	17777	12683	6706	8521
Neuse River	54149	46786	33055	15787	23387
Pamlico Sound	717	49	66	31	120
Total Coastal	9519	717	225	70	438
Total	295235	257139	264991	204001	250625
	1925	1930	1935	1940	1945
Chowan River	11540	12778	17797	12062	18395
Roanoke River	117466	141902	147326	104118	103720
Albemarle Sound	124	20	81	77	921
Tar-Pamlico R.	2238	3467	12806	8382	18452
Neuse River	7596	9605	17459	12417	35555
Pamlico Sound	13	0	4	1	159
Total Coastal	137	20	86	78	1081
Total	138977	167773	195473	137057	177202
	1950	1954	1959	1964	1969
Chowan River	13334	14334	21462	12826	12805
Roanoke River	89233	80048	106233	63502	38854
Albemarle Sound	125	1272	8754	19569	19253
Tar-Pamlico R.	8434	13068	28698	17984	18589
Neuse River	16818	21010	43602	33247	22985
Pamlico Sound	66	186	899	2338	1739
Total Coastal	190	1458	9653	21907	20992
Total	128009	129918	209648	149466	114225
	1974	1978	1982	1987	
Chowan River	28469	10058	64870	31886	
Roanoke River	61646	29983	84923	50776	
Albemarle Sound	26694	19426	70587	49483	
Tar-Pamlico R.	28048	14890	91088	65576	
Neuse River	35863	18566	99534	78998	
Pamlico Sound	3673	1656	9425	7765	
Total Coastal	30367	21081	80012	57248	
Total	184393	94578	420426	284483	

Appendix 3.4a. Tons of Nitrogen Sold as Fertilizer

	1880	1890	1900	1910	1920
Chowan River	164	440	1043	2378	3907
Roanoke River	247	664	1573	3587	5894
Albemarle Sound	51	138	327	747	1227
Tar-Pamlico R.	211	568	1346	3069	5044
Neuse River	316	850	2013	4591	7545
Pamlico Sound	5	13	30	68	112
Total Coastal	56	151	357	815	1338
Total	1046	2818	6671	15214	25000

	1925	1930	1935	1940	1945
Chowan River	6663	4575	3417	3759	5230
Roanoke River	9503	8064	6146	6362	9110
Albemarle Sound	1785	1487	994	1491	2037
Tar-Pamlico R.	8275	7143	5038	4910	7015
Neuse River	11837	10248	7567	7229	10575
Pamlico Sound	197	171	225	205	208
Total Coastal	1982	1658	1218	1696	2245
Total	40185	33618	25322	25895	36120

	1950	1954	1959	1964	1969
Chowan River	6016	9076	8390	17134	14248
Roanoke River	10822	14613	14104	30498	25881
Albemarle Sound	2632	3035	3095	7243	8613
Tar-Pamlico R.	8638	10997	10898	24648	19373
Neuse River	13765	16446	16370	36624	33921
Pamlico Sound	252	369	377	718	846
Total Coastal	2883	3403	3473	7961	9459
Total	44075	56490	55194	118829	104851

	1974	1978	1982	1987
Chowan River	18773	19142	17035	11762
Roanoke River	26999	28488	25801	21223
Albemarle Sound	15085	17645	17440	14338
Tar-Pamlico R.	28382	29976	25055	21612
Neuse River	41668	44641	39992	32044
Pamlico Sound	1186	1352	1792	1629
Total Coastal	16271	18996	19232	15967
Total	134068	143222	129097	104595

Appendix 3.4b. Tons of Phosphorus Sold as Fertilizer

	1880	1890	1900	1910	1920
Chowan River	432	930	2293	5228	6639
Roanoke River	601	1294	3192	7280	9245
Albemarle Sound	81	175	432	985	1251
Tar-Pamlico R.	334	720	1776	4049	5142
Neuse River	500	1077	2656	6058	7692
Pamlico Sound	7	16	39	90	114
Total Coastal	89	191	471	1075	1365
Total	2093	4508	11119	25357	32199
	1925	1930	1935	1940	1945
Chowan River	6807	4673	4472	4964	6524
Roanoke River	8961	7604	7424	7756	10490
Albemarle Sound	1094	912	780	1181	1525
Tar-Pamlico R.	5073	4379	3956	3891	5250
Neuse River	7256	6282	5942	5728	7915
Pamlico Sound	121	105	177	162	156
Total Coastal	1215	1017	957	1344	1680
Total	31237	25885	24686	25623	33804
	1950	1954	1959	1964	1969
Chowan River	6970	10442	9505	9480	7858
Roanoke River	11574	14242	13863	14705	13369
Albemarle Sound	1830	1816	1852	2123	2557
Tar-Pamlico R.	6005	6580	6521	7225	5752
Neuse River	9569	9840	9795	10736	10071
Pamlico Sound	175	221	226	211	251
Total Coastal	2005	2036	2078	2334	2808
Total	38073	45095	43721	46443	41827
	1974	1978	1982	1987	
Chowan River	6208	5921	5150	3486	
Roanoke River	9583	9309	7577	6016	
Albemarle Sound	4503	4630	4135	3194	
Tar-Pamlico R.	8473	7866	5941	4814	
Neuse River	12440	11714	9482	7138	
Pamlico Sound	354	355	425	363	
Total Coastal	4858	4985	4560	3557	
Total	43535	41773	34691	26998	

Appendix 3.5a. Bales of Cotton

	1880	1890	1900	1910	1920
Chowan River	36767	17971	24443	23821	44543
Roanoke River	27184	16805	25959	30617	37445
Albemarle Sound	9611	8063	10229	13407	22855
Tar-Pamlico R.	81565	50841	65111	98006	134161
Neuse River	104197	80523	100556	138952	178777
Pamlico Sound	1372	927	711	4175	5699
Total Coastal	10983	8991	10939	17582	28554
Total	260696	175131	227008	308979	423480
	1925	1930	1935	1940	1945
Chowan River	62331	63383	60825	30970	50064
Roanoke River	51462	49041	40055	15141	38501
Albemarle Sound	21117	11432	13047	3860	12446
Tar-Pamlico R.	136751	88898	82523	30050	79109
Neuse River	157801	101745	97313	38709	96914
Pamlico Sound	2047	1910	1650	956	1783
Total Coastal	23164	13342	14697	4816	14229
Total	431509	316410	295412	119687	278818
	1950	1954	1959	1964	1969
Chowan River	33778	27508	28154	46517	15124
Roanoke River	32947	26910	23232	41056	13013
Albemarle Sound	4703	3356	3398	2852	498
Tar-Pamlico R.	73595	50830	44815	63826	16269
Neuse River	84040	60573	47930	35551	3744
Pamlico Sound	311	167	145	51	3
Total Coastal	5014	3523	3543	2904	501
Total	229374	169343	147674	189854	48651
	1974	1978	1982	1987	
Chowan River	17378	4908	14419	18017	
Roanoke River	14924	4351	10608	15148	
Albemarle Sound	578	168	2540	5214	
Tar-Pamlico R.	20060	8293	17559	21897	
Neuse River	1485	264	891	2965	
Pamlico Sound	0	0	0	0	
Total Coastal	578	168	2540	5214	
Total	54424	17985	46017	63241	

Appendix 3.5b. Bushels of Corn

	1880	1890	1900	1910	1920
Chowan River	2580321	1783225	3395444	3029246	3990502
Roanoke River	6390943	5835343	8012306	7472801	7608621
Albemarle Sound	1652943	1310229	1618098	1087012	1682459
Tar-Pamlico R.	2374348	1798219	3051659	2858427	3932986
Neuse River	3208132	2846654	4335728	5076657	6465703
Pamlico Sound	181492	183185	153446	308657	361435
Total Coastal	1834435	1493414	1771543	1395669	2043894
Total	16388179	13756855	20566681	19832800	24041707

	1925	1930	1935	1940	1945
Chowan River	2704572	3372395	3435016	4376747	4513973
Roanoke River	6613568	7331185	6806592	7816335	8130134
Albemarle Sound	1344970	1308184	2008679	2494120	2401026
Tar-Pamlico R.	2698231	3420667	4433788	5611212	5099416
Neuse River	4341535	5559168	6597272	8809941	8084821
Pamlico Sound	232955	275169	286255	405263	263539
Total Coastal	1577925	1583353	2294934	2899383	2664564
Total	17935831	21266768	23567602	29513618	28492908

	1950	1954	1959	1964	1969
Chowan River	6494775	5738784	7201377	6818532	9302938
Roanoke River	9233717	6868661	8226236	10379137	6443124
Albemarle Sound	2587068	3894377	6213976	5801976	6540886
Tar-Pamlico R.	7644613	6476970	11018351	9463849	10394339
Neuse River	12148043	8885929	17251153	19536249	19426012
Pamlico Sound	245768	443082	628593	780275	865986
Total Coastal	2832835	4337460	6842569	6582251	7406871
Total	38353983	32307804	50539686	52780018	52973285

	1974	1978	1982	1987
Chowan River	13611823	15785668	16169257	5953410
Roanoke River	9492475	11544728	12593749	4748006
Albemarle Sound	10990675	13156736	15444793	7250844
Tar-Pamlico R.	14698451	17080824	18367998	9900133
Neuse River	24502563	24347440	29374311	13487117
Pamlico Sound	1489838	1484495	2362476	1319660
Total Coastal	12480513	14641231	17807269	8570504
Total	74785826	83399891	94312584	42659170

Appendix 3.5c. Tons of Corn Silage

	1880	1890	1900	1910	1920
Chowan River					
Roanoke River					
Albemarle Sound					
Tar-Pamlico R.					
Neuse River					
Pamlico Sound					
Total Coastal					
Total					
	1925	**1930**	**1935**	**1940**	**1945**
Chowan River	4075	9046		8955	
Roanoke River	28929	37497		36250	
Albemarle Sound	352	1053		1656	
Tar-Pamlico R.	1589	3387		3601	
Neuse River	4220	7519		10073	
Pamlico Sound	0	2		4	
Total Coastal	352	1056		1661	
Total	39164	58505		60540	
	1950	**1954**	**1959**	**1964**	**1969**
Chowan River	14835	30458	37518	77414	90188
Roanoke River	55945	96680	135691	321846	542101
Albemarle Sound	3163	2629	3825	8318	12606
Tar-Pamlico R.	5790	15341	27109	40897	83793
Neuse River	8334	26652	40248	82221	145385
Pamlico Sound	5	215	2304	3684	6678
Total Coastal	3168	2844	6129	12002	19284
Total	88071	171975	246695	534379	880750
	1974	**1978**	**1982**	**1987**	
Chowan River	98726	91645	90982	45867	
Roanoke River	519828	625478	588957	340074	
Albemarle Sound	12570	4808	21270	5821	
Tar-Pamlico R.	69044	84118	147682	64657	
Neuse River	122850	126897	152093	63289	
Pamlico Sound	6910	4736	6829	1686	
Total Coastal	19480	9544	28099	7507	
Total	829928	937683	1007813	521393	

Appendix 3.5d. Tons of Hay

	1880	1890	1900	1910	1920
Chowan River		12159	17826	30547	71328
Roanoke River		56644	74909	100828	267320
Albemarle Sound		2490	3623	5841	16934
Tar-Pamlico R.		6992	10466	17859	43976
Neuse River		11650	14328	29311	49570
Pamlico Sound		237	589	1495	1810
Total Coastal		2728	4212	7336	18743
Total		90172	121742	185881	450937
	1925	**1930**	**1935**	**1940**	**1945**
Chowan River	29560	86940	93913	122374	66452
Roanoke River	121940	136268	165126	259755	294935
Albemarle Sound	14673	17120	23567	20771	18212
Tar-Pamlico R.	20900	36523	93189	93189	105376
Neuse River	30521	44008	98366	131238	126279
Pamlico Sound	1323	1358	3530	2039	1666
Total Coastal	15995	18478	27097	22810	19878
Total	218917	322217	477690	629366	612920
	1950	**1954**	**1959**	**1964**	**1969**
Chowan River	53629	63377	56810	47990	31850
Roanoke River	331596	301569	310592	214602	210094
Albemarle Sound	2733	7707	3599	4405	2187
Tar-Pamlico R.	60710	71853	57547	27453	19347
Neuse River	93879	66066	45361	30035	26618
Pamlico Sound	666	648	528	460	748
Total Coastal	3399	8354	4126	4865	2934
Total	543214	511219	474435	324946	290844
	1974	**1978**	**1982**	**1987**	
Chowan River	32328	34199	43668	46380	
Roanoke River	225393	242063	271379	288225	
Albemarle Sound	2642	1344	719	1824	
Tar-Pamlico R.	18052	25816	24680	35723	
Neuse River	30047	44757	42492	42408	
Pamlico Sound	685	988	331	395	
Total Coastal	3327	2332	1050	2219	
Total	309148	349167	383269	414954	

Appendix 3.5e. Bushels of Oats

	1880	1890	1900	1910	1920
Chowan River	386707	341517	168181	136679	35084
Roanoke River	1886163	1722809	1123882	678405	301943
Albemarle Sound	67624	90663	35006	34214	21984
Tar-Pamlico R.	305308	381034	191441	150210	70350
Neuse River	298664	389653	243286	268022	111296
Pamlico Sound	11966	24361	20204	22626	24813
Total Coastal	79590	115024	55209	56839	46797
Total	2956432	2950038	1781999	1290156	565470

	1925	1930	1935	1940	1945
Chowan River	11755	17703	12581	23608	65555
Roanoke River	111841	82064	107769	158210	239399
Albemarle Sound	8714	7097	5703	14107	57463
Tar-Pamlico R.	13085	14935	31859	113601	281787
Neuse River	13274	22805	23259	120010	240640
Pamlico Sound	19932	15177	7677	52219	49859
Total Coastal	28645	22275	13379	66327	107322
Total	178600	159782	188846	481756	934704

	1950	1954	1959	1964	1969
Chowan River	131267	310629	279104	127631	151914
Roanoke River	409194	948772	831315	827771	456825
Albemarle Sound	35936	88759	91170	275456	512172
Tar-Pamlico R.	242227	692799	646177	344859	359026
Neuse River	355281	1040658	878348	555153	572605
Pamlico Sound	38041	55422	30892	25327	64176
Total Coastal	73977	144181	122062	300783	576348
Total	1211947	3137038	2757007	2156197	2116718

	1974	1978	1982	1987
Chowan River	63068	55811	47604	15388
Roanoke River	326768	349033	248465	204652
Albemarle Sound	128250	104960	61917	108318
Tar-Pamlico R.	133162	248459	430836	338685
Neuse River	323151	666404	467676	539835
Pamlico Sound	11598	7926	19304	2918
Total Coastal	139848	112885	81221	111236
Total	985997	1432592	1275801	1209796

Apendix 3.5f. Pounds of Peanuts

	1880	1890	1900	1910	1920
Chowan River		868127	3435236	4574972	6289441
Roanoke River		54276	1016758	1746418	1934532
Albemarle Sound		44089	283921	368065	502844
Tar-Pamlico R.		54415	774099	1309557	919211
Neuse River		22242	116395	252704	45432
Pamlico Sound		346	704	2159	189
Total Coastal		44436	284625	370224	503033
Total		1043496	5627113	8253875	9691649

