

**EVALUATING EUTROPHICATION CONTROL  
ALTERNATIVES FOR THE LOWER  
NEUSE RIVER, NORTH CAROLINA**

by

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May, 1988



**SCHOOL OF ENGINEERING AND  
APPLIED SCIENCE**

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**UNIVERSITY OF VIRGINIA  
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**EVALUATING EUTROPHICATION CONTROL  
ALTERNATIVES FOR THE LOWER  
NEUSE RIVER, NORTH CAROLINA**

**A Thesis Presented to  
the faculty of the School of Engineering and Applied Science  
University of Virginia**

**In Partial Fulfillment  
of the requirements for the Degree  
Master of Science (Civil Engineering)**

**by  
Larry G. Huffman, Jr.**

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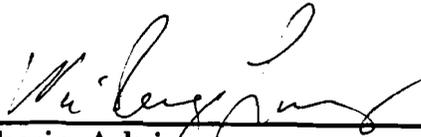
# APPROVAL SHEET

This thesis is submitted in partial fulfillment of the  
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Master of Science (Civil Engineering)

  
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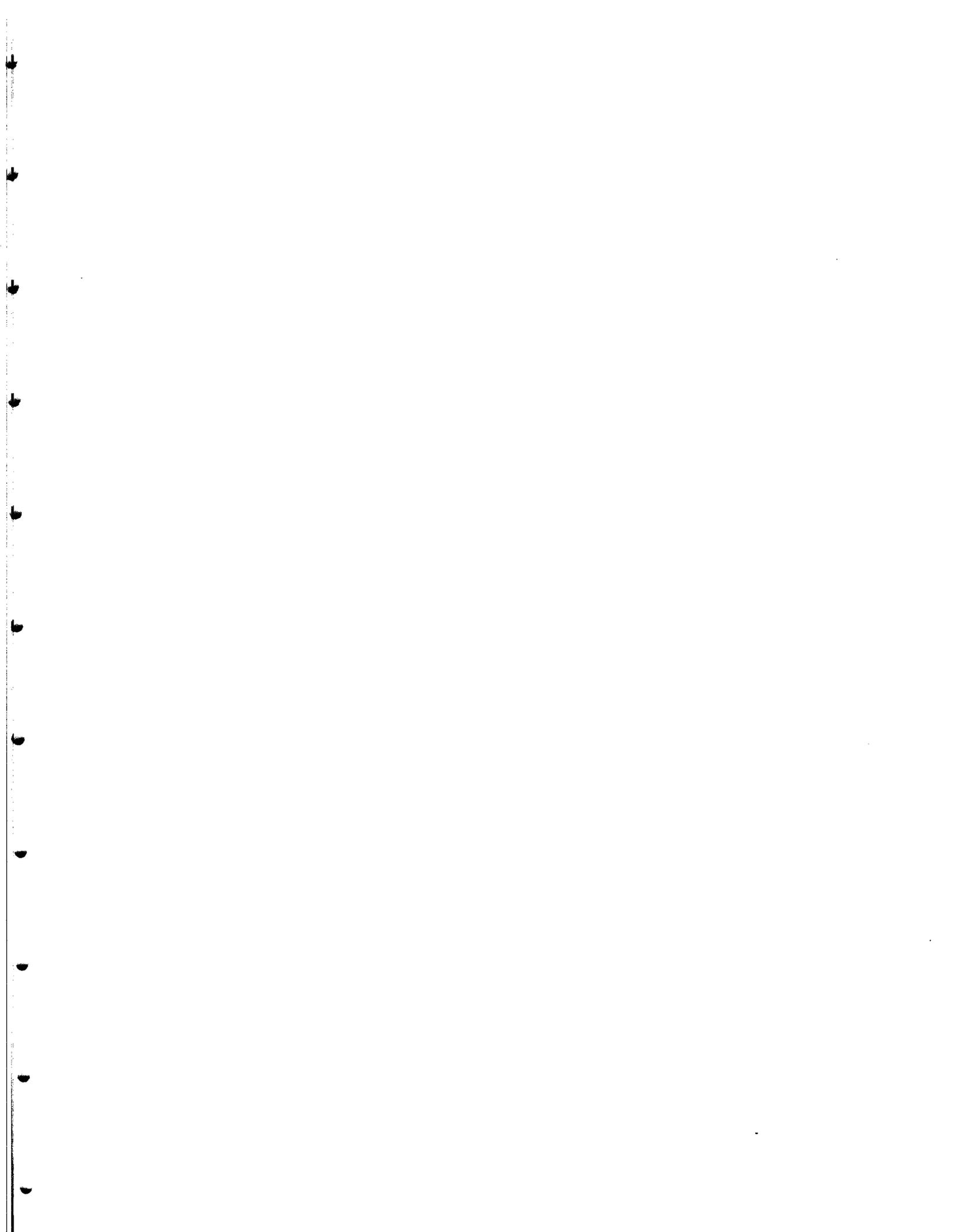
  
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# Abstract

In the past decade, advanced eutrophication has been observed in segments of the lower Neuse River between Goldsboro and New Bern, North Carolina. Eutrophication in the lower Neuse River is characterized by three major symptoms: 1) nitrogen and phosphorus concentrations in the water column that exceed levels required to sustain algal growth; 2) high rates of primary production; and 3) summer and fall blooms of *Microcystis aeruginosa*, a surface-dwelling, non-nitrogen fixing blue-green algae. Blooms occur most often during summers with below-average river flow following winters and springs with high runoff of nutrient-laden water.

Two existing water-quality models were used to evaluate the effectiveness of ten alternatives to control and limit eutrophication and algal growth in the lower Neuse River. Point-source control alternatives involved a stepwise reduction of effluent concentrations of total phosphorus from 6 mg/L to 0.2 mg/L and total nitrogen from 7 mg/L to 3 mg/L. Reductions of current non-point source nitrogen and phosphorus loads by 30% were evaluated both alone and in conjunction with point-source phosphorus and nitrogen controls. A hybrid annual flow scenario featuring high winter-spring flow and summer low-flow was used in the model evaluations to simulate optimum algal growth conditions. Low-flow augmentation was also examined as a method to limit bloom formation.

Model results indicate that a 38% reduction in maximum annual chlorophyll *a* concentrations may be achieved with stringent point-source phosphorus control. Non-point source nitrogen and phosphorus controls of 30% were effective in limiting growth only when used in conjunction with point-source phosphorus control. Flow control simulations suggest that periodic release of water from upstream reservoirs may arrest algal growth during low flows.

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To my fellow graduate students, thanks for the pleasant diversions from work!

Above all, I wish to acknowledge my family for their love and encouragement during all of my academic endeavors.

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# List of Symbols

<u>Symbol</u>	<u>Description and Unit</u>
$BC_{NEEM}$	= $PO_4^{3-}$ boundary condition for NEEM
$BC_{NRM}$	= $PO_4^{3-}$ concentration at Kinston from NRM
$c$	= concentration of the water-quality variable, $[ML^{-3}]$
cfs	= cubic feet per second
DEM	= Division of Environmental Management
$E$	= dispersion (mixing) coefficient due to tides and density and velocity gradients (or diffusion coefficient in the sediment interstitial waters), $[L^2T^{-1}]$
IN	= inorganic nitrogen (ammonia and nitrite/nitrate)
IP	= inorganic phosphorus (orthophosphate)
$K_n$	= half-saturation (Michaelis) constant for the limiting nutrient, mg/L.
lb/day	= pounds per day
lb/yr	= pounds per year
mg/L	= milligrams per liter
$n$	= concentration of the limiting nutrient in the water, mg/L
N	= nitrogen
NEEM	= Neuse Estuary Eutrophication Model
$NH_4^+$	= ammonia nitrogen
$NO_2^-/NO_3^-$	= nitrite/nitrate nitrogen

NPDES	= National Pollutant Discharge Elimination System
NRM	= Neuse River Model
org-P	= organic phosphorus
P	= phosphorus
PAR	= photosynthetically-active radiation
$PO_4^{3-}$	= orthophosphate (inorganic phosphorus)
$Q$	= river flow (discharge) (cfs)
$\bar{Q}$	= average river flow (cfs)
$r_n$	= growth limitation factor of nutrient n
$S$	= sources and sinks of the water-quality variable, representing kinetic interactions, $[ML^{-3}T^{-1}]$
$t$	= time, [T]
$U$	= net advective velocity, $[LT^{-1}]$
UNCIMS	= University of North Carolina Institute of Marine Sciences
$W$	= external inputs of the variable $c$ , $[MT^{-1}]$
$x, y, z$	= longitudinal, lateral, and vertical coordinates, respectively, [L]
$\mu$	= algal growth rate, $[1/T]$
$\mu_{max}$	= maximum growth rate under excess nutrients and optimum temperature and light, $[1/T]$
$\mu g/L$	= micrograms per liter

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## 1. INTRODUCTION

### 1.1. Objectives

During the past decade, advanced eutrophication has been observed in segments of the lower Neuse River between Goldsboro and New Bern, North Carolina (Figure 1-1) (Paerl, 1983). Eutrophication in the lower Neuse River is characterized by three major symptoms: 1) nitrogen and phosphorus concentrations in excess of those needed to sustain algal growth; 2) high rates of primary production; and 3) summer and fall blooms of *Microcystis aeruginosa*, a surface-dwelling, non-nitrogen fixing blue-green algae. These blooms have been most extensive and persistent during summers with below-average river flow following high spring runoff of nutrient-rich water. Blooms occur approximately once every two or three years and may persist for as long as four months.

Often covering the river in bright green mats or scums, blue-green algal blooms can have serious effects on water quality and aquatic life. Because blue-green algae are poor food sources for zooplankton (Porter and Orcutt, 1980), algal biomass is not consumed. Algal blooms block sunlight required for photosynthesis by subsurface phytoplankton and plants (Paerl and Ustach, 1982). In turn, less oxygen is produced in the water column. Subsurface waters and benthic sediments in the lower Neuse River may become anoxic (devoid of oxygen) during prolonged algal blooms (Paerl, 1983). As algae die and settle in the water column, more oxygen is

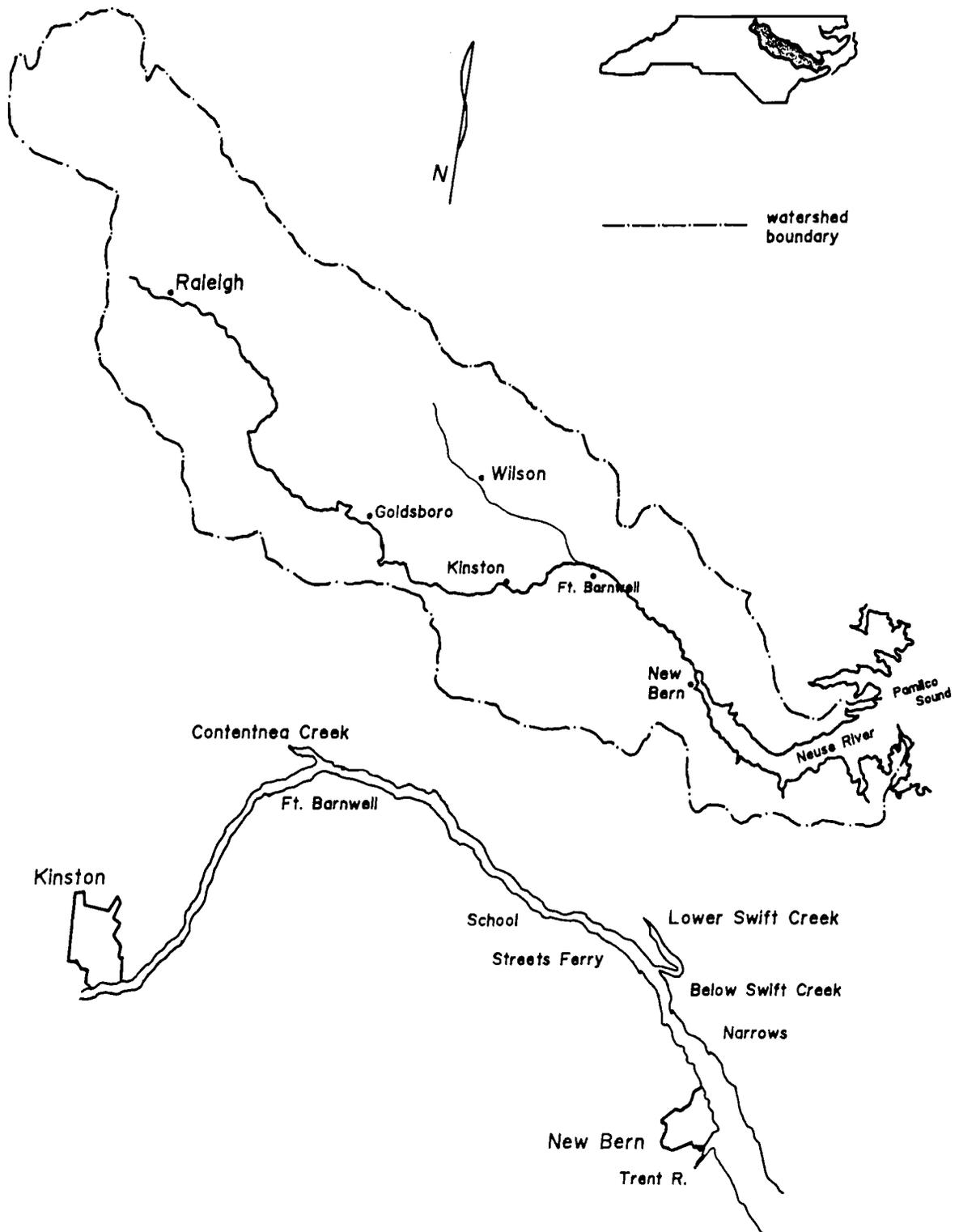


Figure 1-1: Neuse River watershed and study area.

consumed through bacterial decomposition. Blooms clog water-supply filters and may give unpleasant odors and tastes to drinking water (Reynolds and Walsby, 1975). More importantly, bloom-plagued drinking water can be toxic to livestock, wildlife, and man. For example, water contaminated with *Microcystis aeruginosa* has caused headaches, nausea, and gastroenteritis in humans and liver damage and death in livestock (Gorham and Carmichael, 1979).

In order to prevent these potentially harmful effects on flora and fauna in the lower Neuse River, methods to control and limit the formation of blue-green algal blooms are required. Lung and Paerl (1988) found that the initiation and magnitude of blue-green algal blooms in the lower Neuse River between Kinston and New Bern are highly influenced by nutrient supply in the spring and river flow in the summer. Of the many factors that influence the formation of algal blooms, nutrient supply and river flow may be controlled most directly by man. To develop management alternatives to control blooms in the lower Neuse River, these questions must be addressed:

- What are the relationships between flow and nutrient supply, and how do these relationships jointly influence blue-green algal blooms?
- Would major reductions of nitrogen and/or phosphorus inputs from point and/or non-point sources limit future eutrophication and control blooms?
- What level of reduction of nitrogen and/or phosphorus inputs is necessary to limit the initiation of blooms?
- How can river flow be used to control blooms?

These questions will be addressed through the use of two existing mathematical models that were developed to predict and quantify algal growth in the riverine and estuarine portions of the Neuse River. The Neuse River Model (NRM) (Shiple, 1986) will be used to assess the fate and transport of nutrients in the riverine portion. Nutrient boundary conditions at the head of the lower river (Kinston) generated in this analysis will be used in the Neuse Estuary Eutrophication Model (NEEM) (Lung and Paerl, 1988) to evaluate management alternatives to control eutrophication in the lower Neuse River.

## **1.2. Study Area**

The Neuse River originates at the confluence of the Eno and Flat Rivers in Durham County, North Carolina in the Piedmont physiographic province. The river is dammed at Falls, North Carolina to form Falls Lake, a reservoir used for flood-control, augmentation of low-flow, recreation, and water supply for the City of Raleigh. The Neuse River enters the Coastal Plain Province at Smithfield and empties into Pamlico Sound at Maw Point, 250 miles from its source. The river and its tributaries drain 5600 square miles or 11% of North Carolina. Major tributaries of the river include the Little River, entering at Goldsboro; Upper Swift Creek, entering at Smithfield; Contentnea Creek, entering above Fort Barnwell; Lower Swift Creek, entering below Streets Ferry; and the Trent River, entering at New Bern. These tributaries comprise about 30% of the Neuse River's drainage area. The average annual flow at Kinston, the farthest downstream gaging station, is approximately 2900 cubic feet per second (cfs) for a drainage area

of about 2690 square miles (Giese et al., 1985). The estimated average annual discharge at Maw Point is about 6100 cfs.

The flow pattern of the river changes gradually between Fort Barnwell and New Bern from riverine (exclusively freshwater) flow to estuarine flow. Like most coastal rivers in the eastern United States, the Neuse River has three distinct flow zones. From its headwaters to near Ft. Barnwell, the river is free-flowing and exclusively freshwater, and there are no tides. The tidal river begins as far upstream as Ft. Barnwell during very low freshwater flow (Giese et al., 1985). Tides reach this second zone, but there is no salt-water encroachment. Estuarine flow begins about four miles upstream of Streets Ferry during low-flows. Under tidally-averaged conditions, estuarine flow consists of a layer of fresh water moving downstream overlying a layer of saline water moving upstream. As freshwater flow increases because of high rainfall, the upstream-limit of the two-layer flow is pushed downstream by the freshwater flow.

The Neuse River basin is predominantly rural, with the exception of six major urban areas: Durham, Raleigh, Goldsboro, Kinston, and New Bern, all located on or near the Neuse River, and Wilson, located on Contentnea Creek. In 1980, 55% of the basin's population inhabited these urban areas (Division of Environmental Management [DEM], 1983). Each of these cities, as well as several smaller communities in the Neuse River basin, have sewage treatment facilities that discharge wastes containing nitrogen and phosphorus to the river and its tributaries. Census data from 1970 and 1980 indicate a 29% increase in urban population and a 19% increase in

total population of counties within the basin during the 1970's. The majority of agricultural activity in the basin occurs below Smithfield in the Coastal Plain Province. Harvested cropland in the basin increased by 30% between 1967 and 1980 (DEM, 1983). Municipal and agricultural growth has been accompanied by larger point and non-point source waste loads to the Neuse River and its tributaries, resulting in enrichment of bloom-promoting nutrients.

## 2. PHYTOPLANKTON-NUTRIENT RELATIONSHIPS

### 2.1. Nutrient Sources

The primary nutrients for phytoplankton growth in freshwaters are the dissolved inorganic nitrogen species ammonium ( $\text{NH}_4^+$ ) and nitrite/nitrate ( $\text{NO}_2^-/\text{NO}_3^-$ ) and the inorganic phosphorus species orthophosphate ( $\text{PO}_4^{3-}$ ). These nutrients and their organic counterparts enter surface waters through a variety of sources. Runoff from undeveloped land carries nitrogen and phosphorus to surface waters. Nutrients stored in the tissues of dead aquatic plants and animals are liberated through bacterial decay. Inorganic nitrogen and phosphorus bound to sediments are released through chemical processes and the physical action of benthic organisms. Atmospheric nitrogen enters the water column through biological, electrochemical, and photochemical fixation of nitrogen gas to organic nitrogen and through precipitation containing airborne  $\text{NO}_3^-$ . Nitrate is also introduced to surface waters through the movement of groundwater into surface waters.

Anthropogenic point and non-point sources, however, provide the major inputs of nutrients to the Neuse River and its tributaries. Point sources include municipal and industrial wastewater discharges. Non-point sources include agricultural runoff of fertilizers and animal wastes, runoff from forested land and wetlands, and urban runoff from parking lots and streets.

The most extensive blooms in the Neuse River have occurred between Kinston and New Bern, with blooms occurring as far upstream as Goldsboro

during extreme low-flow (DEM, 1983; Paerl, 1987). It is likely that point and non-point sources entering the river at and below New Bern have some effect on algal growth in this section. Nutrients entering the upper layer of the river at and below this point may be entrained in the lower layer of upstream-moving saline water through mixing of the upper and lower layers. These nutrients may be carried upstream with the tide and become available for uptake by algae. In this study, however, the model (NEEM) used to simulate algal growth in the Kinston-New Bern section does not consider point and non-point sources that enter the river below New Bern. Therefore, the control alternatives evaluated in this study apply only to point and non-point sources above New Bern.

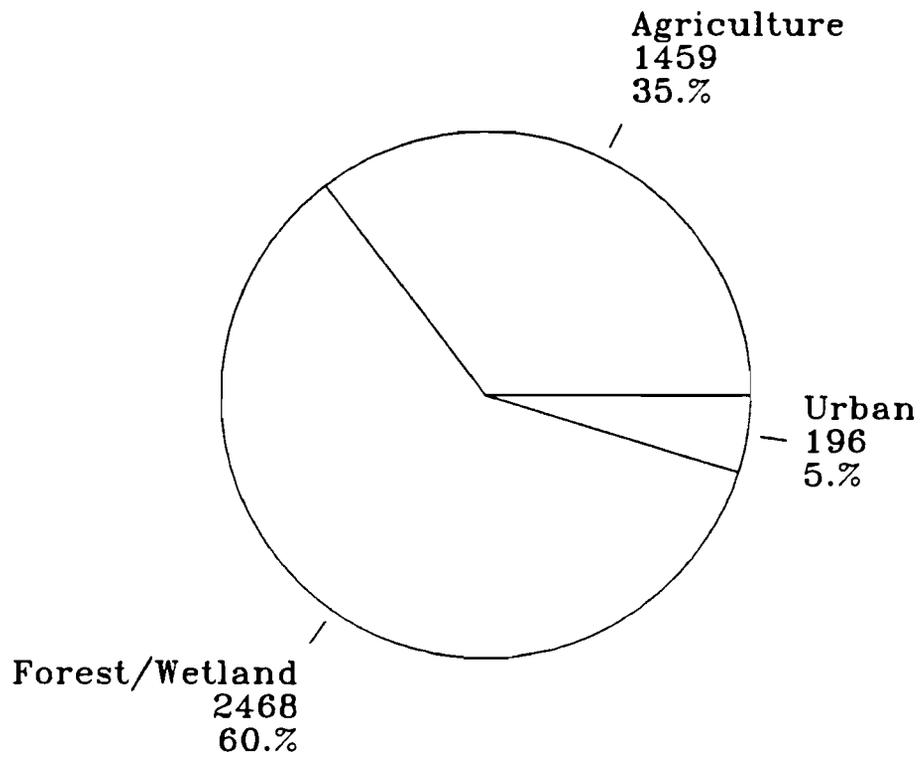
Large amounts of nutrients may be retained in reservoirs on rivers. Reservoirs act as settling basins for the particulate form of nutrients in their organic or inorganic phases. For example, more than 75% of phosphorus inputs and 40% of nitrogen inputs to the Yadkin and Pee-Dee Rivers in North Carolina are trapped by reservoirs (DEM, 1983). Reservoirs are often constructed for this purpose. Removal efficiencies of retention basins for orthophosphate in the German Democratic Republic range from 10-30% for detention times of less than two days to 30-60% for detention times of 2-14 days (Benndorf, et al., 1976). Similar percentages might be retained by Falls Lake on the upper Neuse River, reducing the impact of point and non-point sources above the reservoir on downstream algal growth. In this study, any nutrients that pass through Falls Lake were incorporated in the Neuse River Model as upstream boundary

conditions for the riverine portion of the Falls Lake-New Bern section of the river. Non-point source control alternatives were applied to these boundary conditions, and point source controls were applied to municipal and industrial sources located below Falls Lake.

