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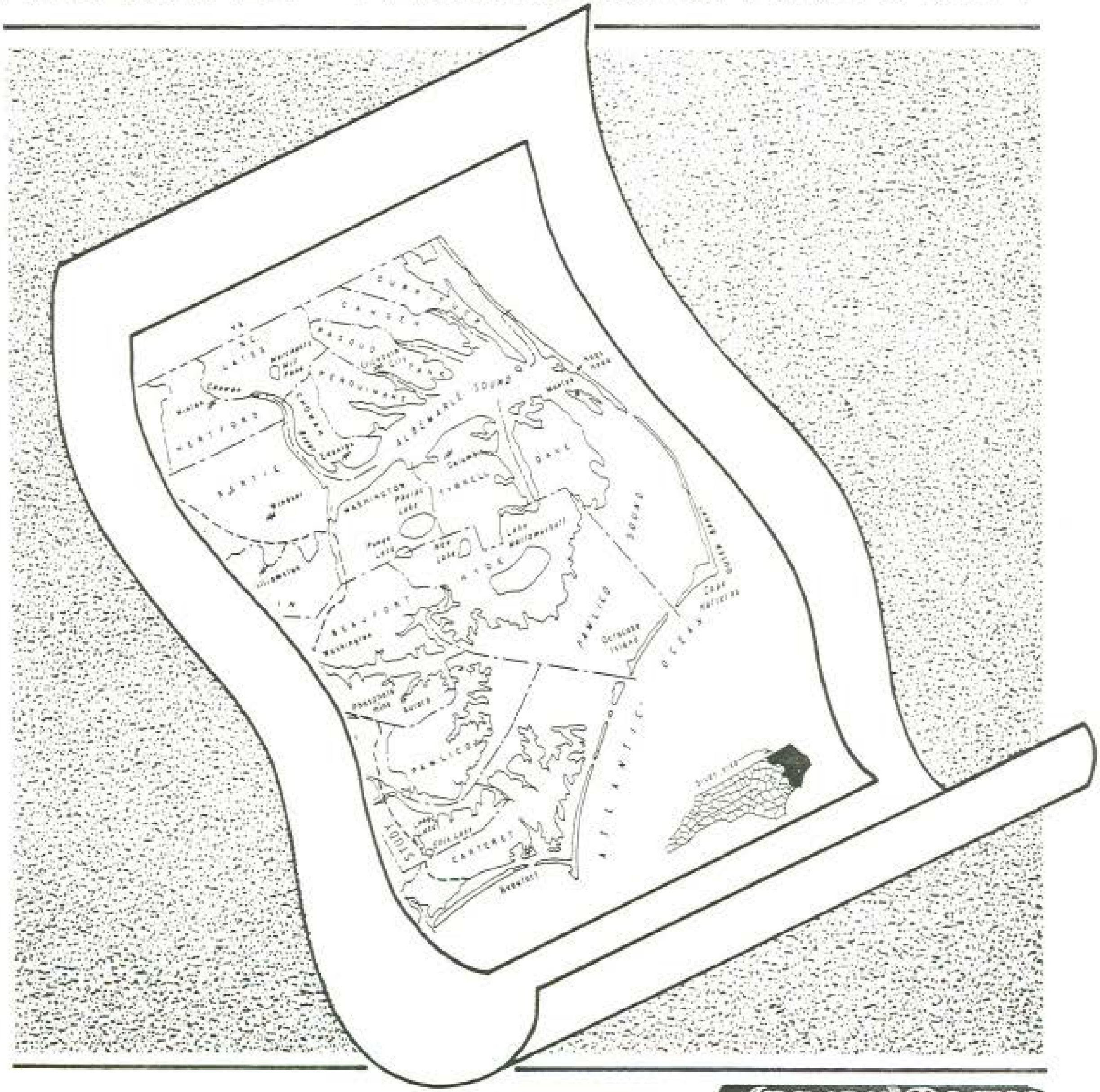
The Potential for Eutrophication and Nuisance Algal Blooms in the Lower Neuse River Estuary

ALBEMARLE - PAMLICO ESTUARINE STUDY



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The Potential for Eutrophication and Nuisance Algal Blooms in the Lower Neuse River Estuary

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The Potential for Eutrophication and Nuisance Algal Blooms in the Albemarle-Pamlico Estuary

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Summary

Phytoplankton primary production and its environmental regulation were examined at 3 stations representative of the lower Neuse River Estuary near the Pamlico Sound interface. This study covered a 3-year period (November 1987-October 1990). We also examined the roles of the major phytoplankton nutrients nitrogen and phosphorus in controlling growth and bloom formation. The overall potential for nuisance blooms and associated episodes of bottom water hypoxia and anoxia was investigated in field studies. The lower Neuse River estuary was well-mixed. Algal biomass and production varied seasonally, with high values in summer and low values in winter. *In situ* nutrient addition bioassays indicated the estuary experienced a general state of N limitation with especially profound limitation during summer periods. Bioassays during spring months showed increased algal biomass and production stimulation with the addition of N and P over that found with N addition alone.

While seasonal patterns predominated, the algal community responded during any season to increased flow and concomitant nutrient loadings by increasing biomass and production levels, often very rapidly. This was most dramatically demonstrated by a large *Heterocapsa triquetra* bloom during late winter of 1989-1990.

Dissolved inorganic nitrogen (DIN) levels were generally low, except during periods of high flow when heavy nutrient loading occurred. Dissolved inorganic phosphorus (DIP; as PO_4^{3-}] levels followed a seasonal pattern of high summer and fall values, and low winter and spring values. However, the highest [PO_4^{3-}] measured was during the winter 1989-90 loading event.

The Neuse River estuary can be classified as a mesotrophic system. Mean summer chlorophyll *a* concentrations were approximately 15-25 ug Chla/l. Annual primary production was 290-340 gC/m^2. While phytoplankton blooms did arise, no nuisance blooms were evident. However, potential nuisance taxa (cyanobacteria, dinoflagellates) were periodically present. No anoxic bottom waters were encountered during blooms, although some oxygen depletion was evident.

The zooplankton community maintained low species richness throughout the study. Abundance peaked in late summer, concurrent with late summer phytoplankton peaks. Zooplankton biomass did not seem to respond to winter or spring phytoplankton blooms.

Our recommendations for a management strategy include reductions in DIN, DIP, and suspended sediment loads in order to maintain the system in a nuisance bloom-free condition. In addition, nutrient-enriched precipitation (acid rain) will be of increasing importance as a source of nutrients (specifically nitrogen), in part because of increasing loads in the atmosphere but also because these nutrients are deposited directly into the lower estuary, bypassing the assimilative processes in the upper estuary. A future management strategy should incorporate both terrigenous and atmospheric nutrient loading when formulating input constraints.

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Introduction

North Carolina is endowed with numerous, ecologically diverse and resource-rich coastal rivers, bays, and estuaries. Among these are the Albemarle and Pamlico Sounds, area-wise the second largest sound system in the Continental United States. Tributaries feeding both estuaries and sound systems are discharging ever-increasing loads of both nitrogen and phosphorus as North Carolina's agricultural, industrial and urban sectors grow and diversify. Annual loading of total nitrogen and total phosphorus to the Neuse River has been estimated to have increased by about 60-70% over the past century (Stanley 1988). Accelerated nutrient loading, particularly over the past two to three decades, has ushered in some ominous and increasingly common symptoms of eutrophication, which to our best knowledge, were extremely rare prior to World War II. Included are: 1) increasing incidences of deoxygenation in sediments and bottom waters of slow-moving, nutrient-laden freshwater river systems and associated oligohaline to euhaline estuaries (including the Chowan, Pamlico and Neuse Systems) (Dubach 1977; N.C.D.N.R.C.D. 1980; Paerl 1987), 2) more frequent and more intense algal bloom activity, particularly of surface scum-forming nuisance blue-green algae, in both the Chowan and Neuse Rivers (Witherspoon et al. 1979; Paerl 1983; 1987), and 3) periodic, and at times persistent, outbreaks of fish and shellfish disease or mortality in the more eutrophic segments of rivers and estuaries (Esch and Hazen 1983; Copeland and Gray 1989; Levine et al. 1990). Research has suggested such outbreaks may be related to toxic reaction to H_2S buildups in sediments, viral and fungal infections (Sea Grant U.N.C. 1982), or dinoflagellate and blue-green algal blooms (N.C.D.N.R.C.D. 1980).

Coastal nutrient-related water quality problems, ranging from gradual eutrophication to massive algal blooms, represent a serious threat to commercial, recreational and aesthetic values of affected freshwater and estuarine habitats in eastern North Carolina. Scientific evidence clearly shows that problems associated with eutrophication have had a negative impact on the economic and environmental well-being of this state (Copeland and Riggs 1984; Epperly and Ross 1986; Levine et al. 1990). Much of North Carolina's freshwater discharges into the Albermarle-Pamlico Sound System (A - P System) (Wells and Kim 1989); a system that supports the state's most extensive fisheries, tourist and recreational resources (Copeland 1986; Epperly and Ross 1986; Copeland and Gray 1989). As such, obvious concerns include: 1) Are inorganic nutrients limiting and hence regulating phytoplankton growth in the A - P System? 2) Which nutrients (N or P) act as growth limiting factors? 3) Is accelerated eutrophication, resulting from nutrient enrichment, occurring in the A - P System? 4) Does the A - P System display symptoms of eutrophication, such as noxious or toxic algal blooms or anoxic bottom water? 5) Does nutrient-related eutrophication represent a threat to fisheries, recreational and aesthetic resources in the A - P System? 6) If the above are true, can we properly manage a system of such size and scope in order to avert or reverse long-term water quality degradation?

Research Objectives

Given the concerns outlined above, the following research objectives were addressed in this project:

1. Determine the relative importance of nitrogen vs. phosphorus as phytoplankton growth-limiting nutrients in the NRE (Neuse River Estuary).

2. Define and evaluate the environmental conditions required for potential "nuisance" (blue-green algal or dinoflagellate) blooms to become established and proliferate in the NRE.

3. Determine if hypolimnetic hypoxia or anoxia are associated with maximum periods of phytoplankton production in the NRE.

4. Utilizing information obtained from objectives 1-3, provide water quality and fisheries management with a sound and rational set of nutrient input control recommendations.

Methods

The following suite of physical, chemical, and biotic field and laboratory measurements were routinely conducted at 1-1.5 month intervals at stations 1, 5, and 6 (Fig. 1), located near the mouth of the NRE. Station 1 is at navigational marker 1 at the confluence of the South River and the NRE. Station 5 is approximately 1 km N-NE of navigational marker 1. Station 6 is across the NRE, approximately 6 km N-NE, at navigational marker 6, southwest of the confluence of Broad Creek and the NRE. These stations form a transect from a segment of the estuary where freshwater input from the South River can have a large influence (station 1) to a segment more characteristic of the vast mesohaline component of this estuary (station 6).

All laboratory analyses were in accordance with methodologies outlined in the original proposal and EPA Quality Assurance Statement. They are summarized and referenced in Table 1. All nutrient addition bioassays were conducted with water collected at station 6, except December 1988 and October 1989 when station 5 water was used. Station 6 was chosen as the location for the bioassays because: 1) it is a representative mesohaline location in NRE, and 2) given budgetary limitations and logistic considerations, research efforts were limited to a specific segment of the A - P System, accessible by small boat, which could be rapidly deployed for sampling during daylight.

A. **Physical and chemical field measurements**

1. Vertical profiles (0.5 m intervals) of temperature, salinity, dissolved oxygen, and photosynthetically active radiation (P.A.R.; 400-700 nm) at stations 1, 5 and 6.

2. Vertical profiles (surface, 0.5m, 1.0m, 2.0m, 3.0m, 3.5m) at station 6, and surface samples at stations 1 and 5, of dissolved inorganic nitrogenous ($NO_2^- + NO_3^-$ hereafter referred to as NO_3^-, and NH_4^+) and phosphorus (PO_4^{3-}) nutrients. Duplicate analyses were performed on a single sample from each depth.

B. **Biological measurements**

1. Surface samples for phytoplankton species composition, and enumeration at stations 1, 5 and 6.

2. Surface, as well as depth-integrated, samples for macrozooplankton (conducted by M. Mallin, partially

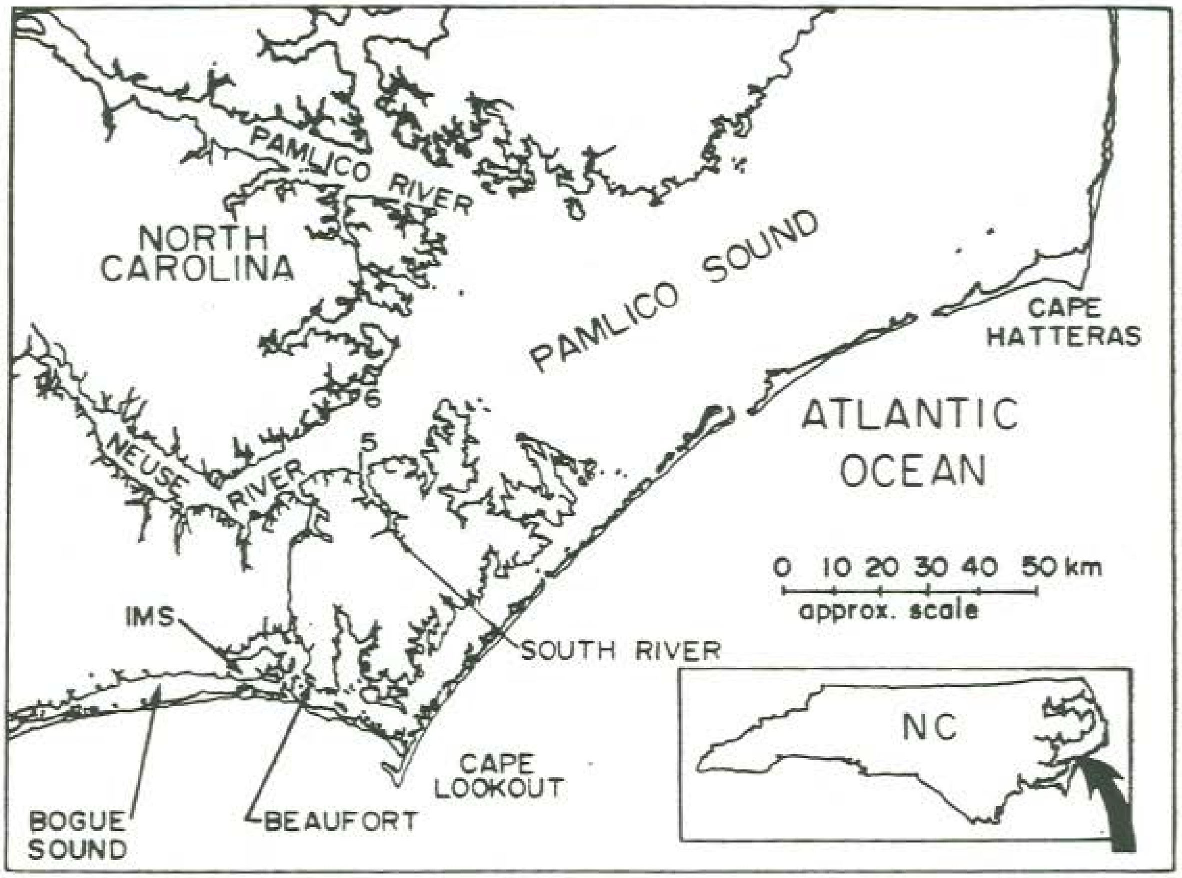


Figure 1. Map of sampling locations (Stations 1, 5, and 6) in the lower Neuse River Estuary.