	1925	1930	1935	1940	1945
Chowan River	4852267	7857887	8376692	203529487	209273601
Roanoke River	2222494	2907866	3541864	79771795	94679528
Albemarle Sound	637763	852723	1078052	24067774	30077984
Tar-Pamlico R.	1090946	2058876	2627873	63326752	79864486
Neuse River	57752	195316	200009	4477110	10743407
Pamlico Sound	318	868	2451	3481	16196
Total Coastal	638081	853591	1080504	24071255	30094179
Total	8861541	13873536	15826942	375176399	424655202

	1950	1954	1959	1964	1969
Chowan River	207193638	160840580	204276530	237366038	282612868
Roanoke River	69206953	67487920	72818431	101851750	109207568
Albemarle Sound	15156266	14887880	15074636	22544474	23070871
Tar-Pamlico R.	53779524	51555148	61993240	88275842	79416764
Neuse River	4500102	4382160	5781551	7612521	8283414
Pamlico Sound	2451	5188	462	348	1139
Total Coastal	15158717	14893068	15075098	22544821	23072011
Total	349838934	299158876	359944850	457650973	502592624

	1974	1978	1982	1987
Chowan River	328300754	382115025	341206623	295386590
Roanoke River	111797996	135771715	127294528	124277990
Albemarle Sound	22639236	25969901	25345996	27115030
Tar-Pamlico R.	89562118	146562587	98692782	92197940
Neuse River	6998270	35740533	8806143	7797900
Pamlico Sound	216	0	0	0
Total Coastal	22639452	25969901	25345996	27115030
Total	559298589	726159761	601346070	546775450

Appendix 3.5g. Bushels of Soybeans

	1880	1890	1900	1910	1920
Chowan River					45548
Roanoke River					9584
Albemarle Sound					289658
Tar-Pamlico R.					60596
Neuse River					46004
Pamlico Sound					42957
Total Coastal					332615
Total					494347
	1925	**1930**	**1935**	**1940**	**1945**
Chowan River		34323	46794	52104	116156
Roanoke River		29069	33684	47453	42204
Albemarle Sound		464078	537930	704247	731619
Tar-Pamlico R.		104572	170183	361723	283479
Neuse River		163651	167586	250994	192794
Pamlico Sound		93359	53649	58735	83836
Total Coastal		557437	591579	762982	815455
Total		889052	1009827	1475255	1450089
	1950	**1954**	**1959**	**1964**	**1969**
Chowan River	236466	465038	1487899	1518075	2045949
Roanoke River	112219	275584	602187	704143	1178296
Albemarle Sound	1316943	1693153	1866033	2368258	3475810
Tar-Pamlico R.	666069	1022885	1866714	2617079	3062273
Neuse River	368139	375981	1089787	2778967	2760935
Pamlico Sound	139682	230326	351806	447476	536108
Total Coastal	1456625	1923479	2217839	2815733	4011918
Total	2839518	4062966	7264427	10433998	13059371
	1974	**1978**	**1982**	**1987**	
Chowan River	2929171	3512261	4828998	3557430	
Roanoke River	1723080	2187226	2924666	2196480	
Albemarle Sound	3817049	4533536	5479864	4025264	
Tar-Pamlico R.	3540330	4791327	6084392	4482856	
Neuse River	4245568	5236890	7366296	5374026	
Pamlico Sound	497502	702853	935811	719397	
Total Coastal	4314551	5236389	6415675	4744661	
Total	16752701	20964094	27620026	20355453	

Appendix 3.5h. Pounds of Tobacco

	1880	1890	1900	1910	1920
Chowan River	6269098	4220492	13699551	15876712	16265270
Roanoke River	56073138	42368301	91989652	86590815	93269843
Albemarle Sound	1212	0	18840	10635	238419
Tar-Pamlico R.	2757909	4760453	31558725	26181703	64068964
Neuse River	2892930	4103194	38346601	45289260	98497641
Pamlico Sound	937	0	17187	7991	189562
Total Coastal	2149	0	36027	18626	427981
Total	67995224	55452441	175630555	173957115	272529699

	1925	1930	1935	1940	1945
Chowan River	18424320	22331862	15855802	32123338	31517197
Roanoke River	149172059	135730521	100850413	167347622	159318828
Albemarle Sound	326747	583447	515514	4923557	1048656
Tar-Pamlico R.	46043627	88175177	77013284	126920402	118536048
Neuse River	78861495	145151157	129685318	217519328	199018836
Pamlico Sound	408669	234638	169135	681150	489941
Total Coastal	735416	818085	684649	5604707	1538597
Total	293236916	392206802	324089466	549515398	509929506

	1950	1954	1959	1964	1969
Chowan River	28969457	30041395	29734396	38666393	28165711
Roanoke River	149750682	174097894	140131708	202389028	152428157
Albemarle Sound	836629	1710682	1793296	2562191	1122894
Tar-Pamlico R.	117955288	138088449	110966851	154115035	113444082
Neuse River	179626088	234193810	183553067	260415723	182744698
Pamlico Sound	459520	905577	2329885	3223609	546659
Total Coastal	1296149	2616258	4123181	5785800	1669553
Total	477597644	579037806	468509202	661371979	478452200

	1974	1978	1982	1987
Chowan River	31000432	32375653	26119977	24507040
Roanoke River	158764930	176451829	143526408	94965940
Albemarle Sound	874867	1474616	1212179	818740
Tar-Pamlico R.	104214173	118533466	115527339	76950630
Neuse River	213084360	243842750	204103936	136178610
Pamlico Sound	591018	914422	555941	439710
Total Coastal	1465886	2389038	1768121	1258450
Total	508529780	573592737	491045782	333860670

Appendix 3.5i. Bushels of Wheat

	1880	1890	1900	1910	1920
Chowan River	213776	159017	171018	128393	156907
Roanoke River	1235672	1507691	1367172	1472155	2131825
Albemarle Sound	40203	3956	997	355	3511
Tar-Pamlico R.	169908	120911	68390	53916	94652
Neuse River	306268	304797	179663	133703	191829
Pamlico Sound	5779	436	453	258	1275
Total Coastal	45982	4392	1450	613	4785
Total	1971605	2096808	1787693	1788781	2579998
	1925	1930	1935	1940	1945
Chowan River	140283	258350	194871	158889	336152
Roanoke River	1320564	1400670	1333794	1214630	1681375
Albemarle Sound	1913	294	1092	719	16616
Tar-Pamlico R.	21900	37910	156452	106429	312899
Neuse River	72842	94246	164333	147263	644666
Pamlico Sound	111	0	26	12	2500
Total Coastal	2024	294	1118	731	19116
Total	1557614	1791470	1850568	1627942	2994209
	1950	1954	1959	1964	1969
Chowan River	236507	350810	263400	344314	629845
Roanoke River	1666350	1879971	1390338	1741241	1563666
Albemarle Sound	1402	30130	1402	664247	959675
Tar-Pamlico R.	115155	315693	115555	603972	848491
Neuse River	214187	514359	214437	1162102	1060861
Pamlico Sound	871	5492	871	77881	77890
Total Coastal	2273	35622	2273	742128	1037566
Total	2234472	3096455	1986003	4593758	5140428
	1974	1978	1982	1987	
Chowan River	1055139	324018	1970039	1245035	
Roanoke River	2161180	896969	2460805	2027765	
Albemarle Sound	1033841	477510	2975475	2653952	
Tar-Pamlico R.	998769	514940	3092312	2684475	
Neuse River	1252918	602222	3258152	3156290	
Pamlico Sound	130467	68359	417439	361765	
Total Coastal	1164308	545869	3392914	3015717	
Total	6632315	2884017	14174221	12129282	

Appendix 3.6. Crop Yields, calculated by dividing harvest by harvested acres

	1880	1890	1900	1910	1920
COTTON (lb/acre)	222	134	247	262	347
CORN (bu/acre)	11.9	10.6	13.8	14.7	18.2
HAY (tons dry/acre)		0.91	1.01	0.96	1.85
OATS (bu/acre)	8.7	9.0	10.2	12.8	13.6
PEANUTS (lb/acre)		523	851	748	1110
SILAGE (tons green/acre)					
SOYBEANS (bu/acre)					11.1
TOBACCO (lb/acre	519	394	636	583	552
WHEAT (bu/acre)	6.7	8.2	6.7	8.8	10.3
	1925	1930	1935	1940	1945
COTTON (lb/acre)	248	219	350	230	490
CORN (bu/acre)	16.8	19.7	18.0	21.6	22.1
HAY (tons dry/ac	0.84	0.75	0.77	0.92	1.22
OATS (bu/acre)	17.9	17.2	18.3	29.0	27.9
PEANUTS (lb/acre	924	1157	1237	1176	1196
SILAGE (tons gre	6.84	7.48		8.35	
SOYBEANS (bu/acre)		9.0	6.1	6.0	3.9
TOBACCO (lb/acre	693	640	821	912	1045
WHEAT (bu/acre)	11.2	10.7	9.5	11.9	16.9
	1950	1954	1959	1964	1969
COTTON (lb/acre)	338	403	423	502	327
CORN (bu/acre)	30.9	26.0	41.0	63.7	72.6
HAY (tons dry/ac	1.15	0.91	1.13	1.15	1.55
OATS (bu/acre)	28.1	34.8	38.4	58.6	62.5
PEANUTS (lb/acre	1163	1326	1595	1981	2115
SILAGE (tons gre	9.35	7.77	9.68	11.55	11.79
SOYBEANS (bu/acr	16.8	18.2	22.3	23.1	26.5
TOBACCO (lb/acre	1060	1151	1381	2179	1800
WHEAT (bu/acre)	17.5	23.8	9.5	30.7	45.0
	1974	1978	1982	1987	
COTTON (lb/acre)	461	598	597	496	
CORN (bu/acre)	77.9	79.5	99.9	57.8	
HAY (tons dry/ac	1.62	1.59	1.64	1.66	
OATS (bu/acre)	53.4	54.3	60.6	62.3	
PEANUTS (lb/acre	2413	3066	2722	2664	
SILAGE (tons gre	13.54	13.32	14.89	9.37	
SOYBEANS (bu/acr	24.4	23.8	26.3	24.0	
TOBACCO (lb/acre	1883	1952	2026	2115	
WHEAT (bu/acre)	36.0	30.5	33.7	42.6	

Appendix 3.7. Inventory of farm animals in the Albemarle-Pamlico basin, 1880-1987. "E" Indicates estimated value

Animal/Basin	Year						
SWINE	**1880**	**1890**	**1900**	**1910**	**1920**	**1925**	
Chowan	128474	95284	160128	159701	190076	126936	
Roanoke	240887	181868	214312	186801	205774	142793	
Tar	128483	100476	132863	130133	146759	95302	
Neuse	206163	168896	211271	221324	217187	156127	
Coastal	70346	64681	68712	74988	90263	74451	
Total	774353	611205	787287	772947	850058	595610	
SWINE	**1930**	**1935**	**1940**	**1945**	**1950**	**1954**	
Chowan	138581	151560	91465	204180	229813	267795	
Roanoke	142702	144226	123065	156362	196259	211582	
Tar	93496	109888	91501	127478	159599	169287	
Neuse	143018	156396	157820	197031	245219	267190	
Coastal	71795	61402	46851	74166	78810	85713	
Total	589592	623473	510703	759217	909700	1001569	
SWINE	**1959**	**1964**	**1969**	**1974**	**1978**	**1082**	**1987**
Chowan	237248	166723	232372	216039	223869	210624	213285
Roanoke	222606	133616	149526	133377	165693	189934	155201
Tar	200209	126394	157550	173467	232205	341675	322168
Neuse	308783	204424	315270	326931	431483	426249	533517
Coastal	81507	69896	97314	107910	184609	184621	194190
Total	1050353	701054	952033	957724	1237859	1353104	1418361
TURKEYS	**1880E**	**1890**	**1900**	**1910E**	**1920**	**1925E**	
Chowan	27571	27571	11145	21042	30938	22412	
Roanoke	57405	57405	31996	46429	60863	46799	
Tar	25287	25287	20235	36022	51810	36884	
Neuse	35888	35888	29730	67998	106266	74470	
Coastal	17610	17610	6802	19530	32258	22844	
Total	163760	163760	99909	191021	282134	203409	
TURKEYS	**1930E**	**1935**	**1940**	**1945E**	**1950E**	**1954E**	
Chowan	13887	5361	2174	4501	4148	21517	
Roanoke	32735	18671	3891	6418	9871	28307	
Tar	21958	7032	2218	2687	3616	2318	
Neuse	42674	10879	4133	6265	10925	22537	
Coastal	13429	4014	1852	3713	6789	4056	
Total	124683	45957	16268	23584	35349	78734	

Appendix 3.7. Continued

Animal/Basin				Year			
TURKEYS	**1959E**	**1964E**	**1969**	**1974**	**1978**	**1982**	**1987E**
Chowan	4241	12359	40	30	143	40	68
Roanoke	11245	10567	1153	592	1421	716	1217
Tar	4812	26547	149	1726	384445	210164	357279
Neuse	17850	21765	64491	123743	612472	1006477	1711011
Coastal	12724	17827	2	41	0	0	0
Total	50871	89065	65834	126132	998480	1217397	2069575
SHEEP	**1880**	**1890**	**1900**	**1910**	**1920**	**1925**	
Chowan	22798	25089	19014	14766	7665	5154	
Roanoke	67916	62638	56381	50636	19130	18024	
Tar	21433	18769	14146	8721	4588	2942	
Neuse	32793	25000	16497	8159	3165	2398	
Coastal	10967	12390	12057	15587	10398	5406	
Total	155907	143886	118095	97870	44946	33924	
SHEEP	**1930**	**1935**	**1940**	**1945**	**1950**	**1954**	
Chowan	9446	6328	4114	4063	4011	5518	
Roanoke	34171	18572	12896	10393	12732	9781	
Tar	4108	3755	2561	3039	2570	2665	
Neuse	2954	2306	1731	1868	1879	1899	
Coastal	11856	8128	6177	6596	6114	4861	
Total	62534	39089	27479	25960	27306	24724	
SHEEP	**1959**	**1964**	**1969**	**1974**	**1978**	**1982**	**1987E**
Chowan	5700	4218	3594	1759	2271	3107	3107
Roanoke	12075	7683	6467	5483	4716	4141	4141
Tar	2848	1440	640	325	66	149	149
Neuse	3077	1787	1613	1054	328	865	865
Coastal	3297	2701	1504	657	902	525	525
Total	26997	17829	13819	9277	8283	8786	8786
MULES	**1880**	**1890**	**1900**	**1910**	**1920**	**1925**	
Chowan	5789	5674	7425	9905	26089	25321	
Roanoke	15079	16212	17910	23645	42357	44583	
Tar	8108	8768	10344	14462	26915	30100	
Neuse	11385	13610	19212	25107	45625	46320	
Coastal	2432	2362	2761	2998	6666	8412	
Total	42793	46627	57652	76117	147654	154735	