Given these two assumptions, it is necessary to quantify only those point and non-point sources that enter the Neuse River between Falls Lake and New Bern. This sub-basin comprises 67% of the total land area of the Neuse River basin. Almost two-thirds of the sub-basin is undeveloped forest/wetland, with slightly more than one-third agricultural land and a small portion (5%) urban (Figure 2-1). Major municipal point sources in this section include the Raleigh, Smithfield, Goldsboro, and Kinston Northside and Peachtree wastewater treatment plants. Industrial point sources include Burlington Industries above Raleigh, E. I. Dupont at Kinston, and Weyerhaeuser pulp and paper mill at the mouth of Lower Swift Creek near Vanceboro. These point sources provide approximately 75 and 76 percent of estimated total nitrogen and total phosphorus point source loads, respectively, to this section of the Neuse River (DEM, 1983).

## **2.2. Nutrient Budget**

The North Carolina Division of Environmental Management has developed a preliminary nutrient budget for the Neuse River basin based on estimates of nutrient loads from point and non-point sources in the basin. Percentages of point and non-point contributions to nitrogen and phosphorus loading for the middle section of the river from Falls Lake to New Bern are presented in Figure 2-2.



**Figure 2-1:** Land use/type in square miles.  
Falls Lake to New Bern.

## Falls Lake to New Bern

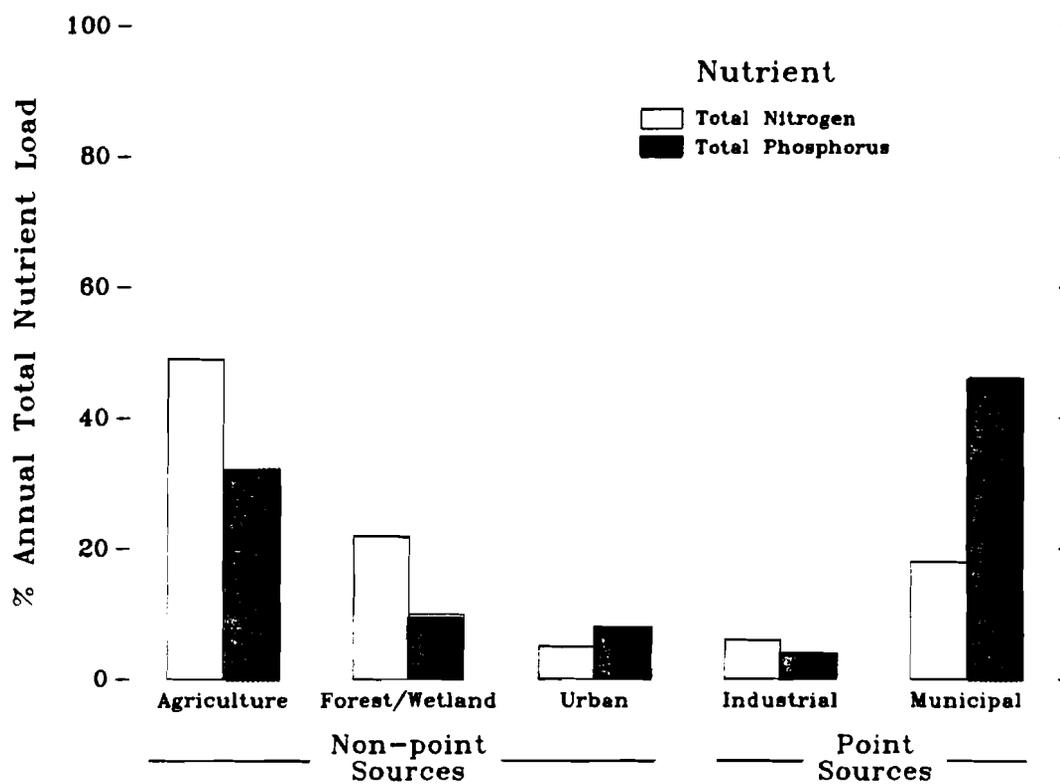


Figure 2-2: Percentages of annual total nutrient loads from point and non-point sources.

Point and non-point sources in this sub-basin contribute about  $107 \times 10^5$  pounds per year (lb/yr) of total nitrogen to the Neuse River. Seventy-six percent of this load comes from non-point sources including farmed land, forest and wetlands, and urban areas. Agricultural activities alone account for 49% of total nitrogen loading in the sub-basin. Municipal wastewater treatment plants contribute the majority of point-source nitrogen loads (18% of sub-basin total). The estimated annual total phosphorus load for the sub-basin is  $142 \times 10^4$  lb which is split evenly between point and non-point sources. The majority of non-point source phosphorus comes from agricultural activities (32%); however, municipal wastewater treatment plants are the dominant source of phosphorus in the sub-basin (46% of sub-basin total).

This nutrient budget illustrates the contributions of both point and nonpoint sources to nutrient enrichment of the lower Neuse River. Clearly, the majority of total nitrogen entering the river comes from agricultural sources, while municipal sources contribute almost half of the total phosphorus.

### **2.3. Hydrologic Characteristics, 1978-86**

River flow often dominates phytoplankton growth, survivability, and mortality. The quantity and timing of flow influence phytoplankton behavior in the Neuse River in three major ways:

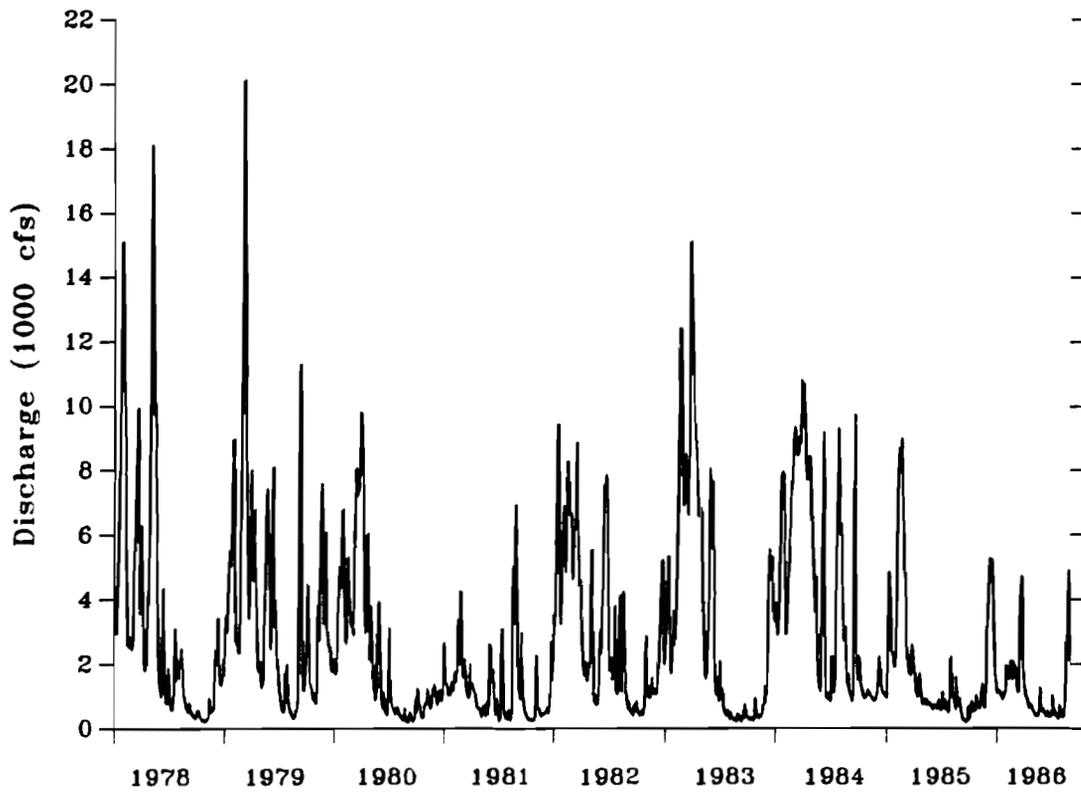
- High winter-spring runoff carries nitrogen and phosphorus from non-point sources to the river, increasing the supply of nutrients available for spring-summer algal growth. Point sources such as municipal wastewater treatment plants provide continuous phosphorus input.

- Algae proliferate during summer low-flow and drought periods because of calm waters and a resulting increase in hydraulic residence time.
- Periodic summer and fall storms flush standing stocks of algal biomass and available nutrients downstream.

The scale of temporal changes in flow in the Neuse River varies from short-term increases in flow of one to three days due to storms to long-term seasonal droughts of up to nine months. Moreover, there may be marked differences in both the quantity of discharge between years and the distribution of discharge within an individual year. Eight calendar years (January-December) of daily flow data at Kinston (U.S. Geological Survey gaging station 02089500) indicate that the majority of discharge and subsequent flow occurs between January or February and April or May (Figure 2-3). Late summer and early fall tend to be the driest seasons in the Neuse River basin, but the length and severity of low-flow periods vary annually. Annual peak flows, characterized by extreme spikes in the hydrograph, generally occur in March or April and in September and range from 10,000 to 20,000 cfs.

Based on the hydrograph in Figure 2-3, three different types of annual flow patterns can be distinguished:

- Dry years, characterized by 1985, 1986, and, to a lesser extent, 1981, in which low peak winter flows (less than 10,000 cfs) were followed by up to nine months of extremely low discharge or drought;
- Wet years, such as 1979, 1982, and 1984, consisting of evenly distributed peak flows throughout the spring and summer and few dry periods;



**Figure 2-3:** Daily discharge (cfs) of Neuse River at Kinston, N.C., 1978-86.

- High flows in winter and early spring followed by extremely low-flows in summer and fall (1978, 1980, and 1983).

Paerl (1987) notes that while distinctions and generalizations may be made about the seasonal distribution of rainfall and discharge in the Neuse River, each year has its own unique temporal flow pattern.

In order to establish flow-nutrient-phytoplankton relationships and evaluate alternatives to control algal growth, three years (1983-85) of hydrologically-diverse flow data will be examined in relation to their effect on nutrient concentrations and loadings and phytoplankton growth. Data from these years were selected for calibration and verification of the Neuse Estuary Eutrophication Model (Lung and Paerl, 1988) and for this study because each year represents a unique flow pattern that promoted equally unique seasonal patterns of nutrient concentrations and phytoplankton growth.

#### **2.4. Nutrient Concentrations**

Currently, available external (water column) concentrations of the three soluble inorganic nutrients  $\text{NH}_4^+\text{-N}$ ,  $\text{NO}_2^-/\text{NO}_3^-\text{-N}$ , and  $\text{PO}_4^{3-}\text{-P}$  are more than adequate to support algal growth throughout most of the year in the Neuse River. Concentrations vary throughout each year, and their distributions can be related to river flow and algal growth. Nutrient and chlorophyll *a* concentrations at Streets Ferry during 1983-85 along with corresponding daily discharge at Kinston are presented in Figure 2-4. Flow at Kinston was related to concentrations at Streets Ferry on a qualitative basis to show the influence of river flow on seasonal patterns of nutrients and chlorophyll *a* concentrations. Surface nutrient and chlorophyll *a* data

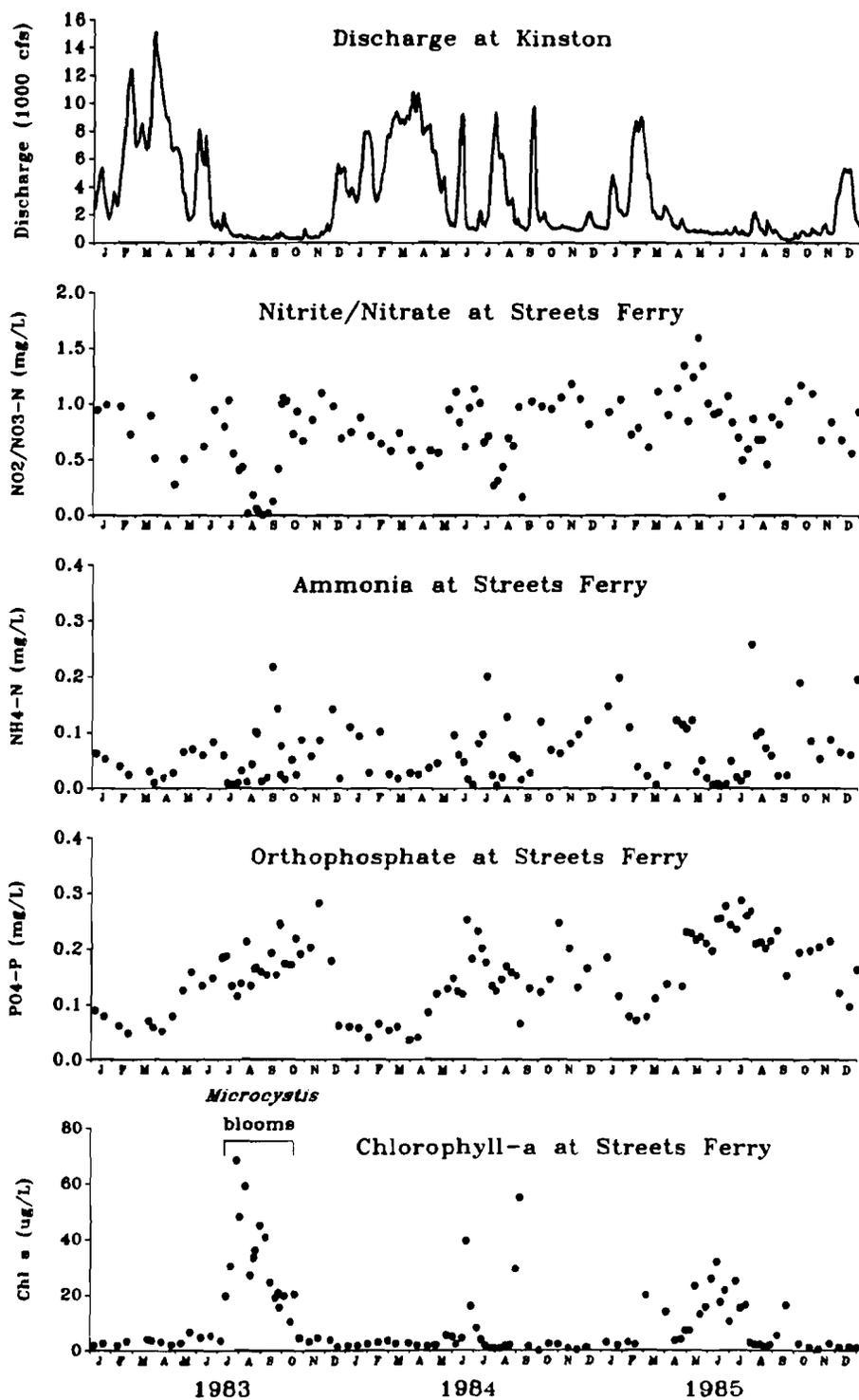


Figure 2-4: Discharge at Kinston and nutrient and chlorophyll *a* concentrations at Streets Ferry.

were collected by the University of North Carolina's Institute of Marine Sciences (UNCIMS) at one to two week intervals during 1981-86. Data is presented for the Streets Ferry sampling site because chlorophyll *a* concentrations at this site were as high or higher than levels at upstream and downstream sites in the Kinston-New Bern study area (Lung and Paerl, 1988). Surface nutrient concentrations are reported because of relatively homogeneous distribution of concentrations in the water column.

Chlorophyll *a* is used as an indicator of the overall amount of phytoplankton biomass in the water column. Concentrations represent four phytoplankton groups -- diatoms, green algae, and blue-green algae, both nitrogen fixing and non-nitrogen fixing species. However, peak chlorophyll *a* concentrations in the summer of 1983 were dominated by non-nitrogen fixing blue-green algae. For example, *Microcystis aeruginosa* accounted for 94% and 96% of surface scums in July and August of 1983, respectively, at a sampling site between Streets Ferry and New Bern (Paerl, 1987). Therefore, summer chlorophyll *a* concentrations should be evaluated with regard to the dominance of non-nitrogen fixing blue-green algae.

$\text{NO}_2^-/\text{NO}_3^-$  are the most abundant inorganic nutrients by concentration at most times of a year, with  $\text{NO}_3^-$  the more plentiful of the two species (Figure 2-4).  $\text{NO}_2^-/\text{NO}_3^-$  concentrations range from 0.13 to 1.6 milligrams per liter (mg/L) with the exception of August and September, 1983, when  $\text{NO}_2^-/\text{NO}_3^-$  levels fell to a median concentration of 0.03 mg/L. This near depletion of  $\text{NO}_2^-/\text{NO}_3^-$  followed massive *Microcystis aeruginosa* blooms and peak chlorophyll *a* levels of about 50-70 micrograms per liter ( $\mu\text{g/L}$ ) during

late July and early August. In fact, closer comparison of the two graphs shows that  $\text{NO}_2^-/\text{NO}_3^-$  concentrations fell while chlorophyll *a* concentrations rose during these months. Only after  $\text{NO}_2^-/\text{NO}_3^-$  levels reached near depletion did chlorophyll *a* concentrations begin to decline in early September. Similar patterns occurred in the summers of 1984 and 1985 but were less pronounced due to the limiting influence of sub-optimal hydrologic conditions on algal growth and the initiation of blue-green blooms. These conditions included periodic summer storms every one to two weeks during 1984 that flushed the river of algal biomass and nutrients and low winter-spring runoff in 1985 that carried lower  $\text{NO}_2^-/\text{NO}_3^-$  loads than in 1983 and 1984.

Seasonal averages of  $\text{NO}_2^-/\text{NO}_3^-$  at Streets Ferry appear to be largely controlled by flow conditions. The average  $\text{NO}_2^-/\text{NO}_3^-$  concentration from December to May for the three-year period was 0.84 mg/L, while the June-November average concentration was 0.72 mg/L. High winter-spring runoff of  $\text{NO}_2^-/\text{NO}_3^-$ -laden waters most likely accounts for the higher average concentration in the winter and spring months. Peak concentrations of 1983 and 1984 correspond with these high winter-spring flows. Concentrations are generally lower in the summer and fall due to algal uptake and reduced runoff from agricultural land. However, the average summer-fall concentrations for 1984 and 1985, 0.78 mg/L and 0.79 mg/L, respectively, were much higher than the average concentration for summer and fall of 1983 (0.58 mg/L). Because of frequent summer rainfall and associated non-point source runoff during the summer of 1984,  $\text{NO}_2^-/\text{NO}_3^-$  concentrations

were higher than those in 1983. The highest  $\text{NO}_2^-/\text{NO}_3^-$  levels, however, occurred in the late spring of 1985 at the beginning of a prolonged drought. These peak concentrations may have been caused by small-scale runoff from fertilized farmland near the sampling site (Paerl, 1987).

In contrast to  $\text{NO}_2^-/\text{NO}_3^-$ ,  $\text{NH}_4^+$  concentrations seemed to be less controlled by hydrologic conditions during 1983-85. Average December-May and June-November concentrations were similar (0.060 mg/L and 0.061 mg/L, respectively), and the temporal pattern of concentration shown in Figure 2-4 does not correspond to the adjoining flow pattern. Apparently,  $\text{NH}_4^+$  is a very small component of non-point source nitrogen loads.  $\text{NH}_4^+$  concentrations ranged from 0.003 mg/L to 0.26 mg/L.

Peak concentrations of  $\text{NH}_4^+$  followed moderate to significant algal growth and bloom events (as noted in chlorophyll *a* concentrations). Most of these peaks occurred in late summer and early fall, but a definite increase in  $\text{NH}_4^+$  was also observed in late fall and early winter of 1984-85. Because these pulses of  $\text{NH}_4^+$  accompany algal growth of bloom and non-bloom proportions, algal biomass may have been the source of the high concentrations.  $\text{NH}_4^+$  was likely returned to the water column by microbial decomposition of dead algae, algal excretion of  $\text{NH}_4^+$ , and excretion by zooplankton consumers of biomass (Paerl, 1987).

$\text{PO}_4^{3-}$  concentrations displayed seasonal patterns similar to  $\text{NH}_4^+$ , with minimum concentrations generally occurring in winter and spring and concentrations reaching a maximum from late summer to late fall (Figure

2-4). Concentrations ranged from 0.035 mg/L to 0.3 mg/L. Inorganic phosphorus concentrations seldom fell below 0.05 mg/L; total phosphorus (inorganic and organic) levels above 0.05 mg/L are considered to be in excess of algal growth requirements in estuaries (FWPCA, 1968). Paerl (1987) showed through bioassays that  $\text{PO}_4^{3-}$  concentrations and loadings never fell to growth-limiting levels from 1981 to 1986, even throughout the extensive *Microcystis aeruginosa* blooms of 1983.