Table 1. Analytical methods for physical, chemical, and biotic samples.

Parameter	Method and Reference
$NO_2^- + NO_3^-$	Cadmium reduction method (Strickland and Parsons 1972)
NH_4^+/NH_3	Phenol-hypochlorite method (Solorzano 1969)
PO_4^{3-}	Molybdate-blue method (Murphy and Riley 1962, Strickland and Parsons 1972)
Chlorophyll a	Trichromatic spectrophotometric method (Strickland and Parsons 1972)
Primary productivity	^{14}C uptake method (Wetzel and Likens 1979)
Phytoplankton identification and enumeration	Membrane filtration method (Crumpton 1987)
Salinity	YSI Salinometer, Model No. 33
Photosynthetically Available Radiation (PAR)	LI-COR Spherical Quantom Sensor, LI-193SB
Dissolved Oxygen	YSI Dissolved Oxygen Meter, Model No.54 and Winkler dissolved oxygen method (Strickland and Parsons 1972)
Temperature	YSI Dissolved Oxygen Meter, Model No.54
Zooplankton identification and enumeration	Circular counting chamber (100-1000 organisms per count)

supported by U. N. C. Sea Grant) at stations 1, 5 and 6.

3. Vertical profiles (surface, 0.5m, 1.0m, 2.0m, 3.0m, 3.5m) at station 6, and surface samples at stations 1 and 5, of chlorophyll _a_ concentrations. Single samples taken at each depth.

C. Nutrient-limitation bioassays

1. Utilizing an _in situ_ Cubitainer bioassay system in a concrete pond situated at the U.N.C. Institute of Marine Sciences, freshly collected water was routinely assayed to determine which, if any, nutrients were limiting algal primary production (Paerl and Bowles 1987) (Cubitainers are flexible containers, 95% transparent to PAR). Triplicate samples were amended with trace amounts of $Na^{14}CO_3$ and enriched with the following nutrients (expressed as final concentrations):

a) No nutrients (control)
b) NO_3^- (14.3 uM)
c) NO_3^- (28.6 uM)
d) PO_4^{3-} (3.2 uM)
e) Trace metals (2 ug/l each of Fe, Mn, Cu, Zn, Co, Mo)
f) NO_3^- (14.3 uM) + PO_4^{3-} (3.2 uM)
g) NO_3^- (14.3 uM) + PO_4^{3-} (3.2 uM) + trace metals (as above).
h) A silica amendment (1.5 ug/l) was substituted for the trace metals amendment (treatment "e" above) in bioassays from April 1989 through October 1989.

1uMN = 14ugN/l; 1uMP = 31ugP/l

Samples were incubated for 4 days. Both chlorophyll a concentrations and cumulative $^{14}CO_2$ incorporation were monitored at daily intervals. Chlorophyll a concentrations were measured on 300 ml samples, filtered onto 934 AH Whatman glass fiber filters with a few ml of a $MgCO_3$ suspension added to buffer against chlorophyll a degradation by any organic acids released by cell lysis during filtration. Assimilation of $^{14}CO_2$ was measured on 50 ml subsamples filtered through 934 AH Whatman glass fiber filters. Filters were fumed with HCl vapors for 30 minutes to remove abiotically precipitated ^{14}C, dried, and ^{14}C content determined in a liquid scintillation counter (Beckman TD 5000 and LS 7000). To facilate the display of the bioassay data set (Fig. 8 and 9), biomass stimulation, as estimated by chlorophyll a minus control, and primary productivity stimulation, as estimated by ^{14}C assimilation minus control, were averaged for each treatment over the 4 days of the experiment. Pooled sample standard error of the means were calculated and averaged over the 4 days of the experiment as well.

In addition to the above-mentioned activities, this project has benefited from the following, related activities contemporaneously undertaken in our laboratory: 1) Parallel (in time and space) *in situ* determinations of primary productivity (supported by U. N. C. Sea Grant project RMER-10). 2) Periodic *in situ* bioassay determinations of nutrient limitation in N. C. Atlantic coastal waters (2 km offshore from Beaufort Inlet) including samples in 1987-1988 dominated by the "red tide" dinoflagellate *Ptychodiscus* brevis (Gymnodinium breve). Lastly, close coordination with the sampling, analytical and modeling activities of Drs. D. Stanley, R. Christian (E.P.A. supported Neuse River nitrogen cycling project; E.C.U.) and J. Wells (parallel Albemarle Pamlico Estuarine Study [A.P.E.S.]) project on sediment dynamics in NRE) has fostered and improved our mutual understanding of nutrient-phytoplankton interactions in the Neuse-Pamlico Sound estuarine region.

Results

In the 36 month period from November 1987 through October 1990, we completed 30 sets of field samplings, in situ bioassays and laboratory determinations. Although we originally proposed sampling intervals of 2-3 months, the dynamic nature of the estuary led us very early on in the project (December 1987), to increase the frequency of sampling to every 1 to 1.5 months.

Especially noteworthy in our findings were the seasonally and hydrodynamically-driven patterns in:

1. ambient concentrations of the potentially limiting dissolved nutrients (nitrogen and phosphorus);
2. in situ primary production characteristics (data supplied through complimentary U. N. C. Sea Grant project (RMER-10) recently completed, December 1989 (H. W. Paerl and R. Leuttich, P.I.'s);
3. nutrient enrichment bioassay results, reflecting phytoplankton production and biomass limitations by nitrogen and/or phosphorus

nutrient availability.

Physical-chemical studies

The lower NRE (stations 1, 5, and 6; Fig. 1) typified a shallow, temperate estuary during the 1987-1990 study period. Low temperatures in winter ranged from 3-7 °C and high temperatures in summer were near 29° C. (Fig. 2).

Salinities were at maximum levels during the winters of 1987-88 (19 ppt) and 1988-89 (21 ppt) and the late summer and fall of 1990 (19 ppt) (Fig. 3). Minimum salinities were generally measured in spring (12 ppt in 1988, 5 ppt in 1989 and, 6 ppt in 1990). Variations in salinity were strongly dependent on river flow and local rainfall levels (Fig. 3), although wind-induced tides were very important in moving water in and out of this estuary (Wells and Kim 1989). Winds out of the north through west tend to push mesohaline Pamlico Sound water into the estuary, while winds out of the south to east tend to move water out of the estuary, allowing replacement by oligohaline Neuse River water. While hydrologic flow data are not available for the lower NRE, the U.S.G.S. (Raleigh regional office) has provided us with mean monthly flows in the Neuse River at Kinston (Fig. 3). Even though Kinston is approximately 50 miles upstream of our sampling sites, discharge at Kinston represents a major portion of the discharge into the lower NRE (Christian et al. 1989, USGS 1990).

Monthly mean flows at Kinston show very low flow conditions prevailing from November 1987 through February 1989 (Fig. 3). Mean flow was only 53 % of the 60 year average during this 16 month period. This reflects the abnormally low rainfall experienced in

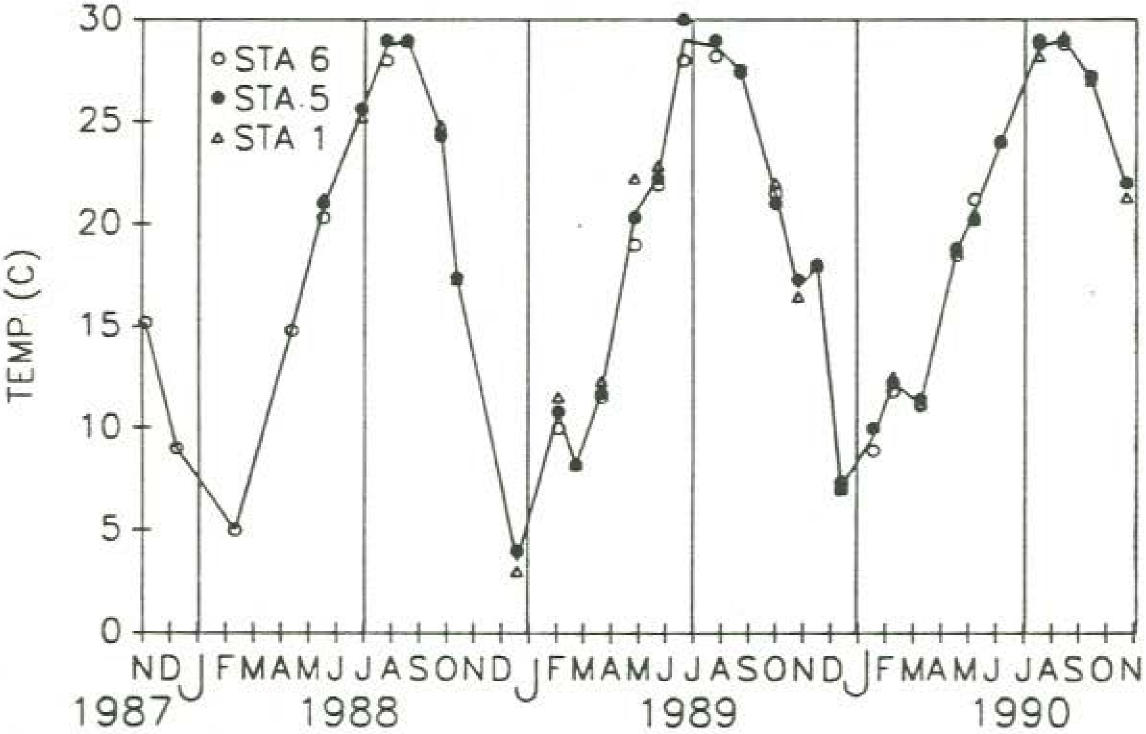


Figure 2. Surface measurements of the temperature at Stations 1, 5, and 6. Line represents mean of stations measured.

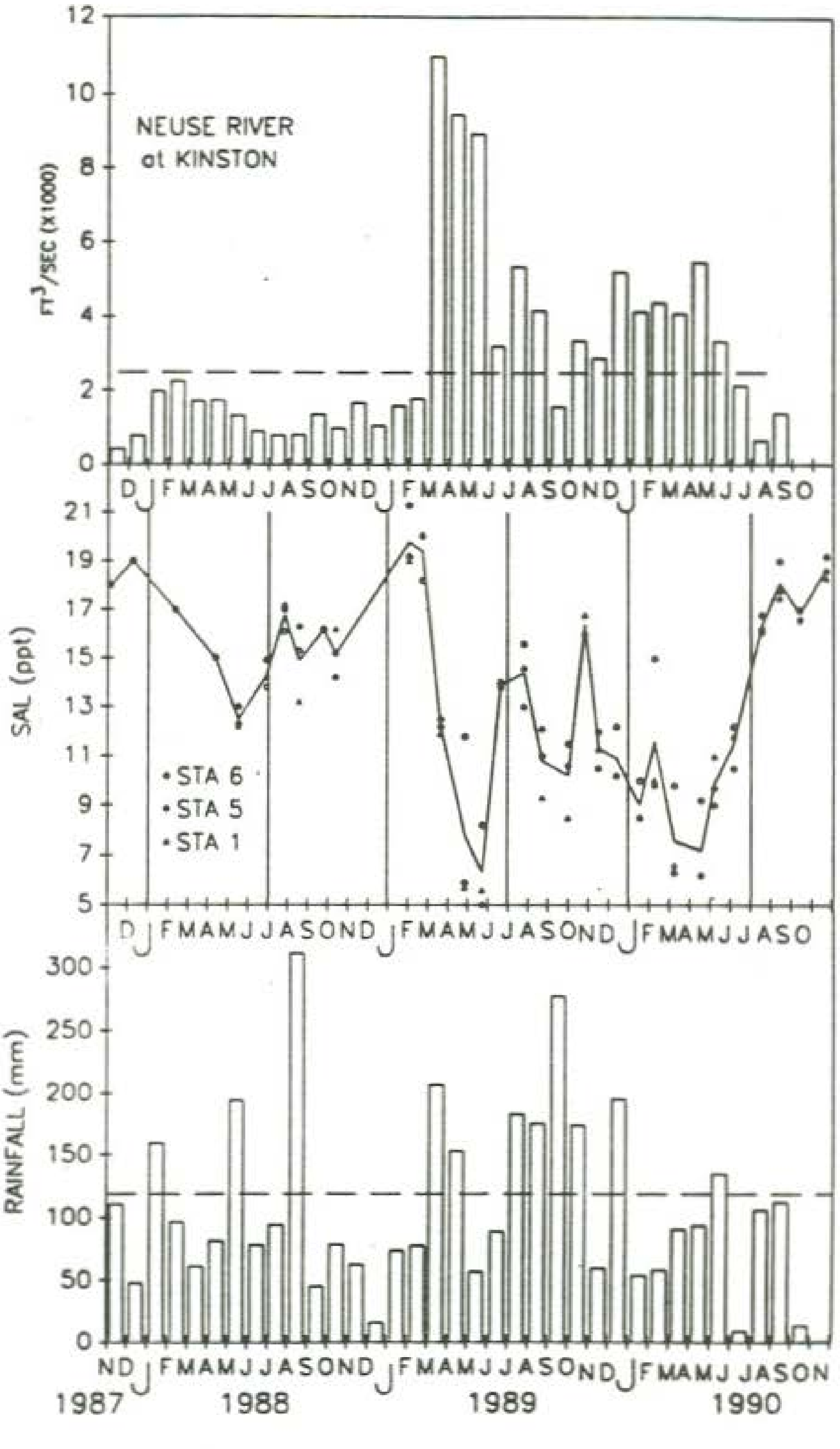


Figure 3. (Top panel) Neuse River mean monthly flows at U.S.G.S. gauging station in Kinston, N.C. Dashed line=60 year average flow (J.D.Bales, U.S. Dept. of Interior, Geological Survey, Water Resources Division, Raleigh, N.C.). (Middle panel) Surface measurements of the salinity at stations 1, 5, and 6. Line=mean of stations measured. (Bottom panel) Monthly rainfall totals at the Institute of Marine Sciences, Morehead City, N.C. Dashed line=average monthly precipitation for southern section of the A.P.E.S. area (118.5 mm/month). (H.Porter, U.N.C. Institute of Marine Sciences, Morehead City, N.C.)

the Neuse River watershed during this period. Monthly mean flows increased dramatically in March 1989 and continued at high rates through May 1989 as a result of increased rainfall in the watershed. In this 3 month period, 50 % of the annual flow was discharged. Monthly mean flows subsequently decreased through summer to a low in September 1989. After September 1989, monthly mean flows generally increased to moderate levels by winter. Overall mean flow in 1989 was 195% of the 60 year average. Moderate flow continued through April 1990 and then decreased to low levels in the summer of 1990. Overall mean flow in 1990 (to 29 September 1990) was 129% of the 60 year average, although 84% of this was discharged by the end of April.