Appendix 3.7. Continued

Animal/Basin	Year						
MULES	1930	1935	1940	1945	1950	1954	
Chowan	27166	26612	28341	26372	23506	15614	
Roanoke	52385	51350	57500	52596	52634	39347	
Tar	37227	36208	38848	36516	40077	29871	
Neuse	50469	50681	54213	52153	52364	35229	
Coastal	9110	9689	8891	6793	3943	2050	
Total	176356	174540	187793	174430	172523	122112	
MULES	1959E	1964E	1969	1974	1978	1982	1987E
Chowan	10699	5784	869	236	86	9	9
Roanoke	27702	16057	4412	1324	639	134	134
Tar	20817	11763	2709	488	208	42	42
Neuse	24003	12777	1551	217	115	9	9
Coastal	1378	706	33	1	1	0	0
Total	84600	47087	9574	2266	1049	194	194
HORSES	1880	1890	1900	1910	1920	1925	
Chowan	14268	14313	21887	22308	20566	14696	
Roanoke	39600	41003	54279	58562	59183	47397	
Tar	11230	10630	16385	16995	17293	11416	
Neuse	15208	13222	16704	18966	19236	12975	
Coastal	6144	6919	8285	8927	8671	7137	
Total	86450	86087	117541	125757	124949	93620	
HORSES	1930	1935	1940	1945	1950	1954	
Chowan	9728	6094	5881	6539	7043	3820	
Roanoke	35106	23388	23173	24847	25460	17595	
Tar	7127	3960	3552	3889	4628	3507	
Neuse	8016	4776	3801	4649	5895	4485	
Coastal	4642	3546	2997	2721	2440	1222	
Total	64620	41764	39404	42646	45466	30629	
HORSES	1959E	1964E	1969	1974	1978	1982	1987E
Chowan	2751	1683	614	1434	1319	1555	1555
Roanoke	12603	7611	2619	5743	5407	6099	6099
Tar	2607	1707	806	1081	1213	1154	1154
Neuse	3364	2242	1121	2111	2459	2708	2708
Coastal	868	514	160	326	288	324	324
Total	22193	13757	5321	10694	10685	11841	11841

Appendix 3.7. Continued

Animal/Basin			Year				
CHICKENS	1880	1890	1900	1910	1920	1925	
Chowan	248923	546144	358650	460843	637982	682309	
Roanoke	609531	1586447	873689	1129686	1548061	1798914	
Tar	266469	527983	380808	467320	670810	774429	
Neuse	381365	838568	466580	705124	1023862	1148988	
Coastal	186188	345410	220181	250780	342566	377316	
Total	1692476	3844552	2299909	3013754	4223281	4781956	
CHICKENS	1930	1935	1940	1945	1950	1954	
Chowan	558679	1027443	514487	803900	613450	599676	
Roanoke	1395187	1735910	1459248	2012887	1524314	1549422	
Tar	547018	801617	615178	945904	739870	714968	
Neuse	832740	1236875	943859	1580610	1221348	1403687	
Coastal	294548	489637	301936	400469	274271	276655	
Total	3628171	5291482	3834708	5743770	4373252	4544408	
CHICKENS	1959	1964	1969	1974	1978	1982	1987E
Chowan	554888	484730	352610	833484	2917956	3030434	3394087
Roanoke	1625556	1389394	1255258	1955185	3387388	3217716	3603842
Tar	761932	686421	898325	1849359	3136309	5622677	6297399
Neuse	1454549	1497263	1916980	3613219	4859982	3609232	4042340
Coastal	324943	232293	160465	153794	898008	1256528	1407311
Total	4721868	4290100	4583638	8405041	15199643	16736587	18744978
CATTLE	1880	1890	1900	1910	1920	1925	
Chowan	56080	58323	55792	55521	48818	35863	
Roanoke	137294	132757	135085	154527	158300	128233	
Tar	57869	41210	43999	46775	37328	28527	
Neuse	74750	55051	54354	58995	51264	40908	
Coastal	31571	30522	27363	27012	23250	14215	
Total	357565	317863	316593	342830	318961	247747	
CATTLE	1930	1935	1940	1945	1950	1954	
Chowan	28272	39551	34260	48733	49700	74553	
Roanoke	114498	152749	139803	182959	198182	237915	
Tar	21241	39278	30895	43026	40989	59769	
Neuse	32655	56598	42201	57662	54688	81014	
Coastal	12494	18260	13829	18890	14212	21639	
Total	209160	306436	260989	351270	357770	474890	

Appendix 3.7. Continued

Animal/Basin				Year			
CATTLE	1959	1964	1969	1974	1978	1982	1987
Chowan	60893	65341	61632	72546	56612	61250	76640
Roanoke	220866	229758	245456	313944	257871	303281	356357
Tar	52409	59887	51059	63681	46568	44567	53464
Neuse	64633	74388	70624	78839	70559	71233	70686
Coastal	16617	21240	18266	18783	11102	8325	11092
Total	415418	450613	447037	547792	442712	488656	568239
BROILERS	1880E	1890E	1900E	1910E	1920E	1925E	
Chowan	0	6628	13255	19883	26511	29824	
Roanoke	0	44999	89998	134998	179997	202496	
Tar	0	48325	96650	144974	193299	217461	
Neuse	0	119239	238477	357716	476954	536574	
Coastal	0	232	463	695	926	1042	
Total	0	219422	438843	658265	877687	987398	
BROILERS	1930E	1935E	1940E	1945E	1950E	1954E	
Chowan	33138	36452	39766	43080	46394	49045	
Roanoke	224996	247496	269995	292495	314994	332994	
Tar	241624	265786	289949	314111	338273	357603	
Neuse	596193	655812	715432	775051	834670	882366	
Coastal	1158	1273	1389	1505	1621	1713	
Total	1097109	1206820	1316530	1426241	1535952	1623721	
BROILERS	1959E	1964E	1969	1974	1974	1982	1987E
Chowan	52358	55672	58986	405246	2527410	2934388	3667985
Roanoke	355494	377993	400493	417427	2073553	2327470	2909337
Tar	381766	405928	430090	384696	1016318	2745128	3431410
Neuse	941985	1001604	1061223	1382506	1963347	3868738	4835922
Coastal	1829	1945	2061	78521	805238	1217358	1521697
Total	1733432	1843143	1952853	2668395	8385866	13093081	16366351

Appendix 3.8. Annual nitrogen and phosphorus production (kg/year) by farm animals in the Albemarle-Pamlico basin (1880-1987).

Nutrient/Basin	Year						
NITROGEN	1880	1890	1900	1910	1920	1925	
Chowan	6302054	6228903	7108818	7265782	7944822	6071906	
Roanoke	14879492	14540027	15308356	16804815	18221559	15269092	
Tar	6378220	5152520	5951295	6364301	6689057	5437007	
Neuse	8852011	7437139	8092455	9057791	9733398	8145700	
Coastal	3414161	3412757	3257875	3409853	3548036	2776870	
Total	39825938	36771346	39718799	42902541	46136873	37700574	
NITROGEN	1930	1935	1940	1945	1950	1954	
Chowan	5540085	6437336	5155960	7508731	7658501	9177731	
Roanoke	14073506	15969026	14980296	18230935	19444816	21159331	
Tar	4961073	6220553	5471179	6764858	7111455	7869522	
Neuse	7242715	8962816	8043846	9806272	10090225	11276384	
Coastal	2538904	2823247	2188981	2781296	2328735	2720594	
Total	34356283	40412979	35840263	45092092	46633732	52203562	
NITROGEN	1959	1964	1969	1974	1978	1982	1987
Chowan	7635426	6759978	6937741	7830546	8933804	9305266	10797441
Roanoke	19495283	18066928	18379813	22867892	21155313	24296835	27655762
Tar	7355499	6470679	5913871	7317532	8430494	11444897	12622176
Neuse	10226898	9067086	9893474	11685701	14013146	14601000	17430805
Coastal	2336814	2391444	2411419	2597154	3736367	3927342	4420564
Total	47049920	42756116	43536318	52298825	56269125	63575340	72926749
PHOSPHORUS	1880	1890	1900	1910	1920	1925	
Chowan	1687262	1664229	1955084	2151673	2182893	1682618	
Roanoke	3911243	3821383	4039684	4518506	4732874	4022536	
Tar	1714675	1413390	1664164	1858726	1873610	1553401	
Neuse	2433313	2114302	2304296	2730436	2694946	2274100	
Coastal	919114	926708	883378	969992	1012074	797343	
Total	10623434	9818735	10643488	11442435	12418499	10092167	
PHOSPHORUS	1930	1935	1940	1945	1950	1954	
Chowan	1535994	1821381	1359372	2081977	2084575	2531156	
Roanoke	3610253	4160759	3755277	4661720	4824546	5273977	
Tar	1330043	1704605	1433532	1876072	1837216	2039961	
Neuse	1970498	2452351	2153667	2692247	2611209	3000478	
Coastal	727860	777248	579855	756408	658424	773717	
Total	9194633	10770553	9428702	12089393	12570494	14031928	

Appendix 3.8. Continued

Nutrient/Basin	Year						
PHOSPHORUS	1959	1964	1969	1974	1978	1982	1987
Chowan	2117461	1852749	1983687	2200765	2582615	2653854	3024132
Roanoke	4896531	4521467	4624691	5715358	5428682	6191163	6953380
Tar	1964310	1731155	1666269	2089553	2588221	3561435	3877072
Neuse	2811170	2493617	2900085	3464430	4332556	4430399	5403074
Coastal	682272	679787	715638	772850	1188220	1251666	1387302
Total	12884382	11361302	11906450	14246302	16122645	18088517	20647094

Appendix 3.9. Estimated point source loadings, 1880-1986. Assumes 4.6 kg N/person/year and 1.1 kg/person/year in untreated sewage

Basin/Type	1880 NKG/Y	1880 PKG/Y	1890 NKG/Y	1890 PKG/Y	1900 NKG/Y	1900 PKG/Y	1910 NKG/Y	1910 PKG/Y
CHOWAN								
Municipal	0	0	4504	1175	15012	3916	32413	8456
Industrial	0	0	0	0	0	0	0	0
Total	0	0	4504	1175	15012	3916	32413	8456
ROANOKE								
Municipal	0	0	155006	40436	219259	57198	226789	59162
Industrial	0	0	0	0	0	0	0	0
Total	0	0	155006	40436	219259	57198	226789	59162
TAR								
Municipal	0	0	32651	8518	78706	20532	172633	45035
Industrial	0	0	0	0	0	0	0	0
Total	0	0	32651	8518	78706	20532	172633	45035
Neuse								
Municipal	0	0	102336	26696	166709	43489	256645	66951
Industrial	0	0	0	0	0	0	0	0
Total	0	0	102336	26696	166709	43489	256645	66951
COASTAL								
Municipal	0	0	14955	3901	29201	7618	38695	10094
Industrial	0	0	0	0	0	0	0	0
Total	0	0	14955	3901	29201	7618	38695	10094
A/P TOTAL								
Municipal	0	0	309452	80727	508886	132753	727177	189698
Industrial	0	0	0	0	0	0	0	0
Total	0	0	309452	80727	508886	132753	727177	189698

Appendix 3.9. Continued

Basin/Type	1920 NKG/Y	1920 PKG/Y	1930 NKG/Y	1930 PKG/Y	1940 NKG/Y	1940 PKG/Y	1950 NKG/Y	1950 PKG/Y
CHOWAN								
Municipal	40060	10450	58888	15362	110144	20907	143644	39646
Industrial	0	0	10000	2500	95000	25000	190000	50000
Total	40060	10450	68888	17862	205144	45907	333644	89646
ROANOKE								
Municipal	495599	129287	680745	177586	817491	213258	1017891	265537
Industrial	0	0	100000	35000	336000	64000	336000	64000
Total	495599	129287	780745	212586	1153491	277258	1353891	329537
TAR								
Municipal	231679	60438	316969	82688	374602	97722	441187	115092
Industrial	0	0	0	0	0	0	0	0
Total	231679	60438	316969	82688	374602	97722	441187	115092
NEUSE								
Municipal	430714	112360	596170	155523	826471	215601	1066754	278284
Industrial	0	0	0	0	0	0	500	0
Total	430714	112360	596170	155523	826471	215601	1067254	278284
COASTAL								
Municipal	69860	18224	78375	20446	90781	23682	99921	26066
Industrial	0	0	0	0	0	0	0	0
Total	69860	18224	78375	20446	90781	23682	99921	26066
A?P TOTAL								
Municipal	1267913	330760	1731147	451604	2219489	571171	2769397	724625
Industrial	0	0	110000	37500	431000	89600	526500	114600
Total	1267913	330760	1841147	489104	2650489	660771	3295897	839225

Appendix 3.9. Continued

Basin/Type	1960 NKG/Y	1960 PKG/Y	1970 NKG/Y	1970 PKG/Y	1980 NKG/Y	1980 PKG/Y	1986 NKG/Y	1986 PKG/Y
CHOWAN								
Municipal	174653	48969	151543	48363	144798	47731	148919	47895
Industrial	578000	88800	578000	88800	578000	88800	379000	88800
Total	752653	137769	729543	137163	722798	136531	527919	136695
ROANOKE								
Municipal	1189291	312130	826474	294070	844729	304012	857012	310711
Industrial	336000	64000	336000	64600	336000	64600	336000	64600
Total	1525291	376130	1162474	358670	1180729	368612	1193012	375311
TAR								
Municipal	401132	122638	382847	129738	427546	143756	490542	165046
Industrial	0	0	70000	400000	70000	535000	70000	391000
Total	401132	122638	452847	529738	497546	678756	560542	556046
NEUSE								
Municipal	1138754	335908	1067645	358045	1214426	415634	1490523	510820
Industrial	1000	1200	256229	22277	256200	22277	256200	22277
Total	1139754	337108	1323874	380322	1470626	437911	1746723	533097
COASTAL								
Municipal	107166	27956	73921	24141	79966	26155	87584	28610
Industrial	0	0	0	0	0	0	0	0
Total	107166	27956	73921	24141	79966	26155	87584	28610
A/P TOTAL								
Municipal	3010996	847602	2502429	854356	2711465	937289	3074580	1063082
Industrial	915000	154600	1240229	575677	1240200	710677	1041200	566677
Total	3925996	1002202	3742658	1430033	3951665	1647966	4115780	1629759

Appendix 4.1. Pamlico River estuary sampling dates, parameters sampled, and data sources

Abbreviations:

ST	Surface water temperature (°C)
BT	Bottom water temperature (°C)
SS	Surface water salinity (ppt)
BS	Bottom water salinity (ppt)
SDO	Surface water dissolved oxygen (mg/liter)
BDO	Bottom water dissolved oxygen (mg/liter)
PH	Surface water pH
PO4	Surface water orthophosphate phosphorus (uM)
TDP	Surface water total dissolved phosphorus (uM)
TP	Surface water total phosphorus (uM)
PP	Surface water particulate phosphorus (uM)
NO3	Surface water nitrate nitrogen (uM)
NH4	Surface water ammonia nitrogen (uM)
TDN	Surface water total dissolved nitrogen (uM)
TN	Surface water total nitrogen (uM)
PN	Surface water particulate nitrogen (uM)
CHL	Surface water chlorophyll *a* (ug/liter)

Key to data source references (see REFERENCES for full citations):

1. Hobbie (1970b)
2. Hobbie (1970a)
3. Hobbie et al. (1972)
4. Hobbie (1974)
5. Stephenson et al. (1975)
6. ICMR (1976)
7. ICMR (1977)
8. ICMR (1978)
9. ICMR (1980)
10. ICMR (1981)
11. ICMR (1982)
12. ICMR (1983)
13. Stanley (1984b)
14. Stanley (1986a)
15. Stanley (1986b)
16. Stanley (1987)
17. Davis et al. (1978)
18. Kuenzler et al. (1979)

* Note: The data from 23 October 1978 through 14 December 1978 are in none of the reports. I have access to the data however. (D.W.S.)