High  $\text{PO}_4^{3-}$  levels were consistently flushed or diluted by high rainfall, runoff, and subsequent flow in all three years. In contrast to  $\text{NO}_2^-/\text{NO}_3^-$ , which generally increased during and following high winter-spring runoff,  $\text{PO}_4^{3-}$  reached maximum levels during extreme low-flow periods in the summers of 1983 and 1985. Figure 2-5 relates nutrient concentrations at Kinston to flow at Kinston (U. S. Geological Survey data). As expected,  $\text{PO}_4^{3-}$  concentrations were lower under high flow than low flow, as shown by the negative slope of the data and the relatively high correlation coefficient ( $r^2$ ) of 0.64. High river flows dilute point-source discharges, the dominant source of phosphorus in the Neuse River basin. Less dilution occurs at lower flows, so  $\text{PO}_4^{3-}$  concentrations tend to be higher than at high flow. This relationship further suggests that point sources such as municipal wastewater treatment plants and industrial effluents are the primary contributors of  $\text{PO}_4^{3-}$  to the river. Similar comparisons between flow and  $\text{NH}_4^+$  and  $\text{NO}_2^-/\text{NO}_3^-$  concentrations reveal no correlation between flow and concentration at this location. In general, comparisons between flow and  $\text{NO}_2^-/\text{NO}_3^-$  exhibit positive slopes suggesting a correlation between

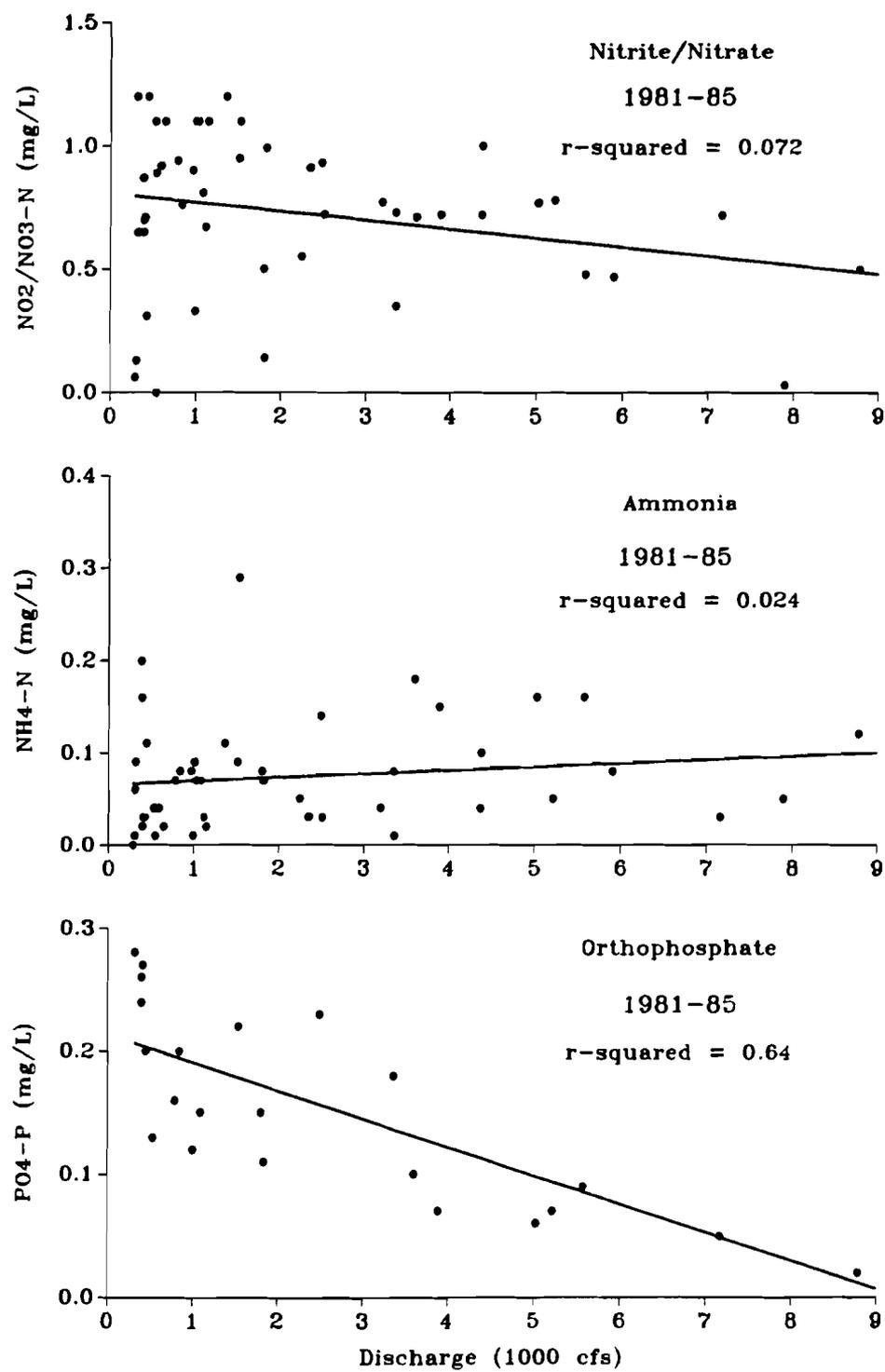


Figure 2-5: Discharge-nutrient relationships at Kinston.

increasing flow and higher  $\text{NO}_2^-/\text{NO}_3^-$  concentrations. However, this trend was not observed in these data.

Like  $\text{NH}_4^+$ , some of the highest levels of  $\text{PO}_4^{3-}$  occurred along with or following significant algal growth and blooms. There are four possible explanations for these peaks: 1) point source discharge of  $\text{PO}_4^{3-}$ -rich effluents during low-flows; 2) release of  $\text{PO}_4^{3-}$  from algal cells by decomposition and excretion by algae and algal predators; 3) release of  $\text{PO}_4^{3-}$  from anoxic sediments; and 4) release of  $\text{PO}_4^{3-}$  from benthic and suspended sediments and colloidal matter by alterations in iron-phosphorus complexes and precipitates facilitated by increases in pH that occur during algal blooms (Paerl, 1987).

## 2.5. Nutrient Loading

Further support for the strong influence of hydrologic conditions on available nutrient concentrations is derived from nutrient loading rates. To calculate loading rates, flows at Kinston were multiplied by corresponding nutrient concentrations at Kinston used as boundary conditions in calibrations of the NEEM. These boundary conditions are 15-day linear interpolations of the raw data collected by the UNCIMS. Loading rates for 1983-85 as well as discharge at Kinston are shown in Figure 2-6.  $\text{NO}_2^-/\text{NO}_3^-$  loads were much greater than either  $\text{NH}_4^-$  or  $\text{PO}_4^{3-}$  loads and were more highly influenced by the magnitude and timing of flow.

The seasonal trend of  $\text{NO}_2^-/\text{NO}_3^-$  loading rates closely resembles the hydrograph. Maximum loading is closely associated with high winter-spring

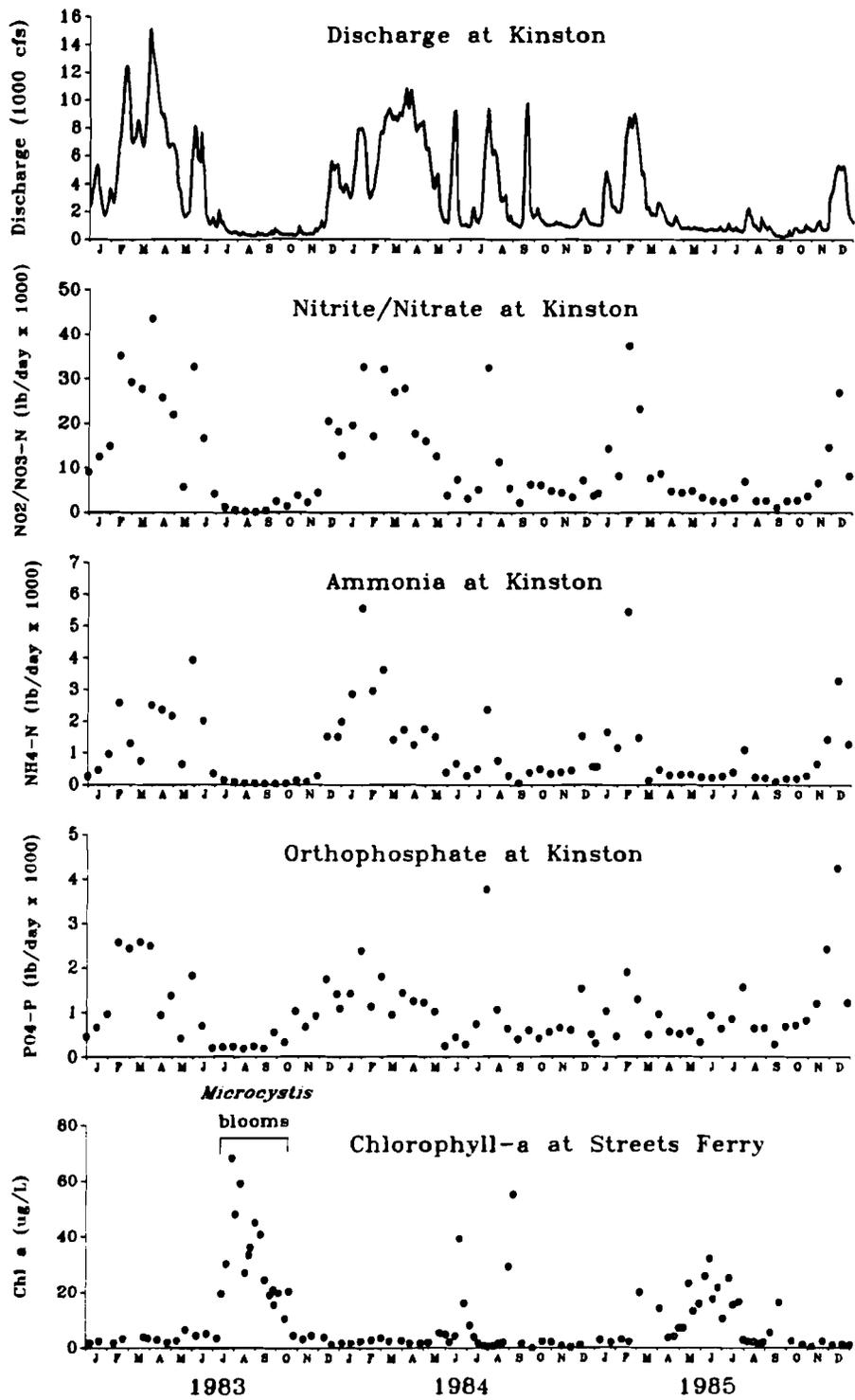


Figure 2-6: Nutrient loading rates at Kinston.

rainfall and discharge, while summer loading rates plummet during summer low-flows. Smaller loading rates occur during the peak flows of the summer of 1984. Because  $\text{NO}_2^-/\text{NO}_3^-$  and  $\text{NH}_4^+$ -based fertilizers are applied to agricultural lands in the late winter and early spring, heavy rainfall entering the river as surface runoff carries  $\text{NO}_2^-/\text{NO}_3^-$  overland and maximizes loading rates. Subsurface runoff carrying soil-based  $\text{NO}_3^-$  and surface runoff over cleared lands, disturbed wetlands, and plowed fields also adds to winter-spring loading rates (Paerl, 1987). Loads were very high in 1983 for this size of river. Loading rates reached almost 44,000 pounds per day (lb/day) in late March. These loads supplied the Neuse River with excessive  $\text{NO}_2^-/\text{NO}_3^-$  concentrations that, coupled with the cessation of rainfall and increase in hydraulic residence time, prompted the extensive *Microcystis* blooms of the summer and early fall.

Calculated  $\text{NH}_4^+$  and  $\text{PO}_4^{3-}$  loading rates were considerably lower than  $\text{NO}_2^-/\text{NO}_3^-$  rates because these nutrients were present in smaller concentrations in the river.  $\text{NH}_4^+$  and  $\text{PO}_4^{3-}$  loads were similar in quantity, with the former ranging from 25 to 5600 lb/day and the latter ranging from 180 to 4200 lb/day. Both  $\text{NH}_4^+$  and  $\text{PO}_4^{3-}$  loadings were influenced by discharge but to a lesser extent than was  $\text{NO}_2^-/\text{NO}_3^-$  loading.

## 2.6. Chlorophyll a Concentrations

As previously mentioned, chlorophyll *a* concentrations provide a useful analog to assess phytoplankton biomass levels and growth. During 1983-85, maximum chlorophyll *a* concentrations occurred exclusively from early summer to early fall when growth factors such as temperature,

photosynthetically-active radiation (PAR), nutrient concentrations, and hydraulic residence times were at optimum levels. Occasional increases in chlorophyll *a* concentrations above the typical 5  $\mu\text{g/L}$  concentrations common in other seasons, like the spring of 1985, may be attributed to rapid phytoplankton growth during brief periods of warm weather accompanied by little or no rainfall and reduced river flow. Maximum levels during optimum growth seasons were as high as 70  $\mu\text{g/L}$  in 1983. Maximum chlorophyll *a* concentrations alone, however, are not a reliable indicator of large-scale or long-term algal bloom events (Paerl, 1987). Peak concentrations in 1984 and 1985 are almost as high as those in 1983, and the maximum chlorophyll *a* concentration for the 1981-1986 sampling period occurred in 1982, a non-bloom year. A more accurate indicator of bloom events using chlorophyll *a* data may be the temporal extent of elevated concentrations.

The concentrations and loading rates of inorganic nutrients have been examined in relation to seasonal patterns of flow to determine the relationships between flow and nutrient supply and their effects upon algal growth and biomass accumulation. In a given year, a basic sequence of hydrologic and environmental events occurs that distributes available inorganic nutrients for algal uptake and growth: 1) high winter-spring loading of nitrogen and, to a lesser extent, phosphorus by runoff; 2) initial algal growth in late spring and early summer as temperatures rise, daylight increases, and rainfall decreases; 3) excess algal growth resulting in surface scums during extreme low-flow in late summer and early fall; and 4)

decrease in growth and dispersion of biomass in the fall by decreases in temperature and daylight and increases in rainfall.

### 3. MODELING APPROACH

Three assumptions underscore the reasoning behind the modeling approach used in this study. First, because the most extensive algal blooms in the Neuse River have occurred between Kinston and New Bern, it is unlikely that point and non-point sources at and below New Bern will have significant impact upon upstream algal growth. Thus, any measures taken to control eutrophication between Kinston and New Bern should be applied to sources above New Bern. Second, Falls Lake on the upper Neuse River may retain large amounts of nutrients from upstream sources, lessening the impact of these sources on downstream algal growth. These two assumptions bracket the application of control measures to nutrient sources below the reservoir and above New Bern. Third, most major point sources below Falls Lake are located at or above Kinston, the upstream boundary of the bloom-problem section. Non-point sources, of course, flank the entire middle section of the river (Falls Lake-New Bern). Unfortunately, available water-quality models are limited in their capacity to assess and simulate the impact of non-point sources on algal growth. Nonetheless, several models can assess the impact of point sources and can also be adapted to at least attempt evaluation of non-point source effects.

Because the majority of point sources in the Falls Lake-New Bern section are located above Kinston in the riverine portion of the river, the eutrophication control alternatives evaluated in this study were applied to

these sources. Excessive algal growth rarely occurs in this section because river velocities prevent the initiation of blooms. However, nutrients from point and nonpoint sources in this section are carried downstream to the lower river where excessive growth occurs. Calibration and verification of the Neuse River Model has shown that nutrient concentrations are not sufficiently attenuated between Raleigh and Kinston (Shipley, 1986). The Neuse River Model was chosen to simulate the fate and transport of nutrients from Falls Lake to Kinston whose sources were subjected to several hypothetical control alternatives. Nutrient concentrations at Kinston predicted by the NRM were then adapted for use as boundary conditions in the Neuse Estuary Eutrophication Model to determine the effectiveness of the alternatives in limiting algal growth in the Kinston-New Bern section of the river.

### **3.1. Conservation of Mass**

The underlying principle supporting the framework of both the Neuse River Model and the Neuse Estuary Eutrophication Model is the principle of conservation of mass. Conservation of mass accounts for all materials entering and/or leaving a body of water, the advection and/or dispersion of these materials by freshwater, brackish water, or estuarine water, and physical, chemical, and biological interactions between materials. A mathematical description of conservation of mass is presented in Appendix 1.

### 3.2. Neuse River Model

Shipley (1986) developed the Neuse River Model to examine relationships between upstream nutrient inputs and downstream nutrient concentrations in the upper Neuse River. The model simulates eight system or state variables under steady-state conditions: phytoplankton chlorophyll *a*, biochemical oxygen demand, dissolved oxygen, organic nitrogen, ammonium nitrogen, nitrate plus nitrite nitrogen, organic phosphorus, and orthophosphate.

Data collected in 1979 and 1985 by the North Carolina Division of Environmental Management were adapted for use in the NRM by Shipley and used in this study. Average datasets for the spring and summer of 1979 were calculated to compensate for inadequate longitudinal resolution of data in the study area. Resolution was adequate for a shorter length of river represented by the 1985 dataset. Shipley used both the spring and summer 1979 averaged datasets to calibrate the model, and the September, 1985 data was used to verify the model.

The model simulates nutrient transport and uptake by phytoplankton from just below the Falls Lake Reservoir to Streets Ferry, a total distance of 165 miles. The section was divided into 50 segments ranging in length from two miles in the upstream portion to six miles in the downstream portion (Figure 3-1). Segment depths range from five to fifteen feet and widths from 135 to 250 feet.

Two major transfer mechanisms are represented by kinetic interactions in the NRM: biochemical transformations of nitrogen and phosphorus, and the

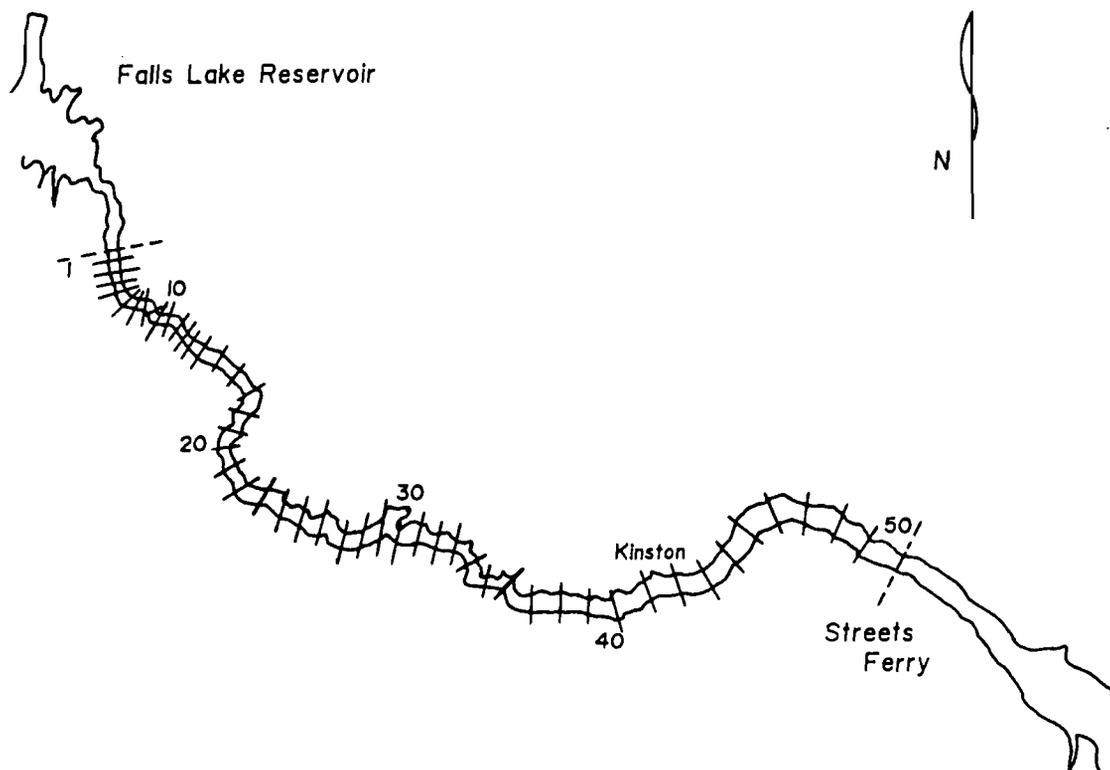


Figure 3-1: NRM segmentation.

