TAR-PAMLICO RIVER BASIN REGIONAL COUNCIL

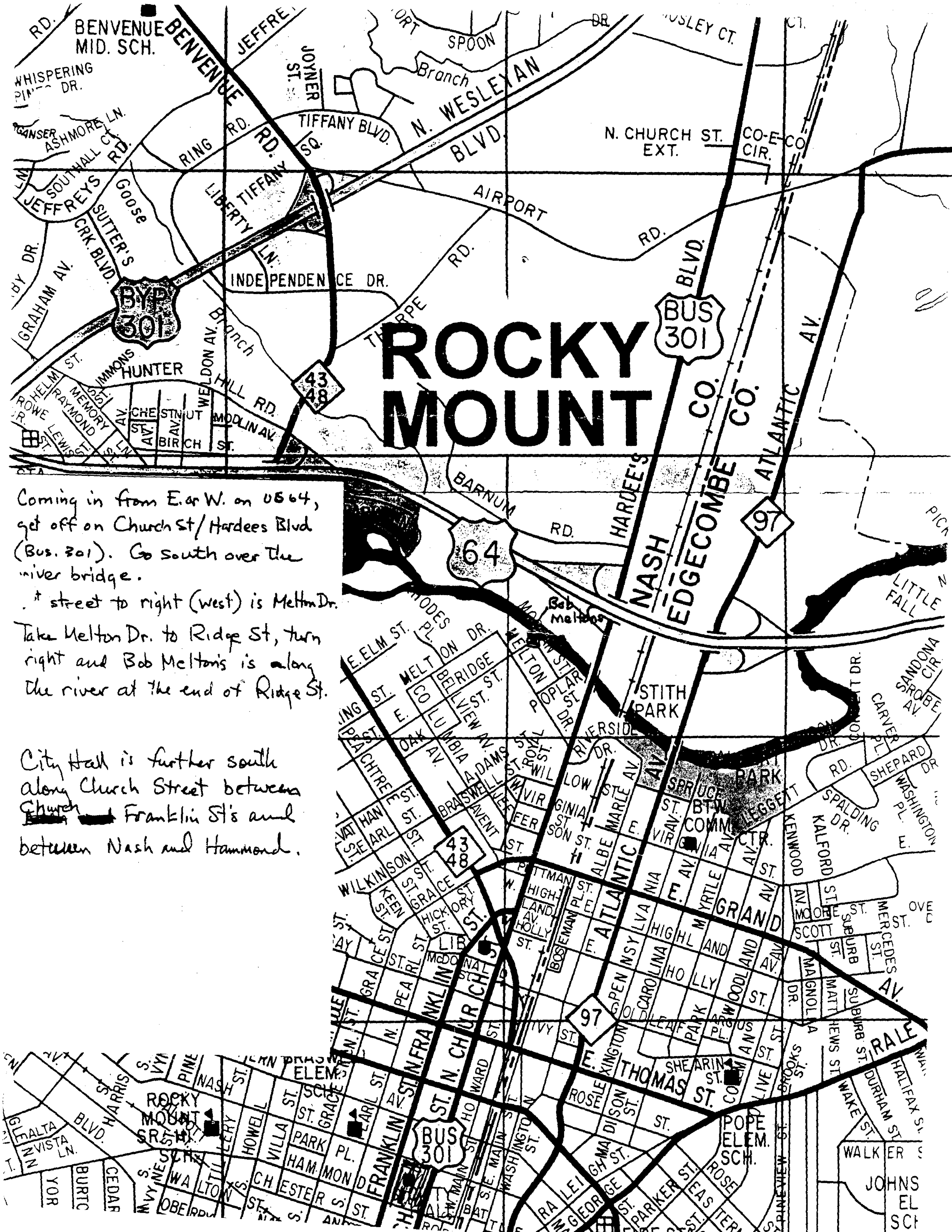
11:15 am LUNCH at Bob Melton's Restaurant
631 E. Ridge Street, Rocky Mount, NC (919) 446-8513

FEBRUARY 20, 1998

City Hall
1 Government Plaza
Rocky Mount, NV
(919) 972-1111

AGENDA

1:00	Call to Order & Welcome	Chairman Earl Bell
1:05	Self-Introductions	All
1:10	Acceptance of Minutes (1/23/98 Meeting)	Chairman Bell
1:20	"History of the Tar-Pamlico River Basin"	Dr. Donald Stanley East Carolina University
1:50	"Water Quality Monitoring in the Tar-Pamlico River Basin"	Callie Childress US Geological Survey
2:20	BREAK	
2:30	"Ambient Water Quality Monitoring in the Tar-Pamlico River Basin"	Norm Bedwell Division of Water Quality
3:00	Appointment of Coordinating Council Delegates	Chairman Bell
3:10	Prioritization of Environmental Concerns Within CCMP Categories: 1. Water Quality 2. Fisheries 3. Vital Habitats 4. Stewardship	Chairman Bell
4:00	New Business/Open Discussion 1. Extension Env. Ed. Agent for the Tar-Pamlico River Basin 2. Formation of a "Science Subcommittee"	Chairman Bell
4:30	Adjourn	



Coming in from E. or W. on US64, get off on Church St/Hardees Blvd (Bus. 301). Go south over the river bridge.
1st street to right (west) is Melton Dr. Take Melton Dr. to Ridge St, turn right and Bob Melton's is along the river at the end of Ridge St.

City Hall is further south along Church Street between ~~Church~~ [illegible] Franklin St's and between Nash and Hammond.

Tar-Pamlico River Basin Regional Council
City Hall
Rocky Mount, North Carolina

February 20, 1998

Meeting Notes

The meeting was called to order at 1:10 p.m. by Chairman Earl Bell. Self-introductions were made, with 23 members present.

A motion was made and seconded to approve the minutes for the January 23, 1998 Regional Council meeting. Motion passed.

Chairman Bell introduced Dr. Don Stanley, biology professor and researcher from East Carolina University, who gave a presentation to the council on trends in watershed nutrient production. Dr. Stanley concentrated on his approximately 20 years of research and monitoring in the Pamlico River portion of the watershed. Copies of the overheads used in his presentation are attached.

Next, Chairman Bell introduced Callie Childress from the U. S. Geological Survey. Ms. Childress spoke on trends in the Tar River basin, reporting on analyses collected monthly from the Tar River at Tarboro over the last 20 years, more or less. Copies of Ms. Childress' overheads are also included in this mailing.

Following Ms. Childress, Norm Bedwell of the North Carolina Division of Water Quality was introduced. Mr. Bedwell gave a presentation on ambient water quality monitoring in the Tar-Pamlico River Basin done by DWQ. There are 28 sites in the Tar-Pamlico basin that are monitored on a monthly basis, with 3 sites set up for daily sampling for nutrients.

The next order of business was the appointment of 3 delegates to the Coordinating Council. After nominations, discussion and voting, Earl Bell was selected to represent interest groups, Vince Bellis was selected to fill the municipal representative slot, and Boyce Cheek was selected for the county representative position. The first Coordinating Council meeting is scheduled for March 31 in Raleigh.

The prioritization of environmental concerns within CCMP categories was tabled until the next meeting, due to time constraints. This will be one of the only agenda items for the next meeting, because we have to complete this task in time for a facilitator to be present at the May 8 TPRBRC meeting to help go from priority concerns to a work program/action plan.

Next, Mary Jane Jennings introduced Mitch Woodward, an Extension Environmental Education Agent currently working in the Neuse River basin, who gave a slide presentation on their program. Currently there are 10 people in Extension dealing with nutrients and water quality in the Neuse basin, but none in the Tar-Pamlico basin. It was brought up that each of us needs to make phone calls to our State representatives to tell them that the Tar-Pamlico basin needs agents like the Neuse basin has. Mary Jane Jennings was nominated as the chair for a new Tar-Pamlico River Extension Environmental Education Subcommittee. Nomination was approved.

The discussion on formation of a Science Subcommittee was tabled, and may be included in the next meeting.

The next meeting of the TPRBRC was set for Friday, April 3, at the DENR Regional Office in Washington beginning at 1:00 pm. (See map enclosed). An informal lunch gathering will be held at the Riverside Restaurant (beginning at 11:30 am) which is located on Hwy. 17 at the foot of the Tar-Pamlcio bridge in Washington. Prior to lunch, members are encouraged to visit the NC Estuarium which is located at 223 East Water Street (right off of Stewart Parkway) also in Washington. The Estuarium opens at 10:00am and charges an admission of $3 for adults and $2 for school children. (See attachment).

The meeting was adjourned at 4:30 p.m.

Attendance
Tar-Pam Regional Council
3-20-98

NAME	AFFILIATION
Jean Giordano	DWQ Staff
Guy Stefanski	DWQ Staff
Norman Bedwell	DWQ Staff
Virico Bellin	Pitt Co.
JESSE A. SULLINS, JR	OXFORD
Joe SHEARON	LOUISBURG Town Council
Roger Simmons	PITT guest
DAN WYNNE	PITT
Tom ALLGOOD	TARBORO
S. EDWIN KNOTT	PERSON COUNTY (ROXBORO)
Timmy Thomas	Person County
B. Warnell	NASH Co.
LARRY S. ODOM	NASH County
William Boyce Cheek	Franklin County
Jim Stephenson	Beaufort Co
Earl Bell	Wilson Co
Jeff Furness	Beaufort County
Callie Childress	U.S.G.S.
Paul Blount	Rocky Mount/Nash County
DOROTHEA AMES	PITT Co.
Mary Jane Jennings	Franklin
Adele Baggett	Franklin
Joan S Muller	Env. Ed @ Inner Banks EE Center Hyde County
Mike Muller	Comm. Fish/Boat building
George C. Stewart	DSWC
Alan Clark	"NC DWQ"
Suzanne	"

(OVER)→

Adrienne Hine	Pamlico County Planner
Walter Cole	Pamlico County EHS

Daily Reflector 1-23-98

A sound resource

Now playing: our most valuable assets

It's about time marshes, mud flats and creeks got their due.

The blue-water rivers and sounds so vital to northeastern North Carolina's economy and culture are easy to see and enjoy. But their more humble components have been long overlooked and misunderstood. Now there is a new resource within arm's length of Pitt County that showcases waterways and encourages broader appreciation of these threads in our region's fabric.

Want to go?

North Carolina Estuarium

Hours:

Tuesday - Saturday
10 a.m. - 4 p.m.

Admission:

Adults: $3
School Children: $2
Preschoolers: Free

The North Carolina Estuarium in Washington teaches visitors and schoolchildren about the Pamlico-Albemarle estuary, an area where fresh and salt water mix and create unique habitats for plant and animal life. It is the only aquarium of its kind in North Carolina and the first project to be completed by the Partnership for the Sounds, a nonprofit organization that nourishes environmental tourism in northeastern North Carolina. The center's exhibits, among other things, explain the brackish marshes, mud flats and creeks that form an estuary and detail the work of wind, tide and water in shaping them. Exhibits also show the relationship between this environment and the heritage of rural communities in the region.

It is a resource in which this region can take particular pride because it promotes a better understanding of the unique ecology beneath the natural beauty of the region's most valuable asset.

The Pamlico-Albemarle estuary is the second largest in the nation, and remains one of the least developed and most productive systems of coastal rivers and sounds. But pollution, development and overfishing have taken their toll. The estuariam puts the region's wide, blue rivers and muddy backwaters on display in a way that captures their appeal, yet does not gloss over the water quality troubles that have clouded the future.

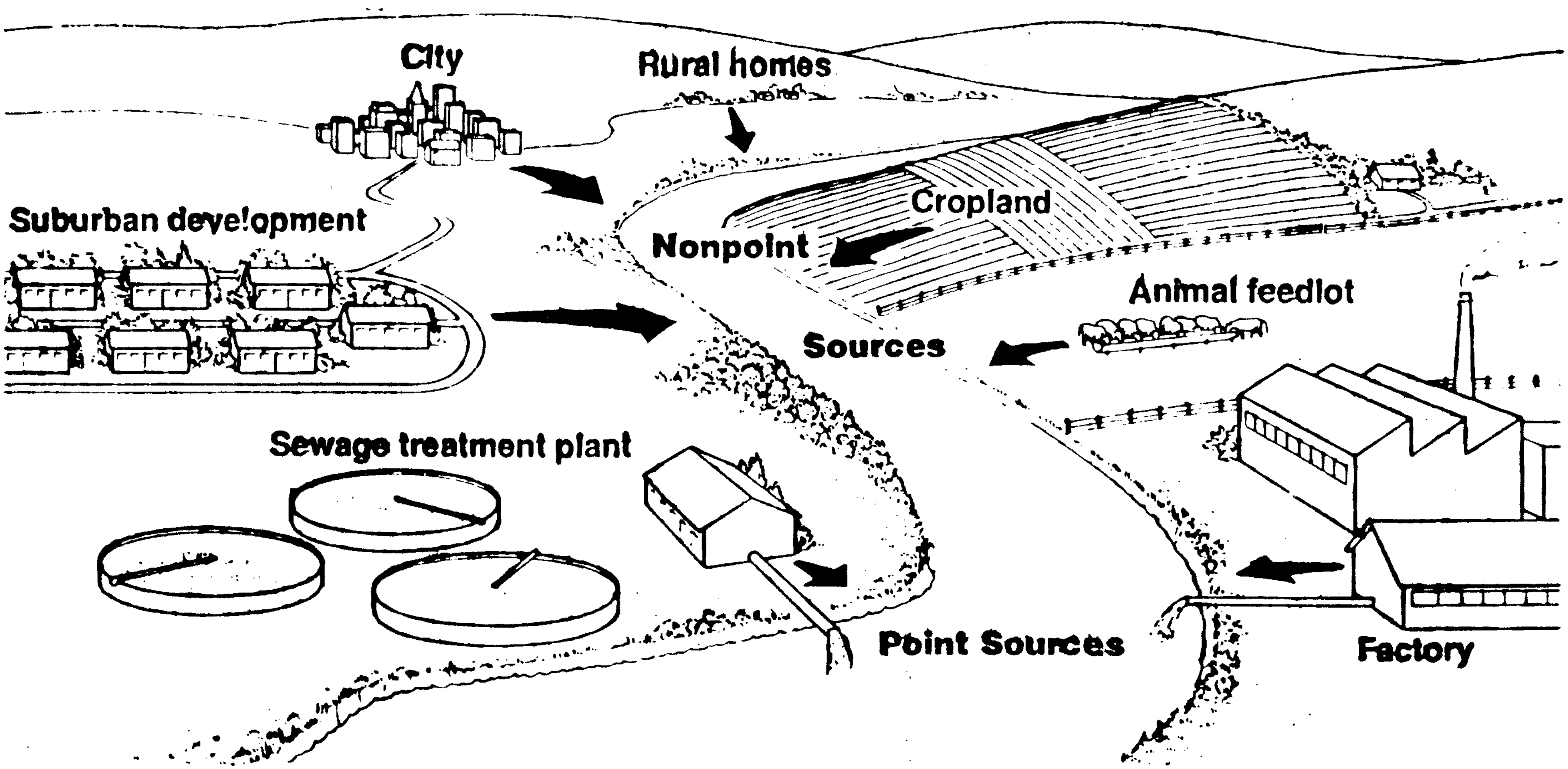
This is a learning center, yes, but it is also an effective and appealing economic development tool. The somewhat isolated communities of northeastern North Carolina have struggled with how to encourage a thriving economy, yet at the same time preserve the rural flavor of the region and protect natural resources. Ecotourism draws people who visit because they want to experience and learn about the environment and the culture. It is a fit for this region.

The new estuarium is an excellent resource, and it should be appreciated by old-timers and newcomers alike. It challenges the region to bring a new level of understanding to the stewardship of its valuable

TRENDS IN PAMLICO RIVER ESTUARY NUTRIENTS, CHLOROPHYLL, DISSOLVED OXYGEN, AND WATERSHED NUTRIENT PRODUCTION

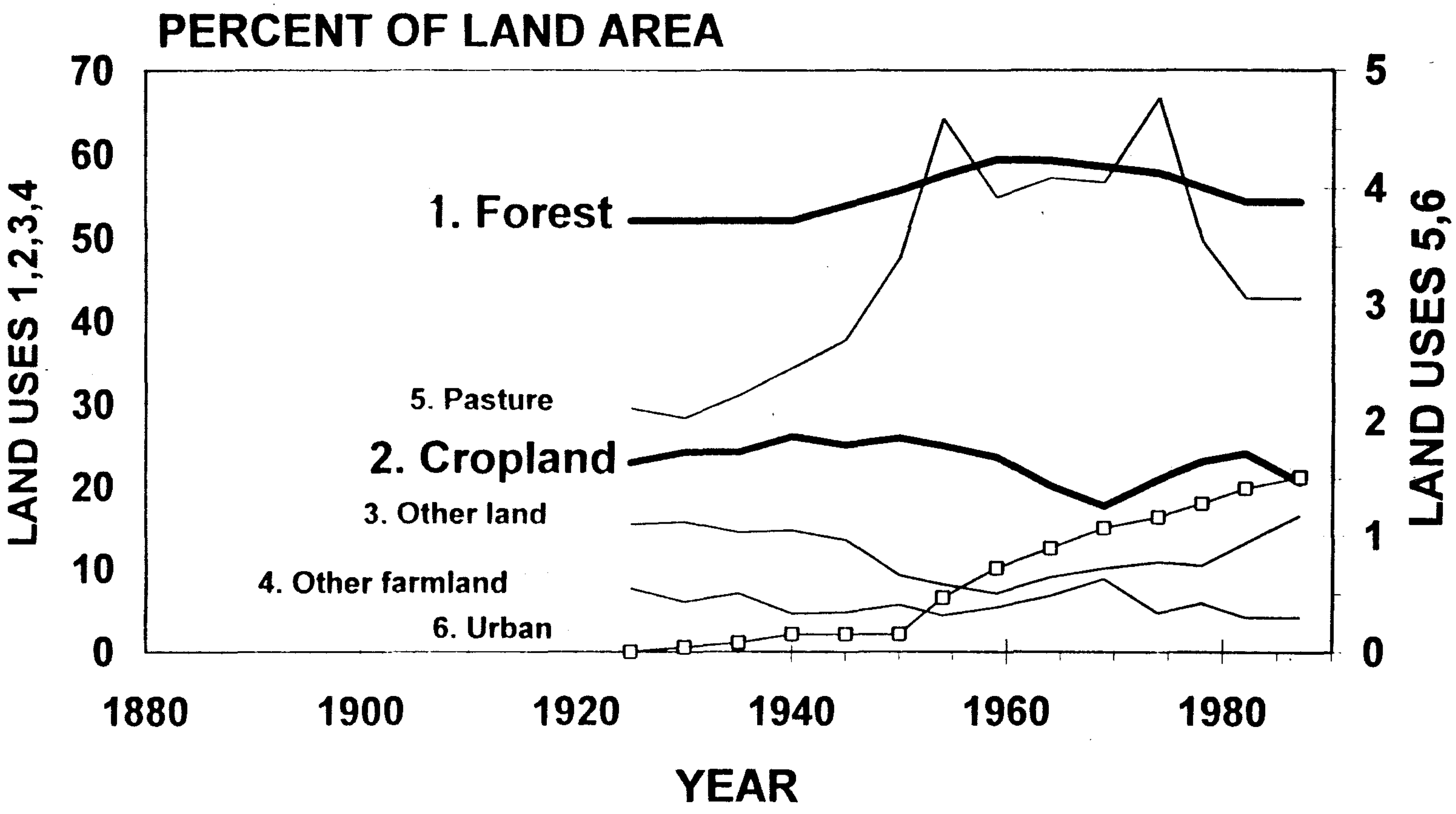
DON STANLEY
Institute for Coastal and Marine Resources, and Biology Department
East Carolina University, Greenville, NC 27858

Monitoring and Research Funding Sources
PCS Phosphate (formerly Texasgulf)
UNC Sea Grant College Program
UNC Water Resources Research Institute
NOAA

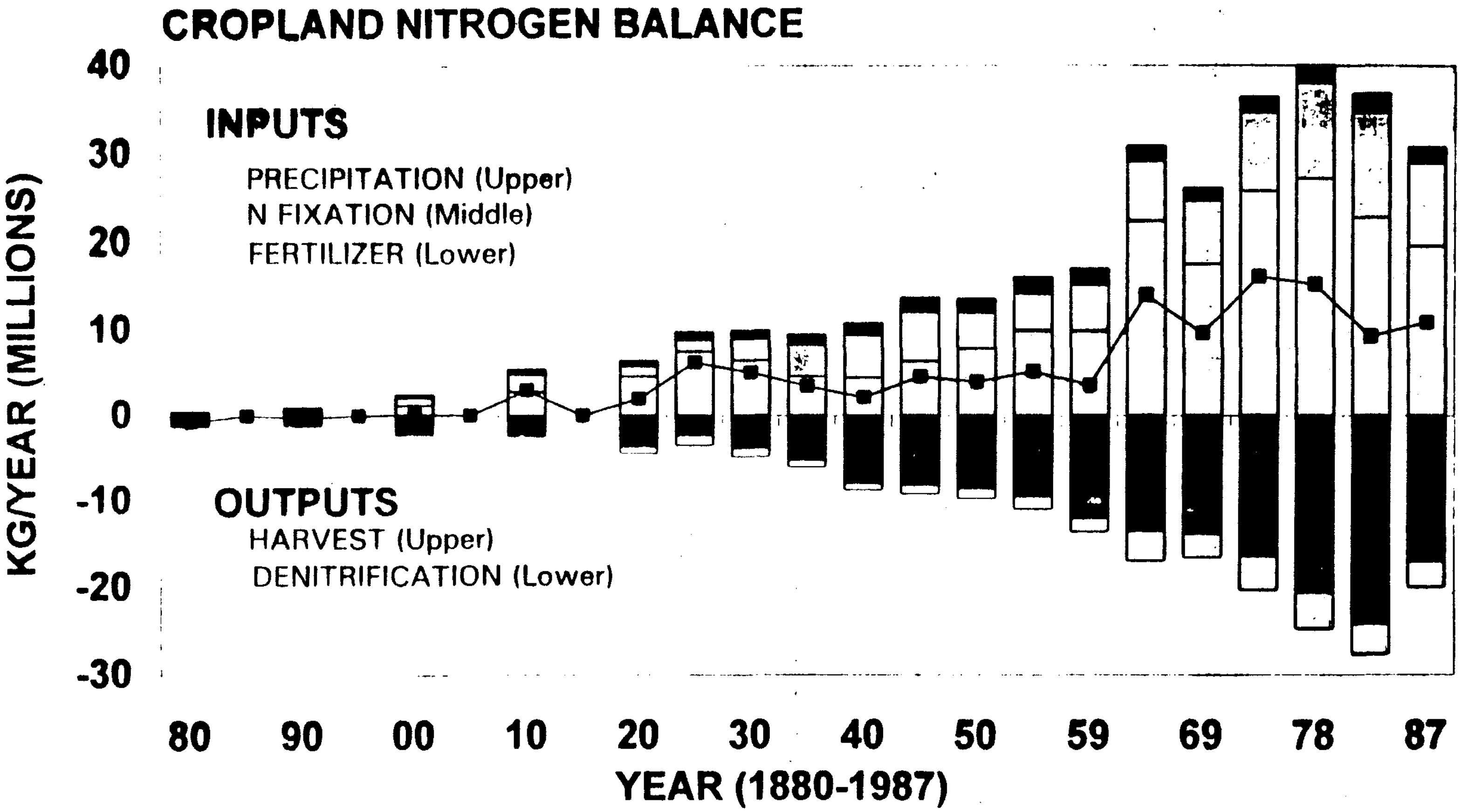


Point and nonpoint sources of water pollution.