Appendix 4.1. Continued

Sample Date			Parameters Sampled and Data Sources																
MO	DA	YR	ST	BT	SS	BS	SDO	BDO	PH	PO4	TDP	TP	PP	NO3	NH4	TDN	TN	PN	CHL
3	9	67	2		2														
3	22	67	2		2														
3	23	67								1	1	1							
4	11	67	2		2					1	1	1							
5	9	67	2		2					1	1	1							
6	7	67	2		2														
6	27	67	2		2														
6	28	67								1	1	1							
7	13	67	2		2					1	1	1							
7	31	67	2		2					1	1	1							
8	23	67	2		2					1	1	1							
8	30	67	2		2					1	1	1							
9	20	67	2		2					1	1	1							
10	3	67	2		2														
10	4	67								1	1	1							
10	17	67	2		2					1	1	1							
10	30	67	2		2					1	1	1							
11	14	67	2		2					1	1	1							
11	28	67	2		2					1	1	1							
12	19	67	2		2					1	1	1							
1	8	68	2		2					1	1	1							
1	29	68	2		2					1	1	1							
2	13	68	2		2														
2	14	68								1	1	1							
2	26	68	2		2					1	1	1							
6	29	68	2	2	2	2				1	1	1							
7	16	68	2	2	2	2				1	1	1							
8	6	68	2	2	2	2				1	1	1							
8	23	68	2	2	2	2				1	1	1							
9	6	68	2	2	2	2				1	1	1							
9	30	68	2	2	2	2				1	1	1							
10	11	68	2	2	2	2				1	1	1							
11	21	68	2	2	2	2				1	1	1							
12	13	68	2	2	2	2	2	2											
1	6	69	2	2	2	2	2	2											
2	6	69	2	2	2	2	2	2		1	1	1							
2	26	69	2	2	2	2	2	2		1	1	1							
4	1	69	2	2	2	2	2	2		1	1	1							
4	15	69	2	2	2	2	2	2		1	1	1							
5	2	69	2	2	2	2	2	2		1	1	1							
6	3	69	2	2	2	2	2	2		1	1	1							
6	19	69	2	2	2	2	2	2		1	1	1							
7	4	69	2	2	2	2	2	2		1	1	1							

Appendix 4.1. Continued

Sample Date			Parameters Sampled and Data Sources																
MO	DA	YR	ST	BT	SS	BS	SDO	BDO	PH	PO4	TDP	TP	PP	NO3	NH4	TDN	TN	PN	CHL
8	6	69	3	3	3	3	3	3	3	1	1	1		3	3				
8	21	69	3	3	3	3	3	3	3	1	1	1		3	3				
9	3	69	3	3	3	3	3	3	3	1	1	1		3	3				
9	17	69	3	3	3	3	3	3	3	1	1	1		3	3				
10	1	69	3	3	3	3	3	3	3	1	1	1		3	3				
10	17	69	3	3	3	3	3	3	3	1	1	1		3	3				
10	29	69	3	3	3	3	3	3	3	1	1	1		3	3				
11	12	69	3	3	3	3	3	3	3	1	1	1		3	3				
12	3	69	3	3	3	3	3	3	3	1	1	1		3	3				
12	15	69	3	3	3	3	3	3	3	1	1	1		3	3				
1	2	70	3	3	3	3	3	3	3	1	1	1		3	3				
1	26	70	3	3	3	3	3	3	3	3	3	3		3	3				
2	11	70	3	3	3	3	3	3	3	3	3	3		3	3				
2	25	70	3	3	3	3	3	3	3	3	3	3		3	3				3
3	11	70	3	3	3	3	3	3	3	3	3	3		3	3				3
3	25	70	3	3	3	3	3	3	3	3	3	3		3	3				3
4	8	70	3	3	3	3	3	3	3	3	3	3		3	3				3
4	22	70	3	3	3	3	3	3	3	3	3	3		3	3				3
5	6	70	3	3	3	3	3	3	3	3	3	3		3	3				3
5	20	70	3	3	3	3	3	3	3	3	3	3		3	3	3	3		3
6	3	70	3	3	3	3	3	3	3	3	3	3		3	3	3	3		3
6	17	70	3	3	3	3	3	3	3	3	3	3		3	3	3	3		3
7	1	70	3	3	3	3	3	3	3	3	3	3		3	3	3	3		3
7	15	70	3	3	3	3	3	3	3	3	3	3		3	3	3	3		3
7	30	70	3	3	3	3	3	3	3	3	3	3		3	3	3	3		3
8	12	70	3	3	3	3	3	3	3	3	3	3		3	3	3	3		3
8	26	70	3	3	3	3	3	3	3	3	3	3		3	3	3	3		3
9	10	70	3	3	3	3	3	3	3	3	3	3		3	3	3	3		3
9	23	70	3	3	3	3	3	3	3	3	3	3		3	3	3	3		3
10	7	70	3	3	3	3	3	3	3	3	3	3		3	3	3	3		3
10	22	70	3	3	3	3	3	3	3	3	3	3		3	3	3	3		3
11	4	70	3	3	3	3	3	3	3	3	3	3		3	3	3	3		3
11	19	70	3	3	3	3	3	3	3	3	3	3		3	3	3	3		3
12	3	70	3	3	3	3	3	3	3	3	3	3		3	3	3	3		3
12	17	70	3	3	3	3	3	3	3	3	3	3		3	3	3	3		3
12	30	70	3	3	3	3	3	3	3	3	3	3		3	3	3	3		3
1	14	70	3	3	3	3	3	3	3	3	3	3		3	3	3	3		3
2	5	71	3	3	3	3	3	3	3	3	3	3		3	3	3	3		3
2	18	71	3	3	3	3	3	3	3	3	3	3		3	3	3	3		3
3	5	71	3	3	3	3	3	3	3	3	3	3		3	3	3	3		3
3	31	71	3	3	3	3	3	3	3	3	3	3		3	3	3	3		3
4	16	71	3	3	3	3	3	3	3	3	3	3		3	3	3	3		3
4	28	71	3	3	3	3	3	3	3	3	3	3		3	3	3	3		3

Appendix 4.1. Continued

Sample Date			Parameters Sampled and Data Sources																
MO	DA	YR	ST	BT	SS	BS	SDO	BDO	PH	PO4	TDP	TP	PP	NO3	NH4	TDN	TN	PN	CHL
5	12	71	3	3	3	3	3	3	3	3	3	3		3	3	3	3		3
5	26	71	3	3	3	3	3	3	3	3	3	3		3	3	3	3		3
6	9	71	3	3	3	3	3	3	3	3	3	3		3	3	3	3		3
6	24	71	3	3	3	3	3	3	3	3	3	3		3	3	3	3		3
7	8	71	4	4	4	4	4	4	4	4	4	4		4	4	4	4		4
7	21	71	4	4	4	4	4	4	4	4	4	4		4	4	4	4		4
8	4	71	4	4	4	4	4	4	4	4	4	4		4	4	4	4		4
8	31	71	4	4	4	4	4	4	4	4	4	4		4	4	4	4		4
9	15	71	4	4	4	4	4	4	4	4	4	4		4	4	4	4		4
10	6	71	4	4	4	4	4	4	4	4	4	4		4	4	4	4		4
10	20	71	4	4	4	4	4	4	4	4	4	4		4	4	4	4		4
11	10	71	4	4	4	4	4	4	4	4	4	4		4	4	4	4		4
11	23	71	4	4	4	4	4	4	4	4	4	4		4	4	4	4		4
12	13	71	4	4	4	4	4	4	4	4	4	4		4	4	4	4		4
1	4	72	4	4	4	4	4	4	4	4	4	4		4	4	4	4		4
1	19	72	4	4	4	4	4	4	4	4	4	4		4	4	4	4		4
2	3	72	4	4	4	4	4	4	4	4	4	4		4	4	4	4		4
2	23	72	4	4	4	4	4	4	4	4	4	4		4	4	4	4		4
3	8	72	4	4	4	4	4	4	4	4	4	4		4	4	4	4		4
3	23	72	4	4	4	4	4	4	4	4	4	4		4	4	4	4		4
4	6	72	4	4	4	4	4	4	4	4	4	4		4	4	4	4		4
4	19	72	4	4	4	4	4	4	4	4	4	4		4	4	4	4		4
5	22	72	4	4	4	4	4	4	4	4	4	4		4	4	4	4		4
6	14	72	4	4	4	4	4	4	4	4	4	4		4	4	4	4		4
7	19	72	4	4	4	4	4	4	4	4	4	4		4	4	4	4		4
8	9	72	4	4	4	4	4	4	4	4	4	4		4	4	4	4		4
9	7	72	4	4	4	4	4	4	4	4	4	4		4	4	4	4		4
10	5	72	4	4	4	4	4	4	4	4	4	4		4	4	4	4		4
10	18	72	4	4	4	4	4	4	4	4	4	4		4	4	4	4		4
11	1	72	4	4	4	4	4	4	4	4	4	4		4	4	4	4		4
12	6	72	4	4	4	4	4	4	4	4	4	4		4	4	4	4		4
1	19	73	4	4	4	4	4	4	4	4	4	4		4	4	4	4		4
2	21	73	4	4	4	4	4	4	4	4	4	4		4	4	4	4		4
3	21	73	4	4	4	4	4	4	4	4	4	4		4	4	4	4		4
4	4	73	4	4	4	4	4	4	4	4	4	4		4	4	4	4		4
4	19	73	4	4	4	4	4	4	4	4	4	4		4	4	4	4		4
7	9	73	4	4	4	4	4	4	4	4	4	4		4	4	4	4		4
7	26	73	4	4	4	4	4	4	4	4	4	4		4	4	4	4		4
8	22	73	4	4	4	4	4	4	4	4	4	4		4	4	4	4		4
1	27	75	5	5	5	5	5	5	5	5	5	5		5	5	5	5		5
2	14	75	5	5	5	5	5	5	5	5	5	5		5	5	5	5		5
2	28	75	5	5	5	5	5	5	5	5	5	5		5	5	5	5		5
3	28	75	5	5	5	5	5	5	5	5	5	5		5	5	5	5		5

Appendix 4.1. Continued

Sample Date			Parameters Sampled and Data Sources																
MO	DA	YR	ST	BT	SS	BS	SDO	BDO	PH	PO4	TDP	TP	PP	NO3	NH4	TDN	TN	PN	CHL
4	17	75	5	5	5	5	5	5	5	5	5	5		5	5	5	5		5
5	19	75	5	5	5	5	5	5	5	5	5	5		5	5	5	5		5
5	30	75	5	5	5	5	5	5	5	5	5	5		5	5	5	5		5
6	18	75	5	5	5	5	5	5	5	5	5	5		5	5	5	5		5
6	24	75	5	5	5	5	5	5	5	5	5	5		5	5	5	5		5
7	11	75	6	6	6	6	6	6	6	6	6	6		6	6	6	6		6
7	21	75	6	6	6	6	6	6	6	6	6	6		6	6	6	6		6
8	2	75	17		17														
8	5	75	6	6	6	6	6	6	6	6	6	6		6	6	6	6		6
8	16	75	17		17														
8	19	75	6	6	6	6	6	6	6	6	6	6		6	6	6	6		6
9	2	75	6	6	6	6	6	6	6	6	6	6		6	6	6	6		6
9	6	75	17		17		17												
9	18	75	6	6	6	6	6	6	6	6	6	6		6	6	6	6		6
10	6	75	17		17		17												
10	10	75	6	6	6	6	6	6	6	6	6	6		6	6	6	6		6
10	19	75	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	
10	21	75	6	6	6	6	6	6	6	6	6	6		6	6	6	6		6
11	5	75	6	6	6	6	6	6	6	6	6	6		6	6	6	6		6
11	5	75	17		17		17												
11	9	75	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	
12	5	75	6	6	6	6	6	6	6	6	6	6		6	6	6	6		6
12	7	75	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	
12	9	75	17		17		17												
12	14	75	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	
12	15	75	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	
12	17	75	6	6	6	6	6	6	6	6	6	6		6	6	6	6		6
1	12	76	6	6	6	6	6	6	6	6	6	6		6	6	6	6		6
1	15	76	17		17		17												
2	24	76	6	6	6	6	6	6	6	6	6	6		6	6	6	6		6
2	26	76	17		17		17												
2	27	76	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	
3	11	76	6	6	6	6	6	6	6	6	6	6		6	6	6	6		6
3	24	76	6	6	6	6	6	6	6	6	6	6		6	6	6	6		6
3	25	76	17		17		17												
4	3	76	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	
4	4	76	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	
4	6	76	6	6	6	6	6	6	6	6	6	6		6	6	6	6		6
4	21	76	6	6	6	6	6	6	6	6	6	6		6	6	6	6		6
5	5	76	6	6	6	6	6	6	6	6	6	6		6	6	6	6		6
5	11	76	17		17		17												
6	7	76	6	6	6	6	6	6	6	6	6	6		6	6	6	6		6
6	23	76	6	6	6	6	6	6	6	6	6	6		6	6	6	6		6