Salinity levels in the lower NRE dropped sharply during the spring 1989 flood period, reflecting increased freshwater input (Fig 3). The spring 1988 salinity minima are not well explained by the mean monthly flows at Kinston or local monthly rainfall totals. Increased local rainfall levels in March and August 1988, however, appear to correspond with decreases in salinity (Fig 3). Low salinities during winter-early spring 1990 co-occurred with increased monthly mean flows at Kinston, the result of heavy rainfall upstream in the Neuse River watershed. There was little precipitation during the remainder of 1990 and increased salinities reflected this (Fig. 3).

The lower NRE appeared well-mixed over the course of our study. Representative vertical temperature and dissolved oxygen profiles from station 6 (Figs. 4 and 5) reveal a general absence of stratification. During some warm periods, dissolved oxygen declined with depth. An example of bottom water oxygen reduction can be seen in Fig. 5, where August 1989 bottom water dissolved oxygen concentrations dropped to approximately 4 ppm or about 60% of the surface concentration. Hence, stratification is possible at this site.

Representative water column transparency profiles from station 6 (Fig. 6) reveal a highly colored, turbid water column. Rapid extinction of photosynthetically active radiation (PAR) was observed on all dates, with light levels at depths of 3 to 3.5 m (bottom) being 5% or less of surface levels. The light extinction coefficient (k) was approximately 1.0 m^{-1} on average at this site (Mallin et al. 1991). Hence, resident phytoplankton in this well-mixed water column experienced a full range of photosynthetic conditions varying from supersaturation at the surface to near compensation levels (where little or no net photosynthesis occurs) at 3.5 m depth. These results suggest that the potential for anoxia exists at 3.5 m, if during stratification, sufficient organic matter is consumed in the presence of extreme low light conditions. Low flow, calm weather and high primary productivity (i.e., bloom) conditions would be prerequisites for such a scenario.

Nutrient status and trends

The major algal nutrients, dissolved inorganic nitrogen (NH_4^+, $NO_2^- + NO_3^-$; listed as NO_3^-) and phosphorus (PO_4^{3-}), are of prime concern as eutrophicating factors in many aquatic systems, including the A - P System. Accordingly, their respective concentrations were monitored at stations 1, 5, and 6, on a 1 to 1-1/2 month interval basis (Fig. 7). During the 36 month period from 1987-1990, the

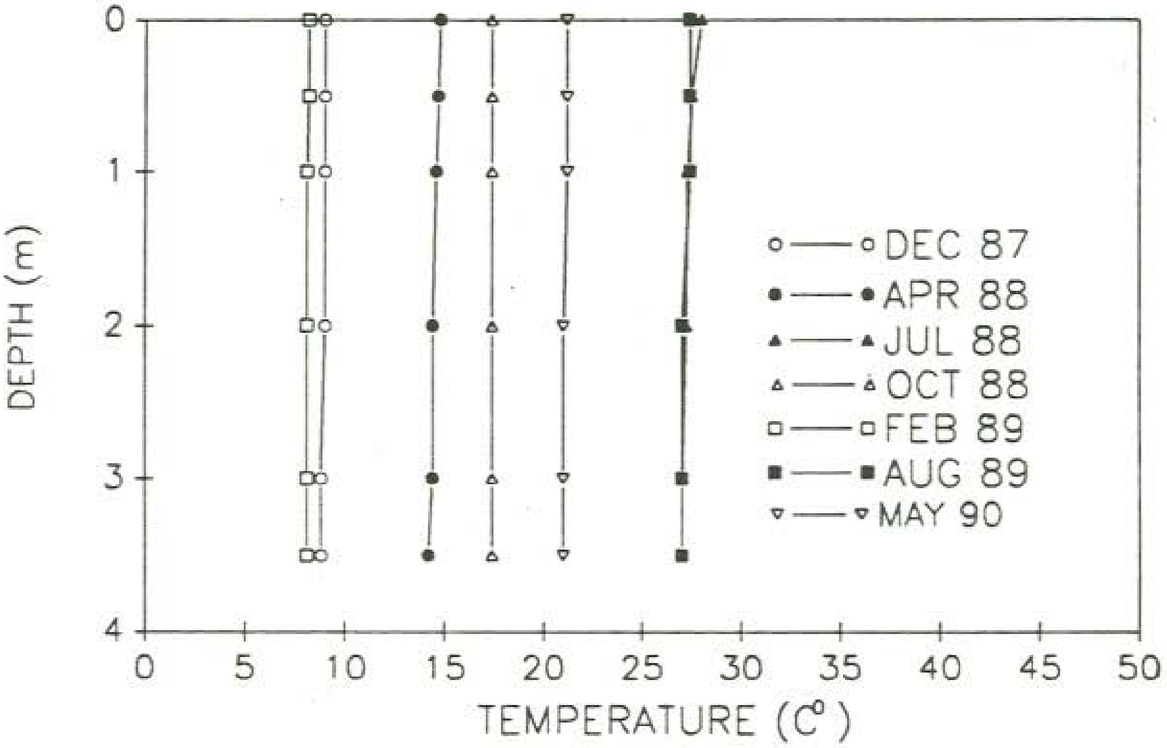


Figure 4. Representative vertical profiles of temperature measured at Station 6.

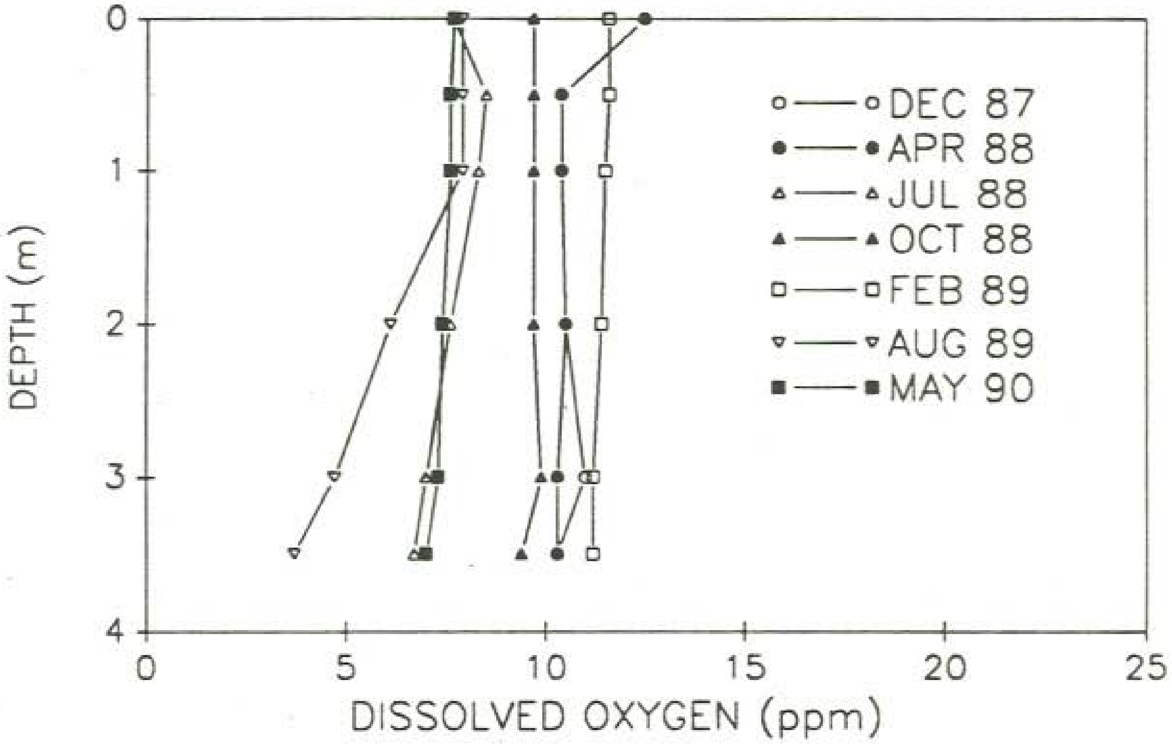


Figure 5. Representative vertical profiles of the dissolved oxygen concentrations at Station 6.

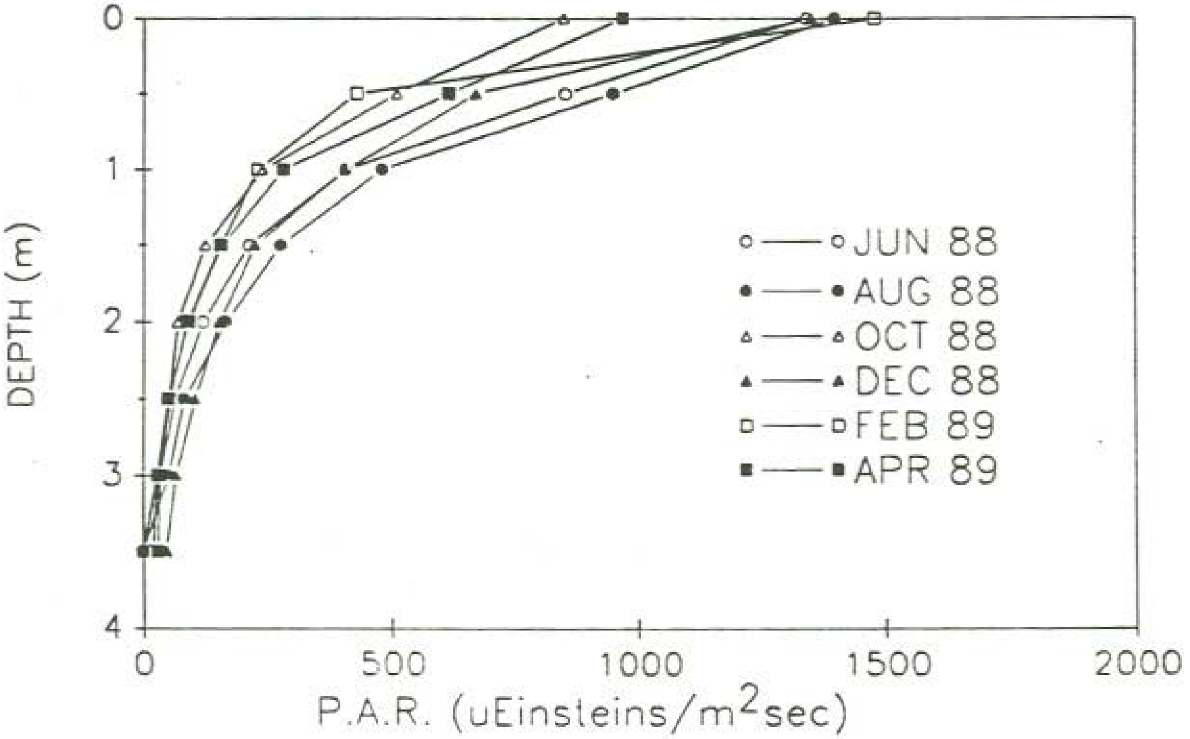


Figure 6. Representative photosynthetically active radiation (PAR) profiles from Station 6.

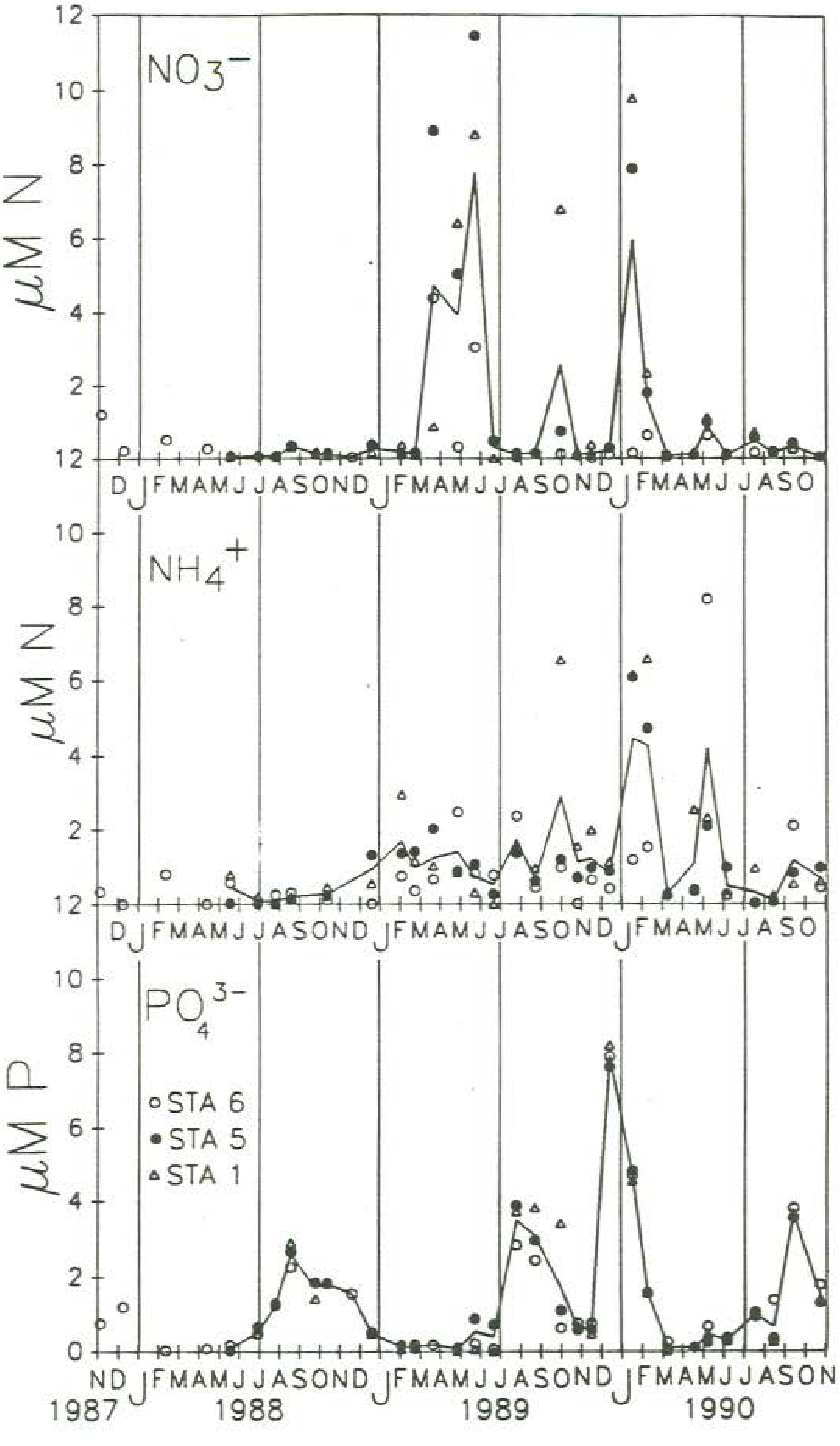


Figure 7. Nitrate (NO_3^-) (top panel), ammonium (NH_4^+) (middle panel), and phosphate (PO_4^{3-}) (bottom panel) concentrations of surface waters at Stations 1, 5, and 6. Line represents mean among stations.

following results characterize nutrient dynamics at these sites.