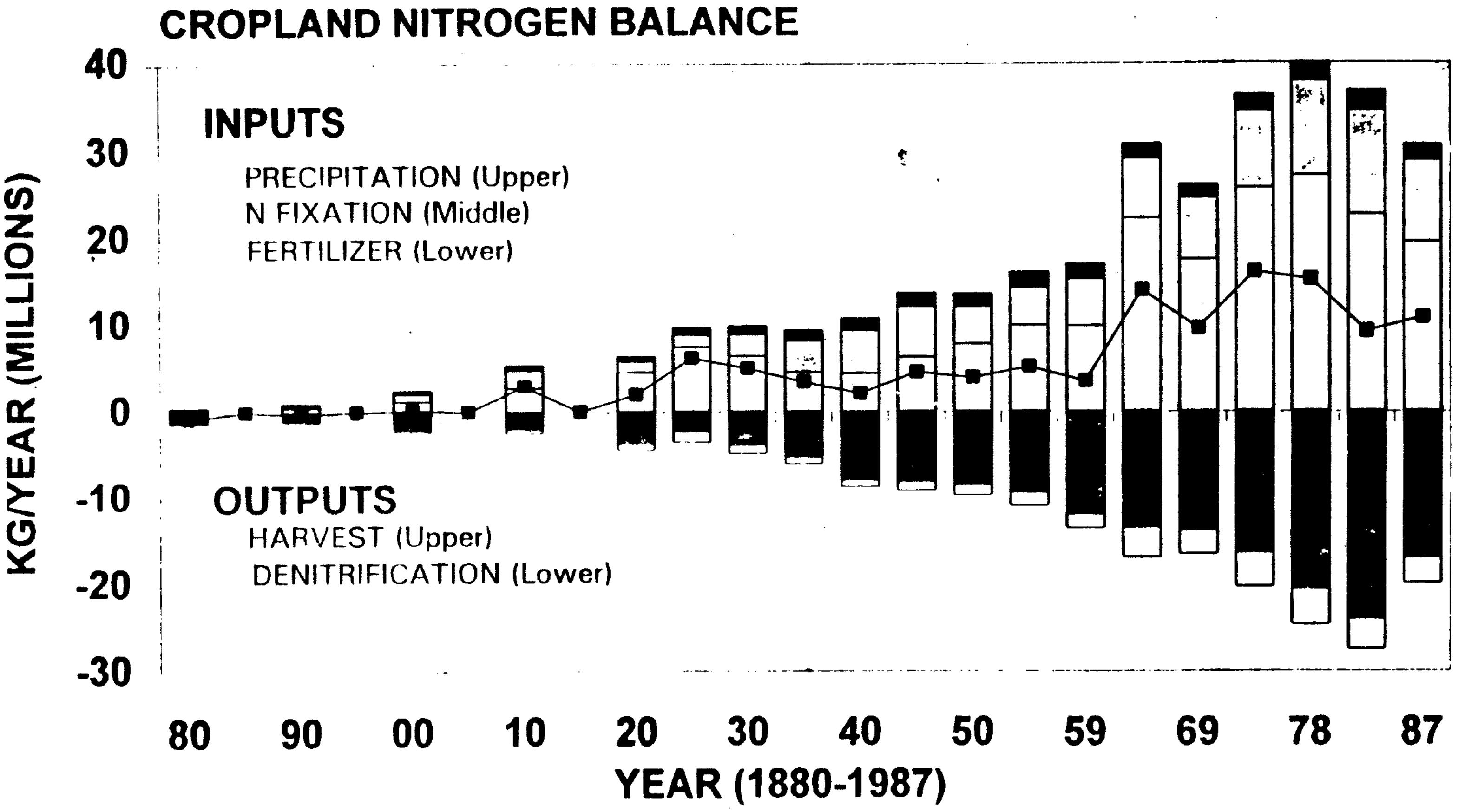
© [illegible] Wadsworth, Inc



- Little change in land use in the Pamlico watershed over the past century (ignoring local changes)
- Forest = 52%-59% of watershed area; cropland = 20%-26% of watershed area



- **N fertilizer use increased sevenfold (1940-1978); little change since**
- **Atmospheric N deposition estimated to have increased fivefold over past century**
- **Cropland N production increase from near 0 to peak around 1974; no trend since then**



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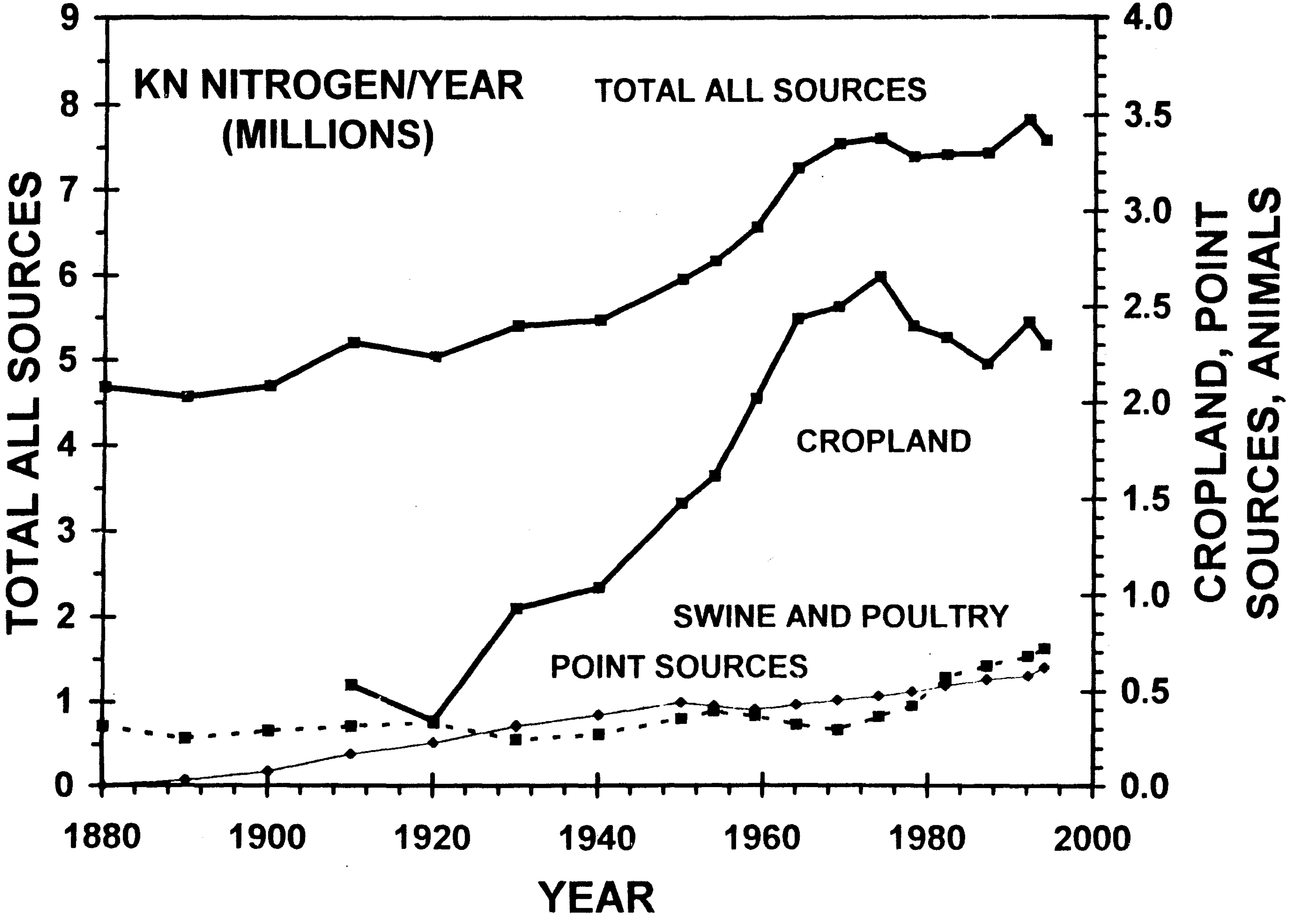
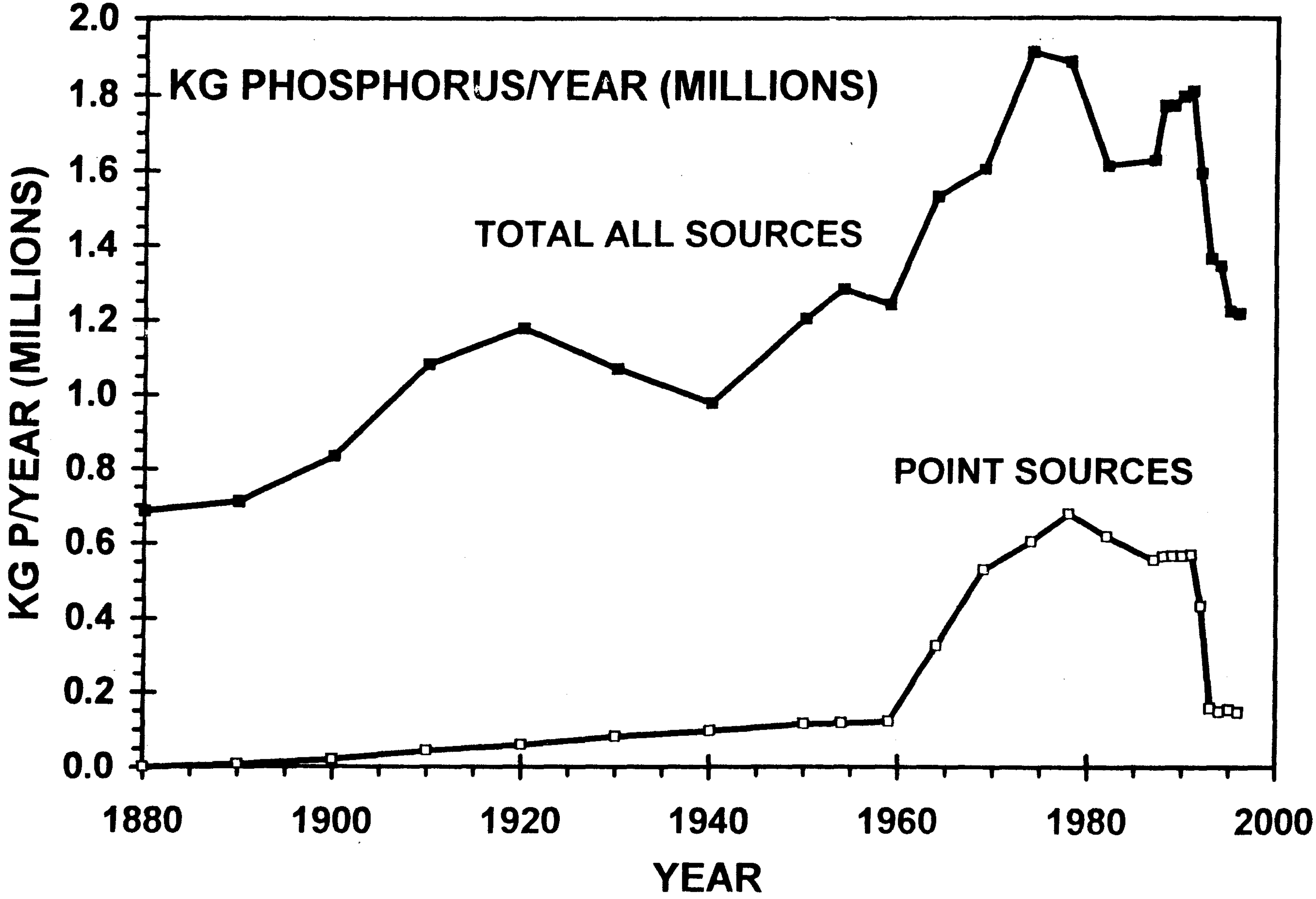

KN NITROGEN/YEAR (MILLIONS)
TOTAL ALL SOURCES
CROPLAND
SWINE AND POULTRY
POINT SOURCES
TOTAL ALL SOURCES
CROPLAND, POINT SOURCES, ANIMALS
YEAR
0
1
2
3
4
5
6
7
8
9
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
1880
1900
1920
1940
1960
1980
2000


KG PHOSPHORUS/YEAR (MILLIONS)
TOTAL ALL SOURCES
POINT SOURCES
KG P/YEAR (MILLIONS)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
1880
1900
1920
1940
1960
1980
2000
YEAR

FUTURE NUTRIENT PRODUCTION IN THE TAR-PAMLICO BASIN

1. MUNICIPAL WASTEWATER

For each doubling of the human population, wastewater treatment efficiency will have to be improved enough to reduce the per capita nutrient production by 50 percent, in order to maintain current nutrient production rates.

FUTURE NUTRIENT PRODUCTION IN THE TAR-PAMLICO BASIN

2. CROPLAND

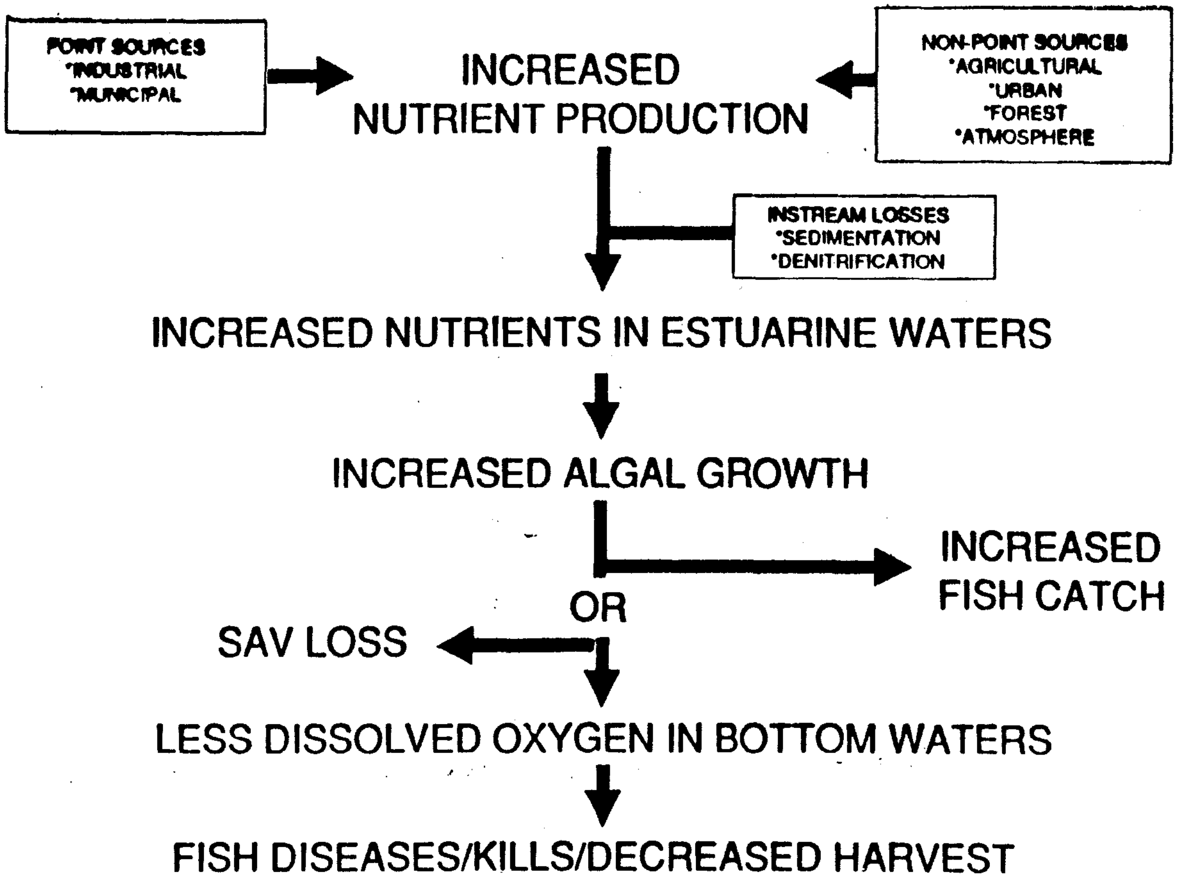
Assuming cropland acreage and fertilizer application rates do not increase substantially, BMPs may further reduce the cropland nutrient production rates.

Apparently, only 1/5-to-1/7 of cropland nutrient production reaches estuary. Therefore, maintenance of wetlands and other watershed features that sequester nutrients (via denitrification and sedimentation) is critical.

FUTURE NUTRIENT PRODUCTION IN THE TAR-PAMLICO BASIN

3. ANIMAL WASTES

- ***Most rapidly-growing nutrient source in the basin:*** **Present swine population in Tar basin equal to human population (one animal equals one-to-two humans in terms of sewage nutrient produced)**
- ***Uneven distribution:*** **Swine are concentrated in the southeastern region of the state. Two counties - Sampson and Duplin - contain 40% of the total NC swine population and 5 times as many as all of the Tar-Pamlico basin, suggesting a large growth potential.**
- ***Prediction difficult:*** **Due to growth potential and uncertainties about future disposal methodologies.**


POINT SOURCES
•INDUSTRIAL
•MUNICIPAL
INCREASED
NUTRIENT PRODUCTION
NON-POINT SOURCES
•AGRICULTURAL
•URBAN
•FOREST
•ATMOSPHERE
INSTREAM LOSSES
•SEDIMENTATION
•DENITRIFICATION
INCREASED NUTRIENTS IN ESTUARINE WATERS
INCREASED ALGAL GROWTH
INCREASED
FISH CATCH
OR
SAV LOSS
LESS DISSOLVED OXYGEN IN BOTTOM WATERS
FISH DISEASES/KILLS/DECREASED HARVEST

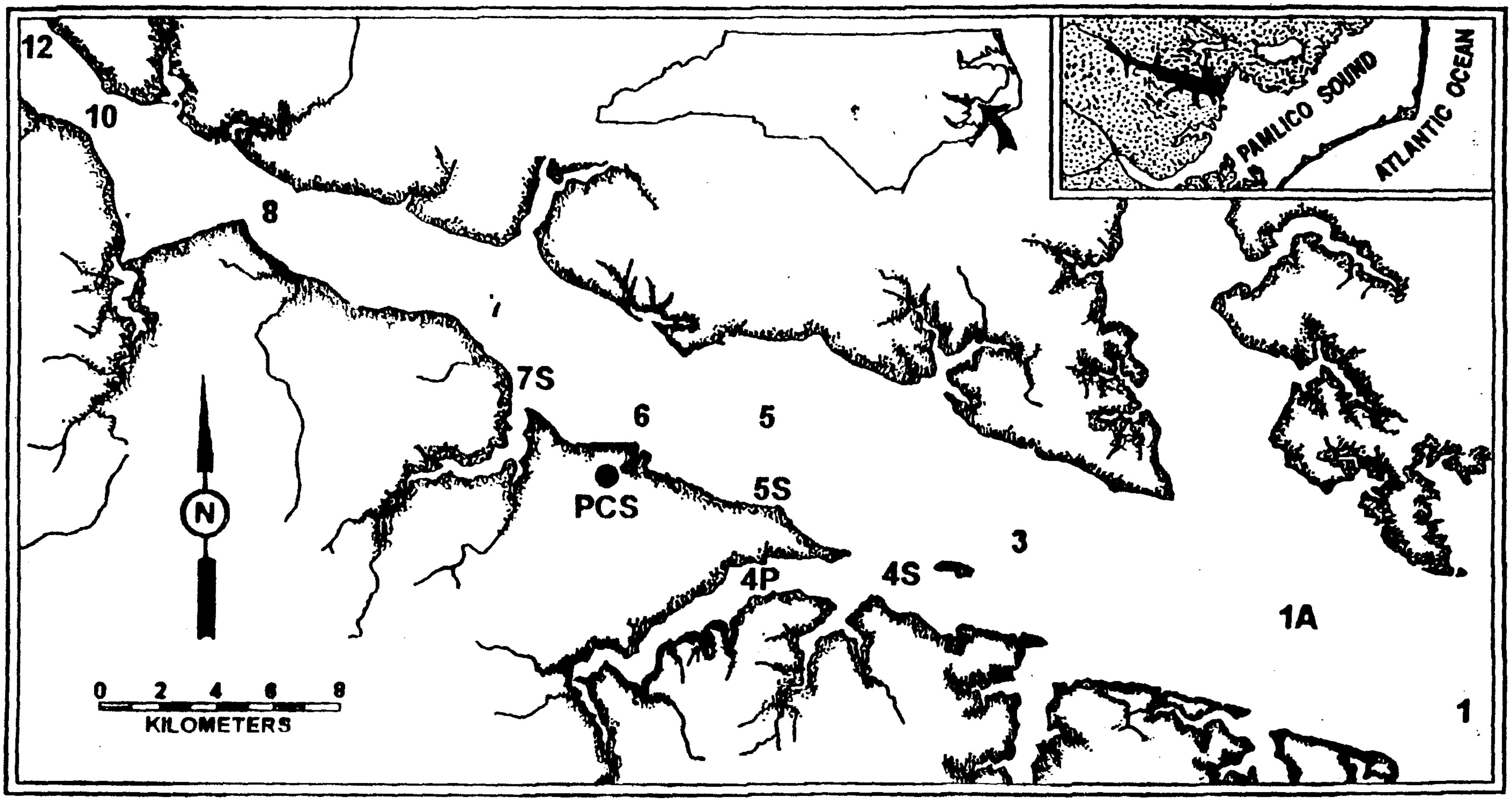


Figure 1. Map of the Pamlico River estuary, showing sampling station locations. "PCS" is PCS Phosphate.

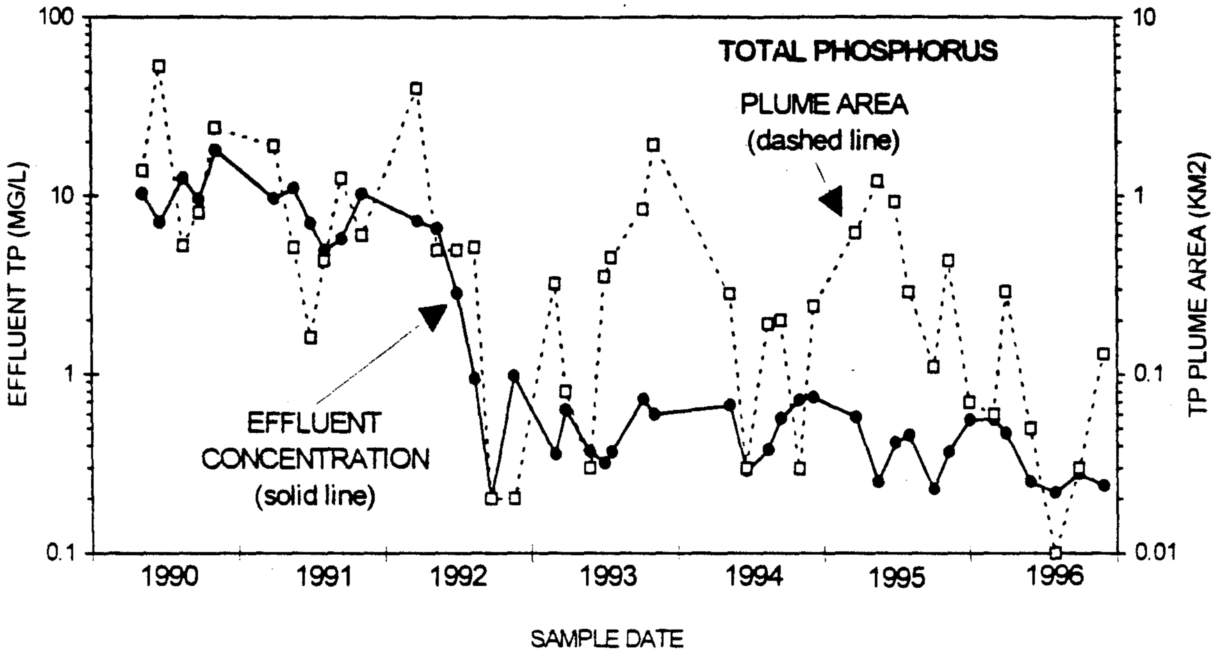


Figure 11. Trends in PCS Phosphate effluent total phosphorus (TP) concentrations and TP plume areas on transect sampling dates, 1990-1996.

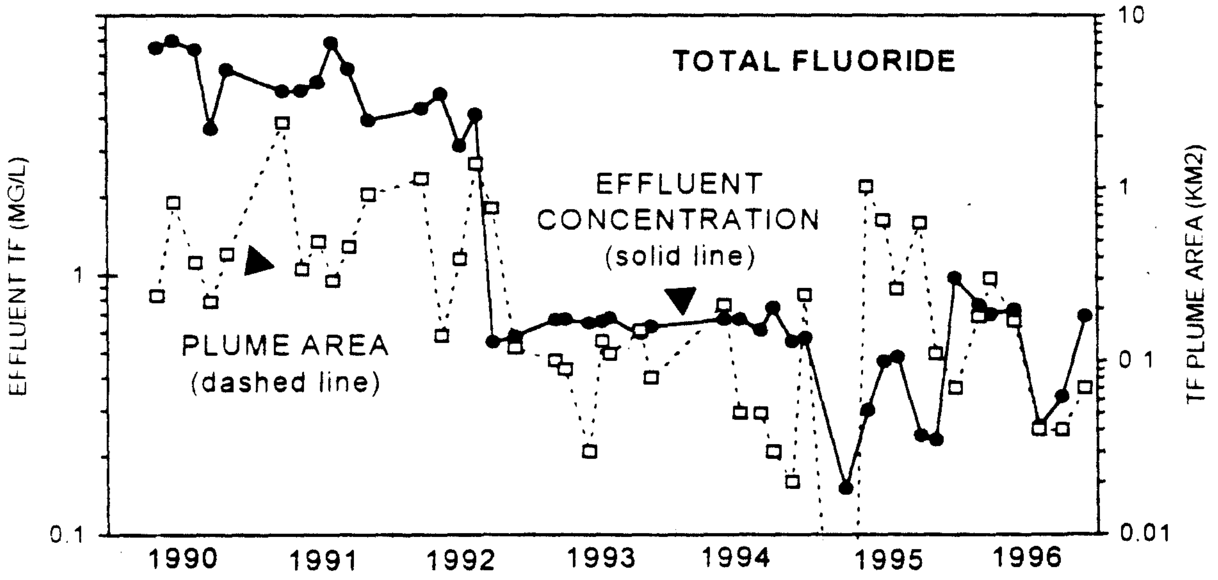
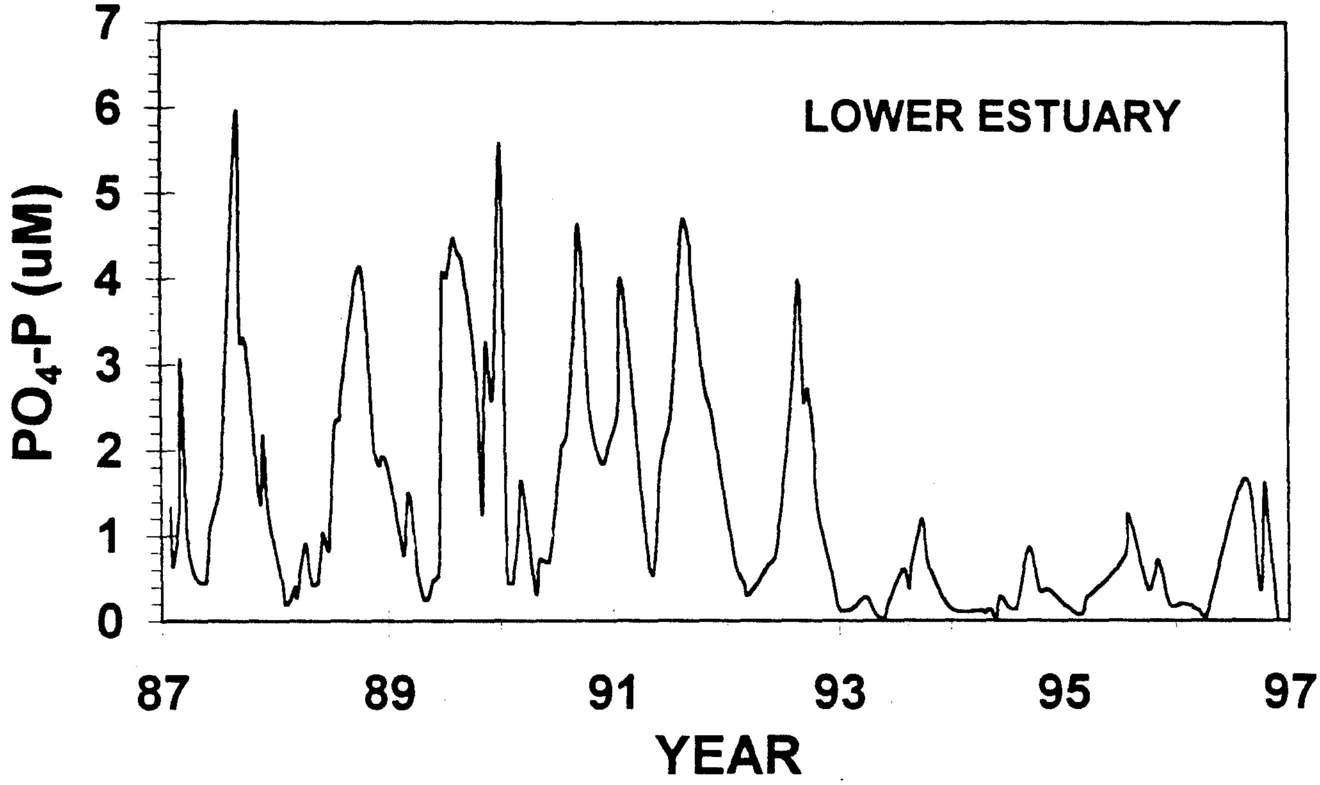
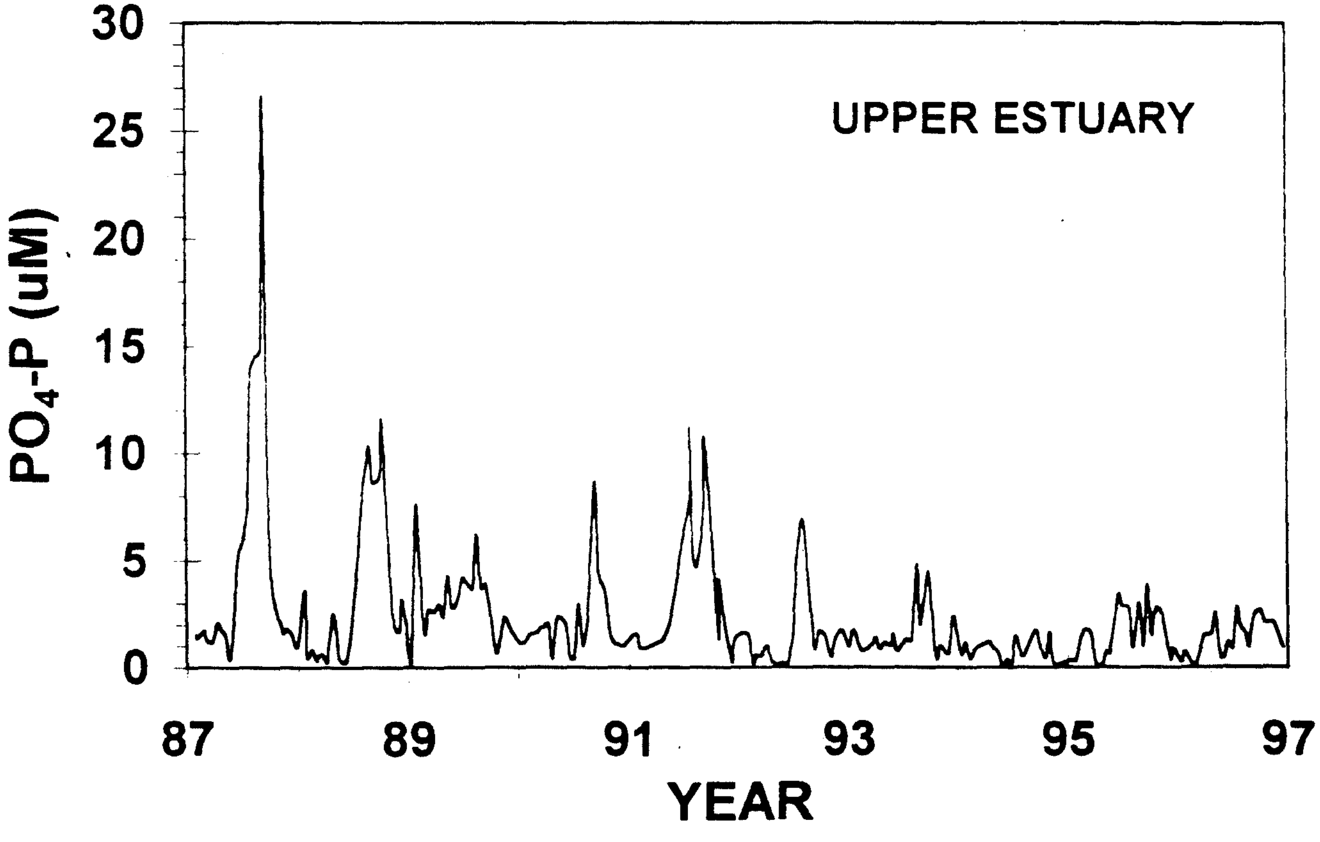


Figure 12. Trends in PCS Phosphate effluent total fluoride (TF) concentrations and TF plume areas on transect sampling dates, 1990-1996.