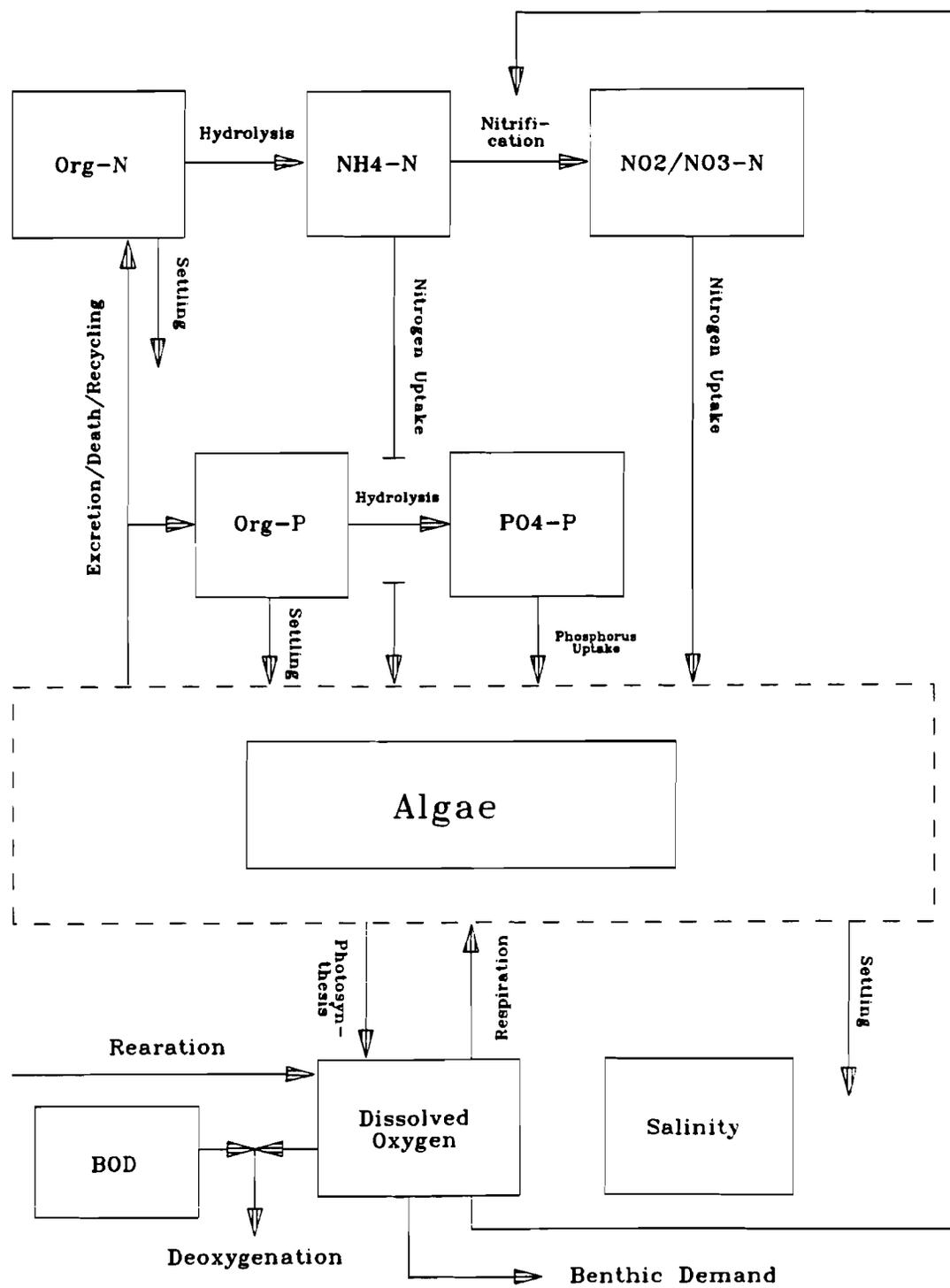


Figure 3-2: NRM kinetics.

growth and death of phytoplankton (Figure 3-2). These reactions are first-order in the model and have temperature-dependent rate coefficients. Temperature and light extinction and intensity are not modeled but are incorporated in the model to influence reaction rates. Model constants and kinetic coefficients used in this study are presented in Table 3-1.

### **3.3. Neuse Estuary Eutrophication Model**

In response to the need for a predictive tool to aid in water-quality management, Lung and Paerl (1988) developed the Neuse Estuary Eutrophication Model (NEEM) to predict and quantify algal growth in the lower Neuse River. The Water Quality Analysis and Simulation Program (WASP) (Di Toro et al., 1981) is used as a framework for NEEM. The two-dimensional model includes four phytoplankton groups: diatoms, green algae, non-nitrogen fixing blue-green algae, and nitrogen fixing blue-green algae. It simulates the following water-quality state variables: chlorophyll *a* levels for each phytoplankton group, organic nitrogen, ammonium nitrogen, nitrite and nitrate nitrogen, organic phosphorus, orthophosphate, dissolved oxygen, and salinity (Figure 3-3).

The model input requires boundary conditions, initial conditions, flow data, kinetic coefficients, exchange coefficients, segment volumes, time functions, and integration control data. Kinetic coefficients were derived from data provided by the UNCIMS. These coefficients and other constants are listed in Table 3-2. The model was calibrated with flow data (U. S. Geological Survey, at Kinston) and water-quality data (DEM) from 1983, 1984, and 1985.

<u>Parameter</u>	<u>Units</u>	<u>Value</u>
Saturated Light	langley/day	350
Available Light	langley/day	225
Light Extinction	/meter	2 (segments 1-50, 1979)
		2 (segments 1-12, 1985)
		3 (segments 13-50, 1985)
Daylight Hours	hours	13.25 (Spring 1979)
		14.25 (Summer, 1979)
		14.25 (September, 1985)
Optimum Growth Rate	/day @ 20°C	1.4
Endogenous Respiration Rate	/day @ 20°C	0.1
Death Rate	/day @ 20°C	0.1
Settling Velocity	ft/day	0.75 (Org-N)
		0.00 (NO <sub>3</sub> <sup>-</sup> -N)
		0.75 (Org-P)
		0.20 (PO <sub>4</sub> <sup>3-</sup> -P)
		0.75 (Chlorophyll <i>a</i> )
Half-saturation Constant (N)	mg/l	0.005
Half-saturation Constant (P)	mg/l	0.001
Carbon/Chlorophyll	mg/mg	50
Nitrogen/Chlorophyll	mg/mg	7
Phosphorus/Chlorophyll	mg/mg	1
Oxygen/Chlorophyll	mg/mg	2.67
Org-N Hydrolysis Rate	/day @ 20°C	0.05 (segments 1-50)

**Table 3-1:** NRM constants and kinetic coefficients.

<u>Parameter</u>	<u>Units</u>	<u>Value</u>
Org-P Conversion Rate	/day @ 20°C	0.05 (segments 1-50)
Nitrification Rate	/day @ 20°C	0.00 (segments 1-50, 1979) 0.20 (segments 13-20, 1985)
Oxygen Transfer	ft/day	3
Deoxygenation	/day	0.08
Benthic Demand	g/m <sup>2</sup> -day	0.0 (segments 1-12) 0.5 (segments 13-17) 0.0 (segments 18-50)
Temperature	°C	18 (Spring, 1979) 26 (Summer, 1979) 21 (September, 1985)
Temperature Coefficient		1.04

Table 3-1, continued.

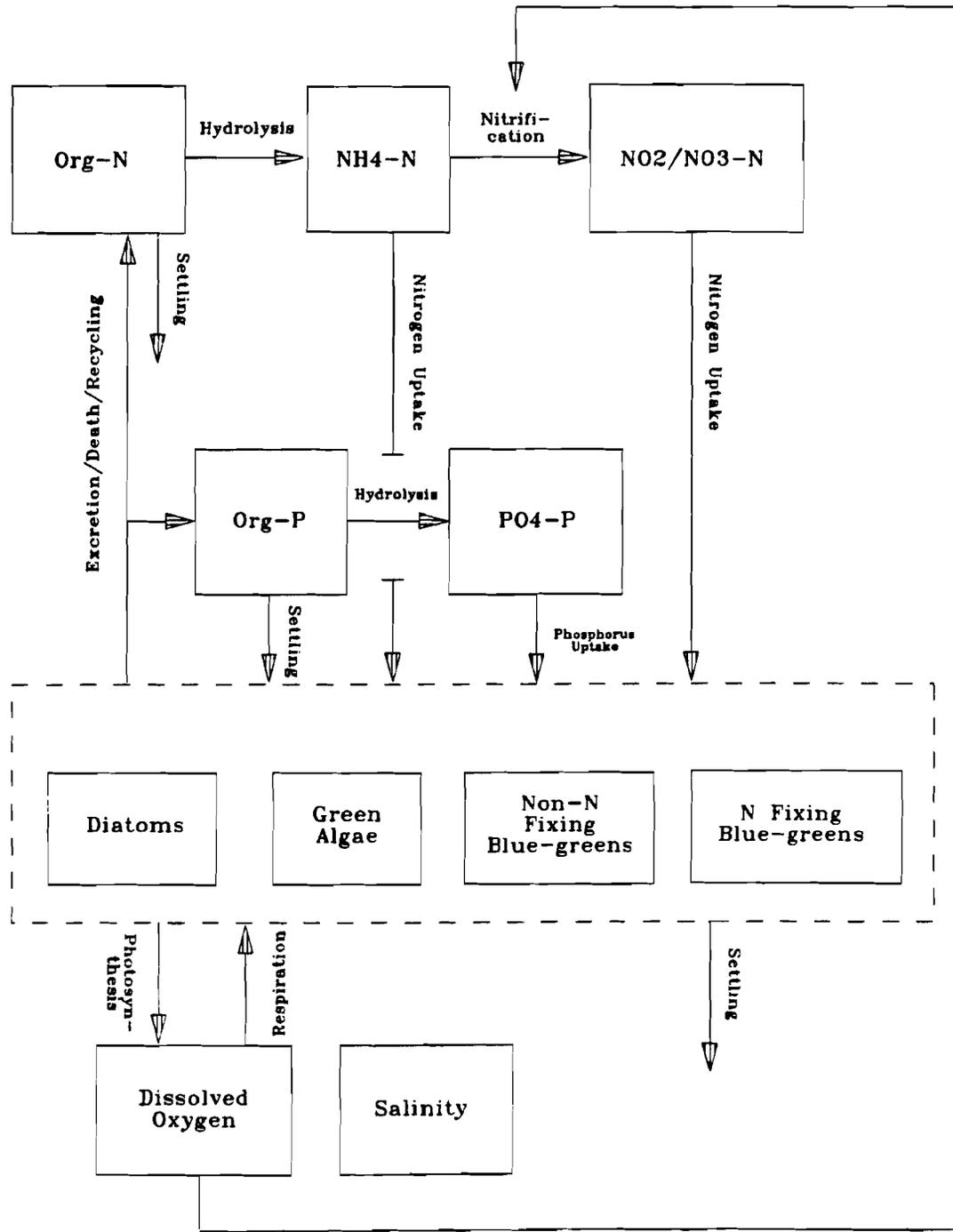


Figure 3-3: NEEM kinetics.

<u>Parameter</u>	<u>Units</u>	<u>Value</u>	
Optimum Light Intensity	langley/day	350	(diatoms, greens)
		250	(blue-greens)
Optimum Growth Rate	/day @ 20°C	2.0	(diatoms)
		1.8	(greens)
		1.3	(blue-greens)
Endogenous Respiration Rate	/day @ 20°C	0.05	
Death Rate	/day @ 20°C	0.05	
Settling Velocity	ft/day	1.50	(diatoms, greens)
		0.05	(non-N fixing blue-greens)
		0.19	(N fixing blue-greens)
Half-saturation Constant (N)	mg/l	0.025	(diatoms, greens)
		0.015	(non-N fixing blue-greens)
		0.000	(N fixing blue-greens)
Half-saturation Constant (P)	mg/l	0.005	
Carbon/Chlorophyll	mg/mg	50	
Nitrogen/Chlorophyll	mg/mg	7	
Phosphorus/Chlorophyll	mg/mg	1	
Oxygen/Chlorophyll	mg/mg	133.5	
Org-N Hydrolysis Rate	/day @ 20°C	0.1	
Org-P Conversion Rate	/day @ 20°C	0.1	
Nitrification Rate	/day @ 20°C	0.05	

**Table 3-2:** NEEM model constants and kinetic coefficients.

The portion of the lower Neuse River from Kinston to New Bern was divided into 18 completely-mixed segments (Figure 3-4). The first eight segments represent the riverine portion of the model, while segments 9-13 and 14-18 represent the surface layer and the bottom layer of the tidal portion of the river (beginning of the estuary), respectively. A two-layer mass transport pattern was used in the estuarine portion of the study area to allow simulation of blue-green algal growth near the surface and salinity intrusions in the bottom layer during summer low-flow. Intrusions occurred during the summers of 1983 and 1985, as represented by the upstream flows in the lower layer of the figure. Two-layer flow patterns were not used to model 1984 data because higher flows during that summer forced the salinity wedge downstream beyond the downstream boundary of the model at New Bern.

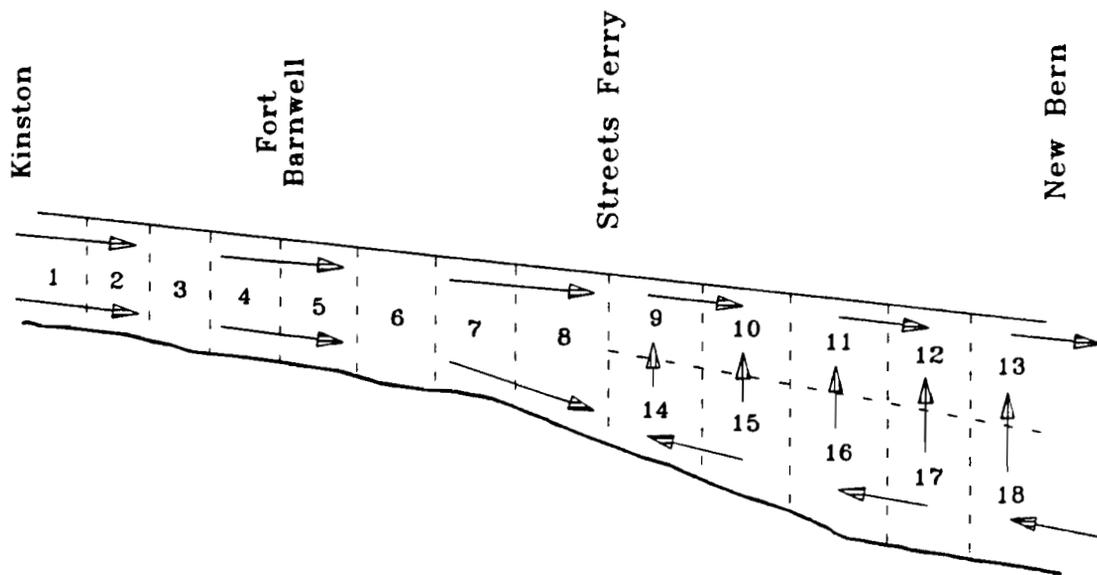


Figure 3-4: NEEM segmentation and mass transport

## 4. CONTROL ALTERNATIVES

### 4.1. Development

Development of the control alternatives evaluated in this study involved consideration of several hydrologic and environmental factors, including seasonal patterns of discharge and their effect upon available nutrient concentrations. The importance of identifying the nutrients that currently limit and those that may potentially limit phytoplankton growth in the lower Neuse River was briefly discussed in Chapter 2, as was the probable need for both nitrogen and phosphorus controls. Further support for dual nutrient control lies in examination of seasonal and spatial patterns of limiting nutrient status.

#### 4.1.1. Limiting Nutrient Status

A nutrient that is present in such low concentrations that phytoplankton depend on its availability for continued growth is a limiting nutrient, i.e., it limits phytoplankton growth. In general, phosphorus tends to limit primary productivity in freshwaters (Schelske and Stoermer, 1972; Schindler, 1981) while nitrogen is limiting in marine waters (Ryther and Dunstan, 1971). There are several indicators of nutrient limitation. Theoretical ratios of total nitrogen to total phosphorus (TN:TP) greater than 10:1 indicate a surplus of nitrogen and phosphorus limitation, while TN:TP less than 5:1 indicate possible nitrogen limitation and phosphorus surplus (Meyers and Iverson, 1981). However, because portions of organic nitrogen and

phosphorus are not readily available for uptake by phytoplankton, comparing TN to TP may not be very accurate. An option is comparing the sum of the concentrations of the inorganic components of nitrogen to inorganic phosphorus that are readily available for algal uptake.

Inorganic nitrogen to phosphorus (IN:IP) ratios are presented in Figure 4-1 for 1983-85 at three sites. IN is the sum of external (water column)  $\text{NO}_2^-/\text{NO}_3^-$  and  $\text{NH}_4^+$  concentrations, while IP is represented by external  $\text{PO}_4^{3-}$ . Salinity varies widely at these three sites: Kinston, exclusively freshwater; Streets Ferry, brackish water due to salinity intrusions; and New Bern, estuarine salinity levels under the full influence of coastal waters. Ratios at Kinston were calculated from NEEM boundary conditions (15-day linear interpolations of raw UNCIMS data) used in 1983, 1984, and 1985 model calibrations. Ratios at Streets Ferry and New Bern were calculated from UNCIMS raw data. A line at IN:IP of 10 is provided as a reference for determining limiting status. This ratio was used as a general threshold level because it matches salinity-level and nutrient-source criteria for the lower Neuse River. For example, for the freshwater region of the estuary (Kinston), non-point source dominated waters with IN:IP much greater than 10 are phosphorus-limited (Thomann and Mueller, 1987). Brackish, transition regions with ratios near 10 may be either nitrogen or phosphorus-limited, and saline regions with ratios much less than 10 are nitrogen limited. The ratio at Kinston appears to have followed the flow pattern for the three-year period. Waters were phosphorus-limited during high winter-spring flows due to excessive loading of  $\text{NO}_2^-/\text{NO}_3^-$  and dilution of available

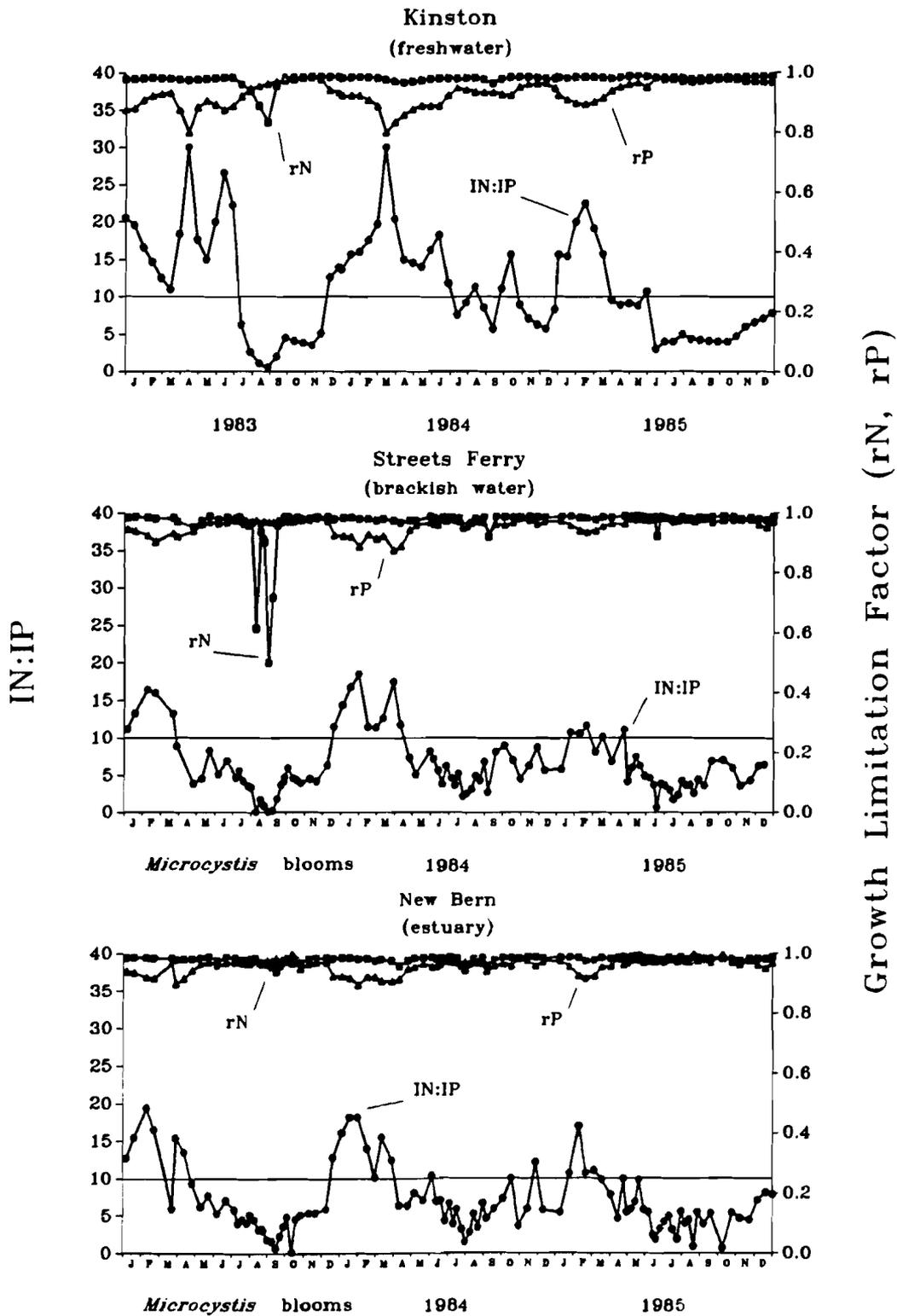


Figure 4-1: Temporal and spatial variation in limiting nutrient status, 1983-85.

$\text{PO}_4^{3-}$  in the water column. During summer-fall low-flows, IN:IP dropped below 5, indicating possible nitrogen limitation as  $\text{NO}_2^-/\text{NO}_3^-$  was depleted by standing stocks of algal biomass. Higher flows during the summer of 1984 ensured less depletion of  $\text{NO}_2^-/\text{NO}_3^-$  by flushing algae downstream: IN:IP was approximately 10, indicating either nitrogen or phosphorus limitation.

Ratios at Streets Ferry and New Bern indicate more periods of nitrogen limitation than at Kinston, possibly due to the intrusion of saline water. Waters were possibly phosphorus-limited during peak flow periods, demonstrating the strong influence of flow in controlling nutrient availability. However, as was mentioned in Chapter 2,  $\text{PO}_4^{3-}$  concentrations never approached limiting levels at Streets Ferry during 1981-86. Because the IN:IP threshold of 10 is only a general reference to indicate the potential of nitrogen or phosphorus limitation, ratios that are not significantly above or below this threshold may not indicate nutrient limitation. For example, none of the ratios that indicate phosphorus limitation at Streets Ferry and New Bern were above 20, while ratios at Kinston were as high as 30. Nitrogen limitation as indicated by ratios below 5 did occur at all three sites, particularly during peak *Microcystis* blooms of August and September, 1983. Another method to assess limiting nutrient status may be obtained through the use of Michaelis-Menten kinetics. Equation 1 quantifies algal growth under optimum light and temperature conditions for a single limiting nutrient (Bowie et al., 1985; Valiela, 1984) :

$$\mu = \mu_{max} \cdot \left( \frac{n}{K_n + n} \right) \quad (1)$$

where:

- $\mu$  = algal growth rate, 1/time;
- $\mu_{max}$  = maximum growth rate under excess nutrients and optimum temperature and light, 1/time;
- $n$  = concentration of the limiting nutrient in the water, mg/L;
- $K_n$  = half-saturation (Michaelis) constant for the limiting nutrient, mg/L.