1. Ammonium concentrations [NH_4^+] were generally low with the majority of values ranging from below detection (0.07 uM) to less than 3 uM. Six samples having [NH_4^+] values ranging from 4.7 to 8.2 uM were measured during the period from September 1989 to May 1990. No seasonally or hydrologically related patterns were detected (Fig. 7).

2. Nitrate concentrations [NO_3^-] were generally low from November 1987 through February 1989, with concentrations ranging from below detection (0.05 uM) to about 1.2 uM (Fig. 7). Very high [NO_3^-] were measured coincident with the high flow of the spring of 1989, ranging from 0.3-11.4 uM (Figs. 3 and 7). It is possible that the heavy rainfall during spring 1989 may have fallen on freshly fertilized farm fields, resulting in highly NO_3^--enriched runoff to the river (Showers et al. 1989). Low [NO_3^-] (>0.5 uM) were again measured during the period from June 1989 until December 1989, except for pulses of elevated [NO_3^-] measured in late September 1989 (following Hurricane Hugo). Elevated [NO_3^-] pulses occurred again in January and February of 1990. Generally, low [NO_3^-] prevailed during the remainder of 1990 except for a small pulse of elevated [NO_3^-] in May.

3. Dissolved inorganic phosphorus concentrations [PO_4^{3-}] seemed to vary on a seasonal basis but also showed dependence on hydrologic factors. The general seasonal pattern observed was very low [PO_4^{3-}] during late winter through spring, increasing to higher levels during summer through fall. Summer maximum

$[PO_4^{3-}]$ were higher in 1989 and 1990 (3.9 and 3.8 uM, respectively) following large winter or spring freshets when compared to the summer of 1988 (2.9 uM) following a relatively dry winter and spring. In the winter of 1989-90, however, hydrologic factors overrode the seasonal influence on $[PO_4^{3-}]$. The $[PO_4^{3-}]$ measured in December 1989 was the highest measured over the entire study period (8.2 uM). High $[PO_4^{3-}]$ continued in January and February 1990, ranging from 1.5 to 4.8 uM. During the spring and summer of 1990 the seasonal $[PO_4^{3-}]$ pattern was reestablished with typical spring lows and summer highs.

Bioassay studies: Nutrient limitation of phytoplankton biomass and production

In situ nutrient addition bioassays conducted at 1 to 1-1/2 month intervals have proven invaluable in identifying those nutrients responsible for regulating and limiting phytoplankton community growth potentials in response to nutrient loading events. The in situ bioassay approach used in this study includes the following key features:

1. the ability to examine nutrient enrichment responses in naturally occurring phytoplankton communities;

2. incubation and assay conditions which closely approximate surface light and temperature regimes in the NRE;

3. the utility of examining 2 parallel complimentary indicators of phytoplankton growth ($^{14}CO_2$ assimilation, chlorophyll content) in triplicated treatments (Paerl and Bowles 1987; Paerl 1987 for

details).

Bioassay results indicate that nitrogen availability is clearly a dominant factor controlling phytoplankton production and biomass (Rudek et al. 1991). Algal biomass and primary production were strongly stimulated by the addition of NO_3^- (when compared to control) in spring, summer and fall seasons (Figs. 8 and 9). In the bioassays conducted from July through October of 1988, 1989, and 1990, addition of higher concentrations of NO_3^- (28.6 uM) resulted in increased stimulation of biomass and primary production when compared to the lower $[NO_3^-]$ addition (14.3 uM) treatments, indicating more severe constraints on nitrogen availability during these months.

During the winter and early spring months between November 1987 and May 1989, NO_3^- additions continued to stimulate biomass and primary production (except in December 1988 and March 1989), though less so than during respective summer and fall months. High NO_3^- additions during these winter and spring months showed no additional stimulation of biomass and primary production when compared to the low NO_3^- addition treatment.

During the winter and early spring months of 1989-90, however, high NO_3^- additions continued to show additional stimulation of biomass when compared to lower NO_3^- additions (except in December). Stimulation of primary production by the low NO_3^- addition was greater in the winter of 1989-90 when compared to the previous 2 winters but no additional stimulation was measured with the high NO_3^- addition.

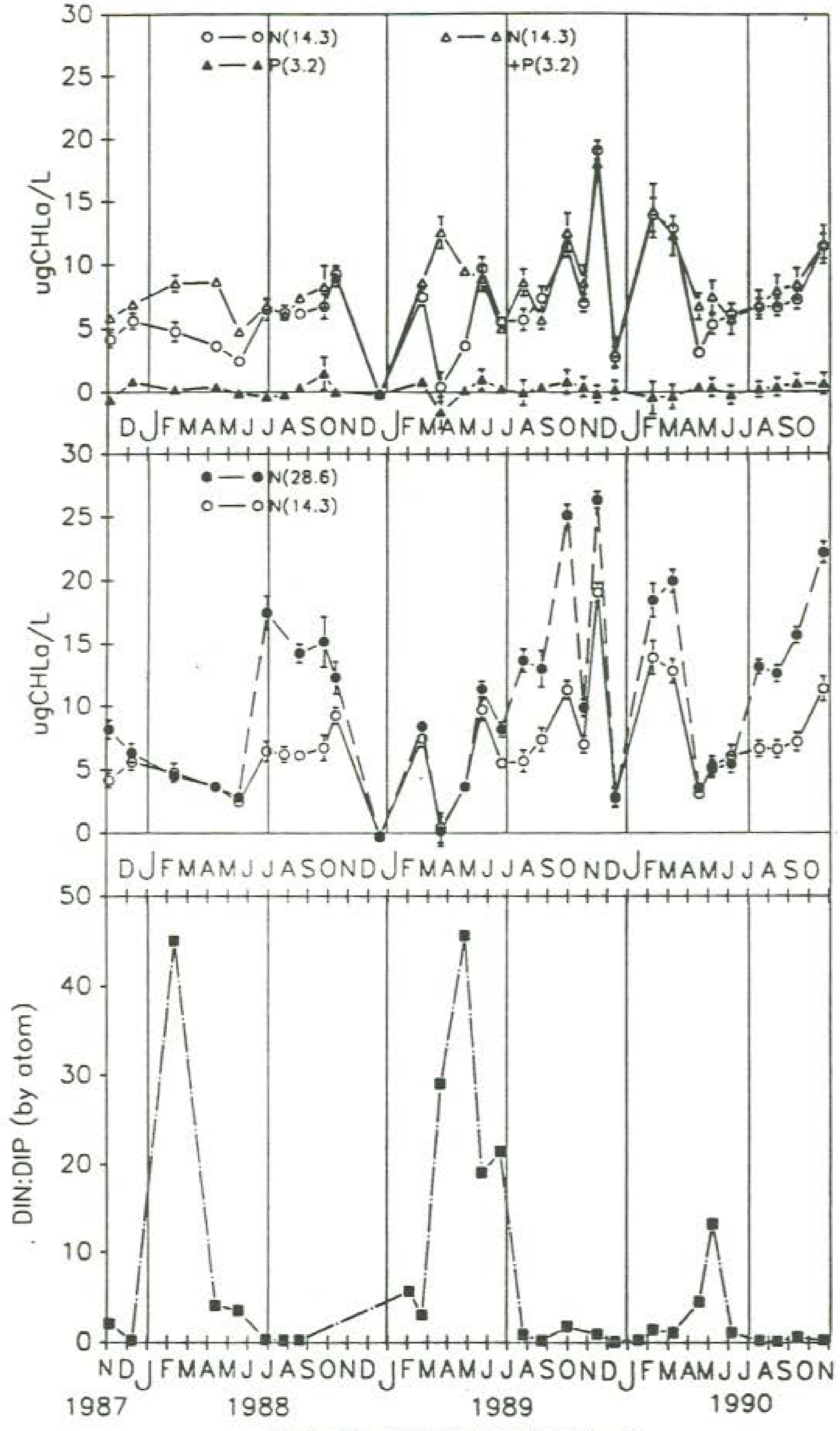
The addition of PO_4^{3-} alone failed to enhance biomass or primary production over controls when averaged over the 4 day bioassay period (Fig. 8 and 9). However, when PO_4^{3-} was added together with NO_3^-, biomass and primary production were stimulated over levels found when NO_3^- was added alone during the spring months of 1988, 1989 and 1990.

Trace metals, either added alone or in combination with nitrogen and phosphorus, failed to exhibit any impacts on algal growth potentials (data not shown); we therefore conclude that natural availability of these metals exceeds phytoplankton growth requirements in the NRE.

Silica (1.5 ug/l) was added as a bioassay treatment from April 1989 through October 1989. Limitation of diatoms by silica depletion may occur in systems that are nutrient enriched (Oviatt et al. 1989). Our bioassay results indicated that silica was not limiting phytoplankton biomass or production in the NRE, at least during the spring, summer, and fall of 1989.

Phytoplankton species composition

An important goal of this project was to assess the potential for toxic or otherwise deleterious phytoplankton blooms in the lower NRE. In doing so, we have identified and enumerated the phytoplankton taxa in water samples taken from May 1988 through February 1990. The dominant species belong to four important taxonomic groups; the Dinophyceae (dinoflagellates), Bacillariophyceae (diatoms), Cryptophyceae (cryptomonads), and Cyanophyceae



ERROR BARS=POOLED SAMPLE SEM (n=3)

Figure 8. (top and middle panel). Chlorophyll a concentration of selected nutrient addition treatments minus controls, averaged over the four days of each bioassay. N(14.3) or N(28.6)= addition of 14.3 or 28.6 ugN/l (respectively) as NO_3^-. P(3.2)= addition of 3.2 ugP/l as PO_4^{3-}. Error bars not visible are smaller than symbol. (bottom panel) Dissolved inorganic nitrogen (DIN) to dissolved inorganic phosphorus (DIP) ratio (by atom). No error bars plotted.

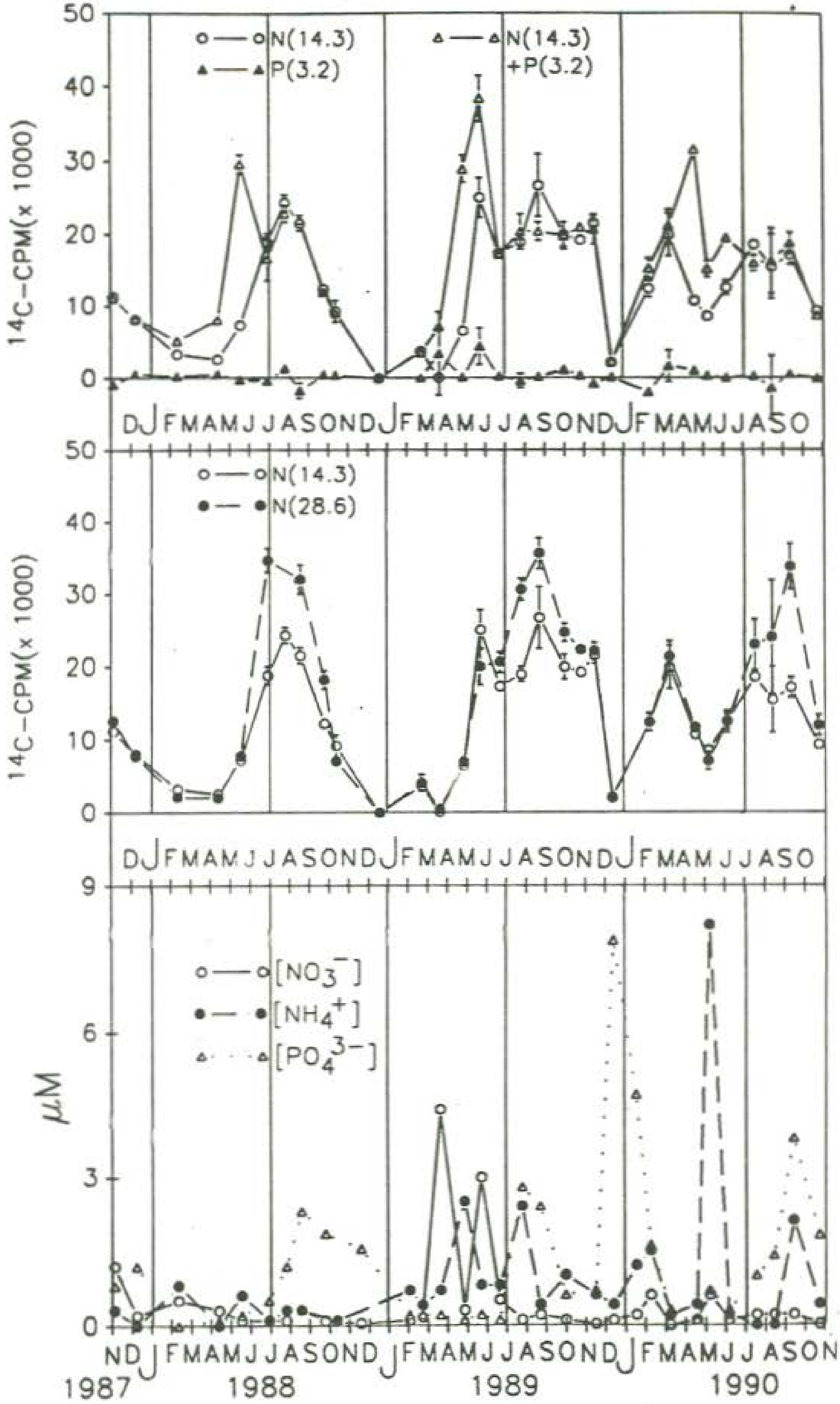


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Figure 9. (top and middle panel) ^{14}C assimilation of selected nutrient addition treatments minus controls, averaged over the four days of each bioassay. Symbols as in Figure 10. (bottom panel) Nitrate (NO_3^-), Ammonium (NH_4^+), and Phosphate (PO_4^{3-}) concentrations of surface waters at Station 6. Dat compiled from Figure 7; presented here for comparative purposes.