Appendix 4.1. Continued

Sample Date			Parameters Sampled and Data Sources																
MO	DA	YR	ST	BT	SS	BS	SDO	BDO	PH	PO4	TDP	TP	PP	NO3	NH4	TDN	TN	PN	CHL
6	23	76	17		17		17												
7	6	76	6	6	6	6	6	6	6	6	6	6		6	6	6	6		6
7	19	76	6	6	6	6	6	6	6	6	6	6		6	6	6	6		6
7	25	76	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	
7	26	76	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	
7	27	76	17		17		17												
8	11	76	17		17		17		17	17	17	17	17	17	17	17	17	17	17
8	15	76	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	
8	16	76	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	
8	23	76	6	6	6	6	6	6	6	6	6	6		6	6	6	6		6
9	5	76	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	
9	6	76	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	
9	9	76	6	6	6	6	6	6	6	6	6	6		6	6	6	6		6
9	24	76	6	6	6	6	6	6	6	6	6	6		6	6	6	6		6
9	26	76	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	
9	27	76	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	
10	7	76	6	6	6	6	6	6	6	6	6	6		6	6	6	6		6
10	16	76	17		17		17		17	17	17	17	17	17	17	17	17	17	17
10	17	76	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	
10	18	76	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	
11	5	76	7	7	7	7	7	7		7	7	7		7	7	7	7		7
11	14	76	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	
11	15	76	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	
12	5	76	17		17		17		17	17	17	17	17	17	17	17	17	17	17
12	10	76	7	7	7	7	7	7		7	7	7		7	7	7	7		7
12	12	76	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	
12	13	76	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	
1	8	77	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	
1	9	77	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	
1	10	77	7	7	7	7	7	7	7	7	7	7		7	7	7	7		7
1	30	77	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	
2	4	77	7	7	7	7	7	7	7	7	7	7		7	7	7	7		7
2	5	77	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	
2	9	77	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	
2	19	77	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	
2	20	77	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	
3	2	77	17	18	17	18	17	18	17	17	17	17	17	17	17	17	17	17	17
3	2	77	18		18		18		18	18	18	18	18	18	18	18	18	18	
3	10	77	7	7	7	7	7	7	7	7	7	7		7	7	7	7		7
3	12	77	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	
3	13	77	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	
3	30	77	7	7	7	7	7	7	7	7	7	7		7	7	7	7		7
4	2	77	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	

Appendix 4.1. Continued

Sample Date			Parameters Sampled and Data Sources																
MO	DA	YR	ST	BT	SS	BS	SDO	BDO	PH	PO4	TDP	TP	PP	NO3	NH4	TDN	TN	PN	CHL
4	3	77	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	
4	14	77	7	7	7	7	7	7	7	7	7	7		7	7	7	7		7
4	25	77	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	
4	24	77	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	
4	26	77	7	7	7	7	7	7	7	7	7	7		7	7	7	7		7
5	12	77	7	7	7	7	7	7	7	7	7	7		7	7	7	7		7
5	15	77	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	
5	16	77	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	
5	23	77	17		17		17		17	17	17	17	17	17	17	17	17	17	17
6	5	77	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	
6	6	77	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	
6	8	77	7	7	7	7	7	7	7	7	7	7		7	7	7	7		7
6	30	77	7	7	7	7	7	7	7	7	7	7		7	7	7	7		7
7	7	77	17		17		17		17	17	17	17	17	17	17	17	17	17	17
7	10	77	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	
7	11	77	7	7	7	7	7	7	7	7	7	7		7	7	7	7		7
7	25	77	7	7	7	7	7	7	7	7	7	7		7	7	7	7		7
8	10	77	7	7	7	7	7	7	7	7	7	7		7	7	7	7		7
9	9	77	8	8	8	8	8	8	8	8	8	8		8	8	8	8		8
9	29	77	8	8	8	8	8	8	8	8	8	8		8	8	8	8		8
11	9	77	8	8	8	8	8	8	8	8	8	8		8	8	8	8		8
12	16	77	8	8	8	8	8	8	8	8	8	8		8	8	8	8		8
1	10	78	8	8	8	8	8	8	8	8	8	8		8	8	8	8		8
2	15	78	8	8	8	8	8	8	8	8	8	8		8	8	8	8		8
3	17	78	8	8	8	8	8	8	8	8	8	8		8	8	8	8		8
4	7	78	8	8	8	8	8	8	8	8	8	8		8	8	8	8		8
4	28	78	8	8	8	8	8	8	8	8	8	8		8	8	8	8		8
5	11	78	8	8	8	8	8	8	8	8	8	8		8	8	8	8		8
5	23	78	8	8	8	8	8	8	8	8	8	8		8	8	8	8		8
6	7	78	8	8	8	8	8	8	8	8	8	8		8	8	8	8		8
6	20	78	8	8	8	8	8	8	8	8	8	8		8	8	8	8		8
7	13	78	8	8	8	8	8	8	8	8	8	8		8	8	8	8		8
7	26	78	8	8	8	8	8	8	8	8	8	8		8	8	8	8		8
8	15	78	8	8	8	8	8	8	8	8	8	8		8	8	8	8		8
8	23	78	8	8	8	8	8	8	8	8	8	8		8	8	8	8		8
10	23	78	*	*	*	*	*	*	*	*	*	*		*	*	*	*		*
11	9	78	*	*	*	*	*	*	*	*	*	*		*	*	*	*		*
11	29	78	*	*	*	*	*	*	*	*	*	*		*	*	*	*		*
12	14	78	*	*	*	*	*	*	*	*	*	*		*	*	*	*		*
2	16	79	9	9	9	9	9	9	9	9	9	9		9	9	9	9		9
3	16	79	9	9	9	9	9	9	9	9	9	9		9	9	9	9		9
4	25	79	9	9	9	9	9	9	9	9	9	9		9	9	9	9		9
5	8	79	9	9	9	9	9	9	9	9	9	9		9	9	9	9		9

Appendix 4.1. Continued

Sample Date			Parameters Sampled and Data Sources																
MO	DA	YR	ST	BT	SS	BS	SDO	BDO	PH	PO4	TDP	TP	PP	NO3	NH4	TDN	TN	PN	CHL
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6	7	79	9	9	9	9	9	9	9	9	9	9		9	9	9	9		9
6	14	79	9	9	9	9	9	9	9	9	9	9		9	9	9	9		9
7	17	79	9	9	9	9	9	9	9	9	9	9		9	9	9	9		9
7	24	79	9	9	9	9	9	9	9	9	9	9		9	9	9	9		9
8	22	79	9	9	9	9	9	9	9	9	9	9		9	9	9	9		9
8	28	79	9	9	9	9	9	9	9	9	9	9		9	9	9	9		9
9	20	79	9	9	9	9	9	9	9	9	9	9		9	9	9	9		9
9	27	79	9	9	9	9	9	9	9	9	9	9		9	9	9	9		9
10	2	79	9	9	9	9	9	9	9	9	9	9		9	9	9	9		9
10	18	79	9	9	9	9	9	9	9	9	9	9		9	9	9	9		9
1	17	80	10	10	10	10	10	10	10	10	10	10		10	10	10	10		10
2	15	80	10	10	10	10	10	10	10	10	10	10		10	10	10	10		10
2	28	80	10	10	10	10	10	10	10	10	10	10		10	10	10	10		10
3	27	80	10	10	10	10	10	10	10	10	10	10		10	10	10	10		10
3	31	80	10	10	10	10	10	10	10	10	10	10		10	10	10	10		10
4	16	80	10	10	10	10	10	10	10	10	10	10		10	10	10	10		10
4	28	80	10	10	10	10	10	10	10	10	10	10		10	10	10	10		10
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6	16	80	10	10	10	10	10	10	10	10	10	10		10	10	10	10		10
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8	1	80	10	10	10	10	10	10	10	10	10	10		10	10	10	10		10
8	14	80	10	10	10	10	10	10	10	10	10	10		10	10	10	10		10
8	25	80	10	10	10	10	10	10	10	10	10	10		10	10	10	10		10
9	9	80	10	10	10	10	10	10	10	10	10	10		10	10	10	10		10
9	29	80	10	10	10	10	10	10	10	10	10	10		10	10	10	10		10
11	4	80	10	10	10	10	10	10	10	10	10	10		10	10	10	10		10
11	20	80	10	10	10	10	10	10	10	10	10	10		10	10	10	10		10
12	4	80	10	10	10	10	10	10	10	10	10	10		10	10	10	10		10
1	16	81	11	11	11	11	11	11	11	11	11	11		11	11	11	11		11
1	29	81	11	11	11	11	11	11	11	11	11	11		11	11	11	11		11
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2	27	81	11	11	11	11	11	11	11	11	11	11		11	11	11	11		11
3	9	81	11	11	11	11	11	11	11	11	11	11		11	11	11	11		11
3	25	81	11	11	11	11	11	11	11	11	11	11		11	11	11	11		11
4	7	81	11	11	11	11	11	11	11	11	11	11		11	11	11	11		11
4	22	81	11	11	11	11	11	11	11	11	11	11		11	11	11	11		11
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6	10	81	11	11	11	11	11	11	11	11	11	11		11	11	11	11		11
6	22	81	11	11	11	11	11	11	11	11	11	11		11	11	11	11		11

Appendix 4.1. Continued

Sample Date			Parameters Sampled and Data Sources																
MO	DA	YR	ST	BT	SS	BS	SDO	BDO	PH	PO4	TDP	TP	PP	NO3	NH4	TDN	TN	PN	CHL
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7	16	81	11	11	11	11	11	11	11	11	11	11		11	11	11	11		11
7	29	81	11	11	11	11	11	11	11	11	11	11		11	11	11	11		11
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9	10	81	11	11	11	11	11	11	11	11	11	11		11	11	11	11		11
9	18	81	11	11	11	11	11	11	11	11	11	11		11	11	11	11		11
10	1	81	11	11	11	11	11	11	11	11	11	11		11	11	11	11		11
10	9	81	11	11	11	11	11	11	11	11	11	11		11	11	11	11		11
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11	3	81	11	11	11	11	11	11	11	11	11	11		11	11	11	11		11
12	4	81	11	11	11	11	11	11	11	11	11	11		11	11	11	11		11
12	23	81	11	11	11	11	11	11	11	11	11	11		11	11	11	11		11
1	7	82	12	12	12	12	12	12	12	12	12	12		12	12	12	12		12
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4	2	82	12	12	12	12	12	12	12	12	12	12		12	12	12	12		12
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7	16	82	12	12	12	12	12	12	12	12	12	12		12	12	12	12		12
7	22	82	12	12	12	12	12	12	12	12	12	12		12	12	12	12		12
8	5	82	12	12	12	12	12	12	12	12	12	12		12	12	12	12		12
8	19	82	12	12	12	12	12	12	12	12	12	12		12	12	12	12		12
9	1	82	12	12	12	12	12	12	12	12	12	12		12	12	12	12		12
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10	21	82	12	12	12	12	12	12	12	12	12	12		12	12	12	12		12
10	29	82	12	12	12	12	12	12	12	12	12	12		12	12	12	12		12
11	10	82	12	12	12	12	12	12	12	12	12	12		12	12	12	12		12
11	30	82	12	12	12	12	12	12	12	12	12	12		12	12	12	12		12
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3	10	83	13	13	13	13	13	13	13	13	13	13		13	13	13	13		13
4	1	83	13	13	13	13	13	13	13	13	13	13		13	13	13	13		13

Appendix 4.1. Continued

Sample Date			Parameters Sampled and Data Sources																
MO	DA	YR	ST	BT	SS	BS	SDO	BDO	PH	PO4	TDP	TP	PP	NO3	NH4	TDN	TN	PN	CHL
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5	5	83	13	13	13	13	13	13	13	13	13	13		13	13	13	13		13
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9	8	83	13	13	13	13	13	13	13	13	13	13		13	13	13	13		13
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3	8	84	14	14	14	14	14	14	14	14	14	14		14	14	14	14		14
3	16	84	14	14	14	14	14	14	14	14	14	14		14	14	14	14		14
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4	27	84	14	14	14	14	14	14	14	14	14	14		14	14	14	14		14
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5	23	84	14	14	14	14	14	14	14	14	14	14		14	14	14	14		14
6	8	84	14	14	14	14	14	14	14	14	14	14		14	14	14	14		14
6	21	84	14	14	14	14	14	14	14	14	14	14		14	14	14	14		14
7	5	84	14	14	14	14	14	14	14	14	14	14		14	14	14	14		14
7	20	84	14	14	14	14	14	14	14	14	14	14		14	14	14	14		14
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8	29	84	14	14	14	14	14	14	14	14	14	14		14	14	14	14		14
9	21	84	14	14	14	14	14	14	14	14	14	14		14	14	14	14		14
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10	10	84	14	14	14	14	14	14	14	14	14	14		14	14	14	14		14
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11	14	84	14	14	14	14	14	14	14	14	14	14		14	14	14	14		14
11	27	84	14	14	14	14	14	14	14	14	14	14		14	14	14	14		14
12	13	84	14	14	14	14	14	14	14	14	14	14		14	14	14	14		14

Appendix 4.1. Continued

Sample Date			Parameters Sampled and Data Sources																
MO	DA	YR	ST	BT	SS	BS	SDO	BDO	PH	PO4	TDP	TP	PP	NO3	NH4	TDN	TN	PN	CHL
12	19	84	14	14	14	14	14	14	14	14	14	14		14	14	14	14		14
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2	21	85	15	15	15	15	15	15	15	15	15		15	15	15	15		15	15
3	28	85	15	15	15	15	15	15	15	15	15		15	15	15	15		15	15
4	12	85	15	15	15	15	15	15	15	15	15		15	15	15	15		15	15
4	24	85	15	15	15	15	15	15	15	15	15		15	15	15	15		15	15
4	30	85	15	15	15	15	15	15	15	15	15		15	15	15	15		15	15
5	7	85	15	15	15	15	15	15	15	15	15		15	15	15	15		15	15
5	21	85	15	15	15	15	15	15	15	15	15		15	15	15	15		15	15
5	31	85	15	15	15	15	15	15	15	15	15		15	15	15	15		15	15
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7	9	85	15	15	15	15	15	15	15	15	15		15	15	15	15		15	15
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8	19	85	15	15	15	15	15	15	15	15	15		15	15	15	15		15	15
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9	19	85	15	15	15	15	15	15	15	15	15		15	15	15	15		15	15
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11	26	85	15	15	15	15	15	15	15	15	15		15	15	15	15		15	15
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1	15	86	16	16	16	16	16	16	16	16	16		16	16	16	16		16	16
2	4	86	16	16	16	16	16	16	16	16	16		16	16	16	16		16	16
2	18	86	16	16	16	16	16	16	16	16	16		16	16	16	16		16	16
3	26	86	16	16	16	16	16	16	16	16	16		16	16	16	16		16	16
4	2	86	16	16	16	16	16	16	16	16	16		16	16	16	16		16	16
4	17	86	16	16	16	16	16	16	16	16	16		16	16	16	16		16	16
5	1	86	16	16	16	16	16	16	16	16	16		16	16	16	16		16	16
5	8	86	16	16	16	16	16	16	16	16	16		16	16	16	16		16	16
5	22	86	16	16	16	16	16	16	16	16	16		16	16	16	16		16	16
6	4	86	16	16	16	16	16	16	16	16	16		16	16	16	16		16	16
6	19	86	16	16	16	16	16	16	16	16	16		16	16	16	16		16	16
7	10	86	16	16	16	16	16	16	16	16	16		16	16	16	16		16	16
7	16	86	16	16	16	16	16	16	16	16	16		16	16	16	16		16	16
7	30	86	16	16	16	16	16	16	16	16	16		16	16	16	16		16	16
8	13	86	16	16	16	16	16	16	16	16	16		16	16	16	16		16	16
8	27	86	16	16	16	16	16	16	16	16	16		16	16	16	16		16	16
9	10	86	16	16	16	16	16	16	16	16	16		16	16	16	16		16	16
9	24	86	16	16	16	16	16	16	16	16	16		16	16	16	16		16	16
10	8	86	16	16	16	16	16	16	16	16	16		16	16	16	16		16	16

Appendix 4.1. Continued

Sample Date			Parameters Sampled and Data Sources																
MO	DA	YR	ST	BT	SS	BS	SDO	BDO	PH	PO4	TDP	TP	PP	NO3	NH4	TDN	TN	PN	CHL
10	30	86	16	16	16	16	16	16	16	16	16		16	16	16	16		16	16
11	7	86	16	16	16	16	16	16	16	16	16		16	16	16	16		16	16
12	9	86	16	16	16	16	16	16	16	16	16		16	16	16	16		16	16
12	27	86	16	16	16	16	16	16	16	16	16		16	16	16	16		16	16

Appendix 4.2. Pamlico River estuary water quality sampling station locations

Note 1. Sample station numbers are arranged by investigator (columns) and river segment (A-J) (rows).