The half-saturation constant is the concentration of the limiting nutrient at which the growth rate is one-half of its maximum. It is a function of the type of algae (total phytoplankton, diatom, green, blue-green, etc.) whose growth rate is evaluated by the equation. Values for the half-saturation constant usually range from 0.005 mg/L to 0.025 mg/L for nitrogen and from 0.001 mg/L to 0.005 mg/L for phosphorus (Lung and Paerl, 1988). This equation results in a hyperbolic growth curve where the growth rate increases almost linearly with low nutrient concentrations but eventually reaches a maximum (growth saturation) when the nutrient is no longer limiting (Figure 4-2). The quotient in Equation 1,  $\frac{n}{K_n + n}$ , is the growth limitation factor,  $r_n$ , of nutrient  $n$ . Growth limitation factors for the three year period were calculated for inorganic nitrogen and phosphorus at Kinston, Streets Ferry, and New Bern with the same data used for the IN:IP calculations. Half-saturation constants of 0.025 mg/L for nitrogen and 0.005 mg/L for phosphorus were used to represent nutrient limitation of total phytoplankton growth (Bowie et al., 1985). The results of these calculations are also shown in Figure 4-1, where  $r_N$  and  $r_P$  refer to growth limitation factors for inorganic nitrogen and phosphorus, respectively.

In general,  $r_N$  and  $r_P$  indicate limiting nutrient status in concert with

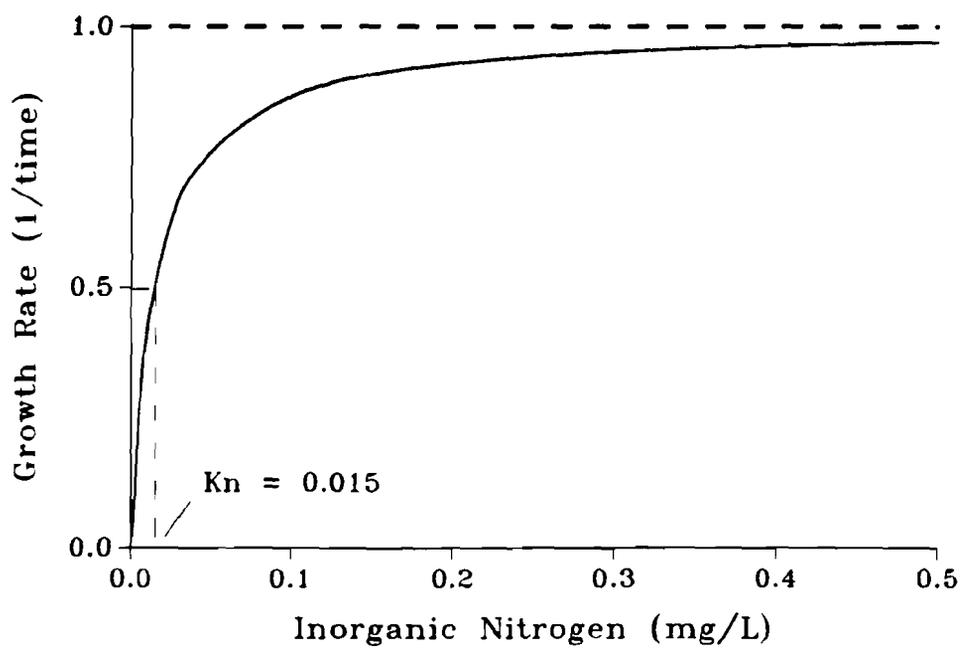


Figure 4-2: Algal growth rate dependency on inorganic nitrogen concentration.

IN:IP. During phosphorus limitation shown by peaks in the IN:IP curve,  $r_P$ , represented by triangles, decreases. Similarly,  $r_N$ , represented by squares, drops when IN:IP suggests nitrogen limitation. The growth limitation factor may provide a means to substantiate the use of IN:IP as an indication of limiting nutrient status. At Streets Ferry,  $r_N$  fell to 0.4-0.5 during the 1983 bloom event. These levels indicate inorganic nitrogen concentrations equal to or less than the half-saturation constant for nitrogen (0.025 mg/L). It is likely that nitrogen fell to limiting levels during August and September, 1983 only and that phosphorus never fell to limiting levels during 1983-85.

There is some difficulty in determining nutrient limitation by examining ratios of water column, or static, concentrations of nitrogen and phosphorus. Algae consume nutrients when they are available, storing them for future use. As the static nutrient concentration falls because of consumption by algal biomass, the static ratio may indicate limitation by the consumed nutrient when, in fact, algae actually have enough of the nutrient available for growth. However, static ratios can be examined along with growth response by phytoplankton that are enriched with a potentially-limiting nutrient to attempt to determine limiting status.

Enrichment bioassays performed by D'Elia et al. (1986) on phytoplankton from the Patuxent River estuary, which also experiences cultural eutrophication and algal blooms, suggest nitrogen limitation in phytoplankton during late summer. Phytoplankton cultures showed enhanced growth when enriched with  $\text{NO}_2^-/\text{NO}_3^-$  or  $\text{NH}_4^+$  during late-

summer low-flows, suggesting that the phytoplankton in the bioassay were nitrogen limited when removed from the river. IN:IP ratios by atoms are typically below 5:1 during this period. During the winter-spring high-runoff season when there is usually a surplus of nitrogen relative to phosphorus, phytoplankton responded to  $\text{PO}_4^{3-}$  enrichment, but the rate of growth was slow compared to growth in response to the late-summer nitrogen enrichment. The authors speculate that the phytoplankton were not phosphorus limited when removed from the river. Because of the similarities in nutrient supply, river flow, and phytoplankton behavior between the Patuxent and Neuse Rivers, these results may substantiate the conclusions that nitrogen limitation occurs periodically and phosphorus limitation seldom occurs in the lower Neuse River.

#### 4.1.2. Description

Lung (1986a, 1986b) has suggested several point source phosphorus control alternatives for the James River and Chesapeake Bay, both of which are subject to advanced eutrophication. For the James River, alternatives are a phosphate detergent ban in the basin and effluent phosphorus concentrations from municipal wastewater treatment plants of 2 mg/L, 1 mg/L, 0.5 mg/L, and 0.2 mg/L. Through analyses of these alternatives with the James River Ecosystem Model, it was shown that the removal of phosphorus at treatment plants would result in greater reductions in algal growth than would a phosphate detergent ban. In addition to point source phosphorus constraints, concurrent non-point source phosphorus as well as point and non-point source nitrogen constraints were recommended to effectively control algal growth.

Dual nutrient constraints are believed to be necessary because of the presence of both nitrogen-fixing and non-nitrogen fixing blue-green algae in the Neuse River. If nitrogen is depleted but other essential nutrients remain available, nitrogen-fixing genera (*Anabaena*, *Aphanizomenon*) begin to dominate, forming blooms and posing as great a threat to water quality as non-nitrogen fixing genera (Paerl, 1983). Simultaneous nitrogen and phosphorus controls may be necessary to prevent excess growth of nitrogen-fixing genera.

Based on these studies and data analyses, a list of possible nutrient control alternatives for the lower Neuse River was developed (Table 4-1). For point sources such as municipal wastewater treatment plants and industries, alternatives consist of restricting total phosphorus and nitrogen concentrations in effluents. This may be achieved by removing these nutrients at the plants or, in the case of phosphorus, through a basinwide phosphate detergent ban. For nonpoint sources, nitrogen and phosphorus loadings are reduced on a percentage basis.

Control alternatives 1-7 involve only municipal phosphorus control. Current effluent concentrations of total phosphorus and nitrogen from municipal sources in the Neuse River basin are 6 mg/L and 7 mg/L, respectively. These levels are well below typical total phosphorus and nitrogen concentrations for untreated domestic wastewater (8 mg/L and 40 mg/L, respectively) (Metcalf and Eddy, 1979). Alternative 2 consists of a basinwide phosphate detergent ban. This method places the burden of phosphorus removal on the consumer through the mandatory use of non-

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<u>Alternative</u>	<u>Municipal</u>		<u>Agricultural</u>		<u>Description</u>
	Effluent P (mg/L)	Effluent N (mg/L)	Reduction N (%)	Reduction P (%)	
1	6	7	0	0	Current controls
2	5	7	0	0	Basinwide phosphate detergent ban
3	3	7	0	0	Municipal P control
4	2	7	0	0	Municipal P control
5	1	7	0	0	Municipal P control
6	0.5	7	0	0	Municipal P control
7	0.2	7	0	0	Municipal P control
8	0.2	3	30	30	Stringent municipal P & N control, high agricultural control
9	0.2	7	30	30	Stringent municipal P control, high agricultural control
10	6	7	30	30	Municipal P control, high agricultural control

**Table 4-1:** Possible Neuse River control alternatives.

phosphate detergents, thereby reducing the amount of phosphorus in domestic wastewater before it reaches the treatment facility. A similar ban proposed for the James River was expected to reduce phosphorus levels at municipal wastewater treatment plants by 15% to 25% (Lung, 1986a). Effluent phosphorus levels are reduced gradually in the next five alternatives, culminating in stringent municipal phosphorus control in Alternative 7. Several levels of phosphorus control are implemented in this range of alternatives, from the upper limit of 2 mg/L of the National Pollutant Discharge Elimination System (NPDES) permit to a lowest technologically-feasible limit of 0.2 mg/L (Shiple, 1986). These seven alternatives are designed to determine the effectiveness of municipal phosphorus control in limiting algal growth in the lower Neuse River.

The remaining three control alternatives involve combinations of municipal and agricultural controls. Alternative 8, the most restrictive of the ten, calls for stringent municipal phosphorus and nitrogen control along with high agricultural control of both nutrients. All inputs except for municipal nitrogen are limited in Alternative 9. Alternative 10 involves high agricultural controls along with minor municipal phosphorus control. These three alternatives were developed to examine the most effective combination of point and non-point source control for limiting algal growth.

## 4.2. Evaluation

### 4.2.1. Upstream Boundary Conditions

Because the majority of point sources discharging wastes to the lower Neuse River are located above Kinston, control alternatives were applied to these sources and to non-point sources in the riverine portion of the river and evaluated with the Neuse River Model.

To reflect the influence of flow on nutrient distribution during a year with optimum flow conditions for excessive algal growth, a *hybrid* year of flow data was assembled. This year combines the high flows of the spring of 1983 with the extreme drought of the summer and fall of 1985 (Figure 4-3). Unlike the NEEM, a time-variable model that requires flow values at 15-day intervals for a one-year simulation, the NRM is a steady-state model that uses a single flow value at its upstream boundary (below Falls Lake). This flow value can be a seasonal average or a peak or low flow of a single day. The year was then divided into three seasons: spring, julian dates 0-165; summer, 180-255; and fall, 270-360. An average flow was calculated for each season (1072, 141, and 305 cfs, respectively) from the hybrid flow data. Using these three flows, the model was run with water-quality data from the spring and summer of 1979 and the fall of 1985.

The ten control alternatives listed in Table 4-1 feature a stepwise reduction of phosphorus and a single reduction of nitrogen at municipal and industrial point sources. The first alternative represents no reductions other than current municipal and industrial phosphorus control. Alternatives 2-9

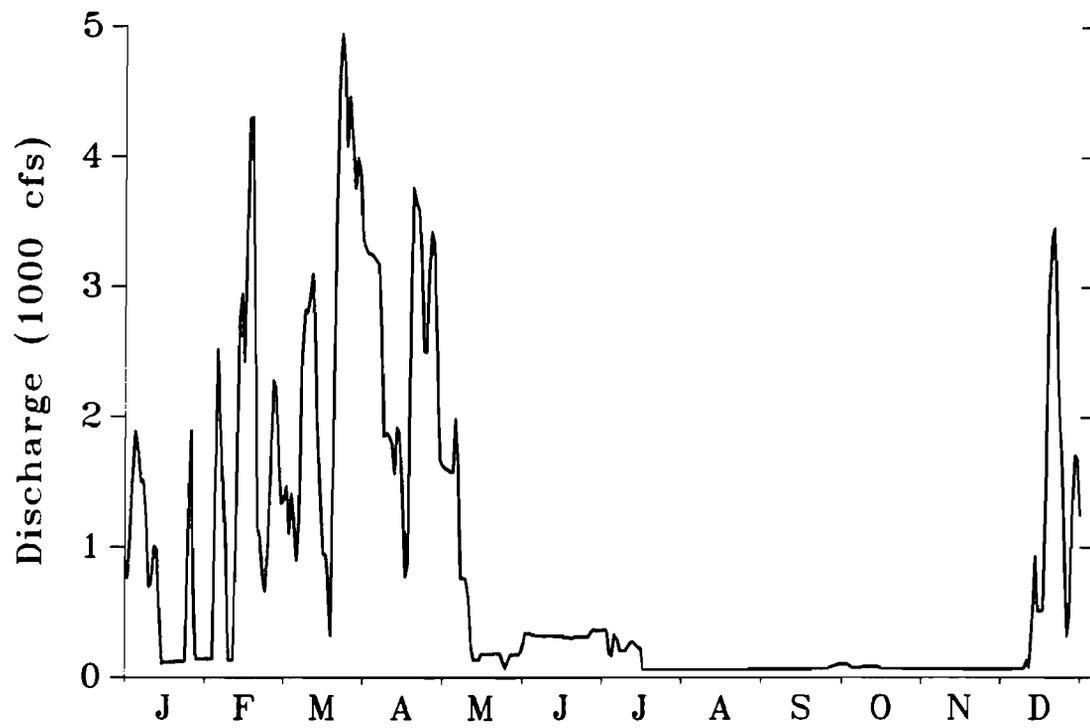


Figure 4-3: Hybrid (1983 and 1985) flow below Falls Lake.

reduce phosphorus by 17%, 50%, 67%, 83%, 92%, and 97%, respectively, while Alternative 8 reduces nitrogen by 57%. Average percentages of the effluent concentrations of the components of total nitrogen and total phosphorus from each point source were calculated for each season. For example, at the Raleigh wastewater treatment plant during spring, 1979, total nitrogen effluents consisted on average of 45% organic nitrogen (org-N), 5%  $\text{NH}_4^-$ , and 50%  $\text{NO}_2^-/\text{NO}_3^-$ . Total phosphorus effluents for the same period consisted of 75%  $\text{PO}_4^{3-}$  and 25% organic phosphorus (org-P). The current total phosphorus and total nitrogen effluent concentrations of 6 mg/L and 7 mg/L, respectively, of Alternative 1 were divided into these percentages and used to calculate loadings for each point source. These concentrations and loadings were then reduced to the levels represented by the percentages in each control alternative. The level of nutrient contribution of a point source to the river was not based on the concentration of its effluent but rather on the size of its effluent load that was calculated with effluent flow and concentration. Therefore, Raleigh's wastewater treatment plant contributed larger phosphorus and nitrogen loads to the river than the Smithfield plant. Reductions in non-point sources were implemented in the NRM by reducing upstream boundary conditions and lateral inflow concentrations for each nutrient to the levels suggested in Alternatives 8-10. An outline of the general procedure used in this study to evaluate the ten control alternatives is presented in Figure 4-4.

Thirty model runs were required to evaluate all of the control alternatives (three seasons for ten alternatives). Computations were initially carried out

Apply ten control alternatives  
to seasonal waste loads

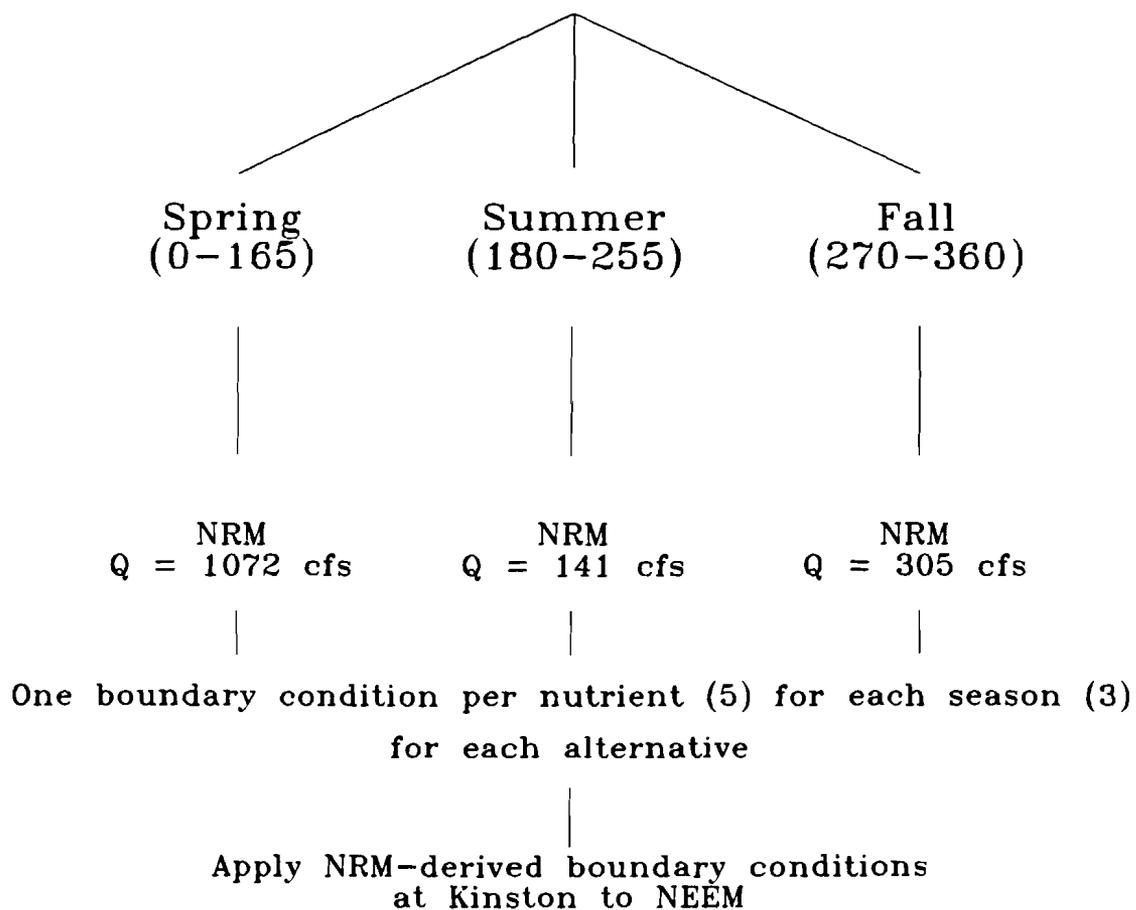


Figure 4-4: Modeling procedure.

on an IBM personal computer equipped with an 8087 math co-processor. Each steady-state simulation required 4-5 minutes of computer time. The NRM was later uploaded to a PRIME 750 minicomputer, which decreased computation times to less than ten seconds. Electronic spreadsheets were used to perform calculations on model input and output.

Model results at Kinston expressed as concentrations for the components of total nitrogen (org-N,  $\text{NH}_4^+$ , and  $\text{NO}_2^-/\text{NO}_3^-$ ) and total phosphorus (org-P and  $\text{PO}_4^{3-}$ ) were collected for use in the NEEM as upstream boundary conditions at Kinston.

#### 4.2.2. Application to Neuse Estuary Eutrophication

##### Model

Values for all individual nutrient components except  $\text{PO}_4^{3-}$  that were calculated by the NRM were used directly as upstream boundary (Kinston) conditions for the NEEM. The following simple equation (or model) was used to adjust NRM-derived  $\text{PO}_4^{3-}$  concentrations to reflect the effects of flow on  $\text{PO}_4^{3-}$  concentrations at Kinston:

$$BC_{\text{NEEM}} = BC_{\text{NRM}} \cdot \left(\frac{Q}{\bar{Q}}\right) \quad (2)$$

where:

$BC_{\text{NEEM}}$  =  $\text{PO}_4^{3-}$  boundary condition for NEEM;

$BC_{\text{NRM}}$  =  $\text{PO}_4^{3-}$  concentration at Kinston from NRM;

$Q$  = flow (cfs) for respective date;

$\bar{Q}$  = average flow (cfs) for respective season.

These upstream boundary conditions were used along with downstream and

tributary boundary conditions, initial conditions, and kinetics coefficients from the 1983 calibration data to evaluate the control alternatives. These data were used in the evaluations because excessive algal growth and blooms occurred during 1983, resulting in a worst-case algal growth scenario. A hybrid year of flow data, similar to that used in the NRM at Falls Lake, was developed for Kinston and used in the NEEM to evaluate the alternatives (Figure 4-5).

Ten model runs were required to evaluate the control alternatives. Computations were performed on a CDC Cyber 180/855 mainframe computer. A one-year simulation required approximately 20 minutes CPU time. Model results were downloaded and processed with electronic spreadsheets.

To examine how flow might be used to limit algal growth during summers when nutrients and environmental conditions (PAR, water temperature) are sufficient for the formation of algal blooms, a NEEM simulation of 1983 flow and nutrients conditions (both optimal for excessive growth) was compared to a simulation of flow conditions for 1984 (wet spring and summer) and 1983 nutrient conditions.

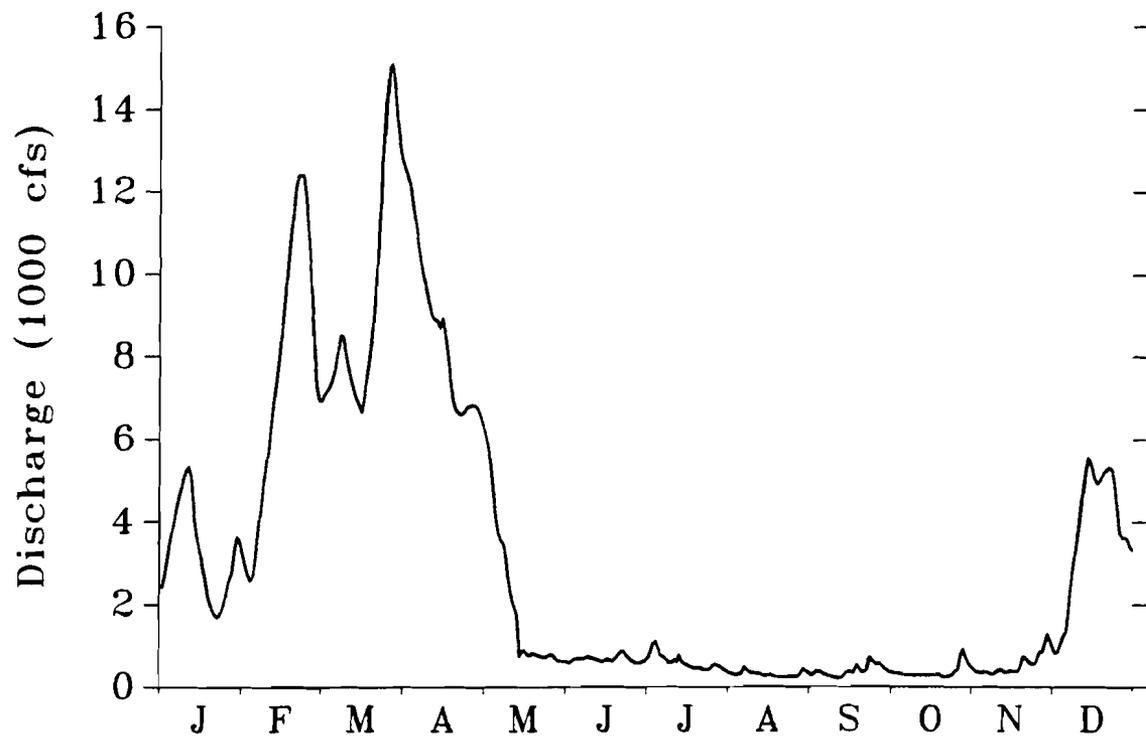


Figure 4-5: Hybrid (1983 and 1985) flow at Kinston.