(blue-green algae). Dominant taxa by month are listed in Table 2. Important dinoflagellate taxa included Katodinium rotundatum (150 cells/ml in April 1989), and Prorocentrum spp. (230 cells/ml March 1989). Small, centric diatoms dominated the Bacillariophyceae with Thalassiosira sp. reaching 600 cells/ml in July 1989, and Cyclotella spp., with a maximum of 2000 cells/ml in March 1989. Small, naked cryptomonads were abundant in the phytoplankton with Cryptomonas testaceae attaining 1100 cells/ml in April 1989, and Chroomonas spp. reaching 350 cells/ml in August 1989. All of these species are non-toxic and of a size and shape easily assimilated by zooplankton. None of the dinoflagellate species encountered thus far during the study are known to be toxic (Paerl 1988). Blue-green algae (also referred to as cyanobacteria) were sparse in the lower estuary throughout the study except during mid-summer of both years. Freshwater nuisance species, including Microcystis aeruginosa and Anabaena flos aquae were not observed in the lower NRE. Previous studies indicated that salinities encountered in the lower NRE arrested growth of these taxa (Paerl et al. 1984). The filamentous Phormidium spp., however, reached abundances of about 400 filaments/ml in August 1989 and a very slender unidentified filament showed an abundance peak of 2000 filaments/ml in August 1989. These organisms are not known to be toxic species (Paerl 1988; Falconer 1989), and noticeable surface scums were not present. Because many blue-green algae are known to be poor sources of nutrition for zooplankton (Arnold 1971; Schindler 1971), these summer increases warrant further trophic evaluation and research.

Special mention needs to be made concerning the appearance and bloom dynamics of the non-toxic dinoflagellate Heterocapsa *triquetra*. This species is normally found in the region during winter and early spring (Hobbie 1971; Kuenzler et al. 1979), but it attained bloom proportions (2600 ml^{-1}) in the NRE in February of 1990 (Table 1). This species blooms periodically in the Pamlico River estuary and has been considered to be an indicator of nutrient enrichment (Hobbie 1971). It did not reach bloom proportions in the NRE during the dry winter of 1988-89 but co-occurred with the high flow during January and February 1990. As such, it might be considered a valuable indicator of hydrologically-induced elevated nitrogen input to the coastal estuarine systems. This species is non-toxic and considered an excellent food source for zooplankton (Uye and Takamatsu 1990). However, its presence in abundance may be interpreted to mean that the potential for blooms of other dinoflagellate species exists in the lower NRE.

Phytoplankton primary productivity and biomass

Phytoplankton primary productivity investigations were performed concurrent with the nutrient limitation studies. Detailed methodologies are found in Mallin et al. (1991). Phytoplankton productivity in the lower NRE was considered high by comparison to other temperate estuaries (Nixon 1986), with typical summer peaks and winter minima (Fig. 10). Annual production was calculated to be 340 gC/m^2 in 1989, and 297 gC/m^2 in 1990. In addition, during 1989 there was a large productivity pulse during April and May. This pulse was concurrent with heavy rainfall, high flow, and subsequent lower salinities in the NRE (Figs. 3) and consisted mainly of small flagellated cryptomonads (Table 2). This spring pulse was likely a result of nutrient-laden agricultural

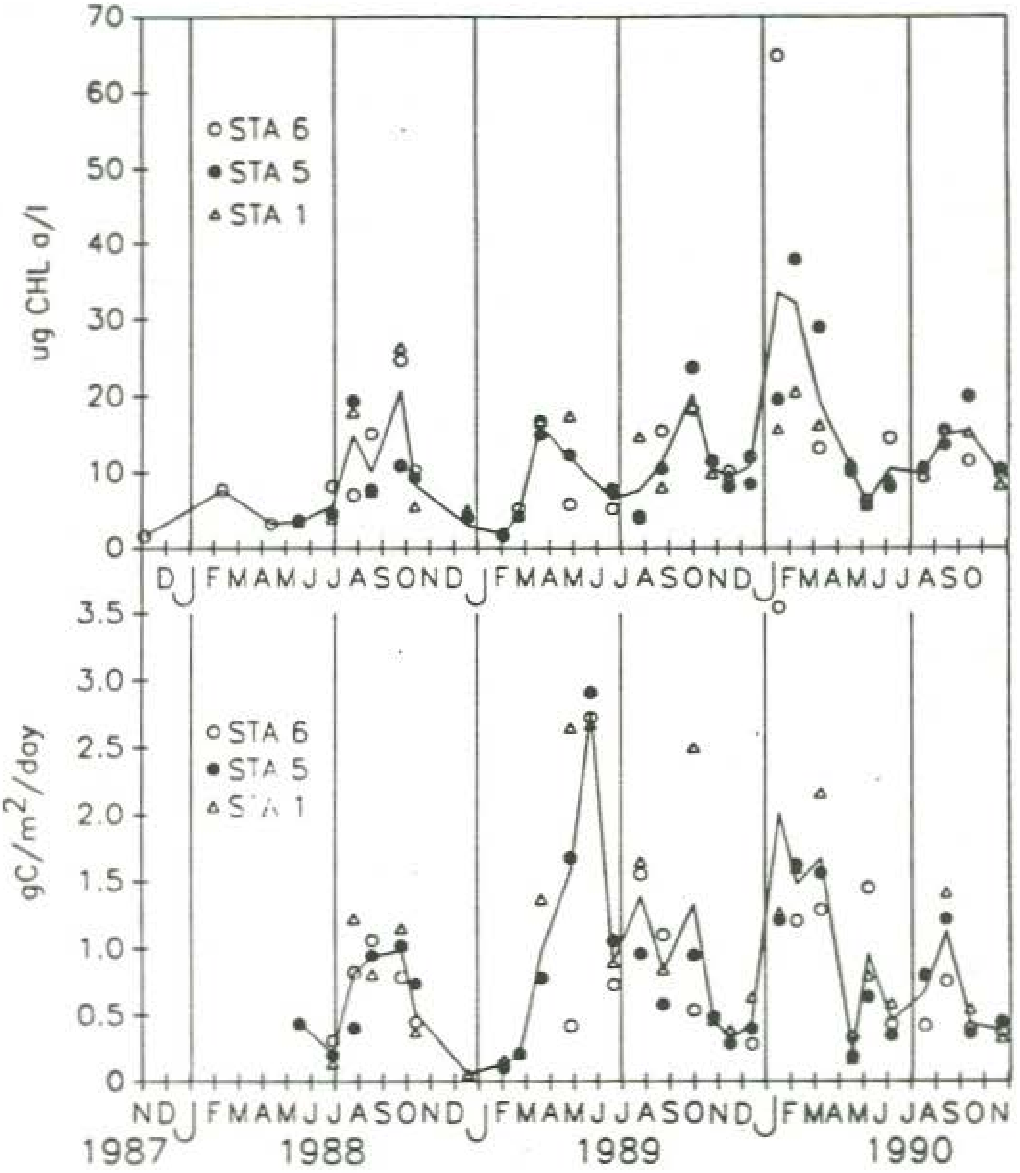

Figure 10. (Top panel) Surface measurements of the chlorophyll *a* at Stations 1, 5, and 6. (Bottom panel) Areal productivity values measured at Stations 1, 5, and 6.Line represents mean among stations measured.

runoff upstream, and direct nutrient input from rainfall deposited on the lower estuary (Paerl 1985; Duce 1986; Paerl et al. 1990).

There was an additional productivity pulse in September of 1989, perhaps responding to increased NO_3^- input to the system following increased mean flow (Fig 3) or locally high precipitation, especially in the week prior to sampling (110 mm). The sizeable early-1990 productivity pulse was largely attributed to a Heterocapsa triquetra bloom. The estuary exhibited a predictable underlying pattern of summer productivity peaks which were associated with the contemporaneous interaction of increased light and water temperature. Our results show that additional productivity peaks in respective seasons of any given year can be stimulated by nitrogen loading pulses, which, in turn, are driven by meteorological/ hydrological forcing in the form of increased rainfall and subsequent runoff (Mallin et al. 1991). The impact of direct rainfall is also important to phytoplankton productivity as rainwater can be nitrogen-enriched, thus serving as a direct source of nitrogen loading to the lower estuary (Paerl 1985; Paerl et al. 1990).

Phytoplankton biomass as chlorophyll a roughly paralleled the primary productivity seasonal cycles (Fig. 10). There were summer increases in all 3 years a spring maxima in 1989, and a winter maxima in 1990. The Heterocapsa triquetra bloom was responsible for the highest chlorophyll levels observed during this study (Fig. 10).

Zooplankton community characteristics

There is currently no published information regarding the zooplankton of the NRE. We sampled the crustacean zooplankton at stations 1, 5, and 6 in the lower NRE for a 20-month period from May 1988 through December 1989. We used a submersible pump to sample both the entire water column and the sediment surface. The methods and results are presented in detail in Mallin (1991).

The crustacean zooplankton community of the lower estuary maintained low species richness throughout the study. Taxa collected included three calanoid copepods (Acartia tonsa, Paracalanus crassirostris, Pseudodiaptomus coronatus), one cyclopoid copepod (Oithona colcarva), several harpacticoid copepods (including Microsetella norvegica, Stenhalia sp., and Zausodes sp.), and two cladocerans (Evadne nordmanni in summer and Podon polyphemoides in winter).

Non-naupliar biomass over the study period consisted of 38.8% A. tonsa, 7.7% P. crassirostris, 21.2% O. colcarva, 23.6% harpacticoid copepods, and 6.0% cladocerans. The remainder of the biomass consisted of P. coronatus and barnacle larvae.

Mean total copepod densities ranged from 600 m^{-3} in May 1988 to 180,000 m^{-3} in August 1988 (Fig. 11). Mean copepod densities for 1989 were 25,000 m^{-3}. Maximum densities during both years occurred during summer, with subsequent decreases throughout the year until early spring. Estuary-wide transient decreases in zooplankton density during the summer maxima in both study years may have been a result of invertebrate predation, possibly caused by the swarms of jellyfish noted periodically during the summer.

Cladoceran abundance displayed distinct seasonality, with Evadne nordmanni occurring only during summer and Podon

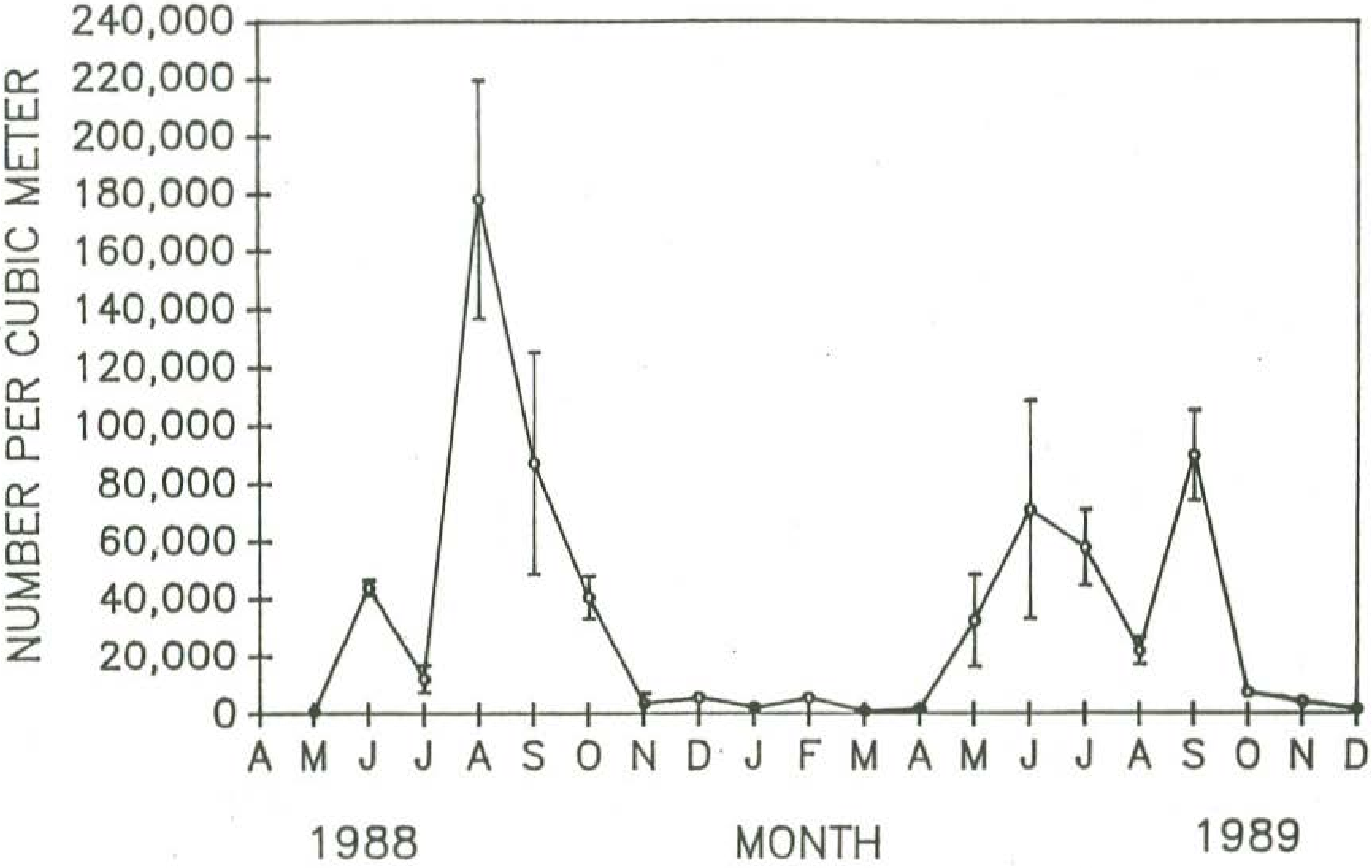

Figure 11. Mean total copepods at Stations 1, 5, and 6. Error bars represent SEM (n=3).

polyphemoides only during winter-spring (Fig. 12). Peak densities were 8500 m^{-3} (Podon) during February 1989.