Note 2. Investigator codes: H1 = Hobbie (March 1967-February 1968)
H2 = Hobbie (June 1968-July 1969)
H3 = Hobbie (July 1969-July 1971)
H4 = Hobbie (August 1971-August 1973)
D1 = Davis (August 1975-July 1976)
D2 = Davis (August 1976-July 1977)
K = Kuenzler (1975-1977)
I1 = ICMR (January 1975-June 1975)
I2 = ICMR (July 1975-December 1986)
Station 7 sampled 1/77-12/86
Station 2N sampled 7/75-7/77
Station 1A sampled 7/80-12/86

Note 3. The "location" notes below refer to geographic features named on National Ocean Survey Charts 11554 (13th. ed., 1981) and 11548 (31st. ed., 1985), published by the U.S. Department of Commerce, National Oceanic and Atmospheric Administration (NOAA), Washington, D.C.

River Segment	Investigator									
	H1	H2	H3	H4	D1	D2	K	I1	I2	Latitude/Longitude/Location
A					22	1		11	12	N35°32'07"-W77°02'55" Mid-river, RR bridge at Washington
A					21				11	N35°29'51"-W77°01'38" Mouth of Chocowinity Bay
B								10	10	N35°28'55"-W76°59'15" Marker "12" off Camp Hardee
B		H17	H17	1						N35°28'22"-W76°58'27" Marker "10", mid-river off Hills Pt.

Appendix 4.2. Continued

River Segment	Investigator									
	H1	H2	H3	H4	D1	D2	K	I1	I2	Latitude/Longitude/Location
B									9S	N35°27'04"-W76°57'32" South Blounts Bay
B									9N	N35°28'50"-W76°57'24" Marker "1", mouth of Broad Ck.
B		H16	H16	2	20	2	1			N35°27'42"-W76°57'33" Marker "9", Blounts Bay
B			A5							N35°28'00"-W76°58'00" West Blounts Bay
C				3						N35°27'27"-W76°56'11" Marker "8", NW of Maules Pt.
C		H11	H11					9	8	N35°27'10"-W76°55'10" Marker "7", NE of Maules Pt.
C				4	19					N35°26'42"-W76°54'13" Test Well "D" off Jack Ck.
C	3									N35°27'20"-W76°53'35" Off Mallard Ck., N side of river
C	2									N35°26'48"-W76°53'37" Between Tripp Pt. and Mallard Ck.
C	1									N35°26'10"-W76°53'40" Off Tripp Point, south side of river
D		H10	H10	5	18		2	8		N35°26'30"-W76°52'22" Between Sparrow Bay and Duck Ck.
D	4									N35°26'45"-W76°50'45" Off Hawkins Landing, N side of river
D		H9	H9		16				7	N35°25'50"-W76°50'30" Marker "5" off Core Pt.

Appendix 4.2. Continued

River Segment	Investigator H1	H2	H3	H4	D1	D2	K	I1	I2	Latitude/Longitude/Location
D				6						N35°26'03"-W76°50'05" Mid-river between Core Pt. and Bath Ck.
D	5									N35°26'10"-W76°50'50" Between Hawkins Lndg. and Core Pt.
D	6									N35°25'43"-W76°50'51" Off Core Pt., near s. shore of river
D									7S	N35°24'04"-W76°49'04" Marker "2" at mouth of Durham Ck.
D					17				7N	N35°27'03"-W76°49'15" Marker "1" at mouth of Bath Ck.
D		H8	H8	8				7		N35°24'45"-W76°48'43" Mid-river between TG and Bayview
D		SH8	SH8	9	15					N35°24'08"-W76°48'40" Off mouth of Durham Creek
D						3	3			N35°25'15"-W76°48'30" Mid-river between Durham Ck. & Bath Ck.
D	7									N35°23'45"-W76°47'52" Off TG, near south shore
D	10				14					N35°25'55"-W76°47'40" Off Bayview, near north shore
D	8									N35°24'20"-W76°47'45" Off TG, near south shore
D	9									N35°25'05"-W76°47'45" Mid-river between TG and Bayview

Appendix 4.2. Continued

River Segment	Investigator H1	H2	H3	H4	D1	D2	K	I1	I2	Latitude/Longitude/Location
D		NH8	NH8	7						N35°25′30″-W76°46′36″ Off Mixon Creek, N side of river
E									6	N35°23′12″-W76°46′07″ Off TG outfall
E		SH7	SH7	12						N35°23′28″-W76°46′20″ Marker "1" at TG barge canal
E		H7	H7	11						N35°24′10″-W76°46′03″ Between Gum Pt. and TG barge canal
E		NH7	NH7	10						N35°24′47″-W76°45′52″ Marker "4" off Gum Pt.
E			A3	14						N35°23′57″-W76°44′39″ Between St. Clair Ck. and Long Pt.
E	14				11			5	5S	N35°23′03″-W76°44′39″ Marker "1" at Ferry Landing
E	12									N35°24′37″-W76°44′25″ Between Gaylord Bay and Ferry Lndg.
E					12		4	6	5	N35°24′10″-W76°44′18″ Between Gaylord Bay and Huddles Gut
E			A2	13						N35°25′10″-W76°44′35″ Off St. Clair Ck., N side of river
E	13									N35°24′45″-W76°44′35″ Off ferry landing, south side of river
E	11				13				5N	N35°25′19″-W76°44′10″ Marker "1" in Gaylord Bay

Appendix 4.2. Continued

River Segment	Investigator H1	H2	H3	H4	D1	D2	K	I1	I2	Latitude/Longitude/Location
E	15									N35°22'03"-W76°41'40" Off Hickory Pt., south side of river
E			A4	15						N35°23'00"-W76°41'40" Off Long Pt., S side of river
E	17									N35°23'25"-W76°41'10" Between Cousin Pt. and Hickory Pt.
E	16									N35°22'47"-W76°41'22" Off Hickory Pt., S side of river
E	18									N35°24'03"-W76°40'55" Off Cousin Pt., N side of river
E	19									N35°24'40"-W76°40'45" Off Cousin Pt., N side of river
F	26									N35°21'22"-W76°41'05" Marker "5" off South Ck.
F	25	H13	H13	32					4S	N35°21'28"-W76°40'37" Marker "4" off South Ck.
F		H6	H6	17						N35°23'45"-W76°40'16" Between Hickory Pt. & Cousin Pt.
F		NH6	NH6	16					4N	N35°24'46"-W76°40'11" Marker "1" at mouth of North Ck.
F		SH6	SH6	18						N35°22'30"-W76°40'29" Between Hickory Pt. & Cousin Pt.
F	24				10					N35°21'20"-W76°39'35" South of Indian Island
F	23									N35°21'55"-W76°39'00" North of Indian Island

Appendix 4.2. Continued

River Segment	Investigator H1	H2	H3	H4	D1	D2	K	I1	I2	Latitude/Longitude/Location
F	21									N35°23′03″-W76°38′20″ North of Indian Island
F	22	H5	H5		9	4		4	3	N35°22′23″-W76°38′47″ Marker "3", north of Indian Island
F	20				8					N35°23′40″-W76°38′07″ North of Indian Island
F		H12	H12							N35°21′12″-W76°38′25″ Marker "2" south of Indian Island
G		SH4	SH4	20						N35°21′10″-W76°37′00″ Off Reed Hammock
G		NH4	NH4	19						N35°22′36″-W76°36′06″ Off Cousin Pt., north side of river
G	35									N35°20′36″-W76°36′32″ Off Reed Hammock, s. side of river
G		H4	H4				5			N35°22′00″-W76°36′30″ Between Reed Hammock and Adams Pt.
G								3		N35°21′40″-W76°36′19″ Mid-river between Wades Pt. & Goose Ck.
G	34									N35°21′02″-W76°36′08″ Between Reed Hammock and Wades Pt.
G					5				2S	N35°20′22″-W76°35′47″ Marker "1" at mouth of Goose Ck.

Appendix 4.2. Continued

River Segment	Investigator H1	H2	H3	H4	D1	D2	K	I1	I2	Latitude/Longitude/Location
G	33									N35°21'24"-W76°35'48" Mid-river between Wades Pt. & Reed Ham.
G	31									N35°22'24"-W76°35'00" Between Reed Hammock and Wades Pt.
G	32				6					N35°21'52"-W76°35'24" Between Reed Hammock and Wades Pt.
G	30				7					N35°22'54"-W76°34'42" Off Wades Pt.
G				21						N35°22'38"-W76°33'24" Marker "PR" at mouth of Pungo R.
G				23						N35°20'18"-W76°33'54" Between Goose Ck. and Cedar Is.
G				22						N35°21'24"-W76°33'33" Mid-river south of mouth of Pungo R.
H			A1	31					2N	N35°23'36"-W76°33'00" At mouth of Pungo River
H		SH3	SH3	26						N35°20'00"-W76°32'06" North of Cedar Island
H		H3	H3	25		5		2	1A	N35°21'20"-W76°31'30" Mid-river between Abel B. & Cedar Is.
H		NH3	NH3	24						N35°23'13"-W76°30'30" S. of Indian Is. Marker "1" at Abel B.
I	38									N35°20'54"-W76°29'14" Between Marker "1" and Willow Pt.

Appendix 4.2. Continued

River Segment	Investigator H1	H2	H3	H4	D1	D2	K	I1	I2	Latitude/Longitude/Location
I	37									N35°19'52"-W76°29'12" Between Pamlico Pt. & Willow Pt.
I	39	NH2	NH2	27	2					N35°21'48"-W76°28'50" Marker at Willow Pt. shoal
I	36	SH2	SH2	29	4					N35°19'00"-W76°28'58" Marker "1" at Pamlico Pt.
I		H2	H2	28	3					N35°20'30"-W76°28'54" Mid-river between Willow Pt. & Pam. Pt.
I				30				1	1	N35°20'06"-W76°27'36" Mid-river between Pam. Pt. & Rose Bay
I		H1	H1		1	6	6			N35°18'47"-W76°27'20" Pamlico Pt. light
J	29									N35°20'31"-W76°44'19" Marker "9" in South Creek
J		H15	H15	34						N35°21'09"-W76°43'43" Marker "8" in South Ck.
J	28									N35°21'03"-W76°42'20" Off Old Field Pt., South Creek
J		H14	H14	33				12	4P	N35°21'14"-W76°42'15" Marker "7", South Ck.
J	27									N35°20'45"-W76°41'40" Marker "2", mouth of Bond Creek

Appendix 4.3.
Changes in sampling and analytical methods

To the best of my knowledge, all the hydrographic and nutrient data reported by Hobbie for the period 1967-1973 were from analyses carried out by students and research technicians at the Pamlico Estuarine Laboratory (PEL) near Aurora, NC. After East Carolina University (ECU) took over the monitoring program in 1975, the analyses continued to be performed at the PEL under the supervision of Mr. Dan Kornegay. In mid-1980 the procedure was changed so that samples were transported to the Institute for Coastal and Marine Resources on the ECU campus in Greenville for analysis. Finally, in March 1985 analysis of the Pamlico samples was shifted to the ECU Biology Department's Central Environmental Laboratory, under the supervision of Ms. Martha Jones. Samples collected by Davis et al. (1978) were also analyzed in the ECU Biology Department lab. Kuenzler et al. (1979) transported their samples to the U.N.C. Chapel Hill campus for analysis in the Limnology Laboratory of the Department of Environmental Sciences and Engineering.

Water Temperature, Salinity, Dissolved Oxygen, and pH: Two kinds of instruments have been used to measure water temperature and salinity in the Pamlico studies. Hobbie used a conductivity bridge with built-in thermistor (Beckman RS5-3 induction salinometer) to measure salinity and temperature *in situ*, except for a few times in 1967 when hydrometers were used for salinity measurement. Presumably a mercury thermometer was used on these occasions to measure water temperature, although such is not stated in the report (Hobbie 1970b). The induction salinometer was used also by Kuenzler et al. (1979) in their Pamlico sampling in 1975, 1976 and 1977. Davis et al. (1978) used a salinity-conductivity-temperature (SCT) meter (Model 33) manufactured by Yellow Springs Instrument Company (YSI). Beginning in 1975, and continuing to the present, the ICMR monitoring program at ECU has also made use of the YSI SCT meter for temperature and salinity measurements. There is no reason to suspect that data from these two instruments are incomparable. All the data have been reported in units of °C for temperature, and parts per thousand (ppt) for salinity.

Dissolved oxygen measurements in the Pamlico studies have been made by two methods: 1) the classical Winkler titrimetric technique, and 2) oxygen sensing electrodes. The Winkler method was used for all the dissolved oxygen analyses reported by Hobbie. Water samples were taken with a Kemmerer sampler, fixed in the field, and titrated in the laboratory. No other details of the procedure are given in Hobbie's reports. Instead, the reader is referred to Carpenter (1965), who described the method as "a modified . . . Winkler determination", and he detailed the modifications, most of which involve the titration equipment. Kuenzler at al. (1979) used an "APHA-type" oxygen sampler to collect replicate D.O. samples from 0.5 m below the surface and 0.5 m above the bottom. Samples were fixed by the addition of manganous sulfate and alkaline iodide for Winkler analysis by procedures given in American Public Health Association (1975). Davis et al. (1978) and ICMR both measured dissolved oxygen by means of a Yellow Spring Instrument Company Model 51A oxygen meter and electrode.

All of the Hobbie dissolved oxygen data was reported as ml O_2/liter. To permit comparison with later data, I have converted the ml O_2/liter values to mg O_2/liter, by multiplying times 1.429 (Head 1985). Dissolved oxygen (DO) percent saturation values were included for some years in the previous Pamlico reports, but the method of calculation was not always given. Therefore, in order to have the data for all years and to insure consistency, I have recalculated percent saturations (DOPS) by the following formula:

DOPS = (mg DO/liter * 100)/(DO Saturation Value),

where

DO Saturation Value = (475 - (2.65 * S))/(33.3 + T).

S is salinity (ppt) and T is the temperature (°C). This is the same formula used by Hobbie (1970b) for some of the early Pamlico data. He indicated that it was developed by Truesdale and Gameson (1957).