## 5. RESULTS AND DISCUSSIONS

### 5.1. Nutrient Controls

To assess the effectiveness of the control alternatives in reducing algal biomass in the lower Neuse River, maximum phytoplankton chlorophyll *a* concentrations ( $\mu\text{g/L}$ ) for each one-year control alternative simulation are presented in Figure 5-1. Peak levels are shown for five sites along the river: Ft. Barnwell, School, Streets Ferry, Narrows, and below the mouth of Lower Swift Creek, to be referred to as Swift Creek (see Figure 1-1). Each site is representative of one of the three distinct flow patterns of the lower Neuse River described in Chapter 1. At Ft. Barnwell, there is no tidal influence (except during extreme summer low-flow), and the river is exclusively freshwater. At the School site, the river is tidal and freshwater. The river undergoes the transition from a tidal freshwater river to an estuary at Streets Ferry, and the water is brackish. Estuarine flow characteristics (variable salinity, tidally averaged two-layer flow) exist at Swift Creek and Narrows. Thus, the level of control that each alternative exerts on algal growth can be assessed at sites in the river with different hydrologic and salinity conditions.

Current average point-source effluent concentrations of inorganic phosphorus and nitrogen in the Neuse River basin are 6 mg/L and 7 mg/L, respectively, and there is no mandatory control of non-point source nitrogen and phosphorus loading. Under these conditions (Alternative 1), the NEEM

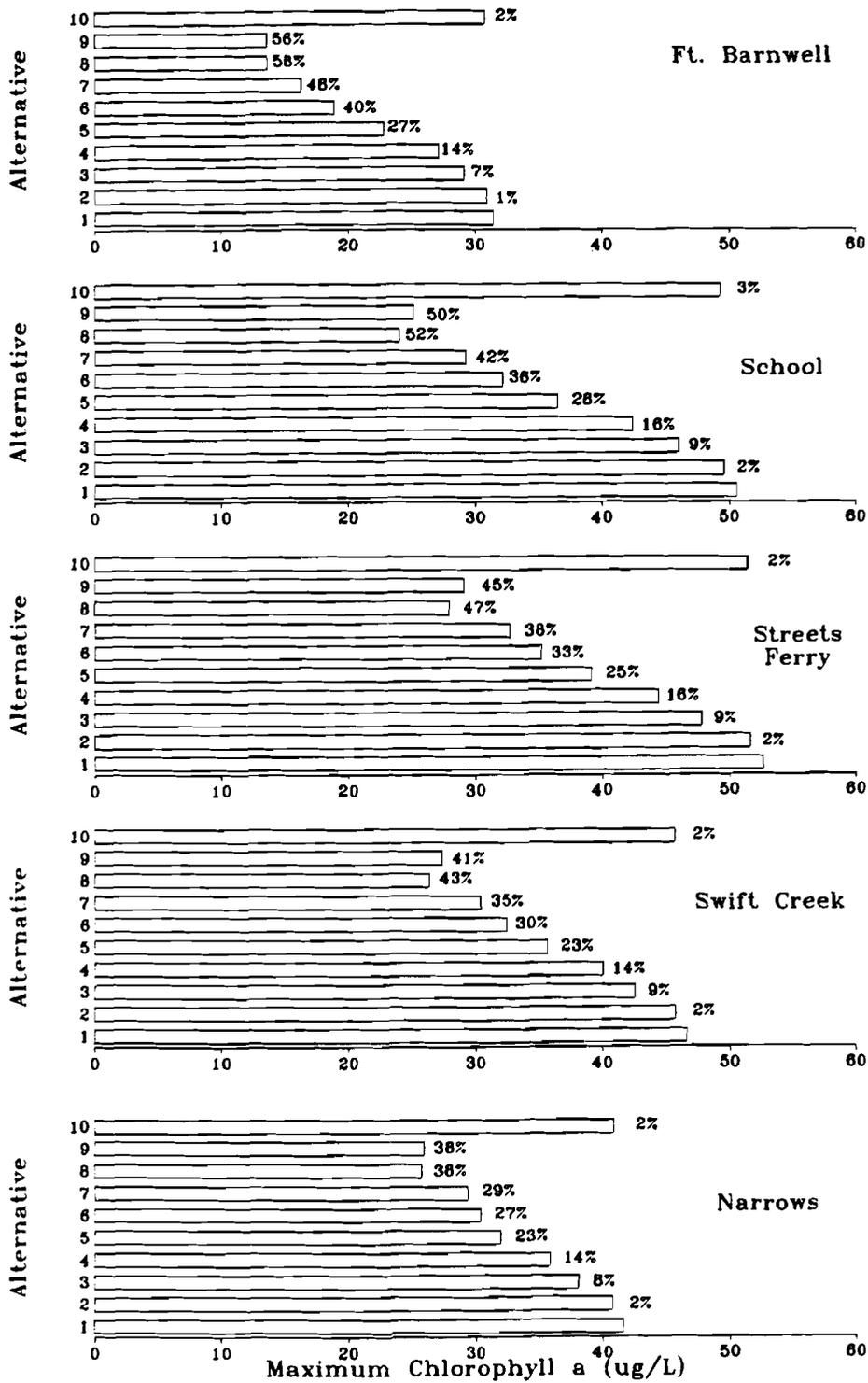


Figure 5-1: Maximum chlorophyll a under control alternatives. Percentages represent reduction from Alternative 1.

predicted peak total chlorophyll *a* levels of 31, 51, 53, 47, and 42  $\mu\text{g}/\text{L}$  at Ft. Barnwell, the School site, Streets Ferry, Swift Creek, and Narrows, respectively (Figure 5-1). Peak levels typically occurred during mid-August at all five sites. These levels are similar to observed field data and to levels generated by the NEEM simulation of water-quality and flow conditions for 1983 (Lung and Paerl, 1988), the year in which extensive *Microcystis aeruginosa* blooms occurred. For example, peak chlorophyll *a* concentrations at Streets Ferry as predicted by NEEM were about 50  $\mu\text{g}/\text{L}$  for 1983 and 53  $\mu\text{g}/\text{L}$  for Alternative 1 (Figure 5-2), while the actual peak chlorophyll *a* concentration was 68  $\mu\text{g}/\text{L}$ . The 1983 model simulation more closely fits the field data than does the simulation for Alternative 1. More importantly, significant algal growth as expressed by total chlorophyll *a* begins about six weeks earlier in the year (mid-May) under Alternative 1 than in the 1983 simulation (early July). In 1983, surface scums of *Microcystis aeruginosa* were observed as early as mid-July. At that time, chlorophyll *a* concentrations (for all phytoplankton) were approximately 20-30  $\mu\text{g}/\text{L}$ . Assuming that NEEM predicts a reasonable response by phytoplankton to nutrient levels under Alternative 1, a blue-green algal bloom might be expected to begin in mid-May to early June under Alternative 1 and the hybrid flow condition. Because algal growth and bloom formation would begin earlier in the year, the onset of bottom-water anoxia and the other harmful effects of blue-green algal blooms may also come sooner and last longer. Therefore, chlorophyll *a* levels projected under Alternative 1 represent a temporal pattern of algal growth that is potentially more detrimental to water quality than the pattern that occurred

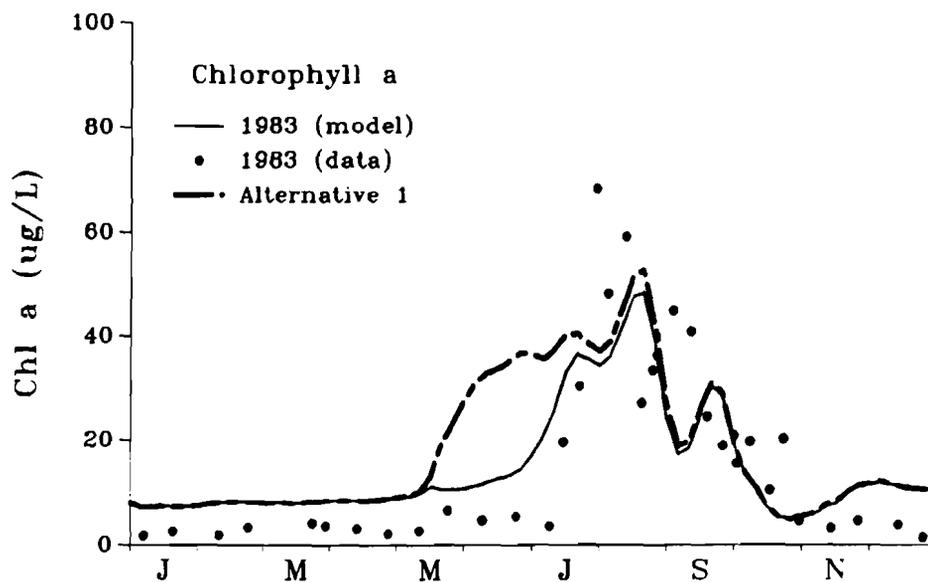


Figure 5-2: Comparison of NEEM simulations of chlorophyll *a* during 1983 and under Alternative 1 with field data at Streets Ferry.

during 1983. Accordingly, chlorophyll *a* concentrations under Alternative 1 can be considered a worst-case algal growth scenario for the lower Neuse River. Peak chlorophyll *a* levels under Alternatives 2-10 will be compared with peak levels under the worst-case scenario of Alternative 1 to assess their effectiveness in controlling algal growth.

Alternatives 2-7 focused solely on point-source phosphorus control. Based on peak chlorophyll *a* levels at all sites, phosphate detergent bans resulting in effluent phosphorus concentrations of 5 mg/L were not as effective as effluent phosphorus concentrations of 3 mg/L achieved through phosphorus removal at wastewater treatment plants. Alternative 7 provided the greatest reduction in chlorophyll *a* resulting from point source phosphorus control alone: A 97% reduction in effluent phosphorus (from 6 mg/L to 0.2 mg/L) reduced peak chlorophyll *a* levels at Streets Ferry by 38% (from 53  $\mu\text{g/L}$  to 33  $\mu\text{g/L}$ ). As expected, chlorophyll *a* levels were lowest at all sites under Alternative 8 because of stringent point source control of phosphorus and nitrogen (0.2 mg/L and 3 mg/L, respectively) and 30% reductions in non-point source nitrogen and phosphorus. For example, at Streets Ferry, where observed chlorophyll *a* levels were the highest in the model study area, the peak chlorophyll *a* concentration was reduced by 47% from 53  $\mu\text{g/L}$  to 28  $\mu\text{g/L}$ . However, point-source nitrogen control of nitrogen was apparently not very effective in reducing algal growth. At best, reduction of effluent nitrogen concentrations from 7 mg/L to 3 mg/L (Alternatives 9 and 8, respectively) provided only an additional 2% reduction in peak chlorophyll *a*. Non-point source nitrogen and phosphorus reductions of 30% were only

effective when used with point-source phosphorus control. Controlling only non-point source nitrogen and phosphorus (Alternative 10) reduced peak chlorophyll *a* levels by only 2-3%. But when non-point source controls were used in conjunction with point-source phosphorus removal (Alternative 9), peak chlorophyll *a* levels were reduced by 38-56%. Moreover, the addition of non-point source controls to stringent point-source phosphorus control (Alternative 9) reduced peak chlorophyll *a* levels by 6-8% more than stringent point-source phosphorus alone (Alternative 7). Clearly, point-source phosphorus control was much more effective than non-point source nitrogen and phosphorus control in reducing algal growth, but the combinations of point and non-point source nutrient controls (Alternatives 8 and 9) resulted in the greatest reduction of algal growth.

Among the less restrictive alternatives (2-5 and 10), there was very little or no difference between the percent reduction of peak chlorophyll *a* levels at each site for a single alternative. However, Alternatives 6-9 were generally more effective in reducing algal growth at sites in the riverine and tidal freshwater zones (Ft. Barnwell, School) than at sites in the brackish and estuarine zones (Streets Ferry, Swift Creek, and Narrows). For example, Alternatives 6-9 reduced peak chlorophyll *a* levels at Ft. Barnwell by 13-19% more than at Narrows.

During an optimal algal growth year (high winter-spring nutrient loading, low summer flows, and adequate PAR and water temperatures), non-nitrogen fixing blue-green algae possess the greatest bloom potential and, therefore, the greatest risk to water-quality. The degree to which the

control alternatives could reduce the growth of non-nitrogen fixing blue-greens as well as diatoms, green algae, and nitrogen fixing blue-green algae was evaluated. Model simulations of the growth of the four algal groups under Alternatives 1 and 8 are presented in Figures 5-3 and 5-4. Concentrations are expressed in  $\mu\text{g/L}$  chlorophyll *a* for the model year. As seen in the figures, non-nitrogen fixing blue-green algae are the dominant group of the four modeled. Peak chlorophyll *a* levels of non-nitrogen fixing blue-greens under Alternative 1 were similar to those during 1983, with significant growth commencing six weeks earlier than observed conditions (Figure 5-2). The NEEM predicted that the nutrient controls of Alternative 8 (0.2 mg/L and 3 mg/L effluent P and N, respectively, and 30% reductions in agricultural N and P loadings) could reduce the peak non-nitrogen fixing blue-green level at Streets Ferry from 25  $\mu\text{g/L}$  to 11  $\mu\text{g/L}$ , a reduction of 56%. A similar level of reduction of nitrogen-fixing blue-green algae would also be possible. Most importantly, the controls implemented under Alternative 8 could reduce overall blue-green algal biomass, thus limiting the potential for blooms. Significant growth still began in mid-May, but the concentrations did not rise to bloom-producing levels. In fact, the temporal pattern of algal growth under Alternative 8 was similar to simulated and actual patterns of growth in 1985 (Figure 5-5). During August, 1985 periodic storms flushed standing algal biomass downstream and prevented the initiation of blue-green algal blooms despite blue-green growth rates that exceeded those of 1983 (Lung and Paerl, 1988). The reduction of algal biomass under Alternative 8 to levels that are similar to those in 1985 indicate that the phosphorus and nitrogen controls of Alternative 8 may limit algal growth and prevent blooms.

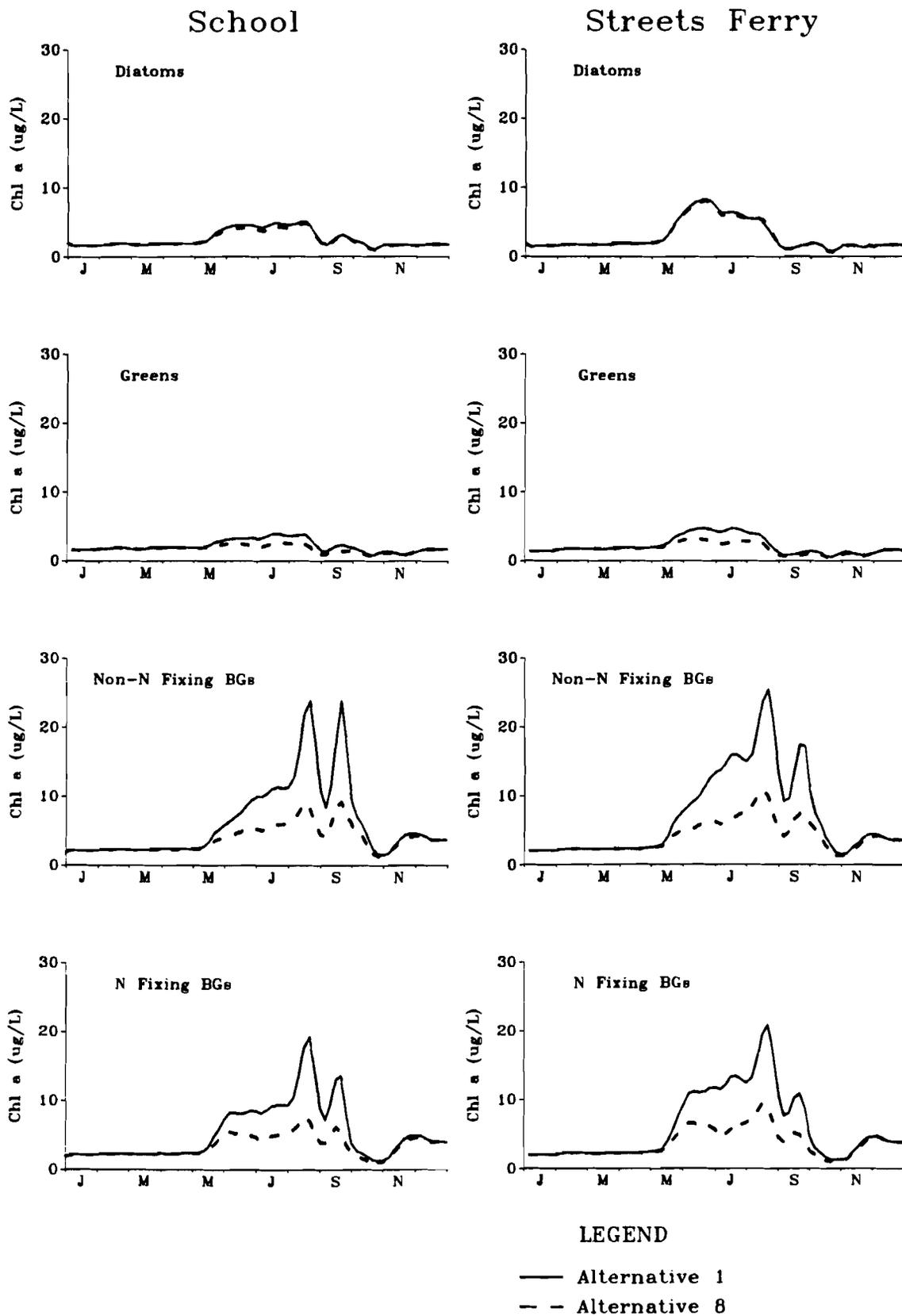


Figure 5-3: NEEM simulation of Alternatives 1 and 8 for each algal group (School and Streets Ferry).



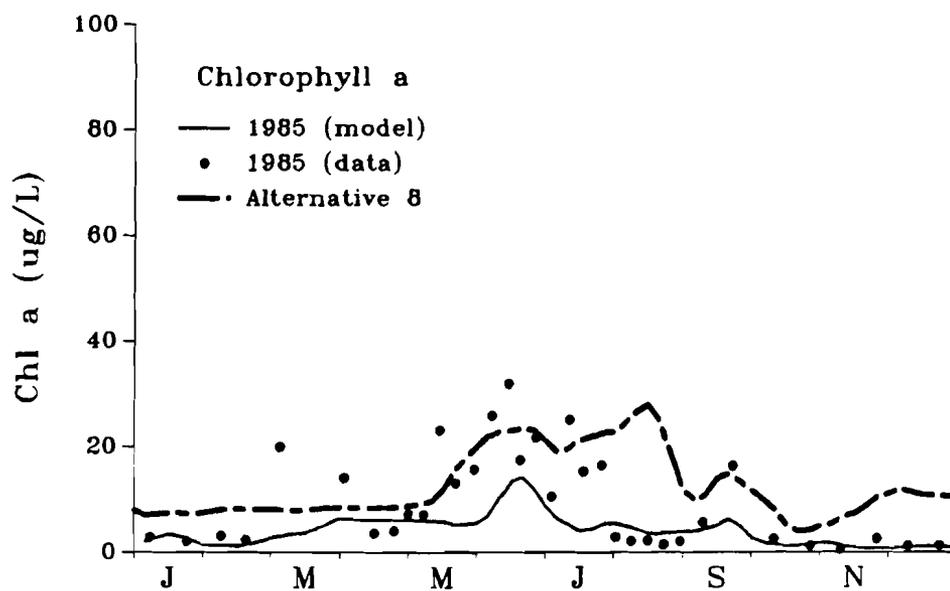


Figure 5-5: Comparison of NEEM simulations of chlorophyll *a* during 1985 and under Alternative 8 with field data at Streets Ferry.

Comparisons between Alternatives 7 and 9 (no non-point source control versus non-point source control) from model results of the four algal groups indicate little reduction in growth among any taxa when non-point source controls are implemented (Figures 5-6 and 5-7). In addition, peak chlorophyll *a* levels and growth patterns for both blue-green groups are very similar under Alternatives 7, 8 and 9 (Figures 5-3 and 5-6). For example, projected peak chlorophyll *a* concentrations for non-nitrogen fixing blue-greens at Streets Ferry are 13  $\mu\text{g/L}$ , 11  $\mu\text{g/L}$ , and 11  $\mu\text{g/L}$  under Alternatives 7, 8, and 9, respectively. These results suggest that the addition of point-source nitrogen control and non-point source nitrogen and phosphorus controls to stringent point-source phosphorus control may not achieve any further significant reductions in blue-green algal growth. Therefore, stringent point-source phosphorus control alone (Alternative 7) may be the most effective alternative evaluated to control algal growth.