Harpacticoid copepods maintained relatively consistent densities throughout the study with the exception of May-June 1989, when a bloom of Microsetella norvegica attained densities up to 24,500 m^{-3} (Fig. 13). The May 1989 harpacticoid abundance peak may have been stimulated by a large spring phytoplankton bloom of cryptomonads and the dinoflagellate Prorocentrum minimum (Table 2).

While zooplankton abundance peaked concurrently with late summer phytoplankton biomass peaks (Fig. 10), generally low zooplankton densities persisted during high 1989 spring and late fall phytoplankton blooms. Copepod density displayed no significant correlation with any of an array of biological and physical variables with the exception of water temperature. Water temperature correlated positively with total copepod abundance ($p < 0.01$, $r = 0.62$) and A. tonsa ($p < 0.05$, $r = 0.54$). Results of this investigation, as well as those from other regional studies (Peters 1968; Fulton 1984), indicate that water temperature is likely the single most important variable capable of predicting zooplankton abundance in the NRE.

Discussion

Seasonal and hydrologic influences on phytoplankton productivity and biomass

Estuaries are generally considered sinks for dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorus (DIP), acting as filters to downstream coastal systems (Fisher et al. 1988a). Dissolved nutrients are assimilated by the nutrient-limited phytoplankton communities in the upper estuary and incorporated into particulate fractions. This filtering capability normally reduces the very high [DIN] and [DIP] in the Neuse River by as much as 2 orders of magnitude as water flows into the estuary (Christian et al. 1989). However, high flow events can bypass this filter mechanism and deliver large amounts of nutrients from nutrient-enriched rivers to their receiving estuaries. Winter to spring maxima in freshwater discharge, and resulting high flows, are characteristic of mid-latitude river systems (Malone et al 1988). In the Neuse River, 60 % of the 1986-1987 annual N load (as NO_3^-) was discharged into the estuary during high flow in January and February (Christian et al. 1989). Similarly, in the Pamlico River (Kuenzler et al. 1982), and in the Chesapeake Bay (Malone et al. 1988), the majority of nutrient loading has been found to occur during the winter-spring high flow periods. Variability in the magnitude and arrival time of large hydrologic events observed in the NRE during this study resulted in disruptions in baseline seasonal patterns of biological production and nutrient availability in the lower estuary. As important as these high flow events were to nutrient delivery, disruptions were relatively short-lived as seasonal patterns were quickly reestablished.

The bioassay results suggest a seasonal pattern in concert with estuarine phytoplankton biomass concentrations and productivity rates. Severe nitrogen limitation occurs in summer when algal biomass and production are high. There is somewhat less profound nitrogen limitation in fall and winter when biomass and production are at annual minima. Nitrogen and phosphorus co-stimulation (or synergism) occurs in spring. With the exception of the winter 1989-

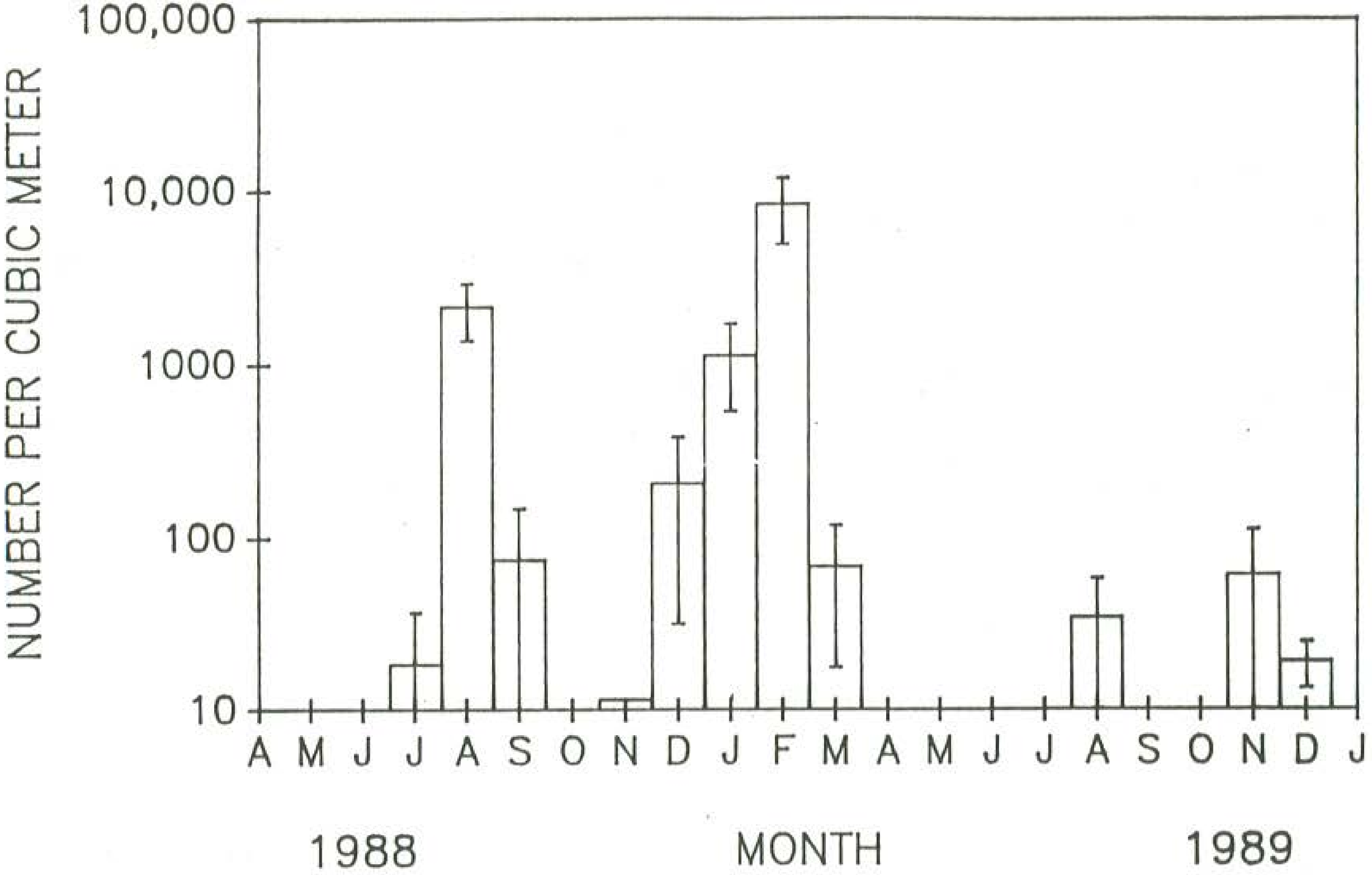

Figure 12. Mean total cladocerans at Stations 1, 5, and 6. Error bars represent SEM (n=3).

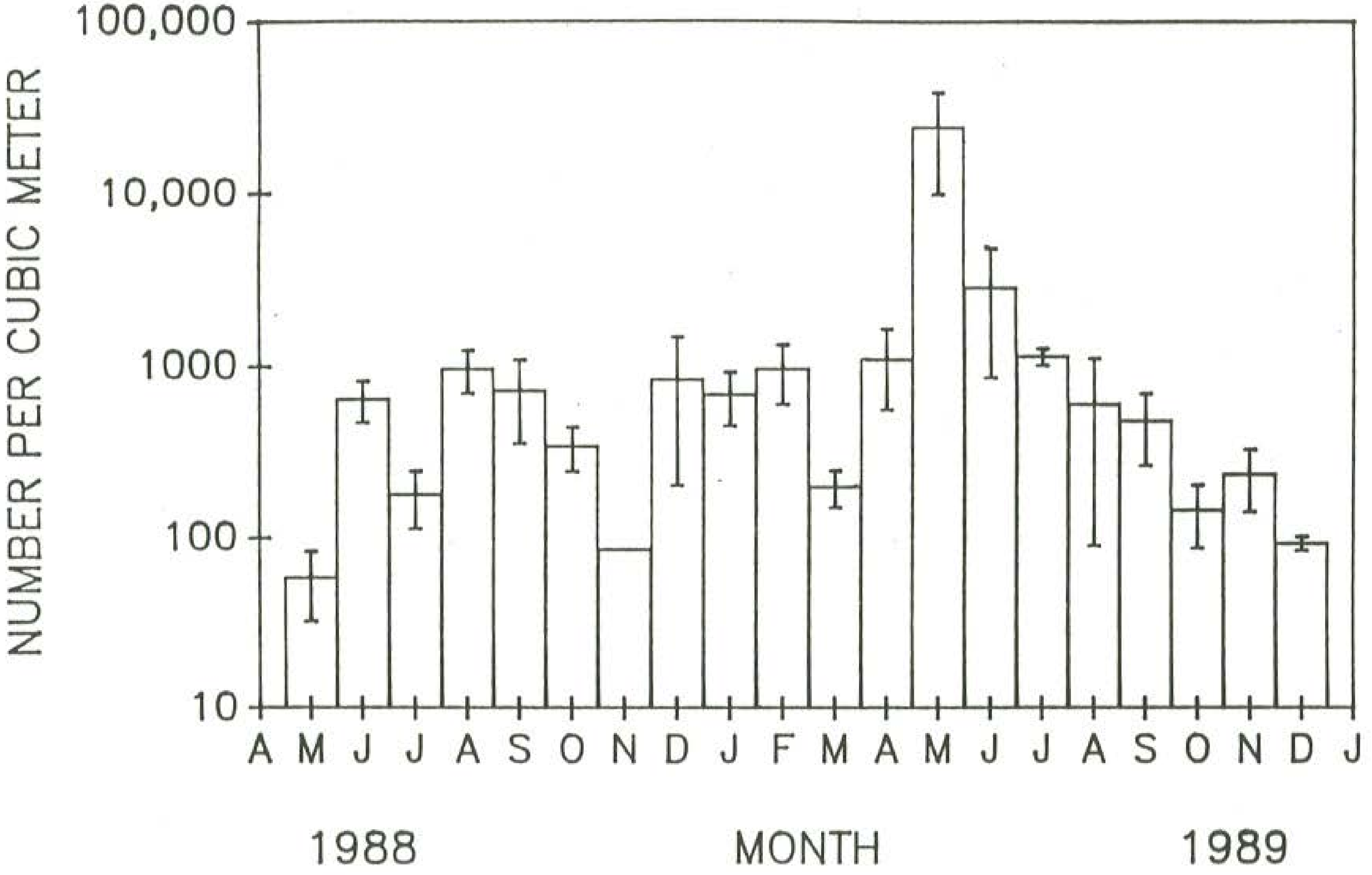

Figure 13. Mean total harpacticoid copepods at Stations 1, 5, and 6. Error bars represent SEM (n=3).

Table 2. Dominant phytoplankton taxa by month in the Neuse River Estuary May 1988-February 1990.

Year	Month	Taxa	Density (units ml^{-1})
1988	May	*Calicomonas ovalis*	178
	June	*Calicomonas ovalis*	105
		Gymnodinium sp.	58
	July	*Gymnodinium* sp.	462
		Thalassionema nitzschoides	40
	August	*Chroomonas* spp.	225
		Phormidium sp.	98
		Thalassiosira sp.	85
		Thalassionema nitzschoides	57
	September	*Chroomonas* spp.	138
		Gymnodinium sp.	56
	October	*Chroomonas* spp.	210
		Gymnodinium sp.	21
	November	*Prorocentrum redfieldi*	113
	December	*Chroomonas* spp.	101
		Katodinium rotundatum	33
1989	January	*Heterocapsa triquetra*	114
		Chroomonas spp.	88
	February	*Melosira distans*	211
		Rhizosolenia sp.	106
		Chroomonas amphioxiae	81
	March	*Cyclotella meneghiniana*	1771
		Chroomonas amphioxiae	270
		Katodinium rotundatum	151
	April	*Cryptomonas testaceae*	1120
		Chroomonas amphioxiae	385
		Prorocentrum minimum	250
	May	*Cryptomonas testaceae*	460
		Chroomonas amphioxiae	383
		Thalassiosira sp.	100

Table 2. continued

	June	*Thalassiosira* sp.	399
		Chroomonas spp.	100
	July	*Thalassiosira* sp.	592
		Chroomonas spp.	206
		Thalassionema nitzschoides	121
		Phormidium spp.	101
	August	unidentified BG filament	1922
		Chroomonas spp.	418
		Phormidium spp.	398
		Thalassiosira sp.	346
	September	*Chroomonas* spp.	1172
	October	*Thalassiosira* sp.	223
		Prorocentrum rostratum	136
		Chroomonas spp.	131
	November	*Leptocylindrus minimus*	491
		Chroomonas spp.	303
	December	*Chroomonas* spp.	715
		Skeletonema costatum	415
1990	January	*Heterocapsa triquetra*	1237
		Thalassiosira sp.	711
		Katodinium rotundatum	420
	February	*Heterocapsa triquetra*	2595
		Thalassiosira sp.	493
		Skeletonema costatum	356

90, these patterns repeated in years when flow and hence loading were low (1988), near average (1990), and high (1989).

The co-stimulation of phytoplankton biomass and production by N and P appears to be associated with periods of relatively high dissolved inorganic N:P (DIN:DIP) ratios in the water column (Fig. 8) which occurred during spring months. During periods when the DIN:DIP ratios were in excess of 10, phosphorus enrichment often played a synergistic role with N in stimulating phytoplankton growth potentials. Stimulation of phytoplankton biomass and productivity by N and P, but not by P, at these times was likely related to [PO_4^{3-}] which were not far in excess of phytoplankton demands. The [NO_3^-] at station 6 in March 1989, for example, was 4.4 uM (Fig 9), which only requires a [PO_4^{3-}] of 0.3 uM to supply nutrients to the phytoplankton if we assume requirements approximate the Redfield ratio. Bioassay PO_4^{3-} enrichments were made at 3.2 uM, resulting in exhaustion of N supplied in the experimental vessels. Other estuaries have been found to exhibit seasonal variations in nutrient limitation. In the Patuxent River estuary, a tributary of the Chesapeake Bay, algal growth was found to be N limited during the summer, low-flow season, and P limited during the late winter, high-flow season (D'Elia et al. 1986). As in the NRE, DIN:DIP ratios were elevated during P limitation. Graneli et al. (1990) also found P limitation in winter, and N limitation in spring and summer in the coastal areas of the southern Baltic Sea.