Of course, no percent saturation values could be calculated when there was not a dissolved oxygen value. However, in those few cases where there was a DO value, but no temperature and/or salinity data, I did estimate the percent saturation. I did this by interpolating to give the missing salinity or temperature values needed for the calculation.

I have not found in any of the Hobbie reports a description of the method used for pH measurements. However, I believe that a pH meter with electrode (model unknown) was used, and that measurements were made on samples after they were returned to the Pamlico Estuarine Laboratory, usually within a few hours after collection. Davis et al. (1978) stored samples in the dark at mean ambient water temperature for up to 4 hours until pH could be measured with a Corning Model 10 meter. Kuenzler at al. (1979) also used a pH electrode, but I don't recall the meter model; no reference to it is made in the project report. Since 1975 various pH meters with electrodes (manufacturers and models have varied) have been used for the ICMR pH measurements. Until 1985 pH was measured in the laboratory, but since then a portable instrument has been used to make measurements on freshly-drawn samples in the field (Stanley 1987).

Nitrogen and Phosphorus: Procedures for the collection of samples for nitrogen and phosphorus analyses have varied somewhat among the four studies. Hobbie stated simply that "surface samples were taken at each station and returned to the laboratory for analysis" (Hobbie 1970a, page 6). Davis et al. (1978) collected samples 0.5 m below the surface, immediately filtered aliquots for dissolved nutrients, and stored all the samples in the dark on ice for transport back to the laboratory. Kuenzler et al. (1979) filled polyethylene carboys with water from a depth of 0.5 m by means of a Guzzler R Pump (Cole-Parmer Instrument Company) fitted with a plastic hose covered at the intake end with 153 um mesh nylon netting to exclude zooplankton. The samples were returned to the Pamlico Estuarine Laboratory (PEL) within a few hours for filtration, followed by freezing and transport to Chapel Hill for later analysis. Finally, samples collected since 1975 by ICMR were taken by dipping 1-liter polyethylene bottles into the water just below the surface. The bottled samples were held on ice in the dark until they were returned to either the PEL or ECU (within 6 hours of collection), where they were filtered and frozen (e.g., ICMR 1982; Stanley 1987).

Other variables associated with the nutrient sample processing include the type of filter used to separate dissolved and particulate fractions, and the type and length of storage of samples between collection and analysis. Hobbie used Gelman A glass fiber filters. Reactive phosphorus was measured as soon as the samples were returned to the laboratory, but water (filtered and unfiltered) for the total phosphorus, total dissolved phosphorus, and nitrogen fractions was frozen in plastic bags immediately after collection by placing the bags onto dry ice (Hobbie et al. 1972). Similarly, Kuenzler et al. (1979) filtered samples through Whatman GF/C glass fiber filters and stored the filtered (or unfiltered) water frozen in polyethylene until the nutrient analyses were run. Gelman type A/E glass fiber filters were used by Davis et al. (1978), and they also froze the samples pending analyses of nutrients. Since 1984 Whatman 934-AH glass fiber filters have been used for the samples analyzed in the ICMR program. There is no record of the kind of filters used between 1975 and 1983. Both filtered and unfiltered samples have been stored frozen, for up to several months in some instances, until the analyses were made.

1. Phosphorus: Nearly all the samples taken during these studies were analyzed for at least three phosphorus fractions; total phosphorus (TP), total dissolved phosphorus (TDP), and orthophosphate phosphorus (OP). TP analyses were performed on unfiltered water samples, while the other two measurements used filtered water. All the TP and TDP samples were first digested by some variation of the persulfate oxidation method of Menzel and Corwin (1965). Subsequent analyses of these digested samples, and undigested orthophosphate samples, was by manual or automated colorimetric methods. All projects used the mixed reagent developed by Murphy and Riley (1962), containing ammonium molybdate, ascorbic acid, and trivalent antimony.

Copeland and Hobbie give further details on the methodology used between 1967 and 1969: "The color development was read in a Beckman DU II spectrophotometer and the optical density calibrated against standards. These standards proved to be constant and a factor of 5.0 multiplied by this spectrophotometer reading gave the concentration. However, it was noted in 1969 that the calibration curve was not linear above 10 ug-at P/liter and the previous readings obtained were underestimates. Therefore, the concentrations measured prior to 14 October 1969 are low and can be corrected by multiplying by a factor of 1.0 at 10 ug-at P/liter and 1.6 at 20 ug-at P/liter. Since this correction makes no difference to the conclusions of this report, it was not applied to the data. It was also found that the curves for total (digested) and reactive (undigested) phosphate concentrations versus extinction had different slopes. Again the differences are slight, but this correction and the correction for the differing factors at high concentrations of phosphorus will clear up most of the discrepancies of the data where the reactive phosphorus is higher than the total phosphorus" (Copeland and Hobbie 1972, pages 24-25).

Apparently the phosphorus methodology did not change between 1969 and August 1973 when Hobbie's sampling ended, since his 1974 report on the 1971-1973 data states on page 12 that "details of the phosphorus analysis are given in Hobbie (1970a)", and the references he cites regarding methodology are the same ones cited in the earlier report; i.e., Menzel and Corwin (1965) for the persulfate digestion and Strickland and Parsons (1968) for the use of the mixed reagent. The same spectrophotometer that had been used earlier was used to read the sample color following addition of the mixed reagent.

Davis et al. (1979) seem to have used the same basic procedure as Hobbie, although they reported few details regarding their phosphorus methodology. They simply state that "phosphorus analyses involved conversion of phosphorus to orthophosphate by persulfate digestion, and subsequent colorimetric determination of soluble orthophosphate." They cite the manual on water and wastewater chemical analyses published by the Environmental Protection Agency (EPA) (1976) as a reference to their procedures. The methods outlined in this document do indeed involve the use of persulfate digestion for TDP and TP and the use of the three-part mixed reagent for phosphate determination.

An earlier edition of the EPA manual (1974) was referenced by Kuenzler et al. (1979) to describe the phosphorus methodology they used for Pamlico samples analyzed in their study between 1975 and 1977. They used slightly different terminology to describe the phosphorus fractions - "filterable reactive P" instead of orthophosphate phosphorus, and "total filterable P" instead of total dissolved phosphorus. The main difference between their procedure and that of Hobbie and Davis et al. was that they automated the analyses using Technicon Autoanalyzer equipment. They state in their report that ". . . precision was controlled in these analyses by running all samples in duplicate. Accuracy was checked in two ways. Where available, EPA controls were analyzed with every run. Also approximately 10% of routine analysis time was spend [sic] determining recovery of known increments of standards (spikes) to samples. . . Standards were routinely run at the beginning and end of each sample run" (Kuenzler et al. 1979, pages 17-19).

Finally, all ICMR samples from 1975 to the present have been analyzed for phosphorus using the same basic chemistry described above; i.e., the mixed color reagent for OP and persulfate digestion to convert TP and TDP to OP. Notes provided to me by the analyst who performed the tests from 1975 through 1980 show that EPA (1974, 1976, 1979) procedures were followed. A block digestor was used between 1975 and sometime in 1977, when it was replaced by an autoclave. Since 1984 the methods for phosphorus analyses have been described in detail in appendices in the annual reports to Texasgulf (Stanley 1986a, 198b, 1987). The most significant change in recent years came in 1985 when the procedures were automated using a Scientific Instruments autoanalyzer similar to the Technicon equipment used earlier by Kuenzler et al. (1979). Details of the autoanalyzer procedure are given in Stanley (1987).

On 28 March 1985 the total phosphorus analysis was dropped and particulate phosphorus (PP) measurements were begun. PP is the fraction of TP that remains on the filter pad following filtration. Therefore, the total phosphorus data used in this study for the period 28 March 1985 through December 1986 are not direct measurements, but rather the sums of the total dissolved phosphorus and PP values.

It has been determined recently that all the total dissolved phosphorus (TDP) data presented in the 1986 annual report (Stanley 1987) and part of the data in the 1985 report (Stanley 1986b) are in error. This error arose during the transition from manual to automated methods of analysis of TDP during 1985. The problem is that the automated analysis gives erroneously high TDP results. The solution to this problem is described above in the Methods section of the report.

2. Nitrogen: From 1969 through 1973 Hobbie analyzed several nitrogen fractions, including nitrate nitrogen, ammonia nitrogen, total dissolved nitrogen (TDN), and total nitrogen (TN). The first three analyses were run on filtered samples, while the fourth (TN) used unfiltered water. Hobbie (1974) referred to the total dissolved nitrogen as "total filtered nitrogen", and to the total nitrogen as "total unfiltered nitrogen".

Hobbie's nitrogen analyses consisted of various pre-treatments of a sample followed by analysis as nitrite. The nitrite was analyzed as an azo dye produced by sulphanilamide plus N-(1-napthyl)-

ethylenediamine. This diazotization technique was adapted for sea water by Bendschneider and Robinson (1952), and it is described in full in Strickland and Parsons (1968), which is the reference cited by Hobbie in his reports. The nitrate was analyzed as nitrite following reduction in a copper-cadmium column (Morris and Riley 1963). Ammonia also was analyzed as nitrite after oxidation of the sample with alkaline hypochlorite, a method developed by Richards and Kletch (1961). It really gives ammonia plus amino acids, (Strickland and Parsons 1968), although the error is small, since amino acids are usually much less abundant than ammonia. Finally, the TN and TFN analyses were carried out using oxidation by strong ultraviolet (UV) light to convert organic forms to a mixture of nitrate and nitrite (Armstrong et al. 1966; Strickland and Parsons 1968).

Davis et al. (1978) indicated that they used the UV spectrophotometric method (APHA 1971) for nitrate determinations. They analyzed ammonium nitrogen by the indophenol method, often referred to as the Solorzano (1969) method. Scheiner (1976) modified the method slightly and Davis et al. cited this paper as their reference. In the indophenol method samples are treated with sodium hypochlorite and phenol in an alkaline citrate medium. Sodium nitroprusside is used as a catalyst, and the blue indophenol color formed with ammonia is measured spectrophotometrically (Parsons et al. 1984). Kjeldahl digestions (EPA 1976) were used for the total nitrogen and total dissolved nitrogen analyses. This is one of the oldest and most widely-used methods for TN and TDN. Organic matter is converted to ammonia by heating with sulphuric acid, and the ammonia determined spectrophotometrically by one of the methods given above.

All of the nitrogen analyses performed during the study by Kuenzler et al. (1979) were automated using Technicon Autoanalyzer equipment and EPA methods. Cadmium reduction followed by nitrite analysis was the method they chose for nitrate nitrogen determinations. They cited EPA (1974) as their reference. Like Davis et al., they also used the indophenol method for ammonia, and they cited EPA (1974) as the reference for the method. Their total dissolved nitrogen analyses were by automated Kjeldahl methods (EPA 1974). Total nitrogen was not measured.

For a brief period (January-June 1975) the ICMR nitrate analyses were made using the brucine colorimetric method, which is based on the formation of a colored complex between nitrate and brucine sulfate in a 13 N sulfuric acid solution at a temperature of 100°C (EPA 1974). However, since July 1975 the ICMR samples have been analyzed by the cadmium reduction method, which was automated in mid-1985.

From 1975 through 1979 the ICMR ammonia analyses were made using an Orion Ammonia Probe (D. Kornegay, personal communication). Unfortunately, this ion-selective electrode was not very sensitive. It could not detect concentrations below 0.1 mg ammonia N/liter (7.14 uM), so that most of the normal range in ammonia levels in the estuary was missed. Beginning in 1980, the indophenol method was adopted (Solorzano 1969), and it has been used continuously since then, although minor modifications have been made at various times. Details of the procedure from 1984 onward, including the switch to the automated procedure in 1985, are given in the annual reports.

Kjeldahl digestions were used for the ICMR total and total dissolved nitrogen analyses beginning in January 1975. Between 1975 and the end of 1979, a block digester was used and the ammonia produced in the reaction was measured by means of the same Orion ammonia probe used for the ammonia analyses. Beginning in 1980, the ammonia was determined by the indophenol blue method, modified slightly at various times. When the analyses were automated in 1985, a combined nitrogen-phosphorus digestion reagent came into use. (Stanley 1987). The ammonia produced by this digestion was analyzed by the indophenol method.

Chlorophyll *a*: Essentially the same method has been used for chlorophyll *a* analyses in all four of the Pamlico studies. Hobbie (1974) gave the following outline of the method: "Water samples were returned to the laboratory . . . and a part of the sample filtered through Gelman A glass fiber filters for later chlorophyll analysis (filters were frozen). . . Chlorophyll *a* was measured by grinding the filters, extracting with 90% acetone, and estimating the pigment spectrophotometrically (Strickland and Parsons 1968). The spectrophotometric results were corrected for phaeophyton (Strickland and Parsons 1968)" (Hobbie 1974, page 12). It is important to note that all the chlorophyll results from the other three studies were also corrected for phaeophyton.

Davis et al. (1978) filtered their samples within 12 hours of collection (filter type not given), and the filters were stored frozen in a dessicator. Analyses of chlorophyll were made within 30 days of sample collection. They cited Strickland and Parsons (1972) as the reference for the procedure they used. Kuenzler et al. (1979) also froze the filter pads (Whatman GF/C) and analyzed for chlorophyll *a* by means of the acetone extraction-spectrophotometric method, following the procedure given in Lorenzen (1967).

ICMR analyses of chlorophyll *a*, like all the others described above, were made by measuring the extinction of an acetone extract of the pigment. The method probably followed Strickland and Parsons (1972) from 1975 through 1980, although no details are certain for that time period. Since 1980, this has been the method, with slight modifications, mostly involving the method of extraction (e.g., grinding or no grinding of filter pads), and the time allowed for extraction before the readings were made. The chlorophyll data from part of 1985 are suspect because of a problem involving unequal dispersion of the pigment in tubes following centrifugation to sediment the glass fiber filter fragments. It seems that most of the pigment was collecting near the bottom of the tube, so that when the sample was decanted into the spectrophotometer cell, erroneously low readings were obtained. This problem was corrected in early 1986.

Phytoplankton Cell Density and Wet Weight Biomass: There have been two major studies of phytoplankton species, numbers, and biomass in the Pamlico. The first was by Hobbie (1971) for the time period August 1966 through April 1968. Two series of stations were sampled; one series from August 1966 to August 1967 and the other from March 1967 to February 1968. These were the same stations sampled for nutrients and hydrographic parameters during these time periods (Hobbie 1970a, 1970b). The first series was sampled to examine the effects of the effluent from the phosphate slime (mining waste) pond located close to South Creek. When the effect could not be found, the sampling was expanded to include most of the estuary (Hobbie 1971).

Phytoplankton in the samples were identified and counted by the Utermohl technique (Utermohl 1958). Briefly, the organisms were preserved in a Lugol's type solution, settled into a small counting chamber, the excess water removed, and the organisms counted with an inverted microscope. Details are given in Hobbie's report. The most important advantage of this method is that it enables counting of the flagellates and nannoplankton as well as less fragile, larger forms (Hobbie 1971).