LOWER ESTUARY
PO$_4$-P (uM)
0
1
2
3
4
5
6
7
87
89
91
93
95
97
YEAR


UPPER ESTUARY
PO$_4$-P (uM)
0
5
10
15
20
25
30
87
89
91
93
95
97
YEAR

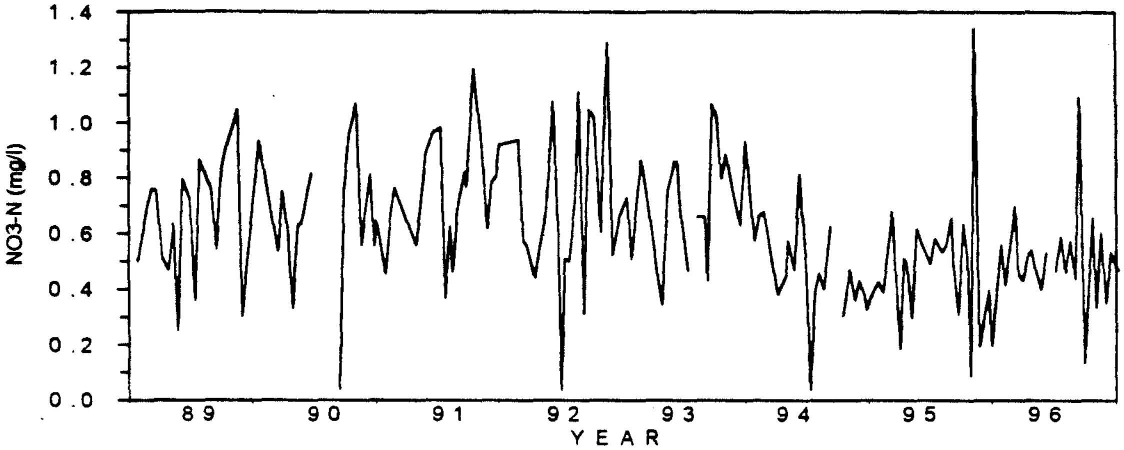


Figure 19. Nitrate nitrogen (mg N/l) at Seine Beach station on the Tar River: 1989-1996

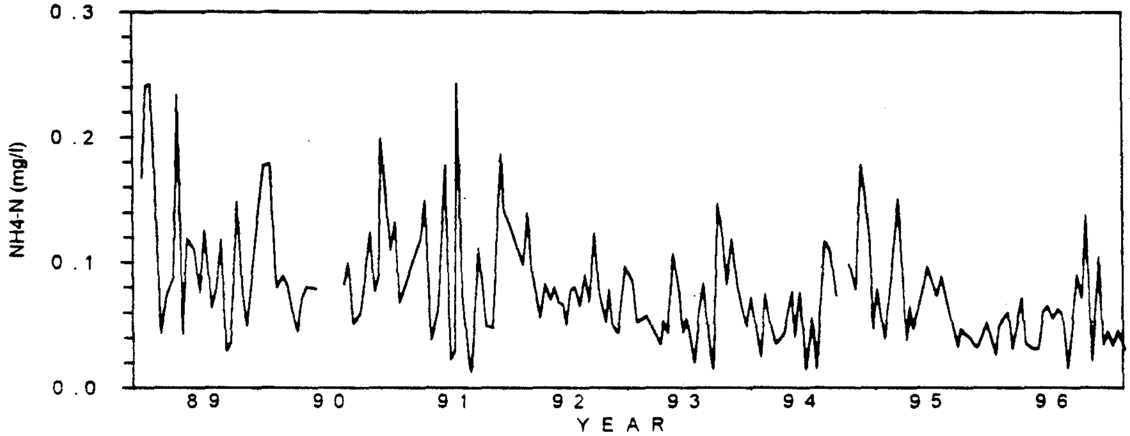


Figure 20. Ammonia nitrogen (mg N/l) at Seine Beach station on the Tar River: 1989-1996

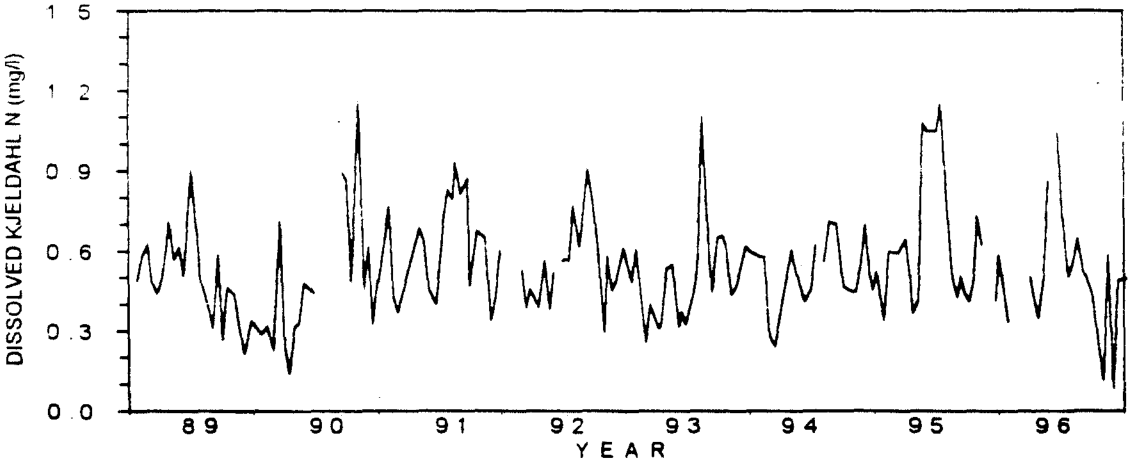
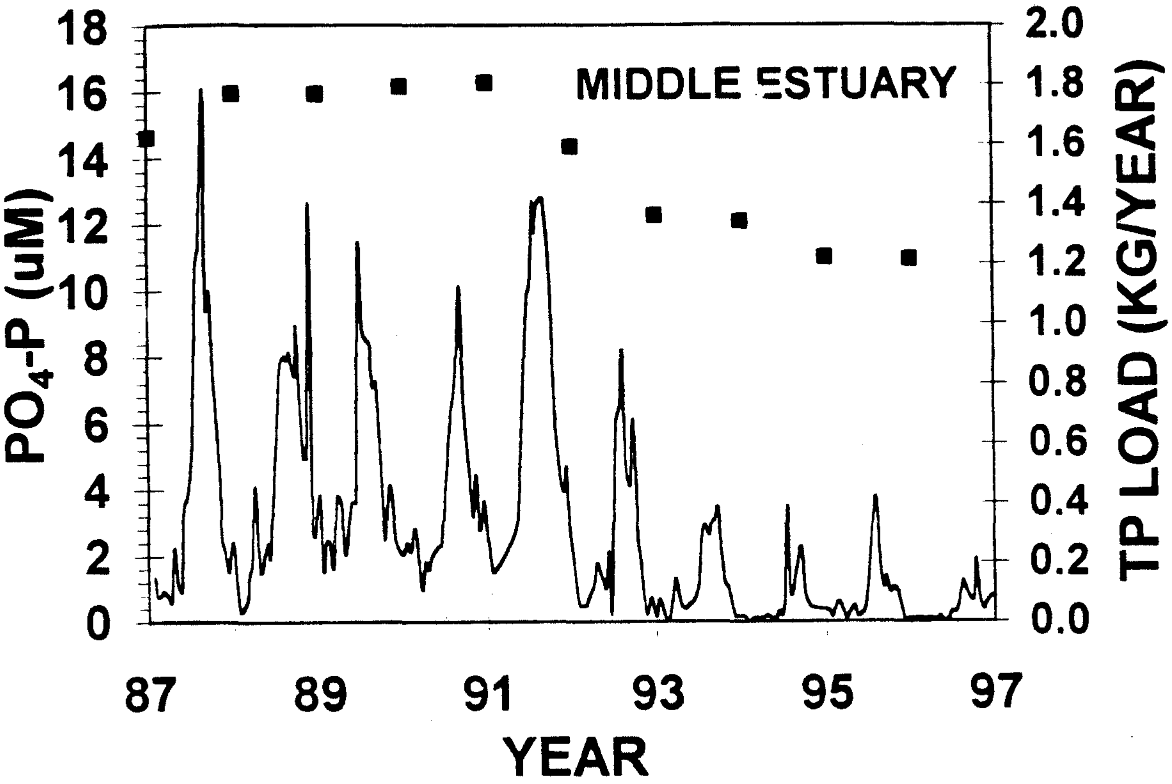
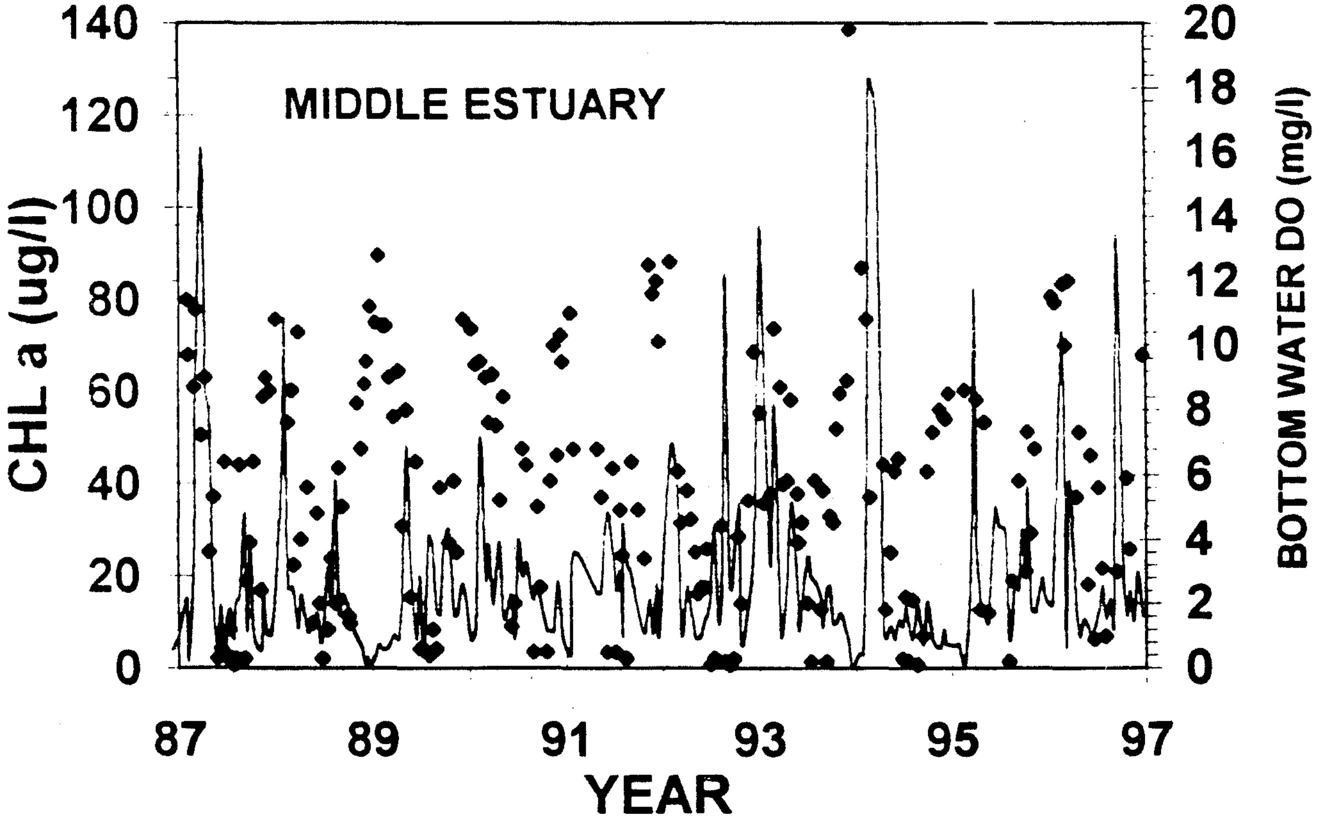


Figure 21. Dissolved Kjeldahl N (mg N/l) at Seine Beach station on the Tar River: 1989-1996


MIDDLE ESTUARY
PO$_4$-P (uM)
TP LOAD (KG/YEAR)
YEAR
0
2
4
6
8
10
12
14
16
18
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
87
89
91
93
95
97


MIDDLE ESTUARY
CHL a (ug/l)
BOTTOM WATER DO (mg/l)
YEAR
0
20
40
60
80
100
120
140
0
2
4
6
8
10
12
14
16
18
20
87
89
91
93
95
97

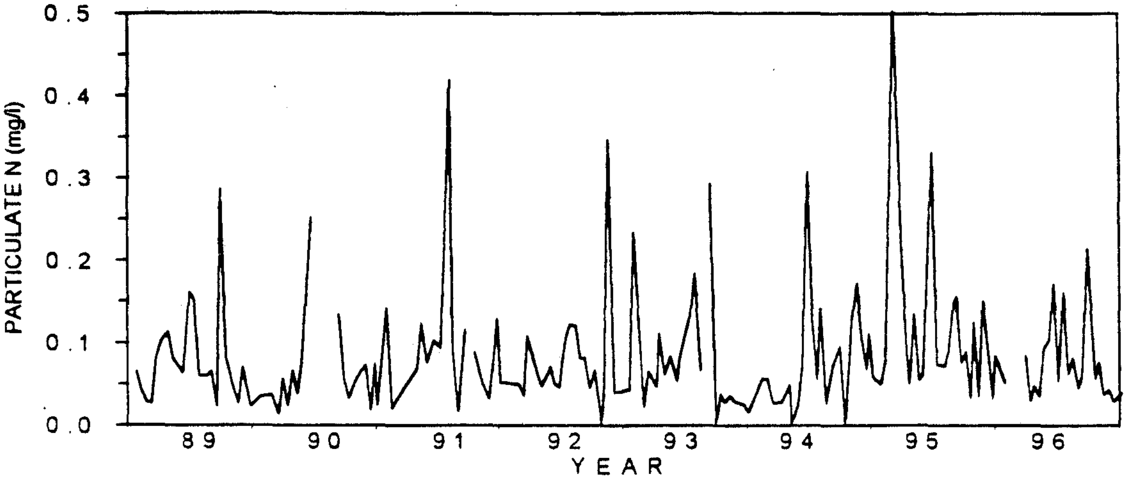


Figure 22. Particulate nitrogen (mg N/l) at Seine Beach station on the Tar River: 1989-1996

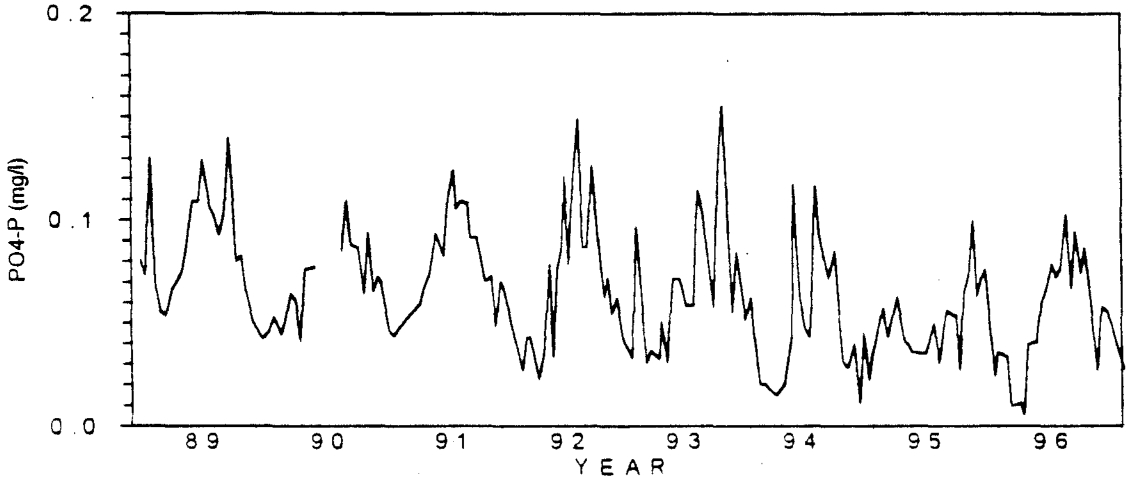


Figure 23. Orthophosphate P (mg P/l) at Seine Beach station on the Tar River: 1989-1996

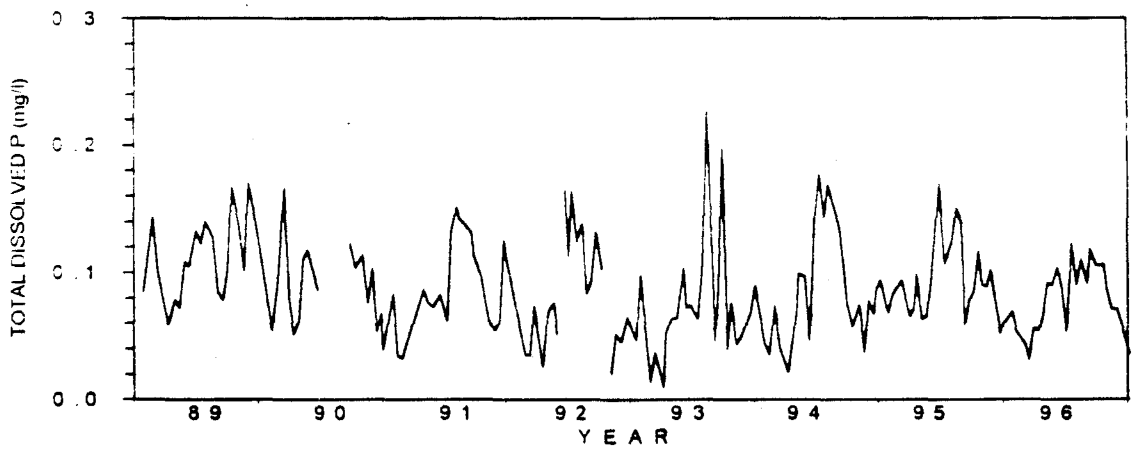


Figure 24. Total dissolved P (mg P/l) at Seine Beach station on the Tar River: 1989-1996

WATER QUALITY IN THE PAMLICO RIVER ESTUARY: 1989-1996

A Report
to
PCS Phosphate
P.O. Box 48
Aurora, North Carolina 27806

(ICMR Technical Report 97-02)

by

Donald W. Stanley

Institute for Coastal and Marine Resources
and
Biology Department
East Carolina University
Greenville, North Carolina 27858-4353

June, 1997

SUMMARY

This report summarizes 1989-1996 results from a continuing study of water quality in the Pamlico River estuary. The project, funded by PCS Phosphate (formerly Texasgulf Inc.) was begun in 1975 following a similar 1967-1973 study that was also funded in part by Texasgulf. There are few, if any, estuaries in the United Stated that have been monitored longer or more thoroughly than the Pamlico for changes in nutrient status and eutrophication.

Ten-to-thirteen stations in the estuary and one on the lower Tar River were sampled approximately every other week. Depth profiles of salinity, temperature, dissolved oxygen, pH and PAR (photosynthetically available radiation (400-700 nm)) were made and surface and bottom water samples were collected for analyses of total dissolved phosphorus (TDP), dissolved orthophosphate phosphorus (PO_4-P), ammonia nitrogen (NH_4-N), nitrate nitrogen (NO_3-N), dissolved Kjeldahl nitrogen (DKN), particulate nitrogen (PN), particulate phosphorus (PP), chlorophyll *a*, and total fluoride.

Water temperatures typically ranged from around 4°C in January to about 30°C in July and August. Strong vertical thermal gradients were rare. Salinity in the estuary is closely linked to Tar River flow which typically peaks in March and is lowest in October. Flow was unusually low in late 1988 and early 1989 so that bottom-water salinities greater than 15 ppt extended all the way up the estuary. From June 1989 through June 1990 river flow was close to the long-term average and summer salinities ranged from 0-2 ppt at the upper end to 15 ppt at the mouth while the winter range was 0-10 ppt. From mid-1990 through mid-1992 flow was below average 90 percent of the time and salinities were higher than normal. Ten ppt or higher salinity was common in the lower half of the estuary year-round, and surface salinities less than 2 ppt were uncommon, even in the upper reaches. The 1992-1993 winter saw a return to normal flows, but the second half of 1993 was another low flow, high salinity period. The 1993-1994 winter was average, but most of 1994 was also a time of low flows and high salinities.

Water column stratification in the Pamlico can form or disappear in a matter of hours, and episodes lasting from one to several days seem to be common. The stratification events result more from salinity gradients than temperature gradients; thus they are tightly coupled with variations in freshwater inflow. It appears that the regions between Stations 8 and 10 (upper estuary), and around Station 1 (mouth) are more prone to stratification than most other areas.

Light extinction coefficients, calculated from the PAR data, were highest in winter in the upper estuary and lowest in summer in the lower estuary. The upstream-downstream ranges were from <1 m^{-1} to 2 m^{-1} when Tar River flow was low, and from 2 m^{-1} to >4 m^{-1} during high-flow conditions. The variability is due partly to changes in phytoplankton abundance, but variation in the silt load brought down by the Tar River is thought to be

more important. Calculations based on the PAR data indicate there is light limitation on phytoplankton growth, particularly in the upper region of the estuary.

The pH of water in the estuary generally ranged between 6.5 and 8.5, which is the same range observed in previous years. River water normally has a lower pH than seawater, which explains the rising pH trend toward the mouth of the estuary. This spatial pattern was strongest when Tar River flows were lowest (i.e., the salinity gradient across the the estuary was largest).

Most surface dissolved oxygen readings were between 6 mg/l and 12 mg/l, which was at or above 80% saturation. Bottom water oxygen was often low in the summer and early fall, because of water column stratification, which isolates the bottom water layer from two major sources of oxygen: atmospheric exchange at the air-water interface, and photosynthesis, which is limited in the bottom layer by low light intensity. Meanwhile, respiration by organisms both in the water column and in the sediments continues, so that inevitably the lower waters become hypoxic or anoxic if the stratification continues. Warm temperatures also plays an important role since they increases the respiration rates. Thus, while stratification may occur in the estuary at any time of the year, anoxia and hypoxia can develop only when the water is warm enough for respiration to consume all the available oxygen before the next mixing event.

Before 1993 summertime PO_4-P levels were mostly in the range 0.2-0.4 mg P/l. Highest concentrations were at the most upriver station, and at a station close to the PCS Phosphate outfall. Winter and spring concentrations were typically less than 0.1 mg P/l. During stratification, bottom water concentrations 0.03-0.31 mg P/l higher than surface concentrations were common in the upper half of the estuary in the summers of 1989-1992. The occurrence of such gradients under these conditions is usually attributed to trapping of remineralized phosphate released from sediments.

The wastewater recycling program begun in the fall of 1992 by PCS Phosphate resulted in an almost immediate major reduction in phosphorus in the estuary. Total phosphorus in PCS effluent decreased about 94% to around 0.4 mg P/l when the recycling began, and has remained at about this level since. In the estuary near the outfall orthophosphate levels quickly dropped to around 0.06 mg P/l in summer and 0.01 mg P/l in winter. Large decreases have also occurred in the upper and lower estuary regions. Comparison of the 1993-1996 data with that for 1989-1992 indicates that the PCS reduction has caused phosphorus concentrations throughout the estuary to decrease by at least 50%.

Before 1993 particulate phosphorus (PP) made up a relatively small fraction of the total P in the estuary. Most surface sample values were in the range 0.03-0.1 mg P/l. There were not strong seasonal or spatial variations, although the higher values were mostly in the upper half of the estuary. Since the PCS effluent contains little PP, there was no noticeable change in its concentration after 1992. Many of the peaks in particulate phosphorus coincided with chlorophyll *a* peaks, which suggests that much of the PP in the estuary is in the algae.