In spring of 1989, very sharp increases in flow (Fig. 3) rapidly flushed nutrients from the watershed into the estuary. This high flow event resulted in elevated [NO_3^-] (Fig 7) and sharply reduced salinities (Fig. 3) near the mouth of the estuary. The runoff which fueled this spring flood may have been excessively high in NO_3^- as a result of recently fertilized farm fields in the watershed. This may explain why so much NO_3^- accumulated in the estuary. It should be noted that ambient nutrient concentrations represent nutrients in excess of that assimilated by the phytoplankton community. The bioassays showed no stimulation of either phytoplankton biomass or production at the beginning of this flood period, indicating N sufficiency. Chlorophyll a concentrations and primary productivity increased almost 4-fold, on average across the estuary, from February to March 1989 (Fig. 10), indicating substantial phytoplankton nutrient assimilation. In April and May there was evidence of freshwater and nutrient discharge from the South River (station 1, Fig. 1) as salinities declined from station 6 to station 1 (Fig. 3) and chlorophyll a (Fig 10) and [NO_3^-] (Fig. 7) increased. By June 1990 salinity increased, and mean flow, [NO_3^-], [chlorophyll a], and primary production had all declined. A bloom of cryptomonads commenced in April and May and declined by June.

A second hydrologic event (Hurricane Hugo) occurred in September of 1989, bringing elevated rainfall to the region (Fig. 3) and a subsequent increase in [NO_3^-] (Fig. 7). This increase in [NO_3^-] led to pulses of primary production (Fig. 10) and phytoplankton biomass (Fig. 10). Cryptomonads dominated the flora during this event (Table 2).

A third major loading event occurred in the winter of 1989-90. Unlike the spring 1988 flood, there was no sharp increase in flow measured at the Kinston gauging station, rather flow appeared to steadily increase through fall. Local rainfall in December 1989 was substantial (Fig. 3) with more than half of it (100 mm) falling the week prior to our sampling date. Salinity transects across the estuary (Fig. 3) from November 1989 through April 1990 suggest an influence of freshwater discharge from the South River (station 1). The accumulation of [PO_4^{3-}] in the water column in December may be a result of high local runoff and sediment loading. However, 20 miles upstream from our stations, the Cherry Point Sewage Treatment Plant reported that 30,000 gallons of raw sewage was discharged into a creek emptying into the Neuse River on 10 December 1989, the day before our samples were collected (Clean Water Fund of North Carolina, 1990). Additionally, a 5000 gallon raw sewage discharge from the same plant was reported on 11 January 1990. The result of the nutrient load to the NRE (from all sources) was a 5-fold increase in [chlorophyll a] and productivity (Fig 10) at station 6 from December to January. A bloom of Heterocapsa triquetra spread across the estuary, from Station 6 in January, to stations 1 and 5 in February (Mallin et al. 1991; see below). By April and May, [chlorophyll a] decreased to levels observed during the previous 2 springs.

The bioassays showed a progression from severe N limitation in the fall of 1989 (high NO_3^- stimulation), to no stimulation in December (loading event), to N limitation during the bloom, to an N and P co-limited algal community in April and May, after the bloom declines. The phytoplankton community in April and May may have been recycling nutrients regenerated from the organic matter previously sedimented to the bottom as a result of the bloom decline in March. While no dissolved oxygen decline was detected during this period, there are several lines of evidence to suggest an autochthonous nutrient source. The DIN:DIP ratio (Fig. 8) in May 1990 was 13.2, close to the Redfield elemental ratio for phytoplankton (106 carbon: 16 nitrogen; 1 phosphorus) and therefore expected if remineralization were operating. Additionally, the [NH_4^+] showed an increase in May 1990 at all stations (Fig. 7) suggesting that ammonification rates were high. After a bloom decline and rapid sedimentation in the Aarhus Bight, Denmark, Jensen et al. (1990) measured a sharp 7.5-fold increase in NH_4^+ sediment flux which lasted approximately a month. The soft, gel-like muds found in the NRE are indicative of rapid sedimentation environments (Wells and Kim 1989). Bottom waters remained oxic during remineralization in the Aarhus Bight but did decline to 60 % saturation. Interestingly, Jensen et al. (1990) also suggested that an increase in denitrification may have accompanied the remineralization of the sedimented bloom. Lastly, the N + P co-stimulation of the bioassays strongly stimulated algal production, while showing less stimulation of biomass. This is indicative of a community fixing carbon with little net gain in biomass. The release of nutrients from sediments has been shown to be important in supplying nutrients for phytoplankton assimilation in the NRE (Christian et al. 1991) as well as in neighboring estuarine systems of A - P System (Fisher et al. 1982; Stanley and Hobbie 1977; Kuenzler et al. 1982, 1984) and the Chesapeake Bay (Malone et al 1988). Grazing can also be an important component in nutrient recycling in algal communities dependent on regenerated nutrients (Litaker et al 1988).

The series of events from fall 1989 through the spring 1990 illustrates how the NRE is dependent on acute loading events to supply nutrients eventually needed for chronic nutrient recycling. However, despite the inter-annual variations in hydrologic and nutrient loading during our study, it is striking how quickly phytoplankton production and biomass levels returned to seasonal levels. The summer production and chlorophyll a levels from 1988-1990 are quite similar with estuarine averages ranging 1.0 to 1.4 g C m^{-2} day^{-1} and 15.4 to 20.6 ug chla l^{-1} (Fig. 10). The fate of the algal biomass produced in the winter-spring floods of 1989 and 1990 is not known, although some was likely converted to increased zooplankton biomass (Mallin, unpublished). Malone et al (1988) have suggested that partially strafied estuaries, like the Chesapeake, are particularly responsive to nutrient enrichment. They found spring flood nutrients were retained in bottom waters after the spring bloom declined, subsequently supporting a summer productivity maximum seasonally out of phase with loading. In contrast, the NRE is well-mixed. Production, chlorophyll a, and loading are all in phase, perhaps suggesting a limited nutrient storage capability. Flushing of nutrients through the Chowan River (Stanley and Hobbie 1977) and the Pamlico River estuary (Harrison and Hobbie 1974) have been recognized as important factors in preserving the water quality of those systems under large nutrient loads. Nowicki and Oviatt (1990) refuted the estuarine filter concept, suggesting that most of the N and P load to well-mixed estuaries is transported offshore as dissolved organic and particulate matter. However, the sounds of the A - P System have extremely limited tidal exchange with offshore waters. Wells and Kim (1989) speculated that very little sediment is likely to escape the sounds through the 3 inlet system. Given this, it would not bode well for the future of Albemerle and Pamlico Sounds if its estuaries were being flushed or transporting their nutrient load as particulate matter downstream. Current flow data presented by Wells and Kim (1989), however, suggests the strong potential for upstream transport of sediments in the Neuse and Pamlico River estuaries. Significant trends of increasing [chlorophyll a] in the NRE since 1970 along with decreasing trends in NO_3^- and NH_4^+ plus organic nitrogen since 1980 (USGS 1990) suggest that the estuary is retaining at least some of the load it is receiving. An investigation of the structure and function of the plankton communities of the Pamlico Sound proper would be desireable as a means of assessing trophic state and eutrophication potential, and to determine if the Sound functions as a "catch basin".

When considering nitrogen loading sources and their specific inputs, atmospheric wet and dry deposition should receive increased attention. This source appears to be of quantitative importance (20-30% of total external N loading) (Placit et al. 1986; Fisher et al. 1988b; Copeland and Gray 1989). In addition, bioassay results (Paerl et al. 1990) revealed a strong stimulatory (on phytoplankton production) impact of atmospheric N deposition at natural dilution levels in NRE. Atmospheric N inputs can occur downstream of regions where terrigenous point and non-point N inputs are stripped out of the water column by mesohaline phytoplankton. Atmospheric sources may therefore constitute a unique source of nitrogenous nutrients in the lower estuarine and open sound components of A - P System (Paerl et al. 1990).

It can be concluded that the availability and hence discharge and loading of both nitrogen and phosphorus must be addressed in future management efforts aimed at regulating eutrophication and bloom potentials in the A - P System. It is of obvious importance (both from the perspective of establishing characteristic base line data as well as nutrient management concerns) to continue close time interval sampling for PO_4^{3-} concentrations in this region, especially in light of our recent finding that phosphorus plays a secondary (in addition to nitrogen) "synergistic" role as a phytoplankton growth-limiting nutrient in the NRE. It is stressed that while phosphorus enrichment impacted (stimulated) phytoplankton growth only during a relatively short (perhaps 3 month) period of the year (April-June), this period is quite important with respect to development and potential proliferation of dominant algal species. Accordingly, it is overly simplistic, and probably ineffective, to solely address nitrogen inputs as the chief nutrient management step for stemming eutrophication and controlling bloom events in this system.

Trophic status and trends

The lower NRE can be classified as a mesotrophic system compared with estuaries elsewhere in the U.S. (Nixon 1986; Day et al. 1989). Distinct seasonal peaks in primary production and phytoplankton biomass accumulation were observed. A mean summer chlorophyll a concentration of approximately 15-25 ug Chl a l^{-1} attests to the highly productive nature of this estuary. At times this system becomes eutrophic for extended (weekly-monthly) periods. The duration of these periods and magnitude of eutrophication depend on nitrogen loading to the system, which is in turn dependent upon rainfall and runoff. Phytoplankton blooms can occur during any season, given the correct appropriate combination of hydrologic and meteorologic conditions. During our study the algal species achieving bloom conditions have been benign. To our best knowledge this biomass represents largely edible and hence desirable phytoplankton taxa. This is in sharp contrast to the upper oligohaline portion of this estuary, which has, over the past decade, shown symptoms of advanced eutrophication in the form of periodic nuisance blue-green algal blooms (*Microcystis aeruginosa* in particular) (Paerl 1983, 1987). When such blooms have materialized and persisted, during stagnant, low-flow periods, bottom water anoxia has been documented (Paerl 1987).

At no time during the study were anoxic bottom waters encountered in the lower NRE. Despite occasional phytoplankton bloom conditions (spring 1989, early 1990), the waters of the lower estuary remained sufficiently mixed by wind and currents to prevent severe stratification (Fig. 3). As our sampling sites were confined to the main stem of the estuary, we are unable to state whether or not anoxia occurred in feeder creeks or more stagnant backwaters of the estuary as a result of phytoplankton blooms. However, the possibility of future trends towards increased bloom activity and intensity, as well as accompanying bottom water anoxia, should not be dismissed for the lower NRE. Given the fact that blooms *can* occur in this system, the possibility remains that noxious or possibly toxic algal species may reach bloom proportions at some time. Since this estuary reveals year-round sensitivity to nitrogen enrichment, as well as spring-time sensitivity to phosphorus enrichment, it is reasonable to assume that increased loadings of both nutrients will accelerate primary productivity and biomass formation. Indeed, the entire Neuse River basin was classified as Nutrient Sensitive Waters (NSW) in May 1988 by the N.C. Department of Environmental Management. Unless the resultant algal biomass can be grazed effectively enough (assuming inedible species do not appear and persist), it appears inevitable that eutrophication will take place. While eutrophication in systems fed by undisturbed watersheds is a natural process, extensive documentation points to a strong relationship between anthropogenic land disturbance, urbanization, fertilization, sewage discharge, atmospheric pollution and accelerated eutrophication. Since A - P System tributaries (Neuse River, Pamlico River, Chowan River) have already exhibited this relationship (Copeland 1986; Copeland and Gray 1989), there needs to be concern that this trend will ultimately move downstream once nutrient loads exceeding critical bloom thresholds of potential nuisance species have been attained. Certainly, overall nutrient loading continues to increase in this estuary (Stanley 1988).

Management Implications

Definitions and Paradigms in Nutrient Limitation

It is important, especially in a report such as this which speaks to a diverse audience, to identify and define key paradigms and phrases. A shared understanding between the reader and the authors, of the vernacular and perspective employed, is crucial to the understanding of the presented results. Therefore, we would like to take this opportunity to discuss both the definition of the phrase nutrient limitation, and the paradigm currently operative in management of nutrient loading to aquatic ecosystems.

The phrase "nutrient limitation" has 3 commonly used definitions in modern scientific literature (Howarth 1988). The first involves assessments of the phytoplankton assemblage present at the time of sampling. This includes such measurements as elemental composition and physiologic activity.

The second involves limitation of the potential rate of net primary production (autotrophic activity) such as measured in nutrient addition bioassays. Measurement of potential net primary production is appropriate if the interest is in the effects of eutrophication. It is in this context that the phrase nutrient limitation has been used in this report.

The third definition involves limitation of net ecosystem productivity. Net ecosystem productivity includes total ecosystem respiration (ie. heterotrophic activity) as well as autotrophic activity. As such, the loading of organic matter (which can be respired), as well as dissolved inorganic nutrients, becomes important.

As for the management of nutrient loading to aquatic systems, the current paradigm dictates that we strive to maintain the natural balances and processes that would exist in these ecosystems without the influences of anthropogenic nutrient enrichment. While this management strategy has its basis in science, it is also supported by law. The Clean Water Act of 1972 mandates that aquatic ecosystems be maintained at conditions present at the time of the bill's enactment. This paradigm is also inherent in aquatic ecosystem classification schemes such as the N.C. Department of Environmental Management's Nutrient Sensitive

Waters (NSW) designation.

The narrow band of coastal waters worldwide is responsible for a substantial amount of marine production. The bounty of coastal production is dependent on nutrients delivered from land and upwelled from the deep waters. Given this, why are we attempting to reduce the loading of nutrients to these waters? The answer is that we don't know enough about these systems to channel enhanced nutrient loading into desirable and potentially harvestable production. Perhaps with further advances in our knowledge we may learn how to use our "waste" products to fertilize the sea without damaging the balances necessary for its proper functioning. Until then, aquatic management must strive to avoid loading these systems with nutrients. We can use today's scientific knowledge to find which nutrients in particular present the highest potential for unbalancing ecosystem-level processes. Management strategies can then be developed to focus on controlling the loading of these "limiting" nutrients.