The general absence of algal growth limitation by either nitrogen or phosphorus in the lower Neuse River was discussed in Chapter 4. Comparisons of the temporal variations of IN:IP with the growth limiting factors  $r_N$  and  $r_P$  for nitrogen and phosphorus revealed that algal growth was possibly N-limited only during the blooms of 1983 and never P-limited during 1983-85. Similar comparisons using model results for IN and IP for Alternatives 1, 7, 8, and 9 are presented in Figures 5-8 and 5-9.

Under current nutrient controls and the hybrid flow condition (Alternative 1), the IN:IP indicates possible phosphorus limitation (IN:IP  $\gg$  20) during April, coinciding with high spring runoff of nitrogen-rich waters.

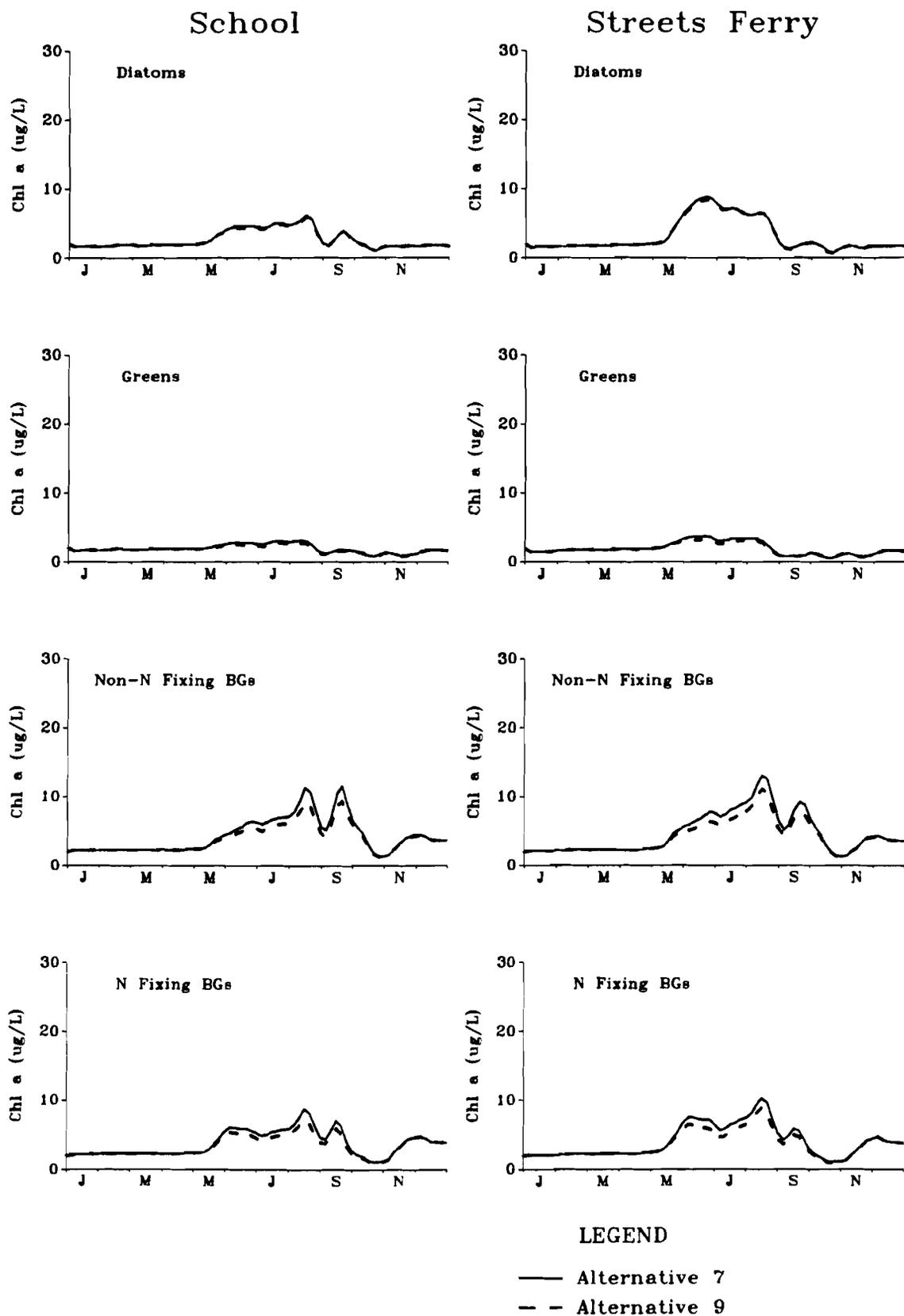


Figure 5-6: NEEM simulation of Alternatives 7 and 9 for each algal group (School and Streets Ferry).

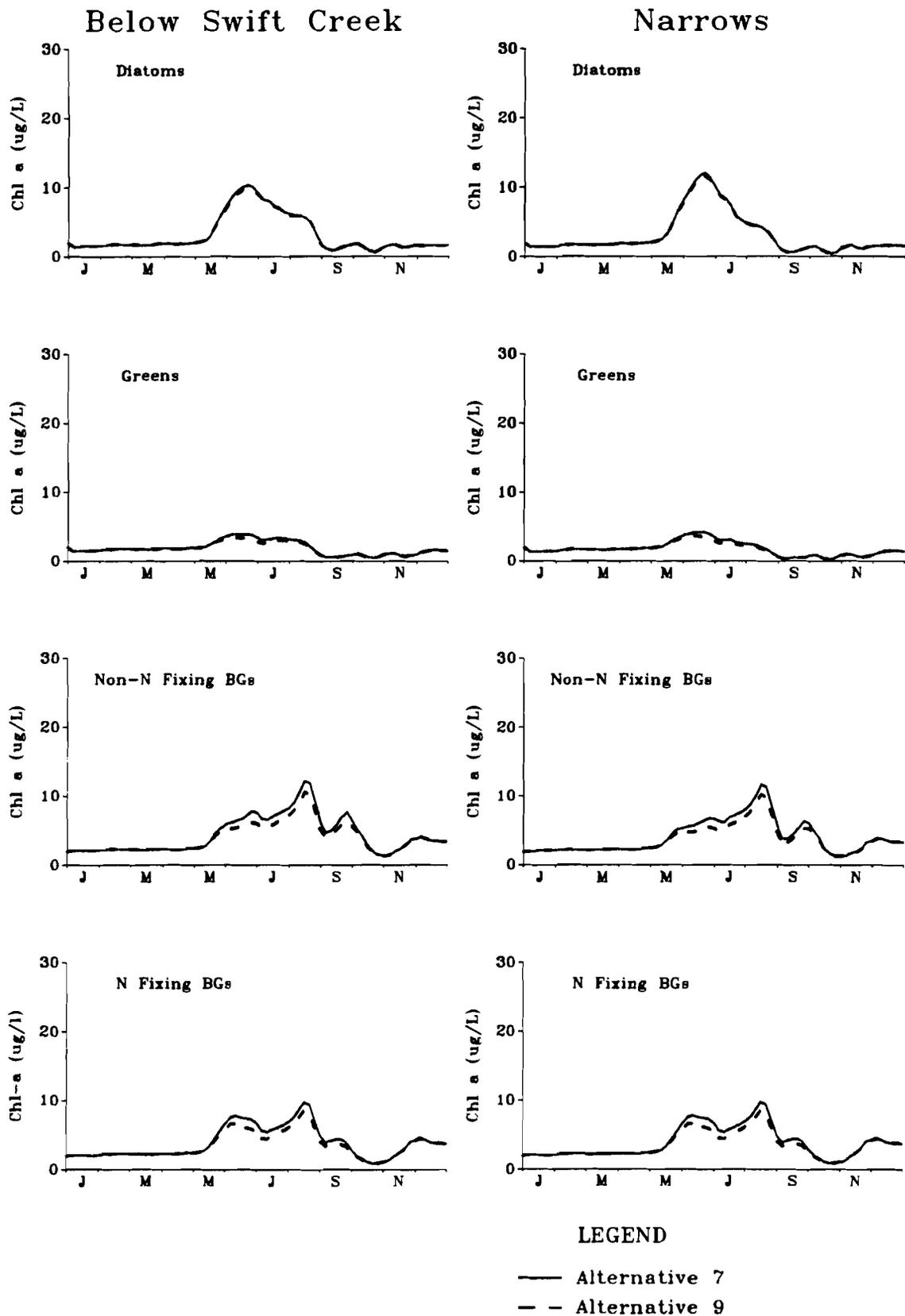


Figure 5-7: NEEM simulation of Alternatives 7 and 9 for each algal group (Swift Creek and Narrows).

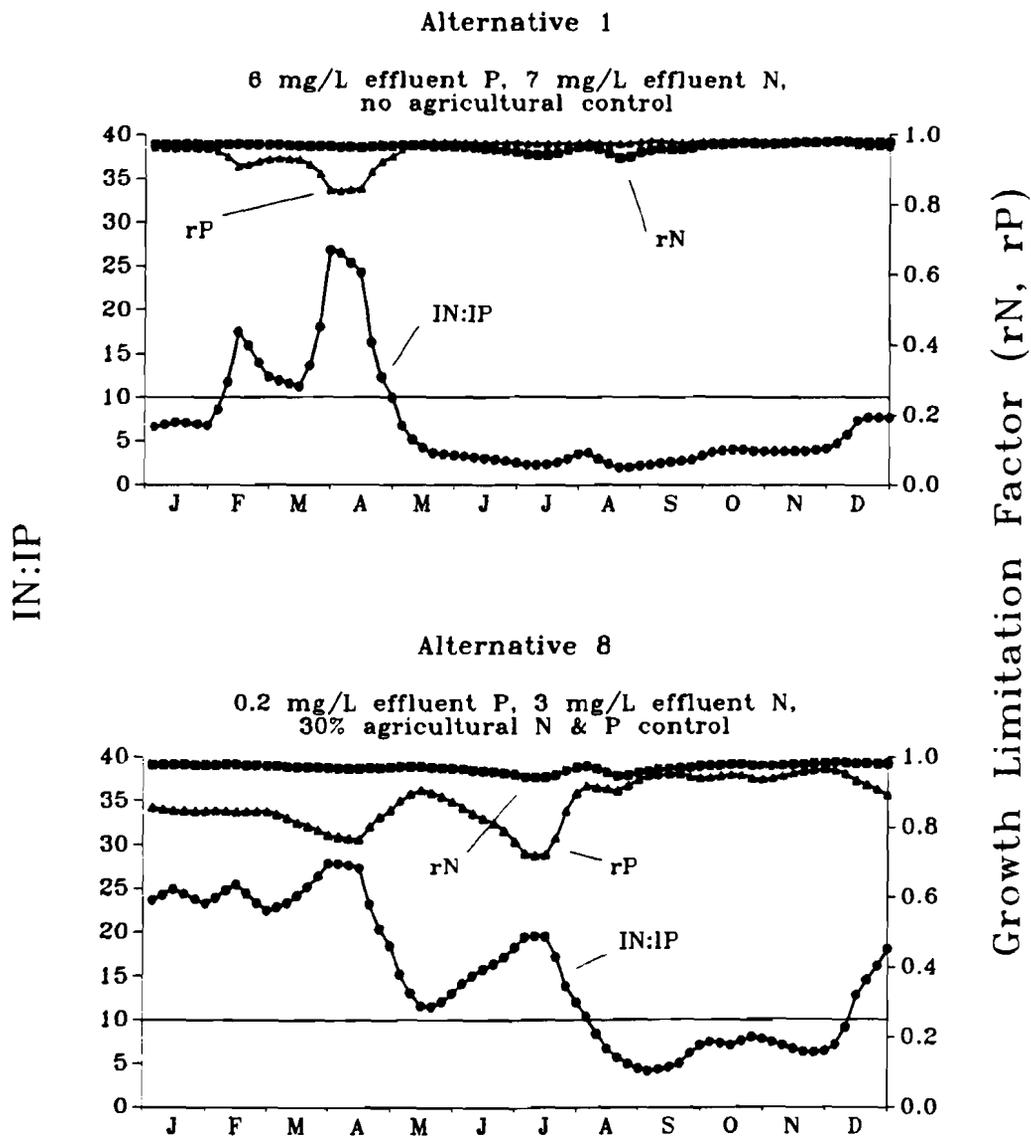
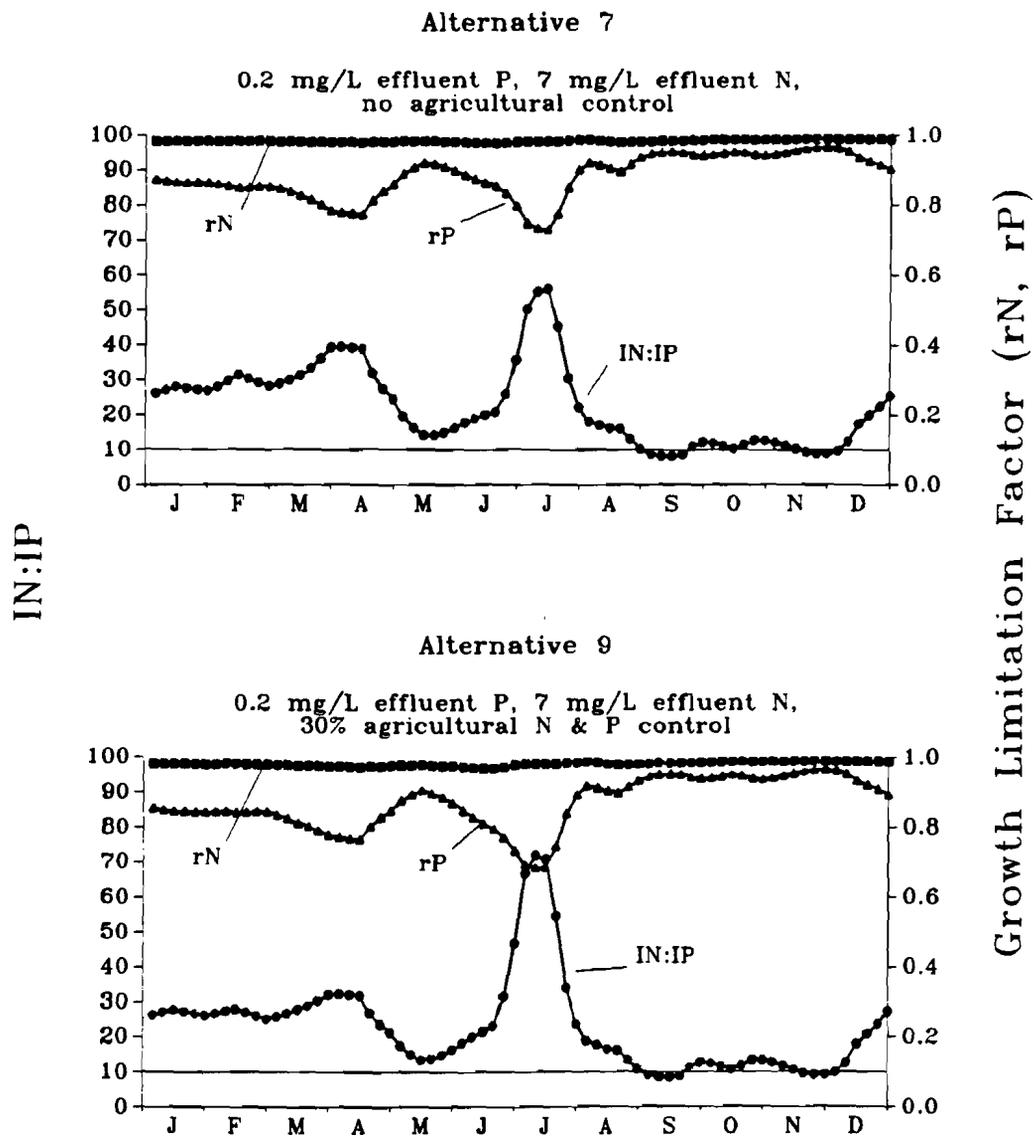


Figure 5-8: Temporal variation in limiting nutrient status for Alternatives 1 and 8 at Streets Ferry.



**Figure 5-9:** Temporal variation in limiting nutrient status for Alternatives 7 and 9 at Streets Ferry.

Conversely, the ratio is less than or equal to 5 during much of the summer and fall. However, neither  $r_N$  nor  $r_P$  fall to or below 0.5, the level at which the nutrient concentration is equal to the half-saturation constant  $K_n$ . The nutrient controls of Alternative 8 raise the IN:IP during the entire year, especially in the winter, early spring, and the early summer (less phosphorus from effluents). Nonetheless,  $r_P$  does not indicate P-limitation at any time. Strict point-source phosphorus control alone (Alternative 7, Figure 5-9) results in a high IN:IP during July. This ratio increases slightly when non-point source nitrogen and phosphorus controls are implemented, but  $r_P$  still does not indicate P-limitation.

## 5.2. Flow Controls

As discussed in Chapter 2, river flow often dominates algal growth. To assess the effectiveness of arresting bloom formation during summer low-flow by increasing river flow from reservoirs, a model simulation of 1983 flow and nutrients conditions was compared to a simulation of flow conditions for 1984 (wet spring and summer) and 1983 nutrient conditions. Model results for  $\text{NH}_4^+$ ,  $\text{NO}_2^-/\text{NO}_3^-$ ,  $\text{PO}_4^{3-}$ , and total chlorophyll *a* at Streets Ferry are presented in Figure 5-10. The model results indicate that under similar winter-spring nutrient loading conditions, significant, periodic pulses of flow during the summer may attenuate algal growth at times when blooms might normally form. During a dry summer, periodic releases from reservoirs in the Neuse River basin may prevent excess algal growth by flushing biomass downstream. Under 1983 flow and nutrient supply conditions, the NEEM predicted a peak chlorophyll *a* concentration of 48  $\mu\text{g}/\text{L}$ . The peak

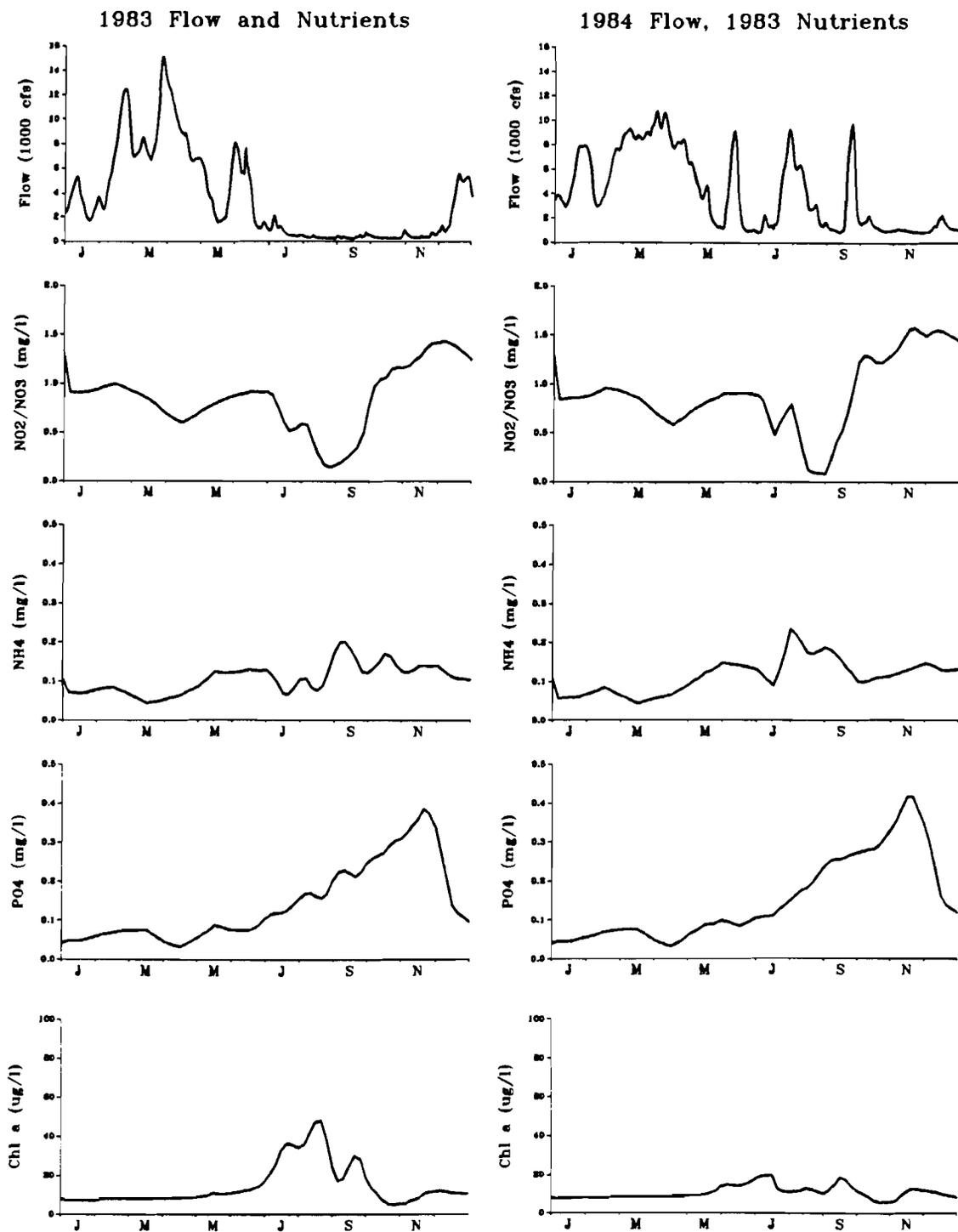


Figure 5-10: NEEM simulations of 1983 flow and nutrient data and 1984 flow with 1983 nutrient data at Streets Ferry.

boundary conditions for the Neuse Estuary Eutrophication Model. Simulations were performed under optimal annual flow conditions for excess algal growth: high winter-spring runoff and summer low-flows.