Concentrations of nitrate-nitrogen in the Pamlico peak upriver during winter; and are lowest downriver during the summer. In the upper third of the estuary wintertime surface nitrate was mostly 0.28-0.7 mg N/l, while downstream the concentrations dropped off to less than 0.014 mg N/l. In the summer, there was not much nitrate anywhere in the estuary. Ammonia nitrogen was somewhat higher in the upper estuary during the early (high flow) months of most years (0.06-0.14 mg N/l) than later in the year (0.01-0.06 mg N/l) when river flow subsided. In the lower half of the estuary, surface concentrations were seldom higher than 0.03 mg N/l. At times during the summers there were strong vertical NH_4-N gradients (bottom water higher than surface water) that coincided with strong water-column stratification. Such gradients are evidence that much ammonification takes place in the sediments and that NH_4-N increases near the bottom as it is released but prevented from being mixed throughout the water column.

Surface water dissolved Kjeldahl nitrogen averaged around 0.28-0.56 mg N/l. There was very little difference between surface and bottom concentrations on most sampling dates. The concentrations were slightly higher in the upper estuary than in the lower half, and in some years were slightly higher in summer than in winter. Particulate nitrogen (PN) often was less concentrated that dissolved Kjeldahl nitrogen, but more concentrated than nitrate or ammonia nitrogen. Most surface sample values were in the range 0.14-0.56 mg N/l. There were not strong seasonal or spatial variations, although the higher values were mostly in the upper half of the estuary. As was noted above for particulate phosphorus, many of the PN peaks coincided with high chlorophyll *a* values, which suggests that much of the PN in the estuary is in the algae.

Chlorophyll *a* concentrations were mostly in the range 10-40 ug/l. In the upper half of the estuary higher concentrations (40-100 ug/l) developed periodically. Farther down the estuary, the biomass peaks were in the late winter, and were probably caused by blooms of dinoflagellate algae that occur almost every year in the Pamlico. Differences between surface and bottom chlorophyll concentrations were rarely greater than 10 ug/l. Overall, the 1989-1996 chlorophyll *a* data are similar to those of the mid-to-late 1980s. Results of a trend test analysis showed that the fifty percent reduction in phosphorus in the Pamlico after September 1992 has had no effect on chlorophyll *a* levels in the estuary.

Total fluoride (TF) concentration in the estuary is determined by the water salinity, and to a lesser extent, the impact of the PCS Phosphate discharge. Seawater TF concentration is 1.32 mg/l, while in river water the concentrations are much lower, averaging less than 0.2 mg/l. Fluoride appears to behave conservatively in estuaries so that a steady increase should be expected in the seaward direction. Between 1990 and September 1992, when wastewater recycling began at PCS Phosphate, the facility's effluent fluoride levels ranged from 3.1 to 8.0 mg/l (mean = 5.53 ± 0.80 mg/l). Since wastewater recycling began, the effluent fluoride levels have decreased by approximately 90% to around 0.15-1.0 mg/l (mean = 0.56± 0.07 mg/l). In the estuary, TF concentrations before September 1992 were >0.4 mg/l from Station 6 (near the PCS outfall) seaward except during high flow periods in late winter and early spring. Since 1992, TF in the middle section of the estuary has decreased to 0.2-0.3 mg/l.

Concentrations of dissolved nitrogen and phosphorus at the Seine Beach station on the lower Tar River were similar to those at the upper end of the estuary. Nitrate nitrogen averaged 0.62 mg N/l (range 0.4-1.3 mg N/l). Ammonia nitrogen was less concentrated, averaging 0.08 mg N/l (range 0.01-0.24 mg N/l), and dissolved Kjeldahl nitrogen averaged 0.54 mg N/l (range 0.08-.17 mg N/l). Orthophosphate phosphorus (PO_4-P) was only slightly lower (0.07 mg P/l) than total dissolved phosphorus (0.09 mg P/l). Both showed the same seasonal pattern as in the estuary in that concentrations were higher in summer than in winter. Both particulate nitrogen (PN) and particulate phosphorus (PP) were less abundant in the river than in the estuary, probably because algal biomass is also much lower in the river. PN averaged 0.09 mg N/l and PP averaged 0.04 mg N/l at the Seine Beach station. Chlorophyll *a* was occasionally greater than 10 ug/l at the Seine Beach station, but the average was only 4 ug/l, compared to an average of around 30 ug/l in the estuary. Low algal abundance in rivers is the norm because severe light limitation and short residence times prevent the buildup of large populations. Finally, total fluoride averaged 0.16 mg/l at Seine Beach, which was about the same as at the upper end of the estuary.

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Long-Term Trends in Pamlico River Estuary Nutrients, Chlorophyll, Dissolved Oxygen, and Watershed Nutrient Production

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Trends in Pamlico River estuary ammonia nitrogen (NH_4), nitrate nitrogen (NO_3), phosphate phosphorus (PO_4), chlorophyll *a* (chl *a*) and dissolved oxygen (DO) during the past 20–24 years were analyzed, and estimates of annual N and P production in the watershed over the past century were computed. The goal of the study was to determine whether or not the estuary is becoming more eutrophic. NO_3 has decreased in the upper and middle regions of the estuary by 3–6% yr^{-1} since 1970, and NH_4 has decreased throughout the estuary at an annual rate of 5.5–7.7% yr^{-1}. Since 1967 PO_4 has increased by 2% yr^{-1} in the lower two thirds of the estuary due to discharges from a phosphate mining facility. Thus the inorganic N:P ratio has decreased, which suggests that N is now potentially more limiting than in the past. In the upper estuary, chl *a* increased at a rate of 6.6% yr^{-1} since 1970, and bottom water DO decreased very slightly; neither showed trends in the middle and lower estuary regions. The weight of the evidence is that the Pamlico has not become more eutrophic during the past two decades. This finding is corroborated by the lack of a trend since 1970 in calculated N and P production from point and nonpoint sources in the watershed. Watershed nutrient production is estimated to have increased severalfold between 1880 and 1970, but appears to have stabilized after 1970, due primarily to decreased application of fertilizer on croplands.

INTRODUCTION

There is a growing perception that coastal environments in the United States and elsewhere are deteriorating, in part due to N and P pollution. Increases in population density, fertilizer use, and conversion of forest land to agriculture are thought to be the primary sources of excess nutrients leading to eutrophication in estuaries. Despite great interest in, and large expenditures for, estuarine water quality management during recent decades, evaluations of long-term trends have been made infrequently [e.g., *Jordan et al.*, 1991; *Officer et al.*, 1984]. Consequently, little is known about the effectiveness of past and present management programs for most of our estuaries [*National Research Council*, 1990]. The problem is compounded by (1) the scarcity of quantitative information on historical trends in N and P production in the watersheds of estuaries, and (2) a lack of quantitative understanding of how changes in inputs are related to conditions in the estuaries. Scores of "snapshot" estuarine nutrient loading computations have been made in recent times. The few available long-term studies of nutrient flux include an estimate of historical P loading trends to the Great Lakes [*Chapra*, 1977] and analyses of water quality trends in United States rivers and streams [*Smith et al.*, 1987; *Lettenmaier et al.*, 1991] and in the Mississippi River [*Turner and Rabalais*, 1991].

This paper summarizes the results of a study of measured long-term trends in water quality in the Pamlico River estuary and estimated changes in annual rates of nutrient production from point and nonpoint sources in the estuary's drainage basin [*Stanley*, 1992]. The primary goal of the study was to determine whether or not the historical record supports the contention that the estuary is becoming more eutrophic [*North Carolina Department of Natural Resources and Community Development*, 1989]. A secondary goal was to learn whether or not trends, or lack of trends, in eutrophication of the estuary could be explained by the historical pattern of nutrient production in the watershed.

METHODS

Study Area

The Pamlico River estuary is a drowned-river valley embayment on the western side of Pamlico Sound in North Carolina (Figure 1). It is approximately 60 km in length and gradually widens from 1 km upstream to about 8 km at the mouth. The average depth is 2.7 m with a maximum depth of 5 m. Lunar tides average only 7 cm in amplitude because of a chain of barrier islands which separate Pamlico Sound from the Atlantic Ocean. However, wind tides of 0.5–1.0 m amplitude are common in the Pamlico River estuary, and they can thoroughly mix the water column. Salinity and nutrient concentrations are strongly influenced by variation in flow of the Tar River, which drains most of the 11,100-km^2 basin area. Average freshwater flow into the Pamlico ranges between 28 m^3 s^{-1} in October and 112 m^3 s^{-1} in February. Typically, surface salinity ranges from <8 ppt during late winter to 10–15 ppt during late fall. Most of the drainage basin is either forested or agricultural, with little urbanization and industrialization. Details of the hydrography and ecology of the estuary are given by *Giese et al.* [1979] and *Copeland et al.* [1984].

Water Quality Data

The nutrient and hydrographic data analyzed in this study are from two long-term monitoring programs. The first ran from 1967 to 1973 and was led by J. Hobbie at North Carolina State University. After an 18-month lapse, the Institute for Coastal and Marine Resources at East Carolina University initiated a new Pamlico River estuary monitoring

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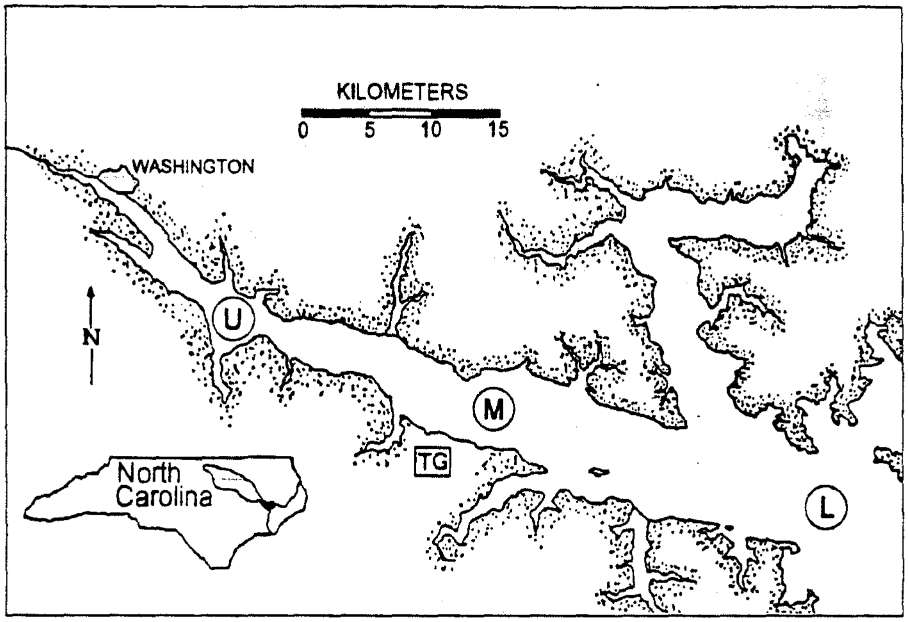

Fig. 1. Map of the Pamlico River estuary. U denotes upper station; M, middle station, L, lower station, and TG, Texasgulf, Inc., phosphate mining facility.

program in January 1975; it has been in operation continuously since then.

At first only "surface" (0.5 m below the water surface) salinity and phosphorus concentrations were monitored. "Bottom" (0.5 m above the bottom) salinity sampling was added in mid-1968, and surface and bottom water dissolved oxygen (DO) measurements were begun in late 1968. Then, in mid-1969, J. Hobbie expanded the program again to include two surface nitrogen fractions, ammonia and nitrate (NH_4 and NO_3). Finally, in 1970, surface water total nitrogen, total dissolved nitrogen, and chlorophyll *a* (chl *a*) were added to the suite of parameters analyzed. Since 1975, sampling has been carried out approximately every other week at stations whose locations have not changed. In the earlier monitoring program, the sampling interval averaged about three weeks. All the monitoring results can be found in technical reports to the sponsoring agencies (see *Stanley* [1992] for a complete listing), but only a small fraction of the data have been reported in the open literature [*Hobbie et al.*, 1975; *Stanley and Daniel*, 1985; *Stanley and Nixon*, 1992]. Tar River daily mean flow data were obtained from records of the nearest U.S. Geological Survey gauging station at Tarboro, North Carolina.

A potentially serious problem in a study of this kind is that sampling and analytical methodologies may vary so much over the years that trend analysis becomes impossible [*Hirsch et al.*, 1991]. Therefore I reviewed the methods of each monitoring program to determine whether or not all the available data were comparable (Table 1). There were substantial changes, particularly during the early years, in the total nitrogen and total dissolved nitrogen methods. These changes affected the completeness of the digestion used to break down the organic constituents, leading to large, easily discernible, step trends in the data [*Hobbie*, 1974; *Stanley*, 1992]. Thus these data sets were omitted from the trend study. Also, the 1975–1979 NH_4 results were not used because the measurements were made using an ion-selective electrode, which was insensitive to most of the normal concentration range in the estuary [*Stanley*, 1992].

Trend Analysis

The seasonal Kendall-tau test was used to analyze the water quality data for monotonic trends. This nonparametric procedure, developed by U.S. Geological Survey investigators [*Hirsch et al.*, 1982; *Hirsch and Slack*, 1984], is suitable for application to water quality data which are often skewed, serially correlated, and affected by seasonality. Also, missing values, or values defined as "less than" the laboratory detection limit present no problems [*Hirsch et al.*, 1991]. In addition to establishing the significance of a trend, the test provides a "slope estimator," the average rate of change over the whole test period. It cannot detect reversals of direction within the test period. Even if there are no reversals, the rate of increase or decrease might vary, but the slope estimator will give no information about these intermediate changes. Examples of the application of the seasonal Kendall test include analyses of U.S. nationwide stream-sampling data [*Smith et al.*, 1987; *Alexander and Smith*, 1988; *Lettenmaier et al.*, 1991], Swedish and Latvian river water quality data [*Karlsson et al.*, 1988; *Tsirkunov et al.*, 1992], and estuarine data sets [*Harned and Davenport*, 1990; *Wiseman et al.*, 1990; *Jordan et al.*, 1991].

For this study, I chose to use water quality data from three locations in the estuary that were sampled in both the 1967–1973 and 1975–1991 periods (Figure 1). The "upper" station is representative of the low-salinity, rapidly flushed region of the estuary a few kilometers downstream from the Tar River. The "middle" station is about 5 km downstream from a major phosphorus point source, the Texasgulf, Inc., outfall. The third, or "lower" station, is representative of the mouth of the Pamlico estuary near the western edge of Pamlico Sound. The seasonal Kendall test requires one value per unit time interval. In this case, measurements

TABLE 1. Methods Used for Pamlico Nutrient and Hydrographic Measurements

Parameter	Years Sampled	Instrument or Method	Reference
Salinity	1967–1973	induction salinometer	Beckman Model RS5-3
	1975–1991	conductivty probe	Yellow Springs Instrument Co. Model 33
Oxygen	1968–1973	Winkler titration	*Carpenter* [1965]
	1975–1991	oxygen electrode	Yellow Springs Instrument Co. Model 51A
Phosphate phosphorus	1967–1973	mixed color reagent	*Menzel and Corwin* [1965] *and Strickland and Parsons* [1968]
	1975–1991	mixed color reagent	*U.S. Environmental Protection Agency* [1979]
Ammonia nitrogen	1969–1973	alkaline hypochlorite/nitrite diazotization	*Strickland and Parsons* [1968]
	1980–1991	indophenol	*Solorzano* [1969]
Nitrate nitrogen	1969–1973	cadmium reduction/nitrite diazotization	*Strickland and Parsons* [1968] *and Morris and Riley* [1963]
	1975	brucine	*American Public Health Association* [1971]
	1975–1991	cadmium reduction/nitrite diazotization	*Strickland and Parsons* [1972]
Chlorophyll *a*	1970–1973	acetone extraction/spectrophotometric	*Strickland and Parsons* [1968, 1972]
	1975–1991	acetone extraction/spectrophotometric	*Strickland and Parsons* [1972]
Phytoplankton	1966–1968	Utermohl concentration/light microscopy	*Utermohl* [1958]
	1982–1985	membrane filtration concentration/light microscopy	*American Public Health Association* [1975]

made within each month were summarized as monthly means.

Watershed N and P Production

Annual total N and total P production in the Pamlico drainage basin were estimated at 4–10 year intervals, depending on the availability of data, for the period 1880–1987. The procedure (which was based on those used by *Chapra* [1977], *Thomas and Gilliam* [1978], *Kuenzler and Craig* [1986], *Lowrance et al.* [1985], and *Jaworski et al.* [1992]) involved computing point and nonpoint source nutrient production on a county-by-county basis and summing the county estimates to give an estimate for the whole watershed. For counties partly inside the basin, the nonpoint data were weighted by the percentage of the county within the basin. Nonpoint sources included (1) harvested agricultural cropland, (2) other nonforested farmland (mostly idle cropland), (3) forested land, (4) pastureland, (5) urban land, (6) all other land areas, and (7) farm animals. Point sources included municipal and industrial discharges.

There can be a large difference between nutrient production within a watershed and nutrient loading to an estuary. Here, nutrient production refers to the sum of (1) point source nutrient discharges, (2) 5% of the nutrients contained in farm animal wastes, (3) nutrients contained in surface runoff from all land areas except harvested cropland, and (4) potential nutrient yield from harvested cropland, estimated by means of a mass balance model. Loading, on the other hand, refers to the quantities of nutrient actually reaching the estuary. The production rate normally exceeds the loading rate because of losses between the sources and the estuary, such as sedimentation of phosphorus and denitrification [*Kuenzler*, 1989; *Jaworski et al.*, 1992]. Loading can be measured directly by multiplying stream discharges times nutrient concentrations. The data for such computations normally come from monitoring flows and concentrations at the head of the estuary. The advantage of that calculation is that 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 the lack of long-term monitoring of N and P concentrations at the mouths of the streams and rivers emptying into the estuary.

Nutrient production by harvested agricultural lands was computed using a mass balance model, similar to those of *Kuenzler and Craig* [1986], *Lowrance et al.* [1985], and *Jaworski et al.* [1992]. It accounts for fertilizer application, nitrogen fixation, precipitation, crop harvest, and denitrification. Estimation of production from other land uses was based on export coefficients. The primary data sources are listed in Table 2. Here "urban" areas are defined as the land areas within the limits of towns and cities with populations greater than 2500. The "other" land use category was calculated by difference. It consists primarily of nonforested, nonagricultural lands outside the boundaries of urban areas (i.e., business properties, house lots, roads, cleared power line right-of-ways, etc.).

For each crop type (e.g., corn or tobacco), the production of N and P was calculated as

$$\text{kg N ha}^{-1}\ \text{yr}^{-1} = (\text{fertilizer N} + \text{precipitation N} + \text{symbiotic N-fixation}) - (\text{harvest N} + \text{denitrification})$$

$$\text{kg P ha}^{-1}\ \text{yr}^{-1} = (\text{fertilizer P} + \text{precipitation P}) - (\text{harvest P}).$$

The total amount of fertilizer applied annually to cropland in a county was assumed to be equal to the amount sold in, or shipped to, the county. Most of the fertilizer data were reported as tons of "mixed fertilizer" and "fertilizer materials." To convert these data into tons of elemental N and P, I multiplied by the percentages of the elements in each type of material sold. Total fertilizer application was apportioned to individual crop types on the basis of recommended fertilizer application rates. The symbiotic nitrogen fixation

TABLE 2. Sources for Land Use, Fertilizer Sales, Point Source Discharges, and Atmospheric Deposition Data

	Source
Agricultural land use, crop harvests, and farm animals inventory	*U.S. Bureau of the Census* [1880, 1890, 1900, 1910, 1920, 1925, 1930, 1935, 1940, 1945, 1950, 1954, 1959, 1964, 1969, 1974, 1978, 1982, 1987] and *North Carolina Department of Agriculture* [1923–1988]
Forest data	*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], and *Bechtold* [1985]
Fertilizer sales	*U.S. Bureau of the Census* [1954, 1959, 1964], *Hargett and Berry* [1985], *Mehring et al.* [1985], and North Carolina Department of Agriculture (various dates between 1956 and 1988)
Population and urban land areas	*U.S. Bureau of the Census* [1949, 1956, 1967, 1972, 1977, 1983, 1988]
Municipal and industrial discharges	*North Carolina Stream Sanitation Committee* [1961], U.S. Public Health Service [1944, 1951, 1958, 1963], *U.S. Environmental Protection Agency* [1971], *Hall* [1970], and North Carolina Division of Environmental Management (unpublished NPDES Self Monitoring Data, 1986–1989)
Atmospheric deposition	*Wells and Jorgensen* [1975], *Wells et al.* [1972], *Olsen and Watson* [1986], *Olsen and Slavich* [1986], *Junge* [1958], *Galloway et al.* [1984], *Kuenzler et al.* [1980], and *Holmes* [1977]

term was included only in the soybean and peanut calculations (105 kg N ha^{-1} yr^{-1} and 112 kg N ha^{-1} yr^{-1}, respectively) [*Kuenzler and Craig*, 1986]. Quantities of N and P in the harvest were determined by multiplying annual yields by the nutrient content per unit of harvest (Table 3). Denitrification rates were assumed to be 15% of the applied fertilizer nitrogen [*Thomas and Gilliam*, 1978].

Estimates of wet and dry N and P deposition onto cropland during the 1980s were based on National Atmospheric Deposition Program wet precipitation measurements at stations in the basin. Total N deposition (wet and dry) was assumed to be twice the wet precipitation deposition [*Stansland et al.*, 1986]. The historical trend in N deposition was estimated by assuming that 1880 deposition was 20% of the current deposition (8.64 kg ha^{-1} yr^{-1}), and that the rate of change has been roughly exponential [*Gschwandtner et al.*, 1985; *Husar*, 1986]. No information on historical trends in atmospheric P deposition was available; therefore a constant rate of 0.5 kg ha^{-1} yr^{-1} was assumed, based on recent measurements in the region.

Nutrient production for each other land use category was calculated by multiplying an export coefficient (kg N and P ha^{-1} yr^{-1}) taken from the literature (Table 4) times the land area (hectares). Animal nutrient production, here defined as the N and P contained in surface runoff, was assumed to be equal to 5% of nutrients in the animals' wastes. Numbers of animals were multiplied by the per-animal waste production rates (Table 4).

Point source nutrient production was calculated for all municipal and industrial discharges in the basin. For industrial sources the annual production was calculated by multiplying daily discharge times the N or P effluent concentration times 365. There are only a few significant industrial dischargers in the basin, and there are historical discharge data available for them. On the other hand, many of the municipal sewage systems were in operation long before effluent flow and nutrient concentration data collection began. Thus N and P production for them had to be estimated by a less

TABLE 3. Nitrogen and Phosphorus Content in Harvested Crop Materials

Crop	Harvest Unit	Concentration, kg/harvest unit	
		Nitrogen	Phosphorus
Corn (grain)	bushel	0.414	0.070
Corn (silage)	ton	1.820	0.205
Oats (grain)	bushel	0.280	0.051
Wheat (grain)	bushel	0.568	0.125
Hay			
Alfalfa	ton	20.455	2.045
Bluegrass	ton	13.636	2.045
Coastal Bermuda	ton	10.511	1.761
Cowpea	ton	27.273	2.500
Peanut	ton	21.212	2.222
Red clover	ton	18.182	2.000
Soybean	ton	20.455	2.045
Timothy	ton	10.909	2.000
Cotton	pound	0.008	0.001
Peanuts (nuts)	pounds	0.016	0.001
Soybeans (grain)	bushels	1.705	0.170
Tobacco (leaves)	pounds	0.017	0.002

From *Gilbertson et al.* [1978] and *Romaine* [1965]. Harvest units are as follows: 1 bushel equals 35.239 L, 1 ton equals 907 kg, and 1 pound equals 0.454 kg.

TABLE 4. Coefficients Used to Compute Nitrogen and Phosphorus Production by Five Different Land Use Categories and by Different Types of Farm Animals

Land Use Category or Animal Type	Nitrogen, kg yr^{-1}	Phosphorus, kg yr^{-1}
Other farmland	3.00 ha^{-1}	0.40 ha^{-1}
Other land	3.00 ha^{-1}	0.40 ha^{-1}
Forest	1.50 ha^{-1}	0.20 ha^{-1}
Pastureland	4.00 ha^{-1}	0.60 ha^{-1}
Urban land	6.00 ha^{-1}	1.10 ha^{-1}
Cattle		
Dairy	121.00 $animal^{-1}$	22.00 $animal^{-1}$
Beef	48.10 $animal^{-1}$	13.10 $animal^{-1}$
Swine	11.90 $animal^{-1}$	4.20 $animal^{-1}$
Horses	46.40 $animal^{-1}$	11.00 $animal^{-1}$
Poultry		
Broilers	0.40 $animal^{-1}$	0.10 $animal^{-1}$
Layers	0.56 $animal^{-1}$	0.20 $animal^{-1}$
Turkeys	1.36 $animal^{-1}$	0.52 $animal^{-1}$

Values for forest are from *Loehr* [1974]; values for other land uses are from *Beaulac and Reckhow* [1982]; values for animals are from *Barker* [1987] and *Robbins et al.* [1972].

TABLE 5. Total per Capita Nitrogen and Phosphorus Loads in Wastewater Effluents as a Function of Treatment Type

Treatment Type	Nitrogen		Phosphorus	
	Load, kg yr^{-1}	Factor	Load, kg yr^{-1}	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

From *Gakstatter et al.* [1978]. Treatment factors are equal to the load for a given treatment type divided by the load for no treatment.

direct method, involving the sewered population, the type of treatment in effect, and the efficiency of N and P removal expected from that treatment. The calculation was as follows:

$$\text{kg N or P yr}^{-1} = (\text{sewered population}) \times (\text{per capita annual N and P production}) \times (\text{treatment factor}).$$

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. Phosphorus treatment factors ranged from 1.0 to 0.74 (Table 5). National Pollution Discharge Elimination System (NPDES) compliance monitoring data files at the North Carolina Division of Environmental Management were searched to provide lists of all current discharges within the Pamlico basin, as well as historical information on discharges. The most difficult parameters to estimate were the treatment factors that would be applied to each municipal discharge. Fortunately, there were periodic inventories of municipal wastewater facilities from 1942 through 1985 (Table 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 North Carolina Department of Health annual reports series, 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, back to the time when the first sewage collection system for the town was constructed.

RESULTS AND DISCUSSION

Water Quality Trends

For the N, P, chl *a*, and bottom DO constituents, there were statistically significant ($p < 0.05$) trends in one or more of the estuary segments (Table 6). Nitrate (Figure 2*a*) decreased in the upper and middle regions by 2.8% yr^{-1} and 6.5% yr^{-1}, respectively, between 1969 and 1991. There was no decrease in NO_3 in the lower estuary. Ammonia (Figure 2*b*) decreased in all three regions at 5.5–7.7% yr^{-1} (1969–1991). On the other hand, from 1967 to 1991 concentrations of PO_4 (Figure 2*c*) increased about 2% yr^{-1} in the lower two thirds of the estuary below the Texasgulf phosphate mine discharge. Upstream from the phosphate mine, there was no trend in PO_4. In the upper estuary, chl *a* (Figure 2*d*) showed an uptrend between 1970 and 1991 while bottom water DO showed a downtrend (1968–1991). The chl *a* levels increased 0.7 μg L^{-1} yr^{-1} (6.6% yr^{-1}), and the DO decreased very slowly at a rate of 0.01 mg L^{-1} yr^{-1} (0.17% yr^{-1}). There were no trends in chl *a* and bottom water DO in the middle and lower estuary regions. Surface DO, salinity, and Tar River flow data were also tested for trends; none were found.