Management Recommendations

Our results strongly point to hydrological forcing as a key determinant shaping physical, chemical and biotic characteristics of the estuary. Large variations in annual flow regimes occurred during the study period, resulting in alterations of nutrient runoff, rain, flushing and salinity regimes. A longer-term continual sampling and analysis program will be needed to "filter out" or discriminate seasonal, annual and perhaps even multi-annual variability in physical and chemical influences on production from long-term trends, including specific rates of accelerating eutrophication. Judging from our current results, a ten-year sampling and analysis plan, based on monthly to bimonthly samplings at several locations of water quality relevance, will be needed to effectively differentiate (seasonal) "noise" from (long-term) "signal". It is stressed that monthly/bimonthly sampling continuity is a key to successful interpretation of signal vs. noise ratios, and ultimately, successful management strategies.

In light of current findings, it would appear reasonable and prudent to consider the following nutrient management strategy. This strategy in part underscores Paerl's (1987) earlier suggestions for stemming algal bloom activity on the upper Neuse River.

1. Our present data set does not allow for a quantitative estimate of the levels of reduction in nitrogen loading needed to maintain nuisance bloom-free conditions in the Neuse River Estuary. Paerl (1987) recommended a strategy for reduction of annual nitrogen loading to the upstream freshwater portion of the Neuse River Estuary to avoid bloom problems. This strategy, combined with the nutrient limitation results presented here, can serve as a starting point for the formulation of nutrient loading reductions needed to maintain desirable water quality in the lower estuary. Nitrogen loading reduction rates could be staggered temporally, so as to maximize input constraints prior to and during algal bloom periods (late February-mid June).

2. Reduce annual phosphorus loading by approximately equal portions (to nitrogen), again with a strong bias towards late winter-spring runoff periods. It is stressed that parallel nitrogen and phosphorus input constraints should be considered during the

critical late-winter early summer months. Based on our current knowledge of this estuary's nutrient assimilation and recycling characteristics, single nutrient input constraints may not achieve the desired criterion of long-term nuisance bloom-free conditions.

3. Since suspended sediments from runoff can be important sources of biologically-available nitrogen and phosphorus in the shallow estuaries typifying A - P System, controls on sediment loading must be considered. In particular, those upstream land practices minimizing soil disturbance and loss should be favored during various development stages. Ideally, any development or disturbance practices likely to accelerate sediment release should be halted.

4. Although it is premature to recommend regional and national cutbacks on anthropogenic atmospheric nitrogen loading, there is little doubt that this aspect of nutrient loading will receive increased attention as we approach the next century. Given current projections of population increases, associated urbanization and changes in land use patterns and development in the Southeast, atmospheric nutrient loading will likely account for an increased percentage of overall loadings (Placit et al. 1986). The relative importance of atmospheric nutrient loading will be of particular concern as terrigenous point and non-point nutrient inputs are reduced following improved management practices.

References Cited

Arnold, D. E. 1971. Ingestion, assimilation, survival, and reproduction by Daphnia pulex fed seven species of blue-green algae. Limnology and Oceanography 16:906-920.

Christian, R.R., J.N. Boyer, and D.W. Stanley. 1991. Multi-year distribution patterns of nutrients within the Neuse River estuary, North Carolina. Mar. Eco. Prog. Ser. (in press)

Christian, R. R., W. M. Rizzo, and D. W. Stanley. 1989. Influence of nutrient loading on the Neuse River estuary, North Carolina. NOAA-NURP Rept. 89-2.

Clean Water Fund of North Carolina, N.C. Sierra Club and Neuse River Foundation. 1990. Trouble on the Neuse: a review of the 23 major dischargers in the Neuse River basin. Clean Water Fund of North Carolina, P.O. Box 1008, Raleigh, N.C., 27602.

Copeland, B.J., R.G. Hodson and S.R. Riggs. 1984. The ecology of the Pamlico River, North Carolina: an estuarine profile. U.S. Fish Wildl. Serv. FWS/OBS-82/06., 83pp.

Copeland, B. J. 1986. Pollution and freshwater intrusion into estuaries supporting primary nurseries. Proc. Water Quality: Agriculture and Community Concerns in the South. Atlanta, Georgia, November 7-8, 1985.

Copeland, B. J. and J. Gray. 1989. Albemarle-Pamlico Estuarine System: Preliminary Technical Analysis of Status and Trends. Albemarle-Pamlico Study Report 89-13A, N. C. Dept. Envir. Health and Natural Resources, Raleigh, NC. 341 p.

Crumpton, W. G. 1987. A simple and reliable method for making permanent mounts of phytoplankton for light and fluorescence microscopy. Limnology and Oceanography 32:1154-1159.

Day, J. W., C. A. S. Hall, W. M. Kemp, and A. Yanez-Arancibia. 1989. Estuarine Phytoplankton. In Estuarine Ecology. John Wiley and Sons, New York. 558 pp.

D'Elia, C.F., J.G. Sanders, and W.R. Boynton. 1986. Nutrient enrichment studies in a coastal plain estuary: Phytoplankton growth in large scale, continuous cultures. Can. J. Fish. Aquat. Sci. 43:397-406.

Dubach, H. W. 1977. North Carolina Coastal Zone and Its Environment. Report for U. S. Dept. of Energy No. 147. Savannah River Laboratory, Aiken, SC.

Duce, R. A. 1986. The impact of atmospheric nitrogen, phosphorus, and iron species on marine biological productivity. pp. 497-529, in The Role of Air-Sea Exchange in Geochemical Cycling, P. Buat-Menard, ed. D. Reidel Publishing Co.

Epperly, S. P. and S. W. Ross. 1986. Characterization of the North Carolina Pamlico-Albemarle estuarine complex. NOAA Technical Memorandum NMFS-SEFC-175.

Esch, G. and T. Hazen. 1983. The Ecology of Aeromonas hydrophila in Albemarle Sound, N. C. Univ. of North Carolina, Water Resources Research Institute Report No. 153, Raleigh, NC.

Falconer, I. R. 1989. Effects on human health of some toxic cyanobacteria (blue-green algae) in reservoirs, lakes, and rivers. Toxicity Assessment: An International Journal 4:175-184.

Fisher, D., Ceraso, J., Oppenheimer, M. 1988b. Polluted coastal waters: The role of acid rain. Environmental Defense Fund, New York

Fisher, T.R., P.R. Carlson, and R.T. Barber. 1982. Sediment nutrient regeneration in three North Carolina estuaries. Estuar. Coastal Shelf Sci. 14:101-116.

Fisher, T.R., L.H. Harding, D.W. Stanley, and L.G. Ward. 1988a. Phytoplankton, nutrients, and turbidity in the Chesapeake, Delaware, and Hudson estuaries. Estuar. Coastal Shelf Sci. 27:61-93.

Fulton, R. S., III. 1984. Distribution and community structure of estuarine copepods. Estuaries 7:38-50.

Graneli, E., K. Wallstrom, U. Larsson, W. Graneli, and R. Elmgren. 1990. Nutrient limitation of primary production in the Baltic Sea area. Ambio 19:142-151.

Harrison, W.G. and Hobbie, J.E. 1974. Nitrogen budget of a North Carolina estuary. Water Resources Research Institute, U.N.C., Report No.86, Raleigh, N.C.. pp. 1-172.

Hobbie, J. E. 1971. Phytoplankton species and populations in the Pamlico River, North Carolina. Univ. of North Carolina, Water Resources Research Institute Report No. 56. Raleigh, NC. 147 pp.

Howarth, R.W. 1988. Nutrient limitation of net primary productivity in marine systems. Ann. Rev. Ecol. 19:89-110.

Jensen, M.H., E. Lomstein, and J. Sorensen. 1990. Benthic ammonium and nitrate flux following sedimentation of a spring phytoplankton bloom in Aarhus Bight, Denmark. Mar. Ecol. Prog. Ser. 61:87-96.

Kuenzler, E. J., D. W. Stanley, and J. P. Koenings. 1979. Nutrient kinetics in the Pamlico River, North Carolina. Univ. of North Carolina, Water Resources Research Institute Report No. 139. Raleigh, NC. 147 pp.

Kuenzler, E. J., K. L. Stone, and D. B. Albert. 1982. Phytoplankton uptake and sediment release of nitrogen and phosphorus in the Chowan River, North Carolina. Univ. of North Carolina, Water Resources Research Institute Report No. 186. Raleigh, NC. 148 pp.

Kuenzler, E. J., D. B. Albert, G. S. Allgood, S. E. Cabaniss, and C. G. Wanat. 1984. Benthic nutrient cycling in the Pamlico River. Univ. of North Carolina, Water Resources Research Institute Report No. 215. Raleigh, NC. 148 pp.

Levine, J. F., J. H. Hawkins, M. J. Dykstra, E. J. Noga, D. W. Moye, and R. S. Cone. 1990. Species distribution of ulcerative lesions on finfish in the Tar-Pamlico Estuary, North Carolina. Diseases of Aquatic Organisms 8:1-5.

Litaker, W., C.S. Duke, B.E. Kenney, and J. Ramus. 1988. Diel Chl a and phaeopigment cycles in a shallow tidal estuary: potential role of microzooplankton grazing. Mar. Ecol. Prog. Ser. 47:259-270.

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

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

Malone, T.C., L.H. Crocker, S.E. Pike, and B.W. Wendler. 1988. Influences of river flow on the dynamics of phytoplankton production in a partially stratified estuary. Mar. Ecol. Prog. Ser. 48:235-249.

Murphy, J. and J. P. Riley. 1962. A modified single solution method for the determination of phosphate in natural waters. Analytica Chimica Acta 27:31-36.

Nixon, S. W. 1986. Nutrient dynamics and productivity of marine coastal waters. pp. 97-115, in Marine Environment and Pollution, R. Halway, D. Clayton and M. Behbehani, eds. The Alden Press, Oxford.

N.C.D.N.R.C.D. (North Carolina Dept. of Natural Resources and Community Development). Div. of Envir. Management. 1980. Working Paper: Neuse River Investigation, 1979.

Nowicki, B.L., and C. Oviatt. 1990. Are estuaries traps for anthropogenic nutrients? Evidence from estuarine mesocosms. Mar. Ecol. Prog. Ser. 66:131-146.

Oviatt, C., P. Lane, F. French, and P. Donaghay. 1989. Phytoplankton species and abundance in response to eutrophication in coastal marine mesocosms. J. Plank. Res. 11:1223-1244.

Paerl, H. W. 1983. Factors regulating nuisance blue-green algal bloom potentials in the lower Neuse River, N. C. Univ. of North Carolina, Water Resources Research Institute Report No. 188. Raleigh, NC. 48 pp.

Paerl, H. W., P. T. Bland, J. H. Blackwell, and N. D. Bowles. 1984. The effects of salinity on the potential of a blue-green algal (Microcystis aeruginosa) bloom in the Neuse River estuary, N. C. Working Paper 84-1, UNC Sea Grant College Program, Raleigh, NC.

Paerl, H. W. 1985. Enhancement of marine productivity by nutrient-enriched acid rain. Nature 316:747-749.

Paerl, H. W. and N. D. Bowles. 1987. Dilution bioassays: Their application to assessments of nutrient limitation in hypereutrophic waters. Hydrobiologia 146:265-273.

Paerl, H. W. 1987. Dynamics of blue-green algal blooms in the lower Neuse River, North Carolina: Causative factors and potential controls. Univ. of North Carolina, Water Resources Research Institute Report No. 229. Raleigh, NC. 164 pp.

Paerl, H. W. 1988. Nuisance phytoplankton blooms in coastal, estuarine, and inland waters. Limnology and Oceanography 33:823-847.

Paerl, H. W., J. Rudek, and M. A. Mallin. 1990. Stimulation of phytoplankton production in coastal waters by natural rainfall inputs: nutritional and trophic implications. Marine Biology 107:247-254.

Peters, D. S. 1968. A study of the relationships between zooplankton abundance and selected environmental variables in the Pamlico River estuary of eastern North Carolina. M.S. Thesis, Dept. of Zoology, North Carolina State University, Raleigh, NC.

Placit, M., Streets, D. G., Williams, E. R. (1986). Environmental trends associated with the 5th national energy policy plan. Prepared for Argonne National Laboratory, ANL-EES-TM-323

Rudek, J., H. W. Paerl, M. A. Mallin, and P. W. Bates. 1991. Seasonal and hydrological control of phytoplankton nutrient limitation in the Neuse River Estuary, North Carolina. Marine Ecology Progress Series, (in press)

Schindler, J. E. 1971. Food quality and zooplankton nutrition. Journal of Animal Ecology 40:589-595.

Sea Grant (U.N.C.). 1982. Albemarle Sound: Trends and Management. U.N.C. Sea Grant Publ. SG-82-02.

Showers, W.J., Einsenstein, D.M., Paerl, H.W. and Rudek, J. 1990. Stable isotope tracers of nitrogen sources to the Neuse River, North Carolina. Water Resources Research Institute, U.N.C., Report No. 253, Raleigh, N.C.. 28pp

Solorzano, L. 1969. Determination of ammonium in natural waters by the phenol-hypochlorite method. Limnology and Oceanography 14:799-801.

Stanley, D.W. and Hobbie, J.E. 1977. Nitrogen cycling in the Chowan River. Water Resources Research Institute,U.N.C. Report No.121, Raleigh, N.C.. 127 pp. 127.

Stanley, D. H. 1988. Historical trends in nutrient loading to the Neuse River estuary, N. C. pp. 155-164, in Symposium on Coastal Water Resources. American Water Resources Association.

Strickland, J. D. H. and T. R. Parsons. 1972. A practical handbook of seawater analysis. 2nd ed. Bulletin Fisheries Research Board of Canada 167:310 pp.

U.S. Geological Survey. 1990. Water-quality trends and basin activities and characteristics for the Albemarle-Pamlico estuarine system, North Carolina and Virginia. N.C.D.E.H.N.R. APES Report No. 89-11, U.S.G.S. Open-file report 90-398, 164 pp.

Uye, S. and K. Takamatsu. 1990. Feeding interactions between planktonic copepods and red-tide flagellates from Japanese coastal waters. Marine Ecology Progress Series 59:97-107.

Wells, J. T. and S-Y. Kim. 1989. Sedimentation in the Albemarle-Pamlico lagoonal system: synthesis and hypotheses. Marine Geology 88:263-284.

Wetzel, R. G. and G. E. Likens. 1979. Limnological Analysis. W. B. Saunders, Philadelphia. 357 pp.

Witherspoon, A. M., C. Balducci, O. C. Boody, and J. Overton. 1979. Response of Phytoplankton to Water Quality in the Chowan River System. Univ. of North Carolina, Water Resources Research Institute Report No. 129. Raleigh, NC.