The second Pamlico phytoplankton study, sponsored by North Carolina Phosphate Corporation, was made during the period April 1982 through December 1985 (Stanley 1983, 1984a; Stanley and Daniel 1985a, 1985b, 1986). The objective was to collect baseline data for future impact assessment of increased phosphate mining in the area. There was a concern that higher nutrient loads could trigger nuisance blooms of algae in the Pamlico like those that had become common by this time in the Chowan River and the Neuse River. Samples were collected approximately every other week from stations in the river and in South Creek, a tributary near the mining sites. The River stations were the same ones used for the Texasgulf nutrient and hydrography study.

Phytoplankton in the samples were identified and counted by D. Daniel. The membrane filtration method was used to concentrate the Lugol's preserved algae prior to counting at 400X magnification (see Stanley and Daniel 1985a for details). This method of concentrating the algae is more rigorous than the Utermohl settling method used by Hobbie in the earlier study, but it apparently did not destroy the fragile flagellates and nannoplankton, so that results from the two studies are comparable.

In both of these phytoplankton studies, the algal biomass was calculated. Volumes of representative individuals of each species were estimated by means of geometric formulae. These volumes were multiplied by the species cell densities and summed to give the total wet weight biomass (ug/liter) for each sample. A specific gravity of unity was assumed (i.e., 1 mm^3 = 1 mg wet mass) (Hobbie 1971; Stanley and Daniel 1985a).

Appendix 4.4.
Review of methods for analyzing water quality time series data

The problem of testing water quality monitoring data for trend in time has received increasing attention during the last decade, primarily for two reasons (Hirsch et al. 1982). First, there is interest in the question of changing water quality arising from environmental concern and activity. State and Federal legislation has resulted in the expenditure of large sums of public and private money for the purpose of water quality improvement, and there is naturally interest in evaluating the consequences of these expenditures. Second, data sets covering a substantial number of years are becoming increasingly common because of the establishment of monitoring programs in the early and mid-1970's. Many of the trend analyses have involved data from national water quality networks such as the U.S. Geological Survey's NASQAN network (e.g., Smith et al. 1982).

Montgomery and Reckhow (1984) outlined a four-step trend detection method: 1) hypothesis formulation - statement of the problem to be tested, 2) data preparation - selection of water quality variables and data, 3) exploratory data analysis, and 4) statistical tests - tests for detecting trends.

Typically, the null hypothesis, H_o, is that there is no change (no trend) in the population of water quality values from which the data were drawn. Consequently, the alternate hypothesis, H_1, may be either that a trend does exist in the data (two-sided test) or that a positive (or a negative) trend exists in the data (one-sided test). If it is known that a parameter either increased or decreased, a one-tail H_1 should be used. A one-tailed test will maximize the probabilities of each outcome by placing all the rejection region (alpha) at one tail of the outcome distribution. However, if the type of change is not known, a two-tailed test should be used. It should be stressed that, when possible, the one-tailed alternative should be chosen.

In order to apply trend detection techniques, there can be only one data point for each time unit. This data preparation problem arises when numerous observations are located in the same time unit, yet one value is needed to represent that discrete time unit. Means or median values may be used as a measure of central tendency to represent the time period. When dealing with multiple data sources, an important consideration is whether the data are mutually compatible. Similar sampling designs, sampling devices, laboratory techniques and instruments may be a prerequisite to data merging; otherwise apparent trends may simply be an artifact of a change in analytical methods. Under some circumstances, the analyst may be able to remove this analytical method effect from the data series.

Once a hypothesis is formed and the data are properly arranged (i.e., one data value per unit time) the data are ready to be explored and analyzed. The data analysis step will provide the necessary information to determine which statistical test should be used to test the null hypothesis. Of particular interest are characteristics of the data related to frequently invoked assumptions. Montgomery and Reckhow (1984) and Smith et al. (1982) discuss these assumptions and corrective measures to deal with assumption violations.

Some of the techniques available for the exploratory data analysis include a graph of the data against time, the five number summary graph which Tukey (1977) calls the box-and-whisker plot, Tukey smoothing, and the autocorrelation function (McLeod et al. 1983). Because no single method can clearly portray everything there is to learn about the data, it is advisable to use a number of exploratory techniques.

Hypothesis testing, the final step for trend detection, consists of the following steps, as summarized by Smith et al. (1982):

1. State the null hypothesis and background assumptions for the test.

2. Calculate an appropriate test statistic from the data.

3. Interpret the value of the statistic in light of the known probability distribution of the statistic.

4. If the value of the test statistic is within preselected limits on the distribution, accept the null hypothesis; or,

5. If the value of the test statistic is outside the preselected limits, the null hypothesis cannot be accepted and a "statistically significant trend" is claimed.

The limits are calculated from a preselected probability - typically denoted by the Greek letter alpha - such that the probability that the test statistic would fall outside the limits is (alpha) if the null hypothesis and all background assumptions were true. A typical value selected for alpha is 0.1. Then one may say that a trend is, or is not, statistically significant at the 10% level. That is, in 90% of the cases, one will correctly say there is no trend when such is true. One may also report test results by a probability value (denote p). This is the probability that the test statistic would depart from its expectation by at least the observed amount, under the null hypothesis.

Most water quality data exhibit certain characteristics which can strongly influence the choice of an appropriate statistical trend test. Thus it is very important that the data be examined to determine whether they exhibit any of these characteristics. The following discussion, taken from Lettenmaier et al. (1982), describes these common features of water quality data which must be recognized before statistical methods can be selected.

1. Seasonality: Most water quality variables are affected directly or indirectly by seasonal climatic changes. For instance, water temperature responds directly to air temperature, although there is usually some lag which depends on the rate of heat transfer into and out of the ground and water. Water temperature affects both the saturation concentration of dissolved oxygen and the rates of oxygen consumption and production by plants and animals in the water column and sediments. Nutrient concentrations reflect both levels of biological activity and freshwater inflow to the estuary, both of which in turn may have large seasonal variability. Most trend analysis techniques require that some procedure be employed to remove seasonality. Montgomery and Reckhow (1984) reviewed some of these procedures.

2. Nonnormal probability distributions: Most water quality variables are positively skewed, since they cannot be negative, but may occasionally take on large positive values. Examples of variables from the Pamlico data set exhibiting this characteristic include nutrients and chlorophyll *a*. On the other hand, some variables have small ranges and often are nearly symetric, and if seasonal variations are removed, may be nearly normally distributed. Examples include temperature, dissolved oxygen, and pH.

Most parametric statistical tests require that the data come from a population that is normally distributed. A combination of intuitive knowledge, graphical methods, and statistical tests should be used to determine whether or not to use parametric tests, or nonparametric tests, which do not require a normal distribution of the parameter. Graphical techniques, involving visual comparisons, can be used to provide qualitative information on the form of the underlying distribution. For larger samples (n>50), the Kolmogorow-Smirnov test (Sokal and Rohlf 1981) can be used to test statistically the assumption of normality. This test, it should be noted, determines only whether the data exhibit significant deviations from normality and not whether they are normal (i.e., supports the alternative hypothesis and not the null hypothesis) (Montgomery and Reckhow 1984).

3. Missing or nonuniformly sampled data: Because of foul weather, equipment breakdown, analytical errors, and changing ideas as to appropriate sampling strategies, long-term time series are likely to have missing data. There may be long periods when no samples were taken, and the intervals between sampling dates are hardly ever uniform over a long period of time. Regardless of the cause, most traditional time series techniques, which assume equal sample intervals, are not appropriate to water quality data. Techniques exist to deal with a few isolated data gaps (Lettenmaier 1976; D'Astous and Hipel 1979) by estimating values for the missing data. However, if there are a lot of missing values, or one or more long gaps exist, the effect of data interpolation on the identification of the stochastic process and the ultimate trend testing become very problematic (Hirsch and Slack 1984).

4. Persistence: Water quality measurements are not, in general, independent, but are instead positively correlated (i.e., small values tend to be followed by small values and large by large), and the correlation usually increases as the sampling interval decreases. This phenomenon is also sometimes termed "autocorrelation" or "serial correlation" (Montgomery and Reckhow 1984). Positive correlation between samples arises because fluctuations from the mean tend to continue for a period that is usually long compared to the sampling interval. Such variations are, from a statistical standpoint, "noise", and may obscure underlying trends. Persistence is usually not a major issue when monthly sampling frequencies are used; for higher sampling frequencies, such as biweekly or weekly, it becomes increasingly important. Various tests for detecting autocorrelation are discussed in Montgomery and Reckhow (1984), Kenkel (1975), and Sen (1978,1979).

5. Streamflow interaction: Some water quality variables display strong concentration gradients between freshwater and seawater. For example, nitrate nitrogen is often 100-fold or more concentrated in rivers than in in the ocean. Consequently, in a low-salinity estuary like the Pamlico River where there is a strong riverine influence, the concentration of nitrate depends largely on Tar River flow, especially in the upper half of the estuary where most of the mixing occurs.

6. Censored data: Censored data are those observations reported as being "less than" or "greater than" some specific value. Examples include concentrations of nitrogen and phosphorus which fall below the limits of detection (LD) of the analytical procedures. Where "less than LD" observations arise in the Pamlico data set, the LD values are used in the trend tests. This causes the distribution of the data to deviate even farther from normality, and so parametric tests become less exact. However, provided that the LD does not change over the period of record, nonparametric tests such as the one used in this study (see below), may be used with no difficulty (Hirsch and Slack 1984).

Statistical tests used for trend analyses fall under one of two categories: 1) classical, or parametric or 2) distribution-free, or nonparametric (Bradley 1968). Classical tests, such as those used in regression, require the estimation of one or more parameters (for example, the slope of the regression line) based on the observed values of the variable and the distribution of the test statistic under the null hypothesis follows from an assumption about the underlying probability distribution of the random variable.

Distribution-free, or nonparametric, tests typically ignore the magnitudes of the the data in favor of the relative values or ranks of the data. The major advantage of distribution-free tests is that the underlying probability distribution of the random variable is immaterial. In fact, any strictly increasing monotonic transformation - such as taking logarithms - changes the values of the data, but does not affect the relative rankings. However, because the magnitudes are ignored, the test provides only a yes-or-no, not a how-much, answer.

The pros and cons of several parametric and nonparametric tests for trend are discussed by Montgomery and Reckhow (1984), Hirsch and Slack (1984), Lettenmaier (1976), and Montgomery and Loftis (1987). Montgomery and Loftis (1987) found that one of the most widely-used parametric tests, the t-test, is robust (i.e., is not appreciably affected by a violation of a given underlying assumption) for non-normal distributions if the distributions have the same shape (either symetric or skewed) and sample sizes are equal. The t-test is also robust for unequal variances if the sample sizes are equal. The t-test appears not to be robust when 1) samples come from two distributions of different shape, 2) samples have unequal variances and unequal sample sizes, 3) serial dependence in observations is present, or 4) seasonal changes in concentrations are present and not removed.

Another common parametric test for trend is based on linear regression of the variable of interest against time. The null hypothesis is that the variable and time are uncorrelated, and the background assumptions are that the data are normal, independent, and identically distributed in time. If the slope of the regression equation is found to be statistically significant, a trend is claimed. Unfortunately, several of the assumptions underlying the derivation of the necessary probability distribution to test for significance are violated by natural data. In general, water quality data have seasonality, are skewed, and serially correlated. These features contradict the assumptions of stationarity, normality, and independence of the random variable (the water-quality variable) required for computing the probability distribution of the test statistic in the regression test for trend. The seasonality inflates the variance used in the t-tests, the skewness increases the standard error in the estimated slope, and the serial correlation raises the actual alpha level relative to the selected alpha level. Any one of these defects may be sufficient to render the test invalid, especially since the amount by which they are present - and therefore, the amount by which the test is being distorted - cannot be known.

The same or similar objections can be raised against virtually every test for trend when applied to almost any water-quality variable. Attempts have been made to alter (transform) the data to remove or reduce the undesirable features. To remove seasonality, one might fit a sine curve to the data (Steele et al. 1974) and use the deviations from the curve as the random variable to be tested. But with the exception of a few variables such as water temperature, there is little reason to believe that the form of seasonality is a pure sine curve. The extent to which the cure works is largely unknowable. To eliminate skewness, one might use the logarithms of the data. Again, the extent to which this is proper is only a guess. Compensating for serial correlation is at best an art. Trying to do all three is extremely difficult, if not impossible. What is needed is a test that is largely unaffected by the three above-mentioned characteristics of the data. That is, the distribution of the test statistic is influenced little by these three characteristics of the data.

Appendix 4.5.
The Seasonal Kendall Trend test for water qulaity data

The distribution-free test which serves as the basis for trend testing in this study is Kendall's Tau (Kendall 1975). The null hypothesis for this test is that the random variable is independent of time. The only necessary background assumption is that the random variable is independent and identically distributed (with any distribution). In this test, all possible pairs of data values are compared; if the later value (in time) is higher, a plus is scored; if the later value is lower, a minus is scored. If there is no trend in the data, the odds are 50-50 that a value is higher (or lower) than one of its predecessors. In the absence of a trend, the number of pluses should be about the same as the number of minuses. If however, there are many more pluses than minuses, the values later in the series are more frequently higher than those earlier in the series, and so an uptrend is likely. Similarly, if there are many more minuses than pluses, a downtrend is likely.

As discussed above, the one common pattern to water-quality variables is that they have a period of one year (other periodicities may exist). Comparing, for example, a January value with a May value does not contribute any information about the existence of a trend, if a seasonal cycle of a 1-year period exists. Thus, Hirsch et al. (1982) defined the Seasonal Kendall test to be the Kendall's Tau test restricted to those pairs of data which are multiples of 12 months apart. Since comparisons are made only between data from the the same month of the year, the problem of seasonality is avoided. The random variables may be nonidentically distributed, provided that the distributions 12 months apart are identical. A complete specification of the Seasonal Kendall test is given below. Its derivation is given by Hirsch et al. (1982).

When all assumptions for the regression test are met, the regression test is the most powerful test for linear trend (Kendall and Stuart 1968). The Seasonal Kendall test is almost as powerful, based on a series of tests using generated random numbers (Hirsch et al. 1982). When skewness and seasonality were introduced into the experiments, the Seasonal Kendall test performed better than the test based on linear regression; and when serial correlation was introduced, it's effect on the Seasonal Kendall test was no more severe than it's effect on linear regression.

In addition to indicating whether a trend exists, it may be desirable to estimate the trend rate, or slope. Hirsch et al. (1982) defined the Seasonal Kendall Slope Estimator to be the median of the differences (expressed as slopes) of the ordered pairs of data values that are compared in the Seasonal Kendall test. Instead of recording a plus or minus for each comparison, one simply records the difference divided by the number of years seperating the data points. The median of these differences is taken to be the change per year due to the trend. A mathematical description of the Seasonal Kendall Test is given in Appendix B, page 32 in Smith et al. (1982).

* U.S. G.P.O.:1992-313-153:60516