The PO_4 increase in the lower two thirds of the Pamlico is almost certainly related to the discharge of large quantities of P from the Texasgulf, Inc., phosphate mine. Monthly P loadings (mostly in the form of PO_4) from Texasgulf increased rapidly following the opening of the mine in 1964 and continued to rise through the 1970s as the plant expanded. Then, from 1980 until 1986 the loadings decreased by about 50%, but since 1986 they have increased again to about the same level as in 1980. Interestingly, PO_4 concentrations in the estuary appear to have responded to the increases in Texasgulf P loading, but not to the 1980–1986 loading decrease. Analyses of the estuarine PO_4 data for the three periods 1967–1980, 1980–1986, and 1986–1991 showed up-

TABLE 6. Seasonal Kendall Trend Test Results

Region	Constituent				
	NH_4-N, μM	NO_3-N, μM	PO_4-P, μM	Chlorophyll *a*, μg/L	Bottom DO, mg/L
Upper estuary					
Change yr^{-1}	−0.313	−0.254	···	0.682	−0.010
Percent change yr^{-1}	−5.5	−2.8	···	6.6	−0.2
p*	<0.0001	0.0012		0.0006	0.0044
Middle estuary					
Change yr^{-1}	−0.311	−0.067	0.063	···	···
Percent change yr^{-1}	−7.7	−6.5	2.2	···	···
p*	0.0001	0.0060	0.0026		
Lower Estuary					
Change yr^{-1}	−0.262	···	0.023	···	···
Percent change yr^{-1}	−7.4	···	1.6	···	···
p*	0.0006		0.0346		

Only data for statistically significant trends are given ($p < 0.05$). Neither salinity (surface or bottom, all three regions) nor Tar River flow (at Tarboro, North Carolina) showed significant trends.

*Here p denotes significance level (two-sided).

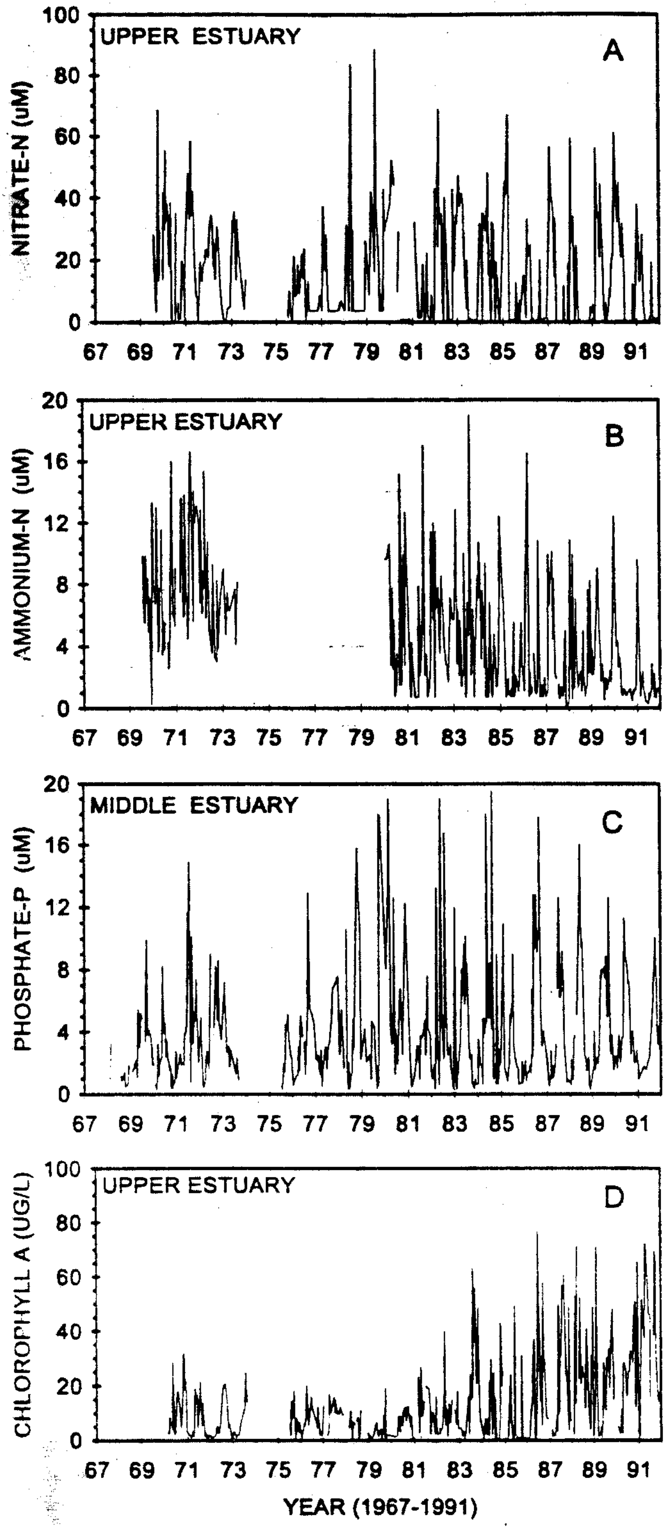

Fig. 2. Trends in NO_3, NH_4, PO_4, and chl *a* at selected stations in the Pamlico River estuary.

trend, no trend, and uptrend, respectively. Perhaps the PO_4 concentrations are maintained by outward flux of accumulated P in the estuary's sediments. It has been shown that there is enough reactive PO_4 in the top 10 cm of sediment (21.7 g m^{-2}) to sustain for 3.4–14 years the measured annual flux of PO_4 from the sediments to the water column (1.55–6.4 g m^{-2} yr^{-1}) [*Matson et al.*, 1983; *Kuenzler et al.*, 1984]. Also, the historical range in Texasgulf P loading is equivalent to a maximum sediment deposition rate of 1–2 g PO_4 m^{-1} yr^{-1} (assuming 100% sedimentation), which is also small in comparison to the sediment P content. Recently, Texasgulf has upgraded its wastewater treatment process, with the goal of eliminating 90% of its P loading to the estuary (W. Schimming, personal communication, 1992). It will be very interesting to track the consequences of this large reduction in total P loading to the estuary.

There is circumstantial evidence that N limitation of algal growth in the Pamlico may have increased over the past decade due to the simultaneous downtrend in dissolved inorganic nitrogen (DIN = NO_3 + NH_4) and uptrend in PO_4. Nitrogen is potentially limiting when the water column DIN:PO_4 ratio falls below 16, the ratio typical of phytoplankton [*Redfield*, 1958]. Actually, studies by *Parsons et al.* [1961] and *Rhee* [1978] indicated that there is some variability in algal composition, and hence it is probably more

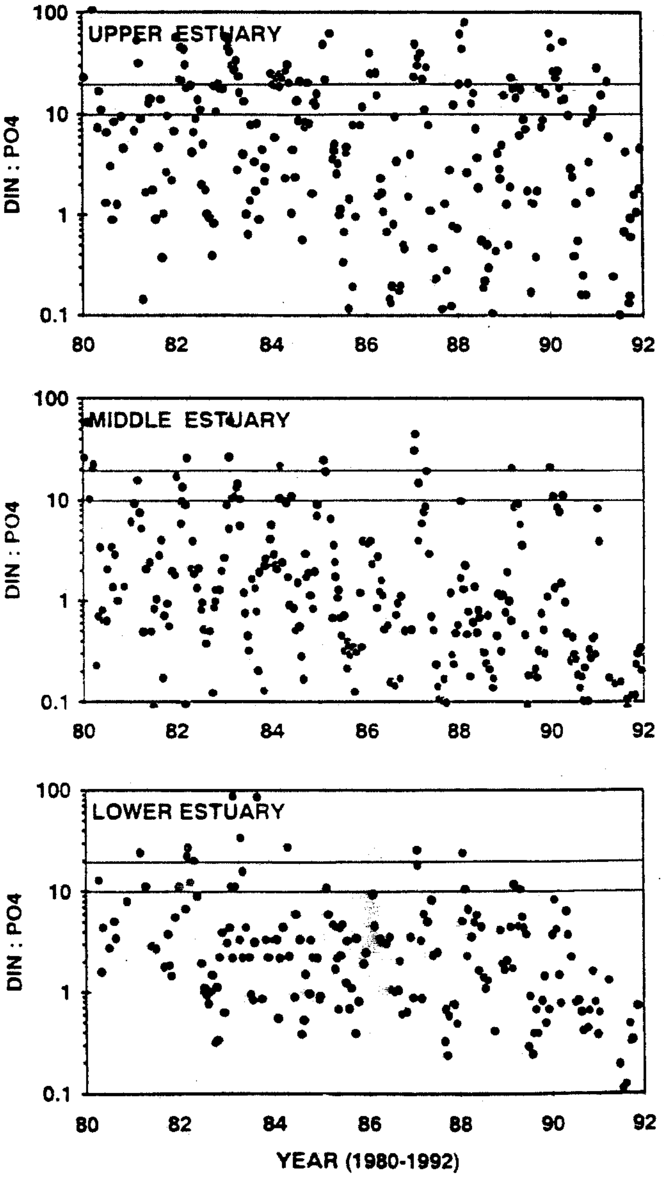

Fig. 3. DIN:PO_4 ratios in the Pamlico River estuary. Normal range of algal N:P ratio indicated by horizontal bars.

realistic to view their N:P ratios as ranging from around 10:1 to 20:1 [*Boynton et al.*, 1982]. There are spatial, seasonal, and long-term components to the Pamlico DIN:PO_4 ratio pattern (Figure 3 and *Stanley* [1992]). Generally, the ratios indicate that N limitation is possible in the upper estuary during the summer and in the lower estuary at all times of the year. In the lower two thirds of the estuary, more than 95% of the DIN:PO_4 ratios measured between 1980 and 1991 were below 10:1. Upriver the ratios increase, more because of increasing NO_3 than because of decreasing PO_4. There is also a strong seasonal pattern in the ratios throughout the estuary. This pattern also is determined primarily by NO_3, which varies seasonally more than either NH_4 or PO_4. Unfortunately, external nutrient ratios are only indirect evidence of N-limited algal growth. As *Hecky and Kilham* [1988] point out, a rigorous demonstration of the relationship between growth and external DIN:PO_4 ratios has not been achieved for marine waters. In addition, it should be noted that regardless of the DIN:PO_4 ratio, other factors such as light and temperature can limit phytoplankton growth.

Indeed, factors other than N and P must be responsible for the trend toward increasing phytoplankton biomass in the upper Pamlico. Although the average annual chl *a* concentration (20 $\mu g\ L^{-1}$) is comparable to averages for other river-dominated estuaries in the region [*Boynton et al.*, 1982], it is nearly threefold higher now than two decades ago. *Harned and Davenport* [1990] analyzed trends in suspended solids concentrations throughout the Albemarle-Pamlico estuarine system and found that since the early 1970s they have decreased in almost all areas, including the Pamlico River estuary. One possible explanation for this decline is improved agricultural practices; the construction of reservoirs also may have played a role. In any case, light limitation in the upper estuary may not be as severe now as in the past, which could help explain the increase in chl *a*. Unfortunately, there is no long-term record of light extinction for the estuary.

The slight downtrend in bottom water DO in the upper estuary could be related to the chl *a* increase. *Stanley and Nixon* [1992] concluded that Pamlico water column respiration rates are sufficiently great that hypoxia can easily result during the 6–12 days they estimated as an average between wind-driven mixings of the water column during the summer. Logically, an increase in phytoplankton could lead to increased respiration rates and even more rapid hypoxia development. However, Stanley and Nixon also showed by means of Spearman rank correlation analyses that there was no significant correlation between bottom water DO and surface chl *a*. In any case, the downtrend in bottom DO, while statistically significant, is very small, amounting to less than 5% over the past two decades.

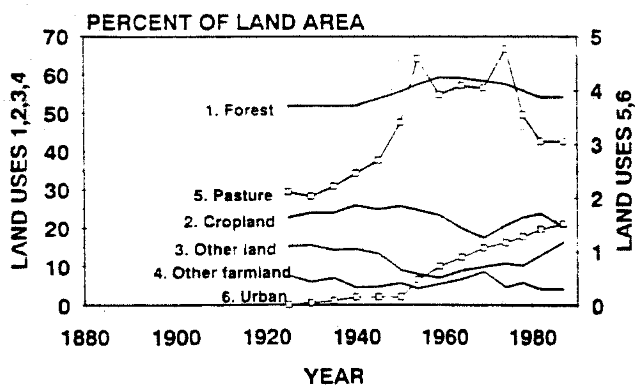

Fig. 4. Trends in land use in the Pamlico River estuary watershed, 1925–1987.

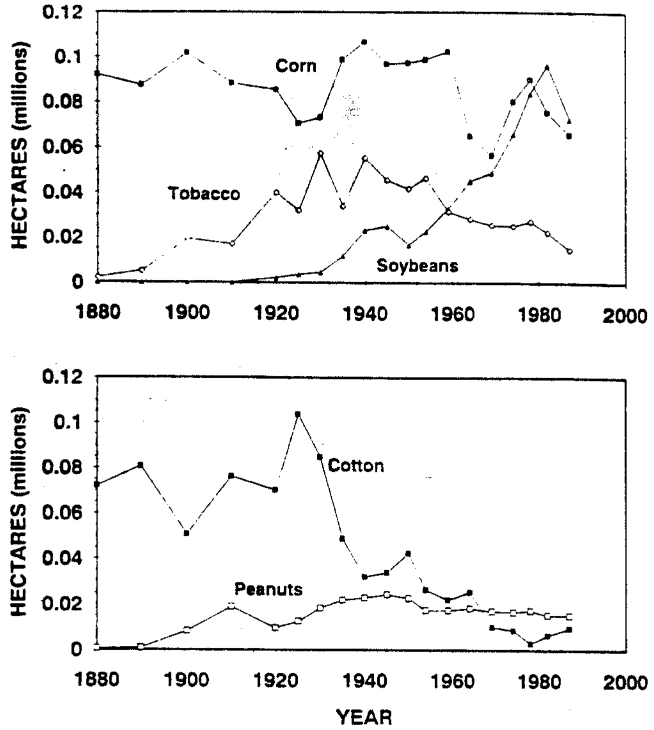

Fig. 5. Trends in plantings of major crops in the Pamlico River estuary watershed, 1880–1987.

Phytoplankton composition has not been monitored continuously in the Pamlico. However, comparison of results from a 3-year-long study (1966–1968) and a subsequent four-year study (1982–1985) showed that it did not change between the two periods [*Hobbie*, 1971; *Stanley and Daniel*, 1985]. Blue-green algae, usually considered to be a sign of advanced eutrophication, have become common in some areas of coastal North Carolina in recent years. In particular, the lower Chowan River and the lower Neuse River experienced severe blue-green algae blooms during some, but not all, summers during the 1970s and 1980s [*Christian et al.*, 1988; *Mallin et al.*, 1991]. The blooms have been restricted to the tidal freshwater zones. No severe blue-green blooms have occurred in the upper Pamlico River estuary.

Nutrient Production Trends

Land use changed little in the Pamlico basin over the past 70 years (Figure 4). Forest has been the most prevalent land use, ranging between 52% and 59% of the total basin area. Cropland, the second most prevalent land use, peaked around 1940 at 26% and has generally declined since then, to 20% in 1987. Thus forest and cropland together have composed 75–82% of the basin area since 1925. Before 1925, there are good data only for the cropland category; thus 1880–1920 values for other categories were estimated. For example, based on data that are available for the period (number of cattle on farms, cropland acreages, and the total land in farms) and the safe assumption that urban land was

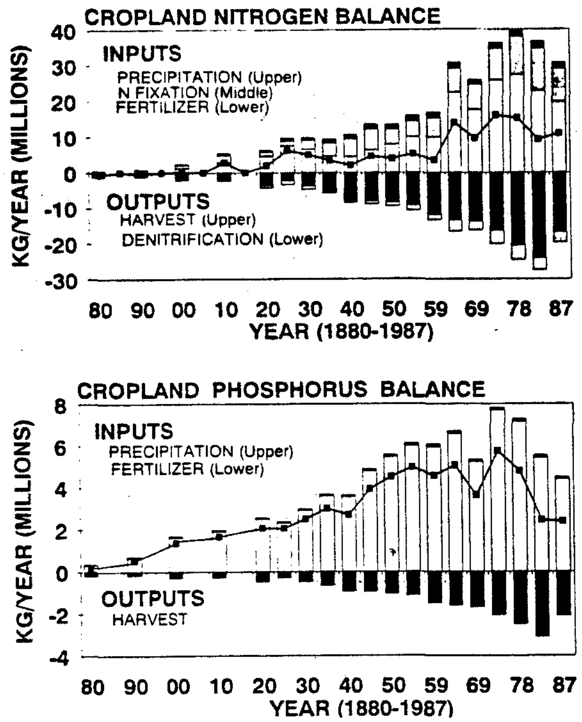

Fig. 6. Cropland N and P balances, 1880–1987. Annual N and P production (inputs minus outputs) is indicated by the solid lines with symbols.

much less than 1% of the total, it can be calculated that forested areas must have been about the same in the late 1800s as in 1925.

Large shifts have taken place in the mix of crops grown in the basin (Figure 5). In terms of area planted, corn has been dominant for most of the past century, accounting for 35–45% of total harvested cropland. The second most widely planted crop today, soybeans, has risen steadily in importance since it was introduced around 1910. On the other hand, tobacco and cotton plantings have declined since 1930. At its peak in the 1920s, cotton was the second most widely planted crop. Peanuts, a relatively minor crop, increased in acreage during the early part of this century up until the 1940s but have decreased slowly since then. Wheat and other small grains have never been important crops in this area.

The use of chemical fertilizers made a great impact on cropland nutrient mass balances over the past century. Phosphorus application rose to a peak of 7.7 × 10^6 kg yr^{-1} in the 1970s, but has declined since then to around 4.4 × 10^6 kg in 1987. Nitrogen fertilizer use increased about sevenfold between 1940 and 1978, when 27.2 × 10^6 kg was applied. Since then, N fertilizer use has declined slightly. Atmospheric N deposition onto Pamlico basin cropland is estimated to have increased fivefold over the past century, but it is still very small in comparison to fertilizer N input and N fixation (Figure 6). As a result of increased fertilizer use, and more productive varieties, increases in yields (and hence nutrient output in harvest) for some crops have been very impressive. For example, corn yield per hectare increased about fivefold, and soybean yield approximately doubled over the past 40 years. There have been impressive increases in the tobacco and peanut yields also [*Stanley*, 1992].

Cropland N production, the difference between inputs and outputs, increased gradually from near zero, or less than zero, in the late 1800s, to around 16 × 10^6 kg N yr^{-1} by 1974, but has not changed much since then (Figure 6). Phosphorus production increased most rapidly in the early 1900s, reaching a peak of about 5 × 10^6 kg P in 1974. Since then cropland P production appears to have stabilized, or perhaps even declined.

During the past two decades, swine and poultry production has expanded significantly in the central coastal plain of North Carolina. Growth of the poultry industry has been one of the most notable developments in southern agriculture since World War II. Total poultry inventories (broilers, chickens, and turkeys) in the Pamlico basin grew slowly from around 0.3 × 10^6 in 1880 to approximately 1.1 × 10^6 in 1959. Since then the numbers have increased at an amazing rate; in 1987 there were over 10 × 10^6. In addition, swine inventories have approximately doubled in the past two decades.

The uptrend in farm animals' nutrient production reflects the rapid growth of swine and poultry production (Figure 7). The N production rose 75% between 1969 and 1987, and in 1987 the P production was about twice the 1969 value. Before 1969, cattle contributed 40–60% of the total N and P in most years, with most of the remainder divided between horses and mules. In recent years the percentages have shifted toward dominance by swine and poultry. Poultry have accounted for most of the long-term increases in total animal N and P production.

Although sewage collection systems had been constructed for most of the larger towns in the early 1900s, as late as 1945 about two thirds of the sewered population in the Pamlico basin were on systems that provided no treatment [*North Carolina Stream Sanitation Committee*, 1946]. About half of the sewage that was treated received only primary treat-

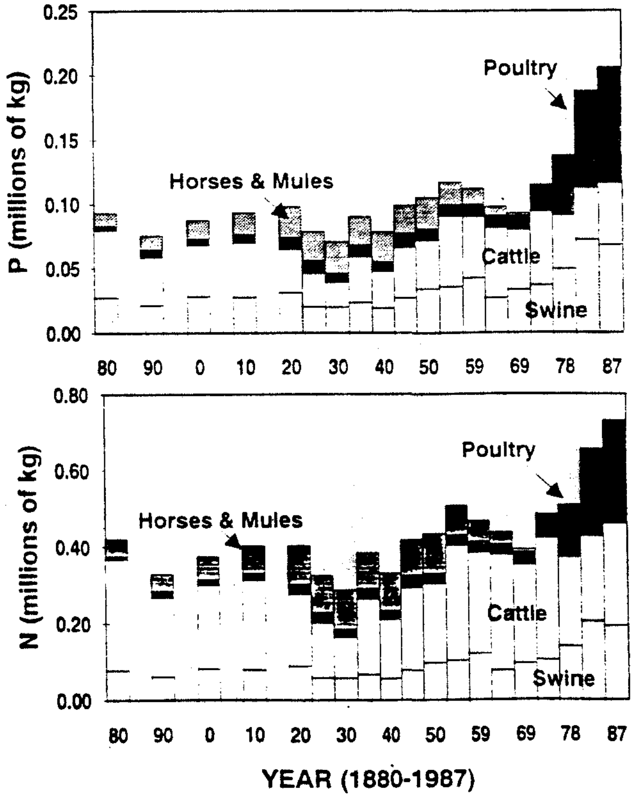

Fig. 7. N and P production by farm animals in the Pamlico River estuary watershed, 1880–1987.

TABLE 7. Estimated Annual N and P Production for Selected Years in the Pamlico River Estuary Basin

	Year															
Source	1880	1890	1900	1910	1920	1930	1940	1950	1954	1959	1964	1969	1974	1978	1982	1987
Nitrogen, million kg yr^{-1}																
Point sources	0.00	0.03	0.008	0.17	0.23	0.32	0.37	0.44	0.42	0.40	0.43	0.45	0.48	0.50	0.53	0.56
Nonpoint sources																
Cropland	0.00	0.00	0.00	2.68	1.72	4.64	1.48	3.24	4.36	2.70	13.22	8.92	15.23	14.30	8.19	10.01
Pasture	0.22	0.22	0.22	0.22	0.22	0.21	0.25	0.35	0.47	0.40	0.42	0.42	0.49	0.37	0.32	0.32
Other farmland	0.59	0.59	0.59	0.59	0.59	0.47	0.36	0.44	0.34	0.42	0.52	0.68	0.36	0.45	0.32	0.29
Forest	2.01	2.01	2.01	2.01	2.01	2.01	2.01	2.16	2.23	2.30	2.29	2.26	2.23	2.17	2.10	2.10
Urban land	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.02	0.07	0.11	0.14	0.17	0.18	0.20	0.22	0.23
Other land	1.54	1.46	1.50	1.36	1.30	1.21	1.13	0.71	0.63	0.55	0.69	0.78	0.84	0.80	1.01	1.60
Farm animals	0.32	0.26	0.30	0.32	0.33	0.25	0.27	0.36	0.39	0.37	0.32	0.30	0.37	0.42	0.57	0.63
Total nonpoint sources	4.68	4.54	4.62	7.19	6.18	8.80	5.53	7.28	8.50	6.85	17.61	13.51	19.70	18.71	12.74	15.18
Phosphorus, million kg yr^{-1}																
Point sources	0.00	0.01	0.02	0.05	0.06	0.08	0.10	0.12	0.12	0.12	0.33	0.53	0.60	0.68	0.62	0.56
Nonpoint sources																
Cropland	0.15	0.53	1.36	3.45	4.24	3.57	2.69	4.51	4.96	4.55	5.06	3.62	5.74	4.78	2.44	2.38
Pasture	0.03	0.03	0.03	0.03	0.03	0.03	0.04	0.05	0.07	0.06	0.06	0.06	0.07	0.05	0.05	0.05
Other farmland	0.08	0.08	0.08	0.08	0.08	0.06	0.05	0.06	0.05	0.06	0.07	0.09	0.05	0.06	0.04	0.03
Forest	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.29	0.30	0.31	0.31	0.30	0.30	0.29	0.28	0.28
Urban land	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.03	0.03	0.03	0.04	0.04	0.04
Other land	0.21	0.19	0.20	0.18	0.17	0.16	0.15	0.09	0.08	0.07	0.09	0.10	0.11	0.11	0.14	0.21
Farm animals	0.09	0.07	0.08	0.09	0.09	0.07	0.07	0.09	0.10	0.10	0.09	0.08	0.10	0.13	0.18	0.19
Total nonpoint sources	0.82	1.17	2.03	4.10	4.89	4.16	3.28	5.10	5.57	5.17	5.70	4.29	6.41	5.46	3.17	3.19

ment, which removes, at best, only about 10% of the N and P. Thus N and P production 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. But there was little additional improvement until recently, when a statewide phosphate detergent ban went into effect in 1988. Thus nutrient production by municipal sources continued to increase in proportion to population growth through 1987, when the annual rates were 0.49×10^6 kg N and 0.16×10^6 kg P. Industrial sources contributed an additional 0.07×10^6 kg N and 0.39×10^6 kg P in 1987.

Trends in N and P production by all sources are summarized in Table 7. Total annual N production is estimated to have about tripled over the past century, from 4.7×10^6 kg in 1880 to 15.2×10^6 kg in 1987. Most of the increases came between 1959 and 1964, due in part to the rapid increase in cropland production in the 1960s, and to increases in farm animals and point source production. The relative importance of some N sources has changed greatly over the past century. For example, in 1880, the most important sources were forest (43% of total) and other nonfarm, nonurban lands (33% of total). A century later the forest and other lands N production is about the same, in absolute terms, but their relative importance is greatly diminished. The most important new nitrogen source is cropland N. Animals, urban runoff, and point sources have also become more important.

Nonpoint source P production began to increase earlier in this century than N production, primarily because of the earlier use of P fertilizers on cropland. Between 1880 and 1920, P production increased about fivefold, to around 5×10^6 kg yr^{-1}. There was little change until the mid-1960s when the phosphate mine discharge began. But despite this major new source, total P production in the basin appears to have stabilized, or even declined during the 1980s, primarily due to reduced fertilizer application to farmland.

Uncertainties in the Nutrient Production Estimates

Nutrient export coefficients are notoriously variable (see reviews by *Beaulac and Reckhow* [1982] and *Frink* [1991]). For example, the range of measured N export coefficients for forests spans at least an order of magnitude (0.10–12.0 kg ha^{-1} yr^{-1}, as reported by *Frink* [1991]). *Beaulac and Reckhow* [1982] discussed factors that affect the coefficients and urged that for application to a particular geographic area, only those coefficients from studies in similar areas be considered. Following their advice, I chose values derived from studies made in the coastal plain region of the southwestern United States, when possible.

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 them to be 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 N ha^{-1} denitrified in a poorly drained soil; both sites were in the Tar River basin. The figure of 15% applied N lost by denitrification that I used is frequently used in computations of N balances. *Thomas and Gilliam* [1978] concluded that it is generally accepted as being as accurate as any.

Estimating trends in atmospheric N and P deposition onto cropland is difficult, because of the weak historical data base for precipitation chemistry. Before 1955 there were only sporadic measurements (none in the Pamlico basin) and *Stansland et al.* [1986] have concluded that their reliability is so questionable that they should not be used for trend analysis. Thus my indirect estimates of the trends are based on three assumptions: (1) 1880 N concentrations in Pamlico basin precipitation were the same as those measured today in remote areas unaffected by anthropogenic NO_x emissions, (2) N deposition since 1880 has increased monotonically, and (3) there has been no trend in P deposition. The present-day N deposition rate used in the calculations (8.64 kg ha^{-1} yr^{-1}) is well within the range of recent measurements for the southeastern United States [*Jaworski et al.*, 1992]. Since atmospheric deposition accounts for only about 5% of the calculated N input and 2% of the P input to cropland, modest errors in estimating this source would not appreciably affect cropland nutrient production calculations.

The 5% value used as an estimate of the fraction of animal waste in surface runoff is highly uncertain. It is based solely on the report of *Robbins et al.* [1972]. This value may be increasing, which, in combination with recent dramatic increases in swine and poultry production, could have a significant impact on total nutrient production in the Pamlico basin. Modern animal operations involve the use of feedlots or buildings in which hundreds (swine) to tens of thousands (poultry) of animals are confined in very small areas. These become essentially point source 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 [*North Carolina Department of Natural Resources and Community Development*, 1986].

Potential sources of error in the municipal nutrient production estimates include the sewered population values and the treatment factors. The sewered populations for years before the first municipal treatment plant inventory in 1942 were assumed to be equal to the populations of the cities and towns. This caused an overestimation of the nutrient production. However, this error makes an insignificant difference in total nutrient production since the urban population was so small. The problem with using treatment factors is that the facilities in a given city often do not perform 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 North Carolina during the 1950s [*North Carolina Stream Sanitation Committee*, 1961]. This problem would result in an underestimation of the actual municipal production of N and P by the technique I have used. However, a comparison calculation that I have made did show that, for recent times at least, results from the treatment factors method are comparable to those obtained by a more direct method, i.e., summing the products of measured effluent flows times measured effluent N and P concentrations for all cities and towns in the basin [*Stanley*, 1992].

There is evidence that, as expected, nutrient production is considerably higher than nutrient loading to the Pamlico River estuary. Two recent sets of loading estimates are available; both are based on river flow and measured instream nutrient concentration data. One, prepared by the *North Carolina Department of Natural Resources and Community Development* [1989], is for the year 1987; the other, which I have made, is for 1991. They gave similar results; annual N and P loadings were about one fifth and one ninth of the 1988 N and P production estimates given in Table 7, respectively. The discrepancies can be explained in part by losses between the sources and the estuary due to groundwater infiltration and sedimentation of P and N and volatilization and denitrification of N. In particular, lowland swamp forests along coastal rivers like the Tar are a major sink for nutrients. *Kuenzler and Craig* [1986] estimated that in eastern North Carolina these systems are capable of removing 83% of the total nitrogen and 51% of the total phosphorus from water draining through them. Of course, as noted above, the nutrient production estimates themselves may also be in error. I am particularly suspicious of the harvested cropland estimates. When converted to areal rates, they are high (47.7 kg N ha^{-1} and 11.33 kg P ha^{-1} for 1987) in comparison to literature values for measured "edge of field" nutrient fluxes (15–30 kg N ha^{-1} and 1–5 kg P ha^{-1}) [*Frink*, 1991]. I suspect that the problem lies in the output side of the production mass balance. There are probably significant unaccounted for losses before the nutrients have a chance to get to the field's edge. For example, *Lowrance et al.* [1985] concluded that on upland agricultural areas of coastal Georgia, most of the 50 kg N ha^{-1} yr^{-1} of the N input (precipitation, fertilizer, and N fixation) that was unaccounted for in the harvest probably left the field via subsurface flow and denitrification.

CONCLUSIONS

The weight of the evidence is that the Pamlico River estuary has not become more eutrophic over the past two decades. While the increase in chl *a* in the upper estuary could be considered indicative of cultural eutrophication, it cannot be due to elevated nutrients, given the very strong downtrends in NO_3 and NH_4 and the lack of a trend in PO_4 in that part of the estuary. Less severe light limitation due to reduced suspended sediment loads in the Tar River is a possible explanation. Clearly, chl *a* levels in this part of the estuary need to be followed carefully in the future, and research needs to be undertaken to try to establish the cause of the increase. Farther down the estuary, increased PO_4 levels resulting from the phosphate mine discharge have not promoted eutrophication, as evidenced by the lack of trends in chl *a* or bottom water DO in the lower two thirds of the estuary. This interesting, long-term P enrichment "experiment" lends support to the notion that this element is often not a factor limiting estuarine primary production [*Ryther and Dunstan*, 1971; *Hecky and Kilham*, 1988]. Results of the watershed nutrient production calculations seem to corroborate the finding that N and P levels have not increased in the upper estuary in recent years. While nutrient production is estimated to have increased severalfold during the past century, it has changed little since 1969, due primarily to the fact that fertilizer application to croplands has not increased during the past two decades.

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Stratification and Bottom-Water Hypoxia in the Pamlico River Estuary

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ABSTRACT: Relationships among bottom-water dissolved oxygen (DO), vertical stratification, and the factors responsible for stratification-destratification in this shallow, low tidal-energy estuary were studied using a 15-yr set of biweekly measurements, along with some recent continuous-monitoring data. Hypoxia develops only when there is both vertical water-column stratification and warm water temperature (>15°C). In July, 75% of the DO readings were <5 mg l^{-1}, and one-third were <1 mg l^{-1}. Severe hypoxia occurs more frequently in the upper half of the estuary than near the mouth. Both the time series data and correlation analysis results indicate that stratification events and DO levels are tightly coupled with variations in freshwater discharge and wind stress. Stratification can form or disappear in a matter of hours, and episodes lasting from one to several days seem to be common. Estimated summertime respiration rates in the water and sediments are sufficient to produce hypoxia if the water is mixed only every 6–12 d. There has been no trend toward lower bottom water DO in the Pamlico River Estuary over the past 15 yr.

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, New York (Swanson and Sindermann 1979; Falkowski et al. 1980), and the northern Gulf of Mexico (Harper et al. 1981; Boesch 1983) 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 infuencing vertical mixing. But, so far, only a few such studies have been made. In Chesapeake Bay, multiyear 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 <5m (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

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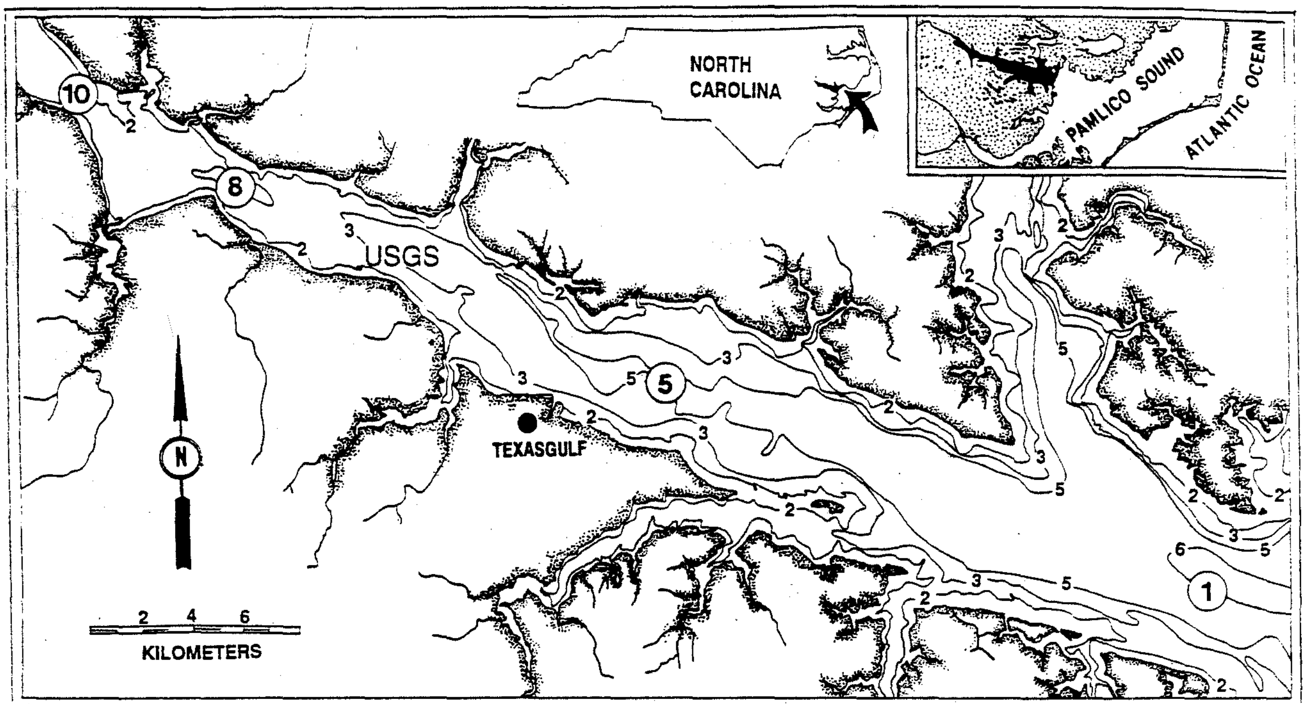

Fig. 1. Location of water quality sampling stations (10, 8, 5, and 1) and the United States Geological Survey (USGS) continuous-monitoring station in the Pamlico River Estuary. Depth contours in m.

the factors responsible for stratification-destratification in the Pamlico River Estuary in North Carolina. The study is based primarily on a 15-yr 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, North Carolina, to the western edge of Pamlico Sound (Fig. 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 acutally the estuary of the Tar River, which drains most of the 14,000 km^2 basin area. Total freshwater flow into the Pamlico typically ranges between 28 m^3 s^{-1} in October and 112 m^3 s^{-1} in February (Giese et al. 1979). Freshwater flushing times corresponding to this flow range are estimated to be between 80 d and 28 d. 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‰ during the late winter and early spring. The salinity increases to maximum values (10–15‰) during fall. However, there is considerable interannual variability. During drought years the salinity may approach that of Pamlico Sound (20–24‰). 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).

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 newpaper 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 (Fig. 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*, nitrogen, and phosphorus were collected only at the surface. Chlorophyll *a* was measured by the method of Strickland and Parsons (1972), and the nitrogen and phosphorus analyses were by methods given in United States Environmental Protection Agency (1979) and American Public Health Association (1985).

In addition, we will present excerpts from a time-series (3-h 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 United States Geological Survey (USGS), using a Minimonitor, a USGS-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 United States Coast Guard navigation channel marker), which is about halfway between our stations 5 and 8 (Fig. 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-wk 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 (Fig. 1). Wind speeds were converted to stress using the quadratic law with a drag coefficient of 1.5×10^{-3} (Garratt 1977). Daily mean Tar River discharge data are from the USGS gauge at Tarboro, North Carolina, 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 (Daniel 1978; Conover 1980). The computed coefficient (R) will range between -1 (perfect inverse relationship) and $+1$ (perfect direct relationship). The Spearman test is included 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

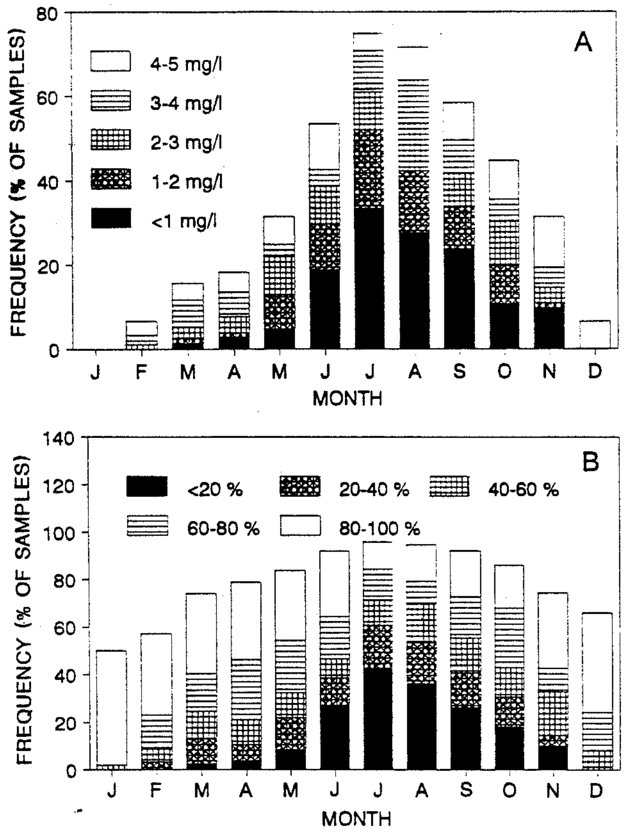

Fig. 2. Frequency of five DO concentration ranges (A) and percent saturation ranges (B) for each month. All data from four monitoring stations for the period 1975–1989 included.

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.

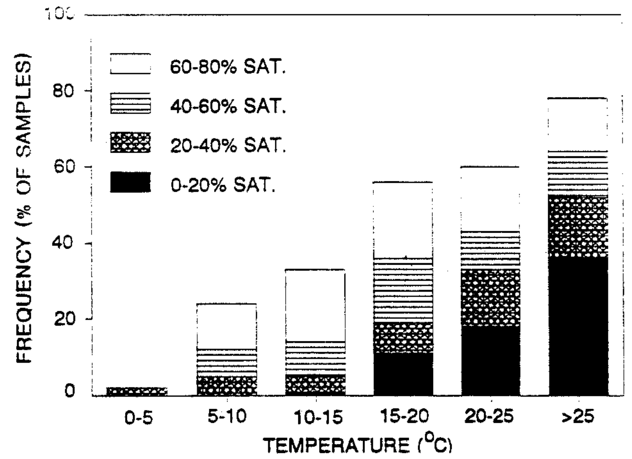

Fig. 3. Frequency of four DO percent saturation ranges for six temperature ranges. Includes all data from four monitoring stations for the period 1975–1989.

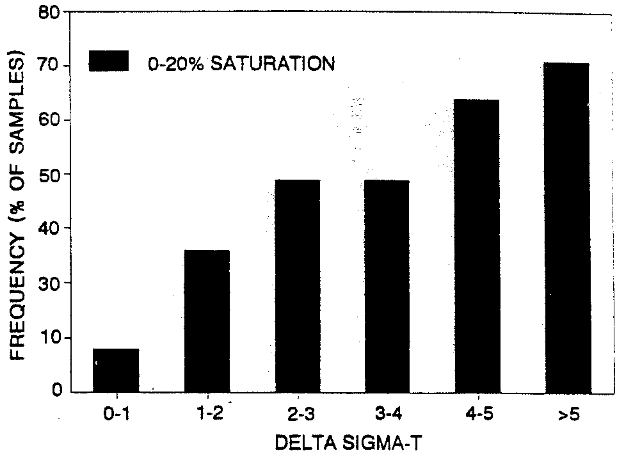

Fig. 4. Frequency of samples with <20% DO saturation for six delta sigma-t ranges. Includes only measurements made when water temperature was >15°C.

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 (Fig. 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 (Fig. 2B). 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 satura-

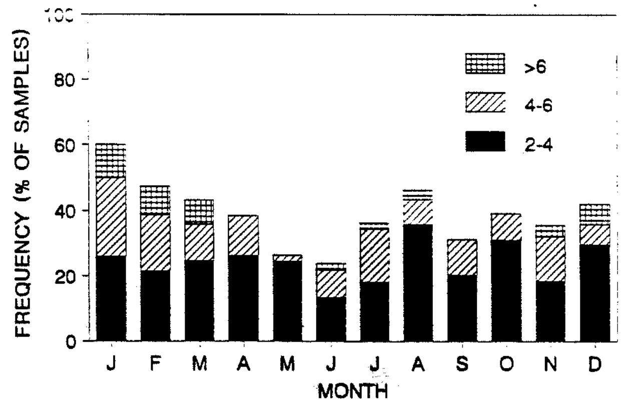

Fig. 5 Frequency of three delta sigma-t ranges (bottom water–surface water) for each month. Includes all data from four monitoring stations for the period 1975–1989.

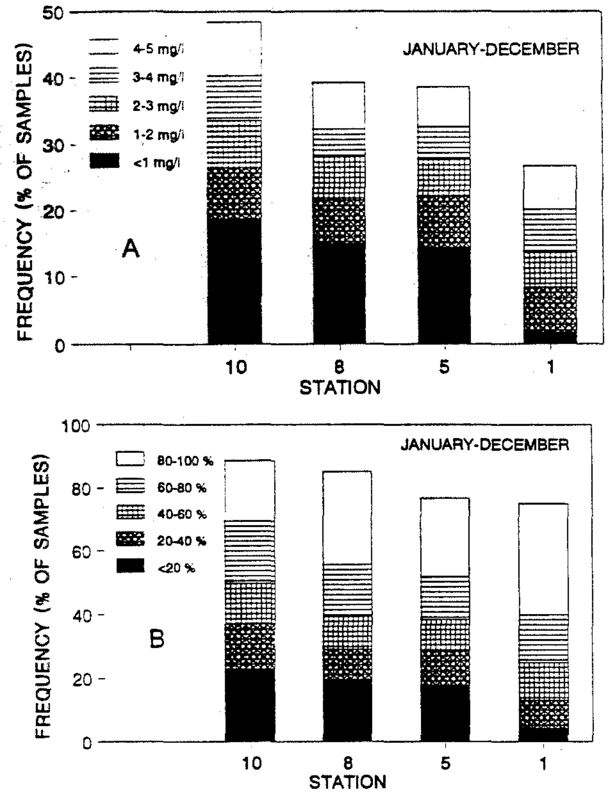

Fig. 6. Frequency of five DO concentration ranges (A) and percent saturation ranges (B) for each monitoring station. Includes all data for the period 1975–1989.

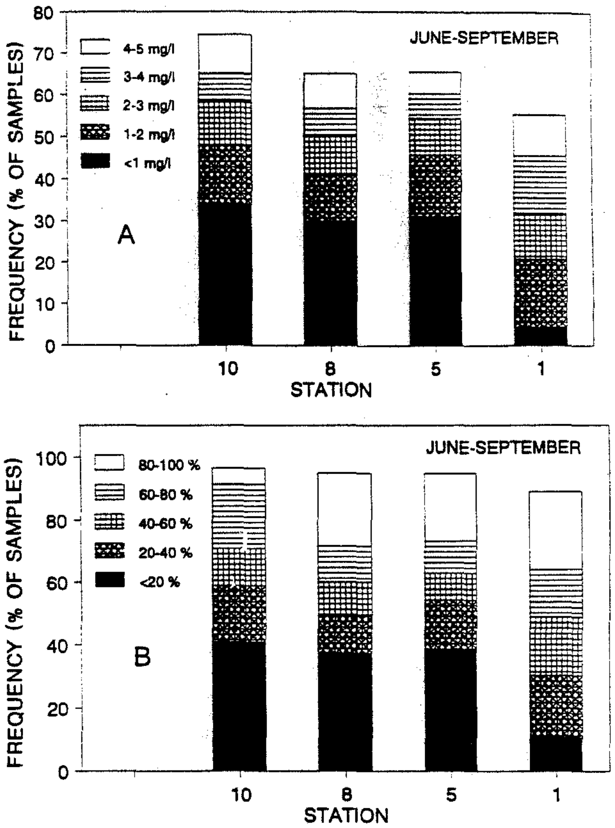

Fig. 7 Frequency of five DO concentration ranges (A) and percent saturation ranges (B) for each monitoring station. Includes only June-September data for the period 1975–1989.

tions, grouped into six water temperature ranges (Fig. 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, Fig. 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 (Fig. 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 (Figs. 6 and 7). When data for all months are considered, around 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} (Fig. 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 (Fig. 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; that is, low oxygen is still most common in the upper regions of the estuary (Fig. 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

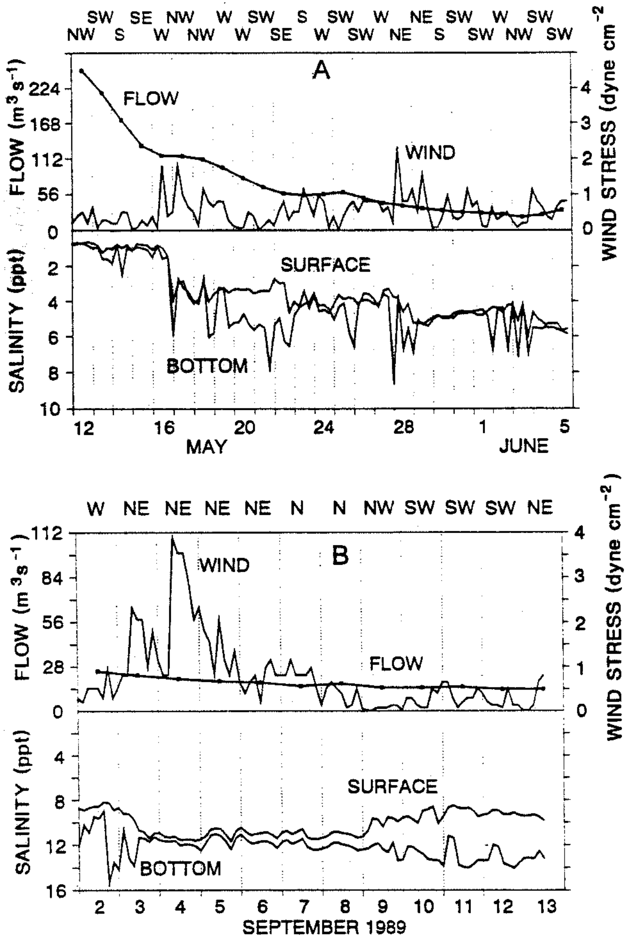

Fig. 8. Surface and bottom salinity, Tar River flow, and wind stress and direction for two periods during 1989. Salinity and wind data are plotted at 3-h intervals, and flow is the daily mean.

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 (2–3 wk). 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.

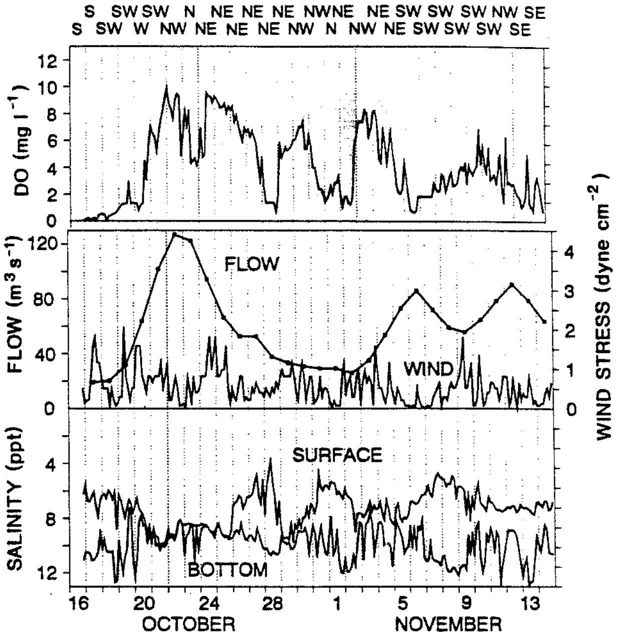

Fig. 9. Surface and bottom salinity, Tar River flow, wind stress and direction, and bottom water DO concentration for the period October 16–November 14, 1989. Salinity, wind, and DO data are plotted at 3-h intervals; flow is the daily mean.

The first time-series covers a period characterized by rapidly declining Tar River discharge (Fig. 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 and 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‰ early in the period to 5‰ 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 dominant control then. But as flow decreased, wind became more important, as demonstrated by the development of weak stratification (2‰) on May 19 after wind stress subsided below 1 dyne cm^{-2}. This stratification was broken up 3 d 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 (September 2–13) 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‰), and weak stratification (Fig. 8B). A lens of saltier water in the vicinity appears to have intruded twice for brief periods on September 2 and 3. 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 September 6, salinities throughout the water column had risen to about 11‰. Gradually, over the next 4–5 d, the wind shifted back to the SW, and surface salinities decreased slowly to 8–9‰. Also, the wind velocities declined, allowing a vertical salinity gradient of about 5‰ to develop. After September 9 both increasing bottom salinity and decreasing surface salinity contributed to the widening vertical salinity gradient.

No oxygen data are available for the first two sequences, but there are DO data for the final sequence, spanning the period mid-October to mid-November 1989 (Fig. 9). This sequence is also interesting 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 October 16. Tar River flow had declined from a previous peak to 20 $m^3 s^{-1}$, winds were blowing slowly from the south, and there was a 6‰ 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 October 21. 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 d, reaching a peak of 125 $m^3 s^{-1}$ at Tarboro on October 22. That pulse reached the estuary station 3 d later, quickly reducing the surface salinity to 5‰, and setting up the second stratification event, which eventually amounted to a 5‰ vertical gradient. Bottom-water DO fell rapidly from 6 mg l^{-1} on October 27 to around 1 mg l^{-1} the following day. This seems to be a clear example of stratification caused by a moderate pulse of fresh water 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 seven 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 h, another stratification event had begun to develop (October 30). This time, winds switched from the NE to the NW, and decreased in velocity. This event lasted about 4 d, with a vertical salinity gradient of about 4–6‰ and bottom water DO reduced to around 2 mg l^{-1}. It ended late on October 2 following increased wind stress the previous night. The fourth episode began almost immediately, and for the next 3 d (November 4–6), 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‰ for the remainder of the sampling period. Bottom DO also fluctuated, mostly between 2 mg l^{-1} 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 1975–1989 samplings when the water temperature was >15°C were used (Table 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 d, seemed to be less important, as the only significant combination was the 5-d lagged flow at station 1. The significant positive correlations between bottom oxygen and surface NO_3-N are interpreted as resulting 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

TABLE 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-d, 10-d and 15-d lagged flows. WS = wind stress on day of DO measurement; WS-1 and WS-2 = 1-d and 2-d 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***

* $p < 0.05$.
** $p < 0.01$.
*** $p < 0.001$.

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 2). Flows were lagged 0, 5, 10, and 15 d, and wind stress was lagged 0, 1, and 2 d. The computed correlation coefficients between flow and delta sigma-t were significant ($p < 0.05$) for only station 10 at the upper end of the estuary. As would be expected, time lags of 0 d and 5 d gave the strongest correlation for the upper stations, whereas 10-d and 15-d 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 trend 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 2) at all stations when the wind of the previous day was considered, but only at one station when a 2-d 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

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

Variable	Station			
	10	8	5	1
	−0.210*	−0.081	0.009	0.111
F	−0.204*	−0.085	0.027	0.128
F-5	−0.173	0.110	0.114	0.205
F-10	−0.199*	0.030	0.159	0.231*
F-15	−0.184*	−0.257*	−0.197*	−0.221*
WS	−0.202*	−0.319**	−0.234*	−0.300**
WS-1	−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	−0.084	0.000

* $p < 0.05$.
** $p < 0.01$.
*** $p < 0.001$.

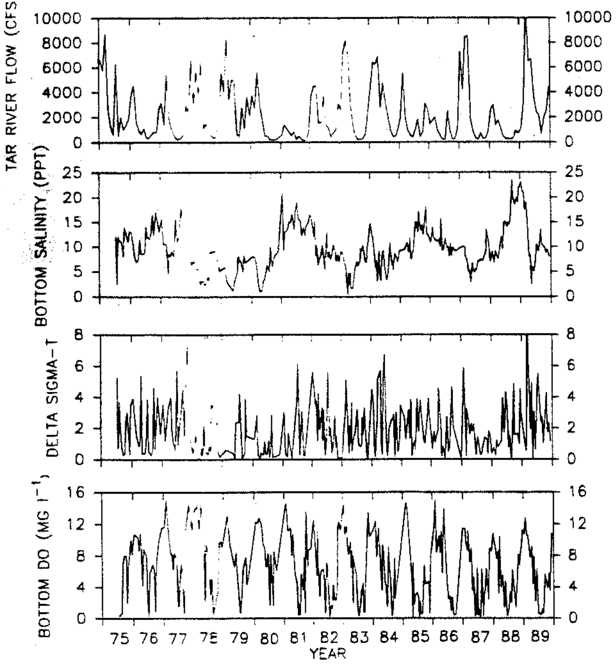

Fig. 10. Time series plots of Tar River flow, and Pamlico River estuary bottom salinity, delta sigma-t, and bottom water DO for the period 1975–1989. Tar River flow data are from the USGS gauge at Tarboro, and all other data are for monitoring station 5 in the estuary.

TABLE 3. Results of the Seasonal Kendall-Tau test. Alpha is the level of significance of the test.

Parameter	Station	Alpha
Tar River flow		0.803
Bottom salinity	1	0.453
	5	0.454
	8	0.476
	10	0.651
Bottom DO	1	0.114
	5	0.168
	8	0.272
	10	0.208
Delta sigma-t	1	0.193
	5	0.321
	8	0.470
	10	0.329

the late winter and early spring when freshwater inflow is highest (Fig. 10). 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.

Water column stratification in the estuary is much more variable than bottom salinity on a short-term basis, as indicated by the very jagged shape in the delta sigma-t time-series plot (Fig. 10). 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 1978–1979 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 (Table 3). 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 co-axial (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 $km^2\ d^{-2}$ or an axial vector equal or greater than 50,000 $km^2\ d^{-2}$ (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 4 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 d during June, every 11.5 d during July, every 12.4 d during August, and every 6.5 d during September.

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

TABLE 4. 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

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 322.2×10^6 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 d 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 Fig. 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 Fig. 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 5-d 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 d to 12.4 d. 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 (Fig. 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 distribution 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 (North Carolina Department of Natural Resources and Community Development 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-Altantic and Gulf coasts of the United States (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 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 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 nitrogen 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.

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Trends in the Tar River Basin--1980-97

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U.S. Geological Survey

Water quality trends in the Tar River at Tarboro

- NASQAN network 1975-95
  - major ions, nutrients, trace elements
- NAWQA network 1992-
  - major ions, nutrients, synthetic organics

USGS

Seasonal Kendall Trend Test

- Non-parametric test of **monotonic** trend.
- accounts for seasonal variations in concentration by comparing data from like seasons.
- Concentrations are adjusted for streamflow so that results are not biased by unusually wet or dry years.

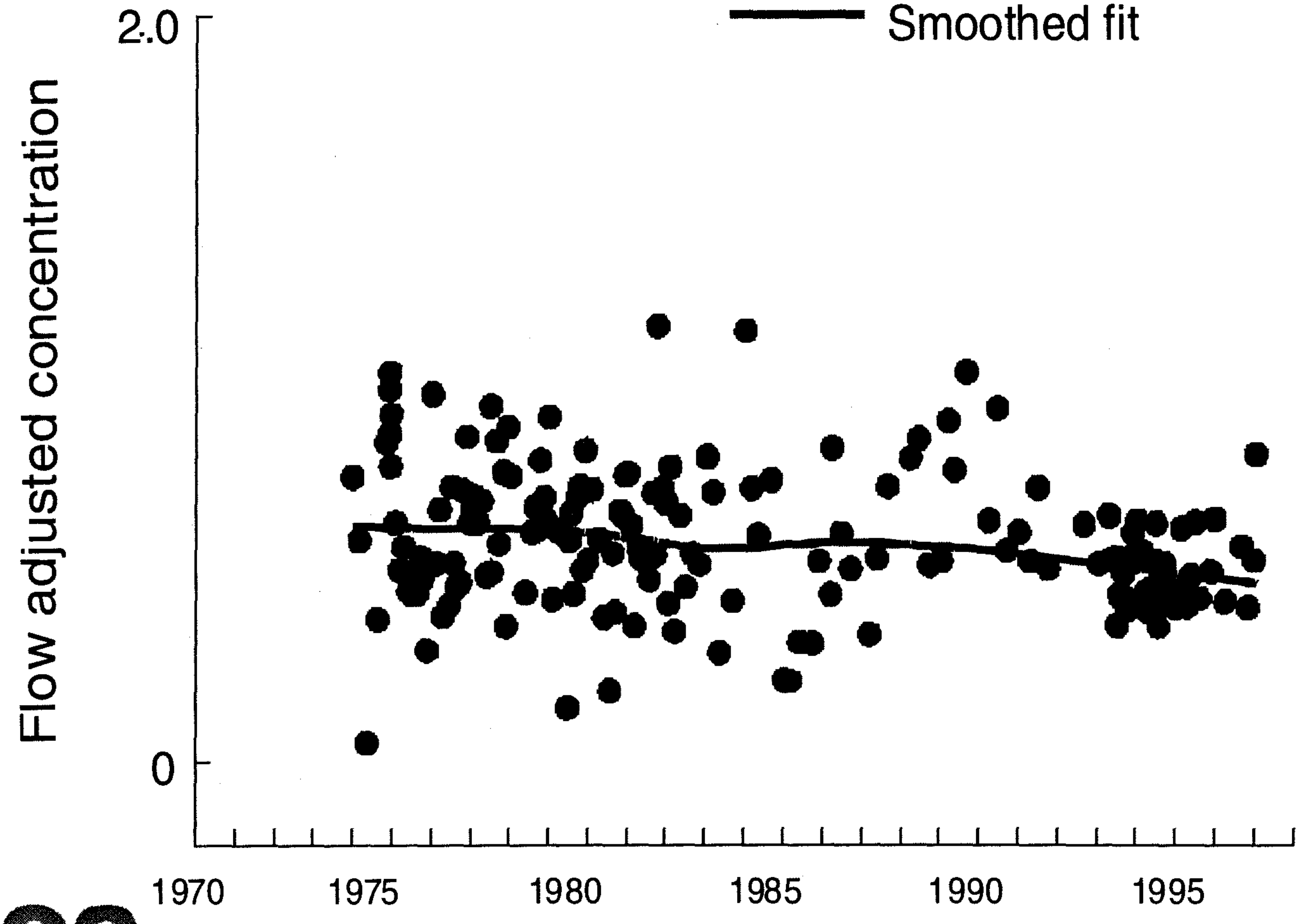
USGS Trends Reports

- Harned and Davenport, 1990
    - 1955-88
- Harned and others, 1995
    - 1980-89
- Updated analysis
    - Tar River at Tarboro, 1980-96

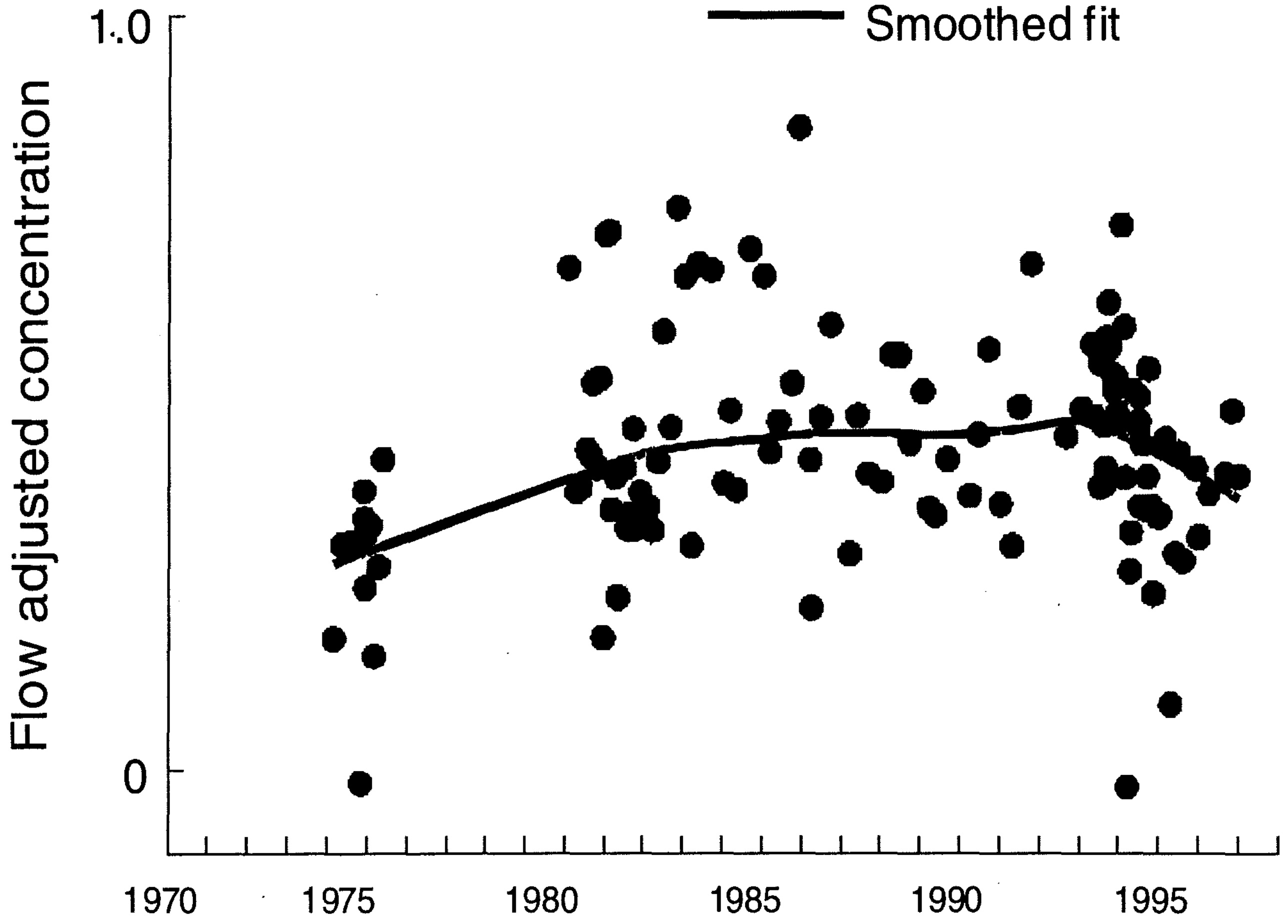
Tar River at Tarboro

Constituent	*Harned and Davenport (1990)*	*Harned and others (1995)*	*Analysis of data through 1996*
Turbidity	--	--	⇔
Specific conductance	█	⇔ USGS █ DWQ	█
Dissolved oxygen	--	--	⇔
pH	⇓	--	█
Alkalinity	--	--	█
Nitrogen	--	--	⇓
TKN	--	⇔	⇔
NO3	--	⇔	⇓
Phosphorus	█	⇔	⇓
Potassium	--	█	█
SO4	--	--	█
Silica	--	--	⇓
TDS	█	⇓	█
Sediment	--	⇔	⇓

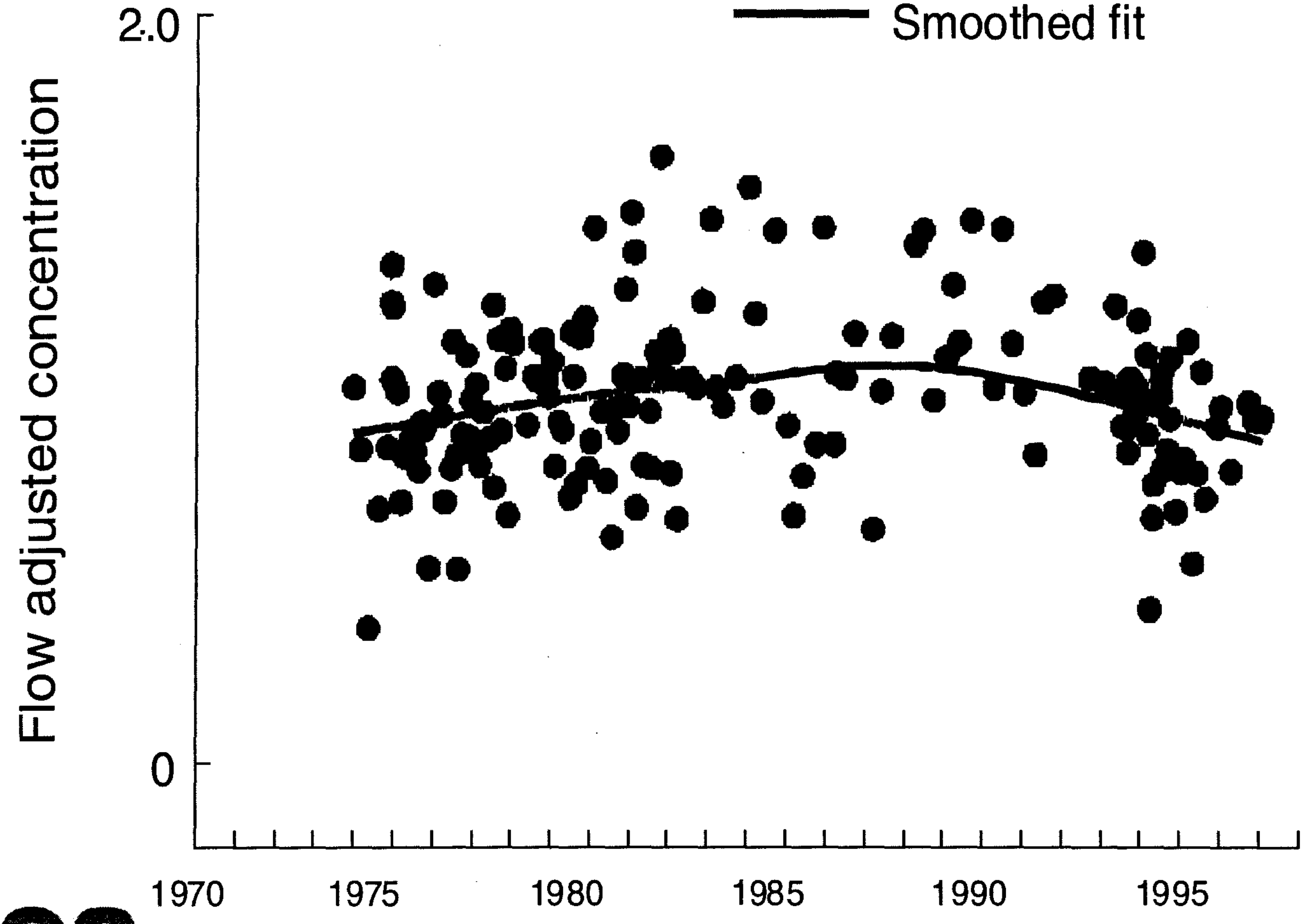
Ammonia plus organic N



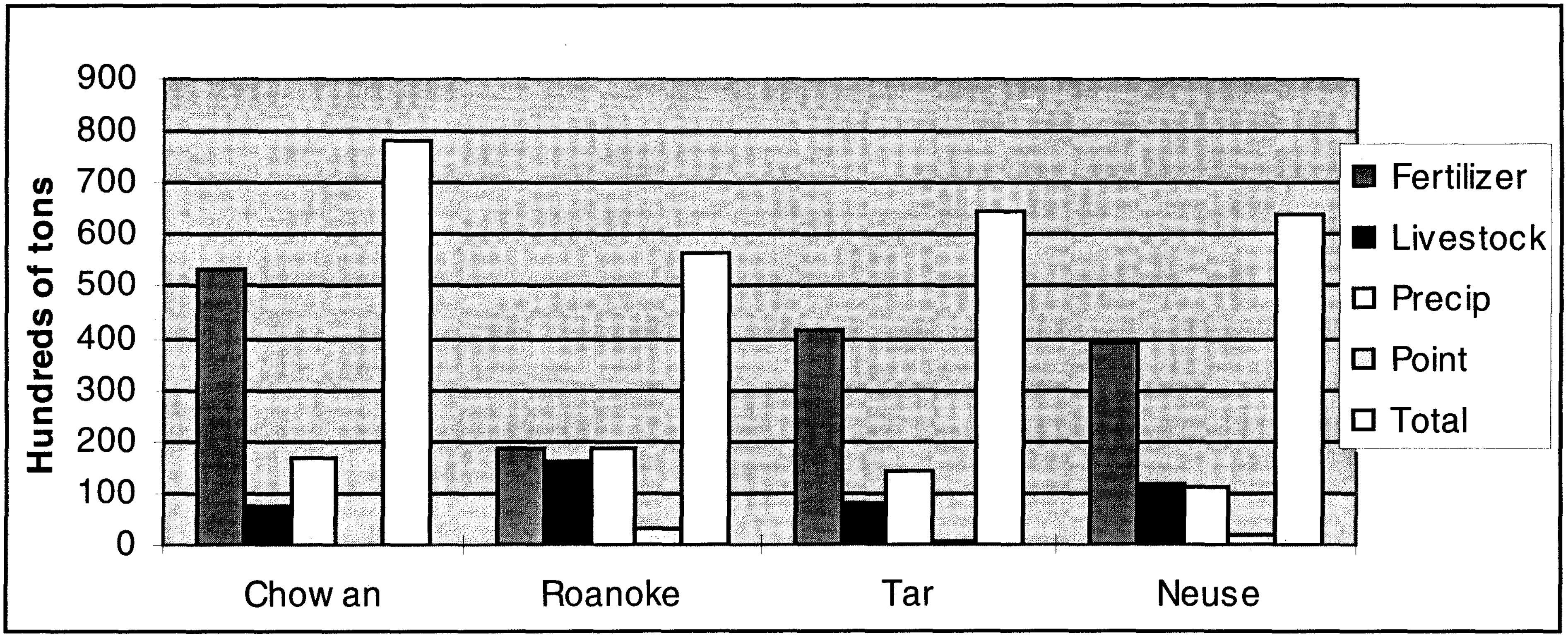
Nitrate plus nitrite



Total Nitrogen

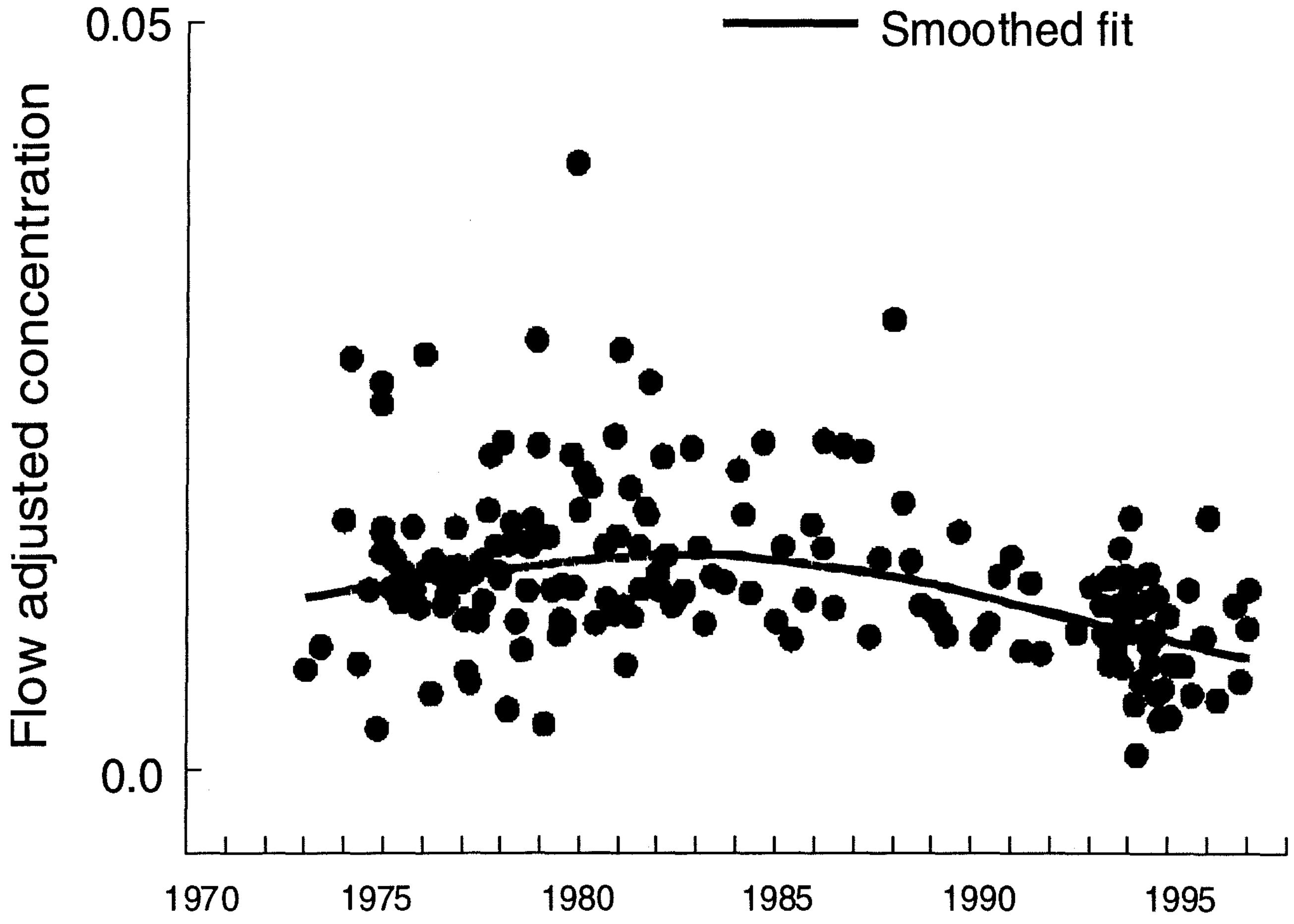


Sources of nitrogen -- Albemarle-Pamlico basin



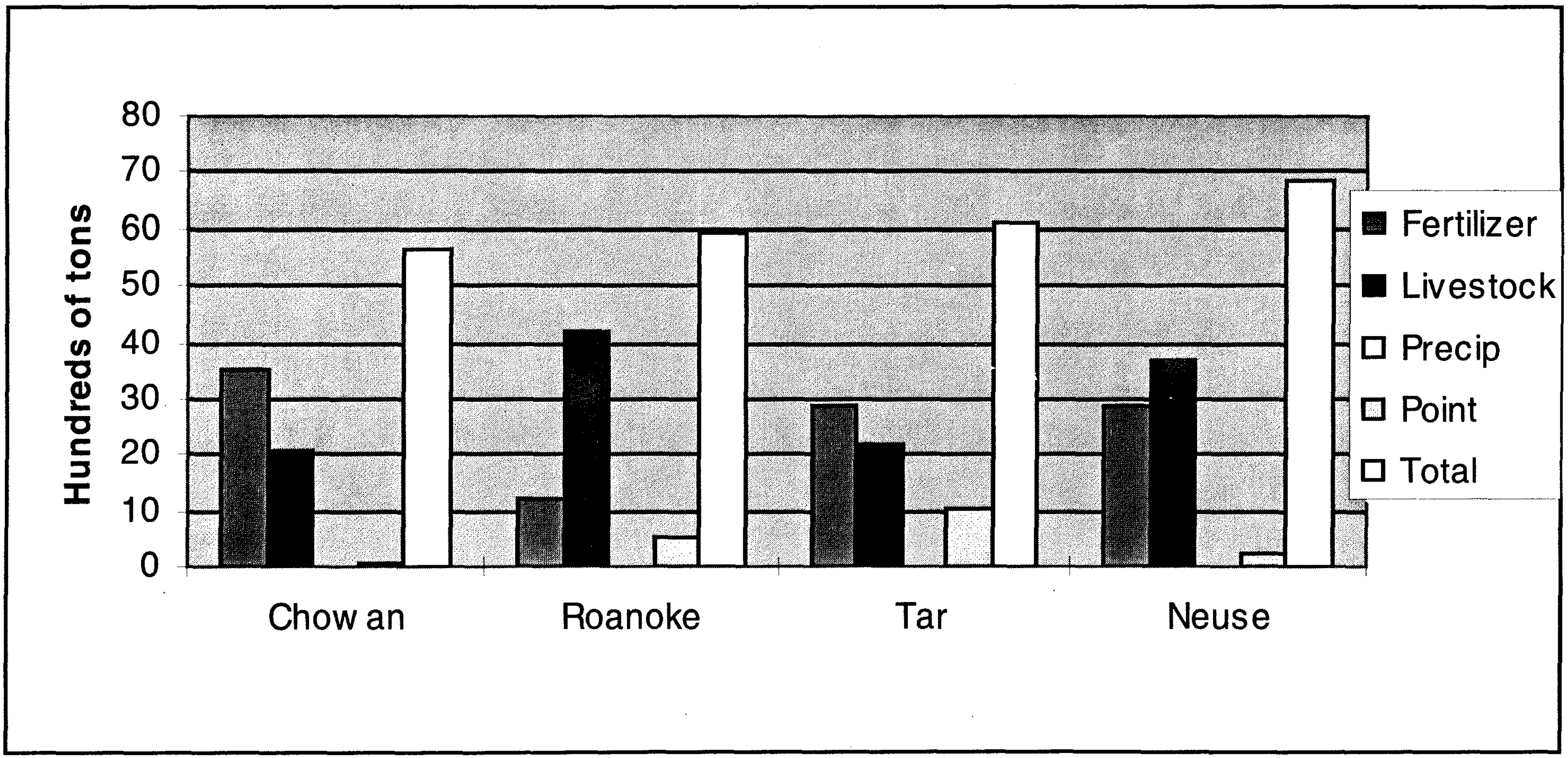
USGS

Total phosphorus

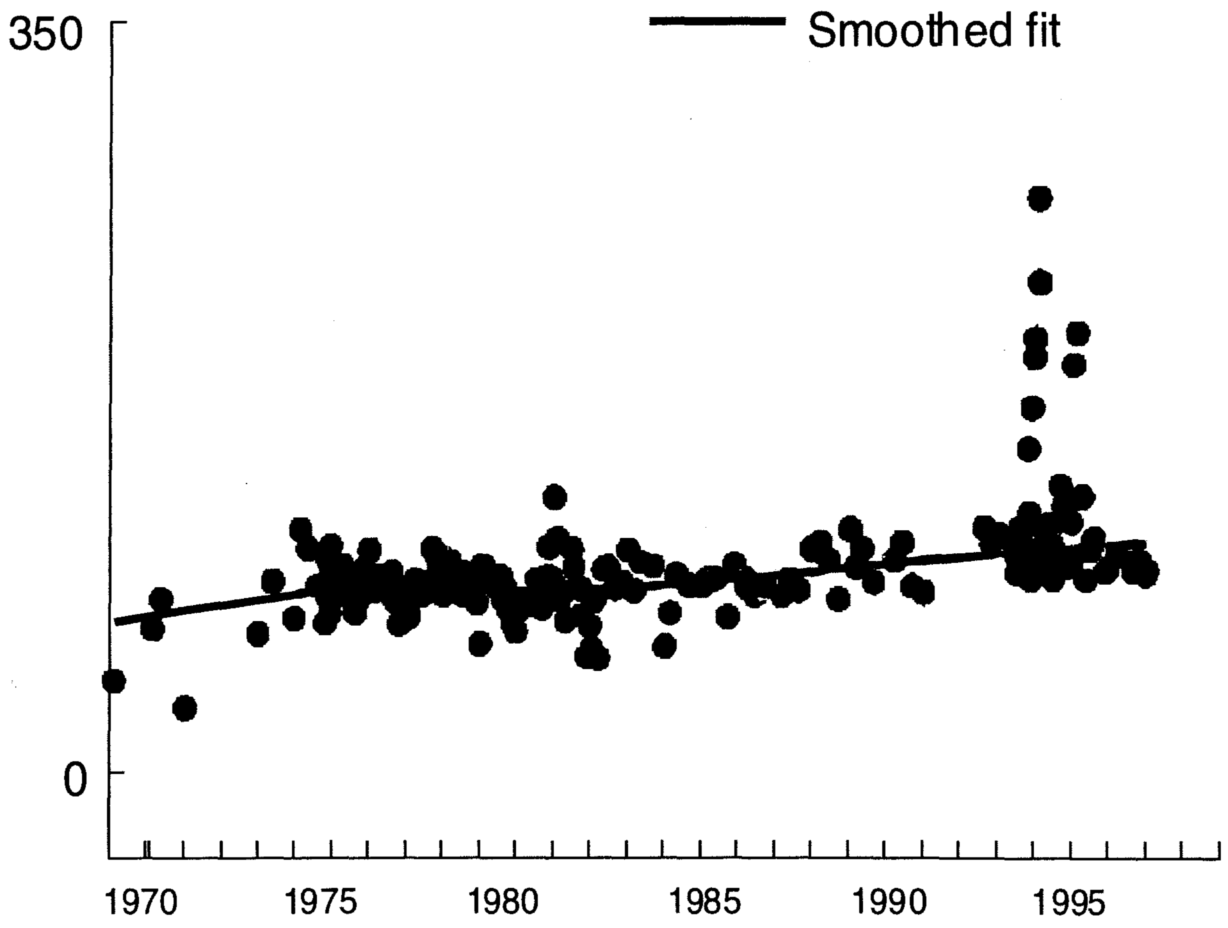


USGS

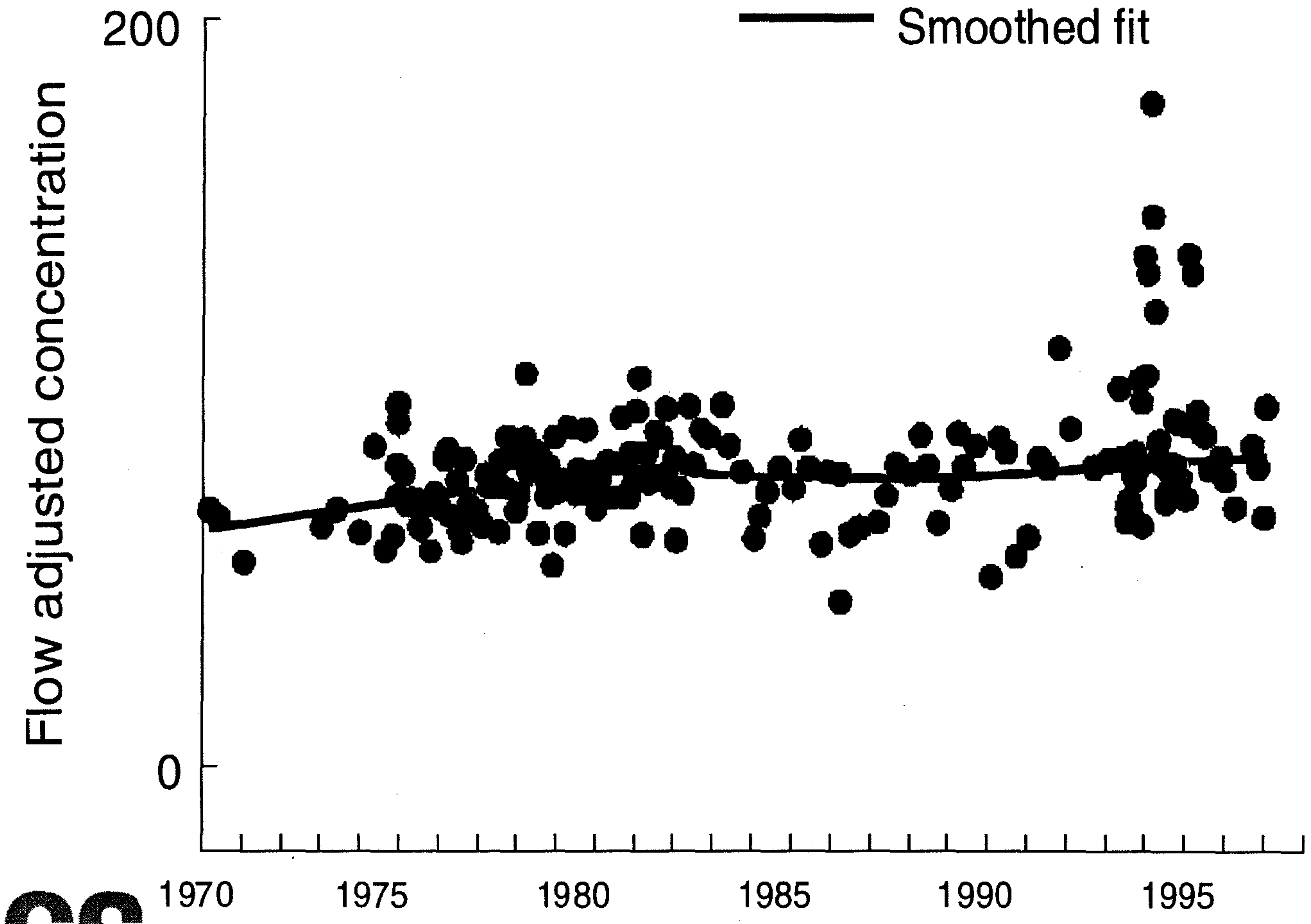
Sources of phosphorus -- Albemarle-Pamlico basin



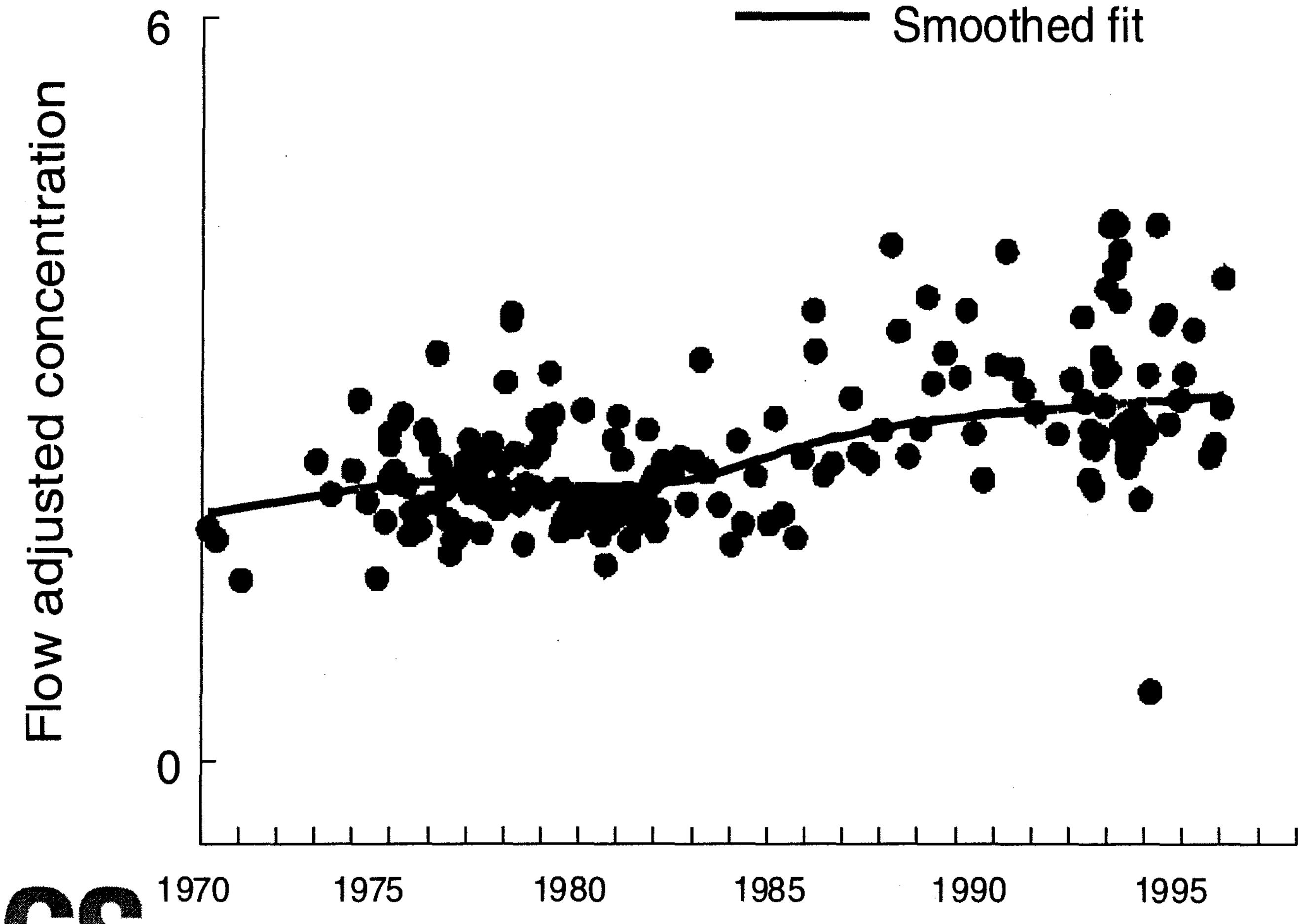
Specific conductance



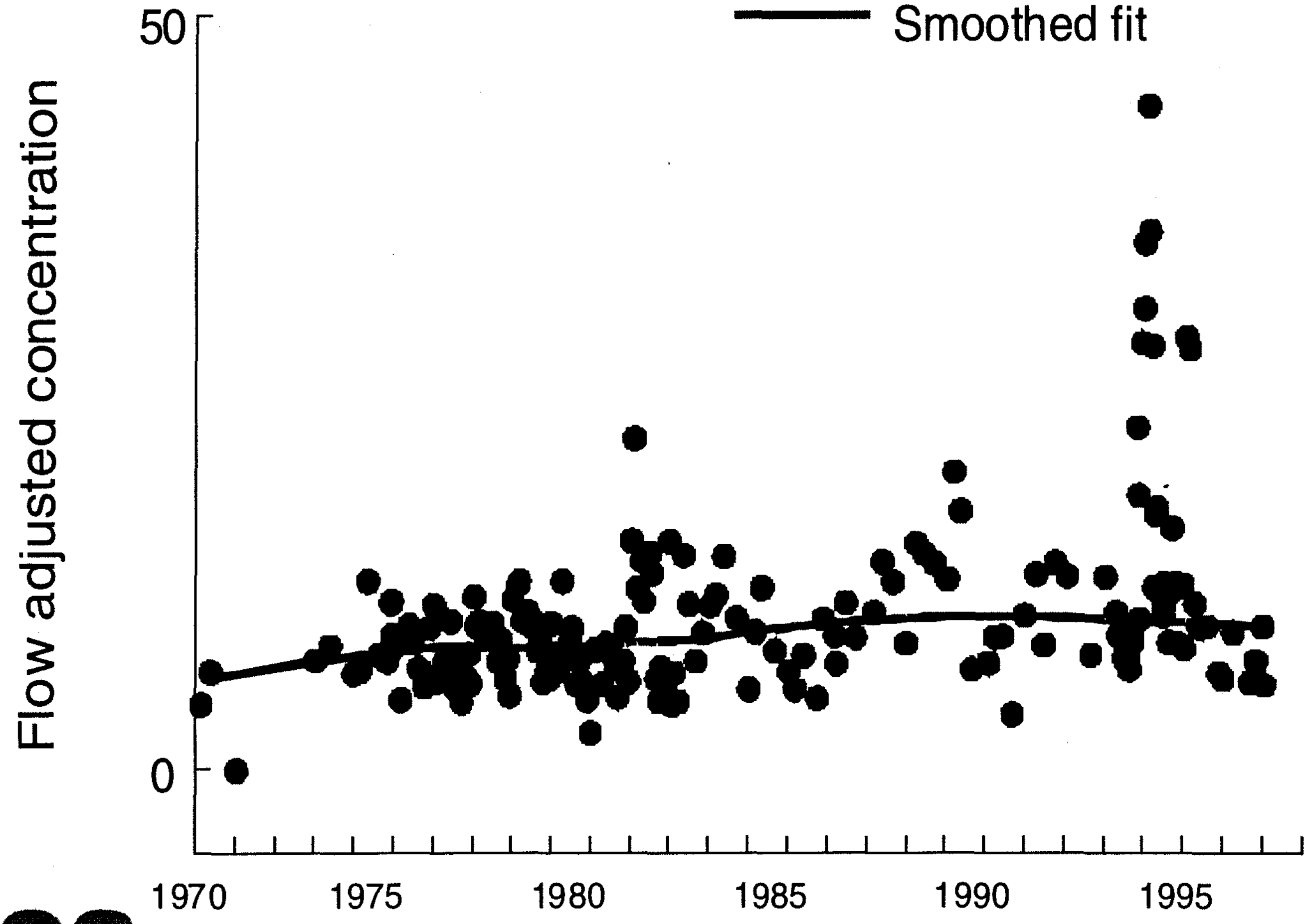
Total dissolved solids



Potassium

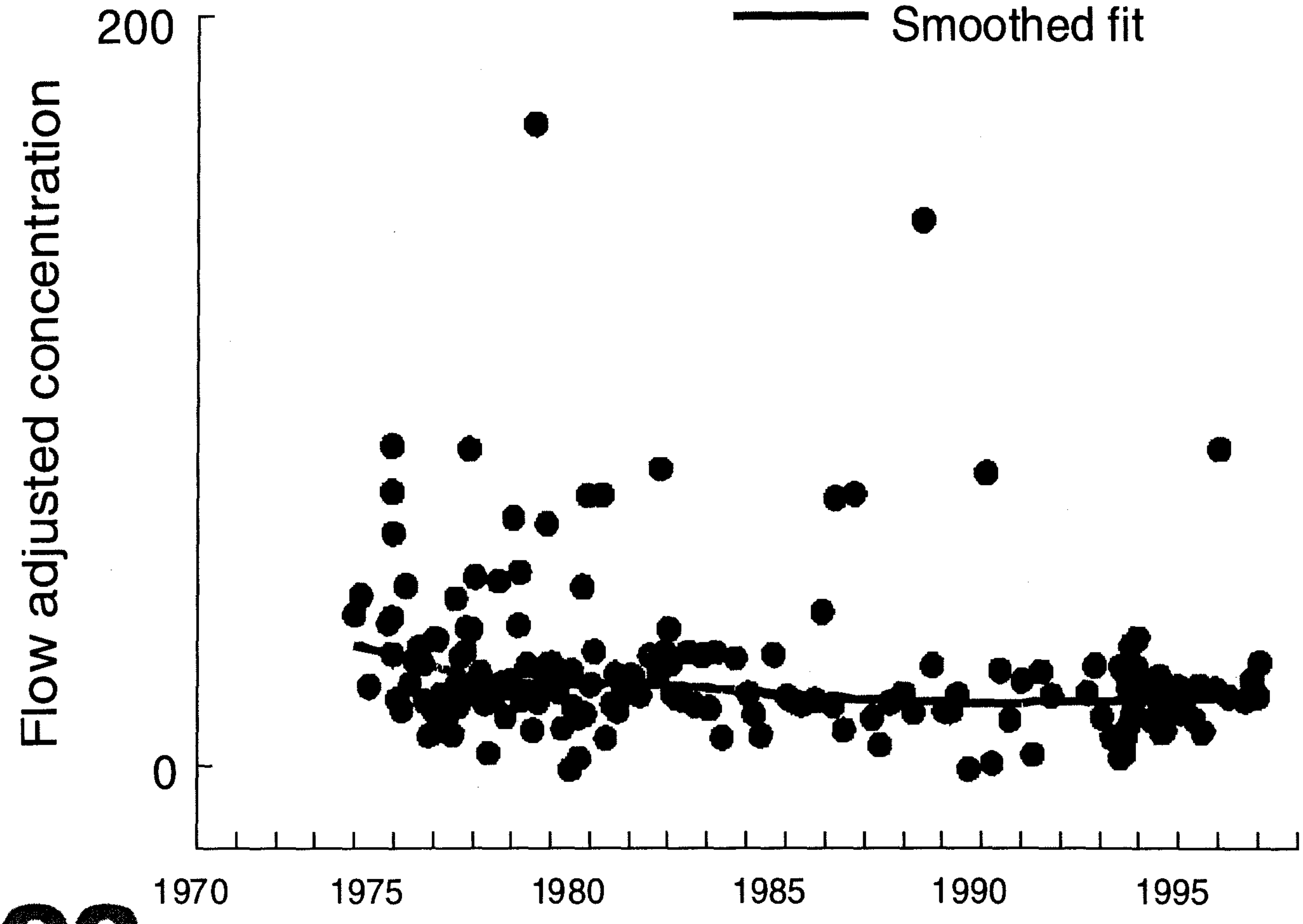

Smoothed fit
Flow adjusted concentration
6
0
1970
1975
1980
1985
1990
1995

Sulfate

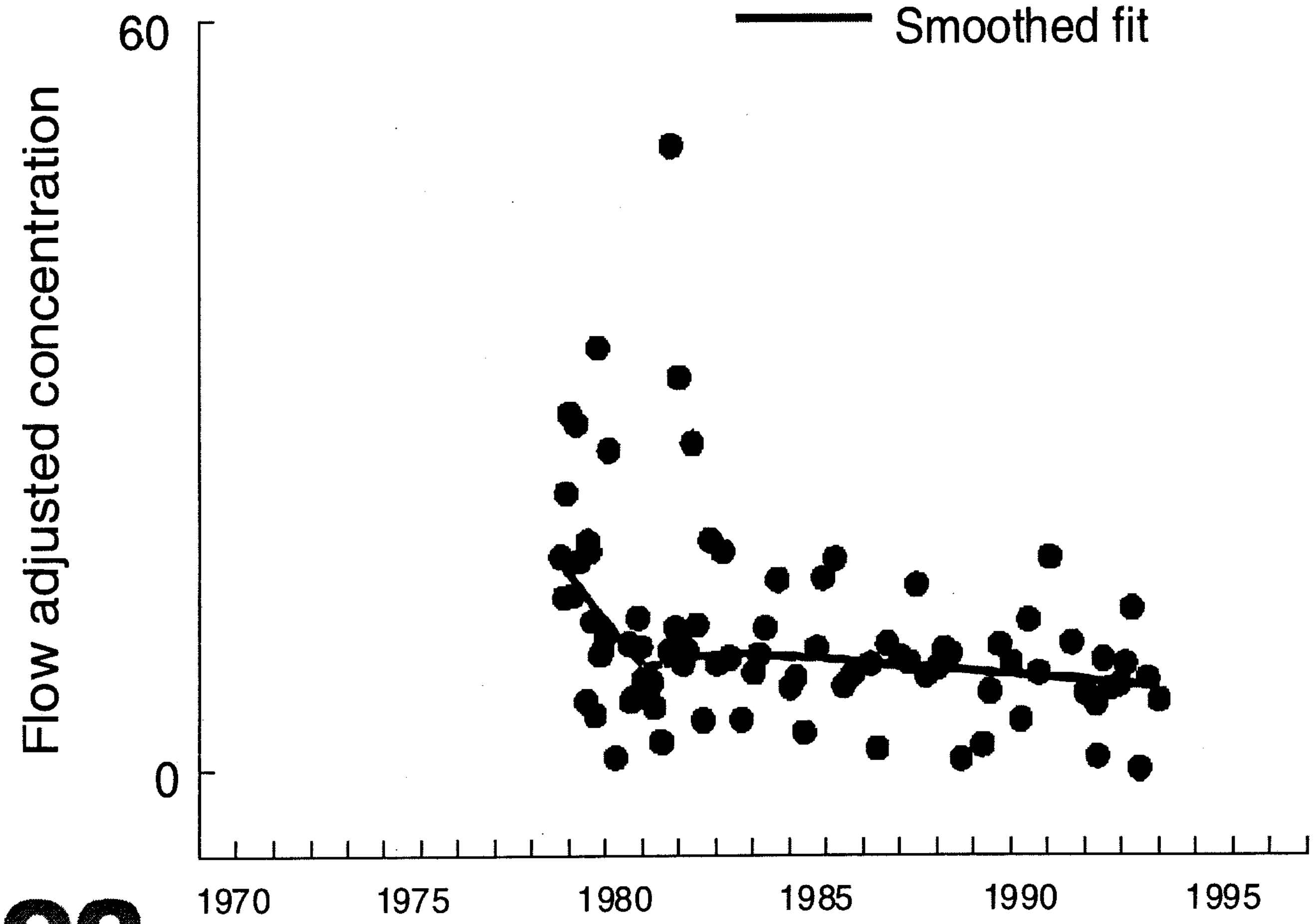


Smoothed fit
Flow adjusted concentration
50
0
1970
1975
1980
1985
1990
1995

Suspended sediment

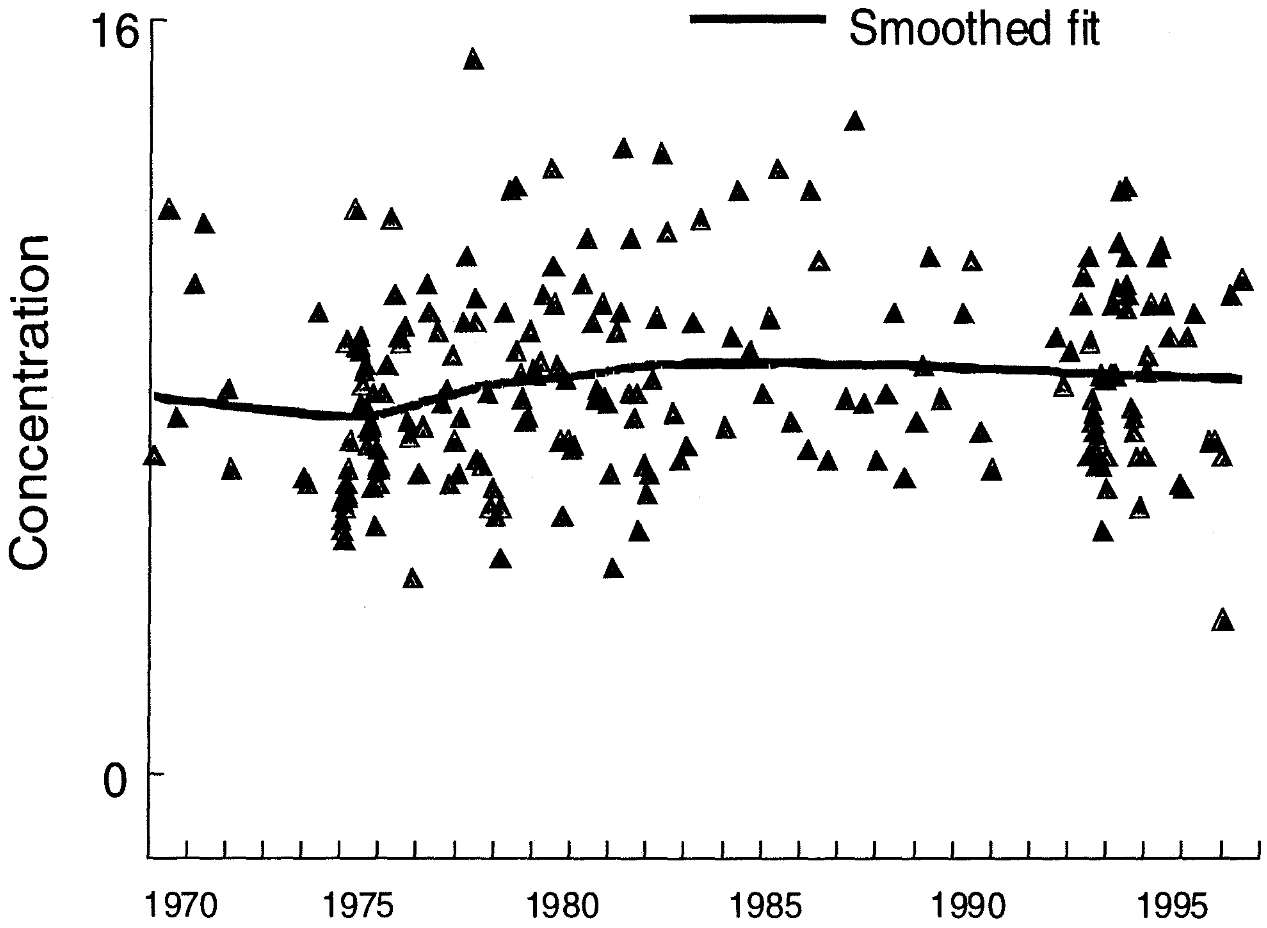


Turbidity



USGS

Dissolved oxygen



USGS

Summary

- Results of monotonic trend analysis in the Tar River may vary according to time period analyzed. (e.g. phosphorus)
- For the past 15 years, downward trends are observed for nitrogen, phosphorus, and suspended sediment.

USGS

Summary

- Downward trends in N and P are from
  - improvements in agricultural practices
  - enhanced wastewater treatment
  - improvements in resource management practices such as the phosphate ban.

Summary

- For the past 15 years, upward trends are observed for some major ions including total dissolved solids and specific conductance, potassium, and sulfate.

- Trends in these major ions may be from increased wastewater discharges.

USGS