Model results indicate that significant reduction in maximum annual chlorophyll *a* concentrations may be expected when only point-source phosphorus controls are implemented. A reduction in total effluent phosphorus from 6 mg/L to 0.2 mg/L resulted in a 38% reduction in peak chlorophyll *a* levels. Further significant reduction in chlorophyll *a* concentrations were not achieved when point-source nitrogen and non-point source controls were added. Point-source nitrogen control alone was not effective. A 57% reduction in effluent nitrogen brought only a 2% reduction in maximum chlorophyll *a* levels. Non-point source control featuring a 30% reduction in both nitrogen and phosphorus was found to be effective only when used in conjunction with point-source phosphorus control. Most importantly, the combinations of point and non-point source nutrient controls were very effective in reducing maximum concentrations of both non-nitrogen and nitrogen fixing blue-green algae. Flow control simulations indicate that periodic pulses of flow during summer low-flow may attenuate algal growth when nutrient levels, water temperatures, and sunlight are at optimum growth levels. The maximum chlorophyll *a* concentration predicted under 1983 nutrient concentrations was reduced by 58% when flow data from the wet year of 1984 was introduced. Of the eutrophication control alternatives evaluated in this study, low-flow augmentation was found to be the most effective means of reducing peak chlorophyll *a* levels during an otherwise optimum year for bloom development.

## Appendix I

### CONSERVATION OF MASS

The underlying principle supporting the frameworks of both the Neuse River Model and the Neuse Estuary Eutrophication Model is the principle of conservation of mass. Conservation of mass accounts for all materials entering and/or leaving a body of water, the advection and/or dispersion of these materials by freshwater, brackish water, or estuarine water, and physical, chemical, and biological interactions between materials. If an infinitesimal volume of water is oriented along the longitudinal axis of a three-dimensional coordinate system, the conservation of mass can be expressed mathematically as

$$\frac{\partial c}{\partial t} = \underbrace{\frac{\partial}{\partial x}(E_x \frac{\partial c}{\partial x}) + \frac{\partial}{\partial y}(E_y \frac{\partial c}{\partial y}) + \frac{\partial}{\partial z}(E_z \frac{\partial c}{\partial z})}_{\text{dispersive transport}} - \underbrace{\frac{\partial}{\partial x}U_x c - \frac{\partial}{\partial y}U_y c - \frac{\partial}{\partial z}U_z c}_{\text{advective transport}} \pm \underbrace{S(s,y,z,t)}_{\text{sources or sinks}} + \underbrace{W(x,y,z,t)}_{\text{external inputs}}$$

where:

$c$	= concentration of the water-quality variable, $[\text{ML}^{-3}]$ ;
$t$	= time, $[\text{T}]$ ;
$E$	= dispersion (mixing) coefficient due to tides and density and velocity gradients (or diffusion coefficient in the sediment interstitial waters), $[\text{L}^2\text{T}^{-1}]$ ;
$U$	= net advective velocity, $[\text{LT}^{-1}]$ ;
$S$	= sources and sinks of the water-quality variable, representing kinetic interactions, $[\text{ML}^{-3}\text{T}^{-1}]$ ;
$W$	= external inputs of the variable $c$ , $[\text{MT}^{-1}]$ ;
$x,y,z$	= longitudinal, lateral, and vertical coordinates, respectively, $[\text{L}]$ .



## Appendix II

### MODEL RESULTS

On the following pages, results for each NEEM simulation of the ten control alternatives are presented for the Ft. Barnwell, Streets Ferry, and Narrows sites on the lower Neuse River. The following water-quality constituents are presented:  $\text{NO}_2^-/\text{NO}_3^-$ -N,  $\text{NH}_4^+$ -N,  $\text{PO}_4^{3-}$ -P, salinity, chlorophyll *a*, and dissolved oxygen.

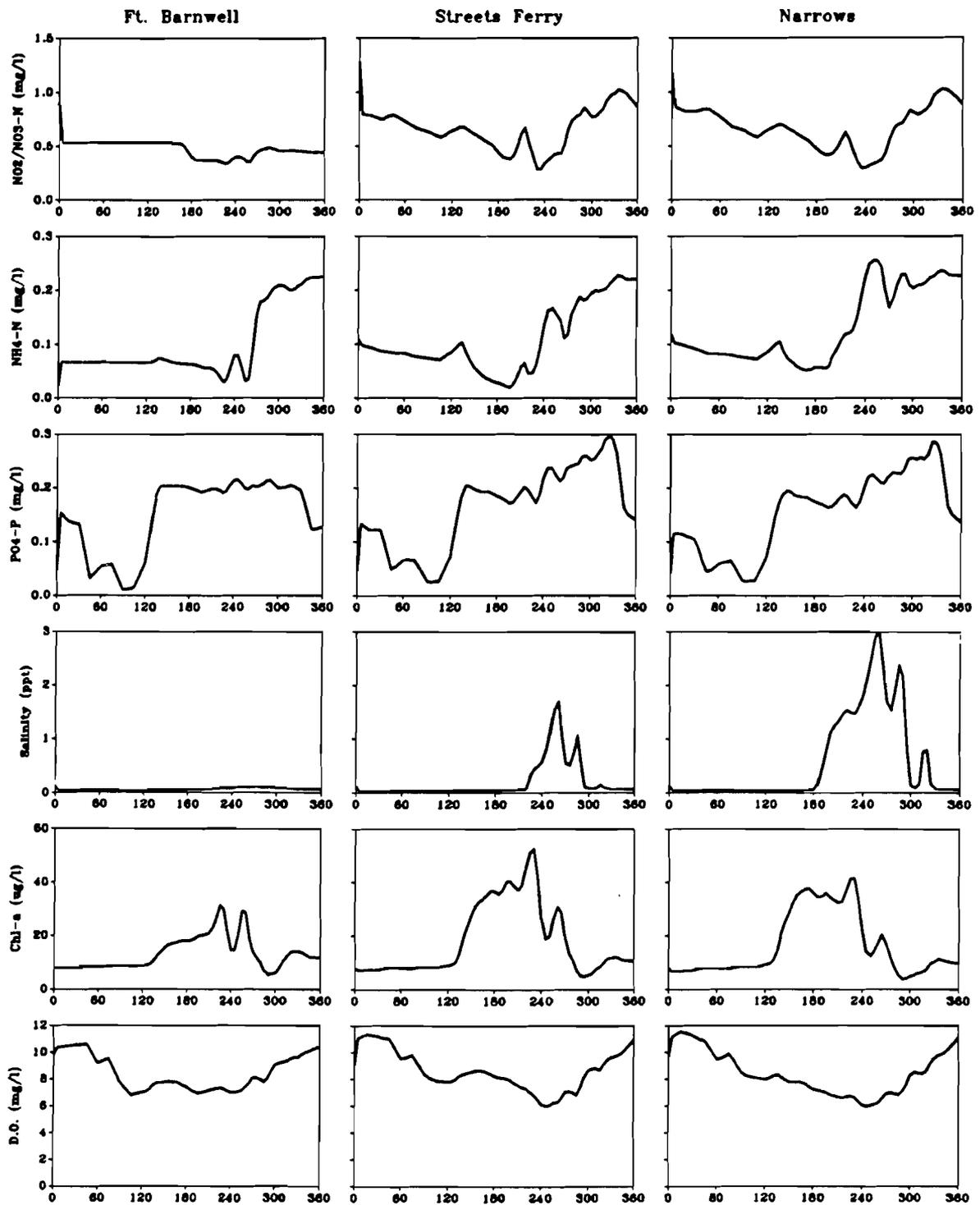


Figure II-1: Alternative 1 (6 mg/l P, 7 mg/l N).

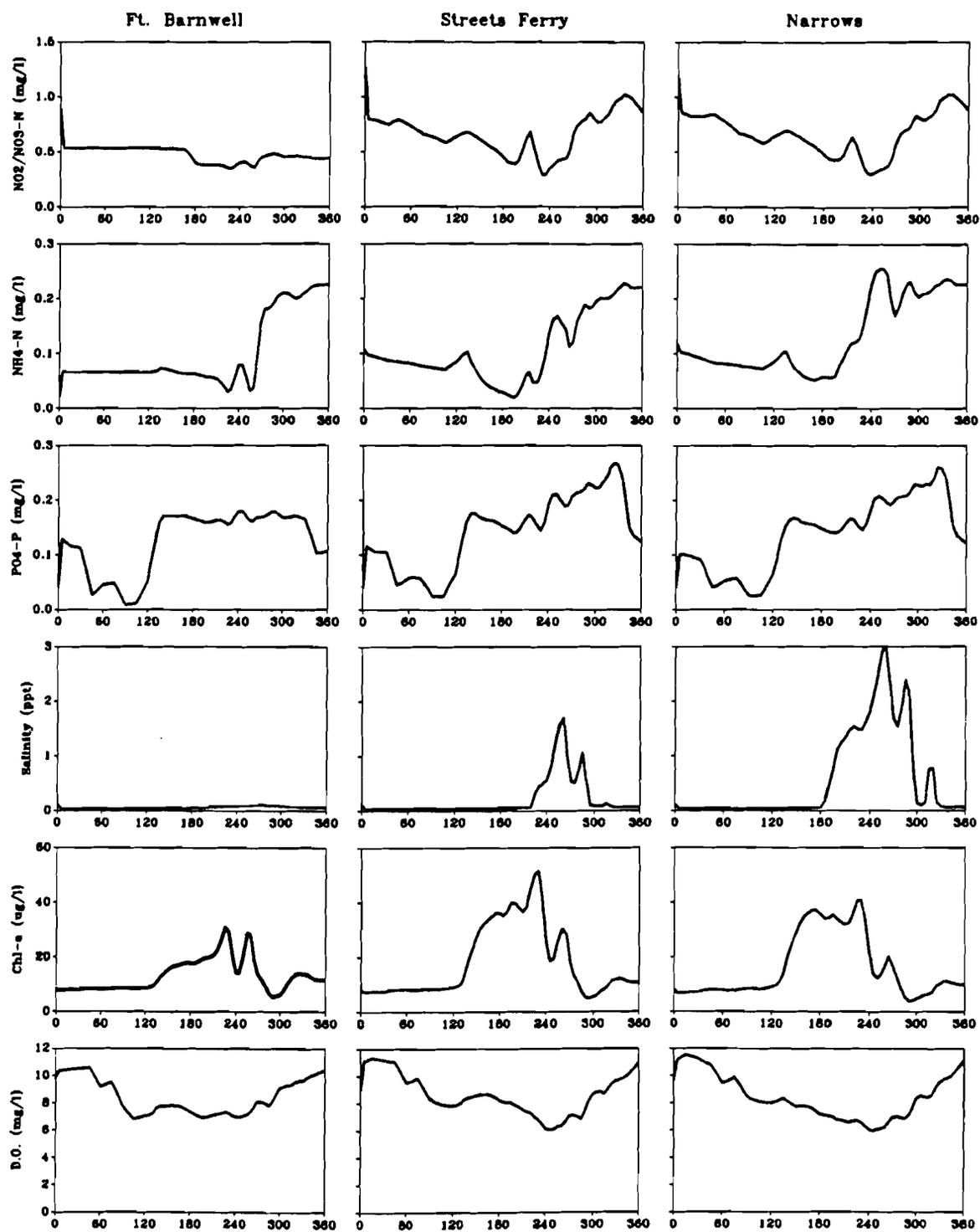


Figure II-2: Alternative 2 (5 mg/l P, 7 mg/l N).

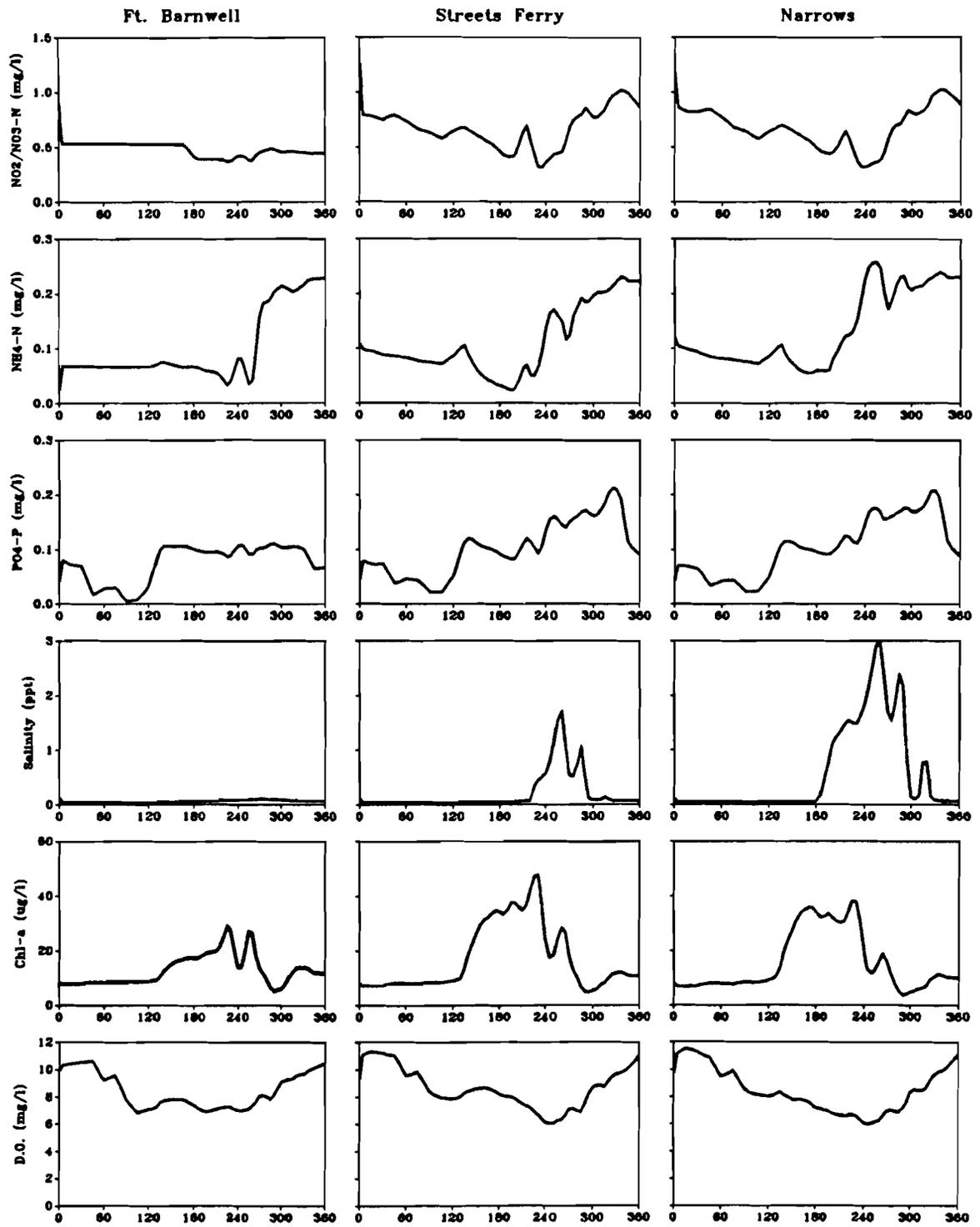


Figure II-3: Alternative 3 (3 mg/l P, 7 mg/l N).

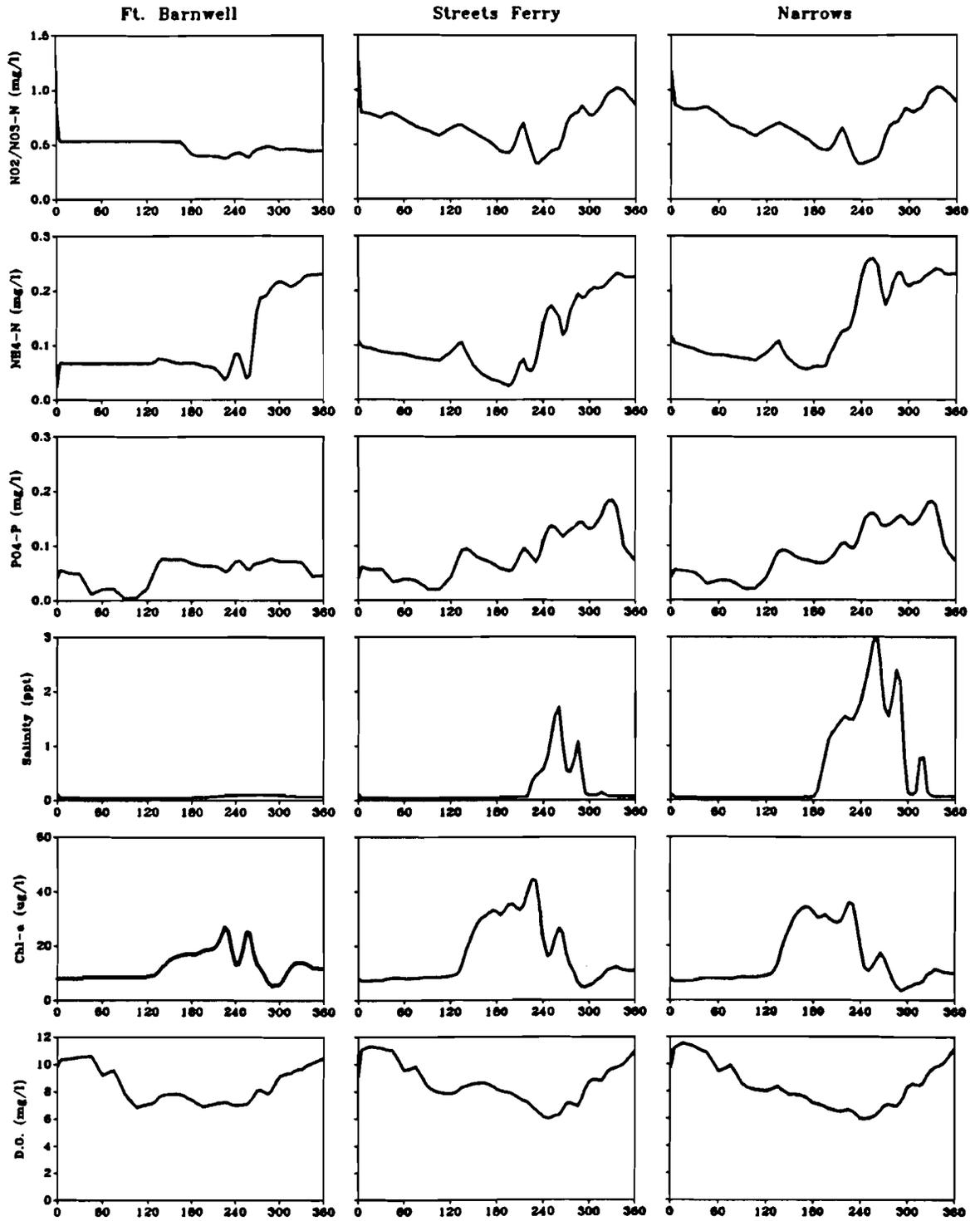


Figure II-4: Alternative 4 (2 mg/l P, 7 mg/l N).

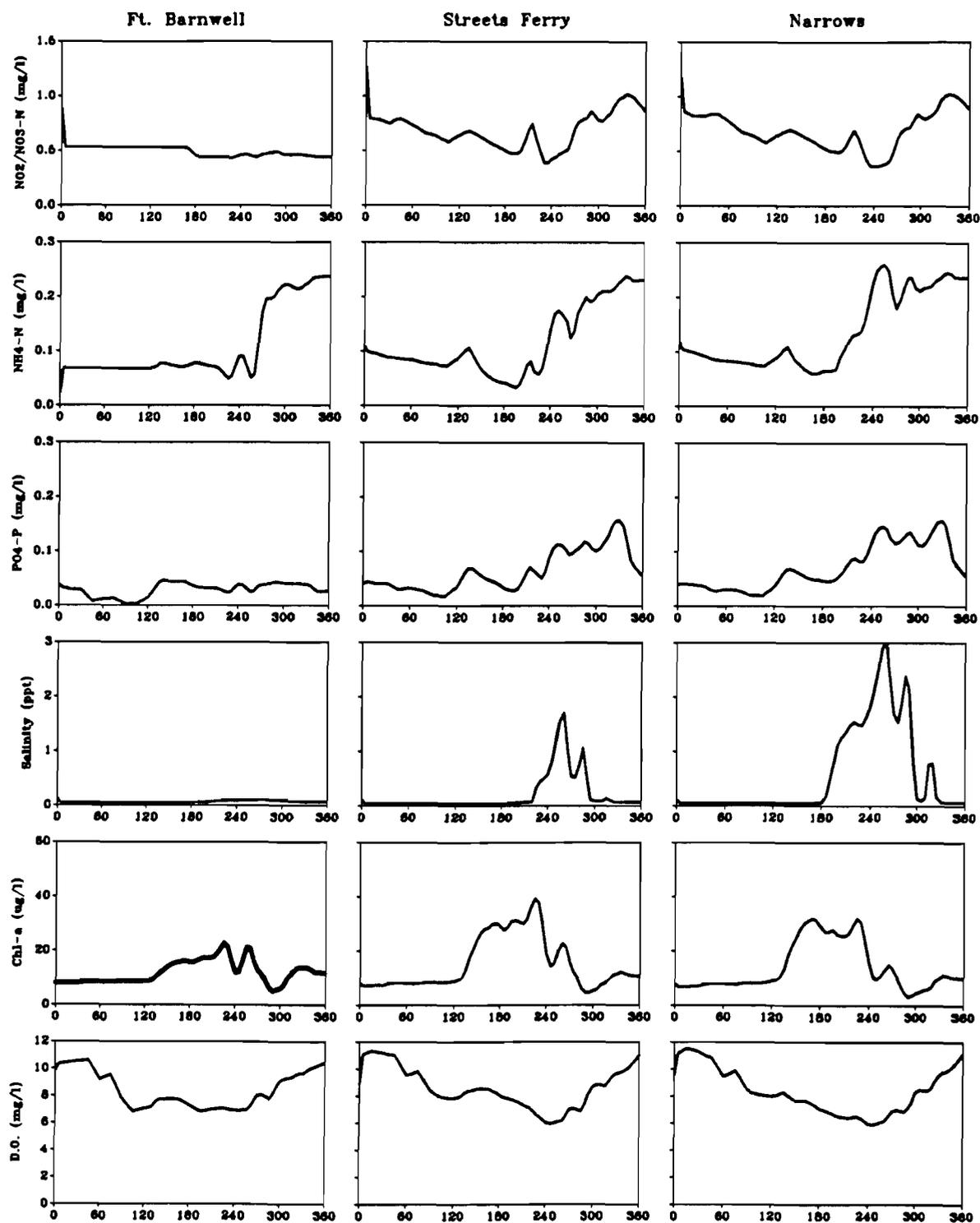


Figure II-5: Alternative 5 (1 mg/l P, 7 mg/l N).

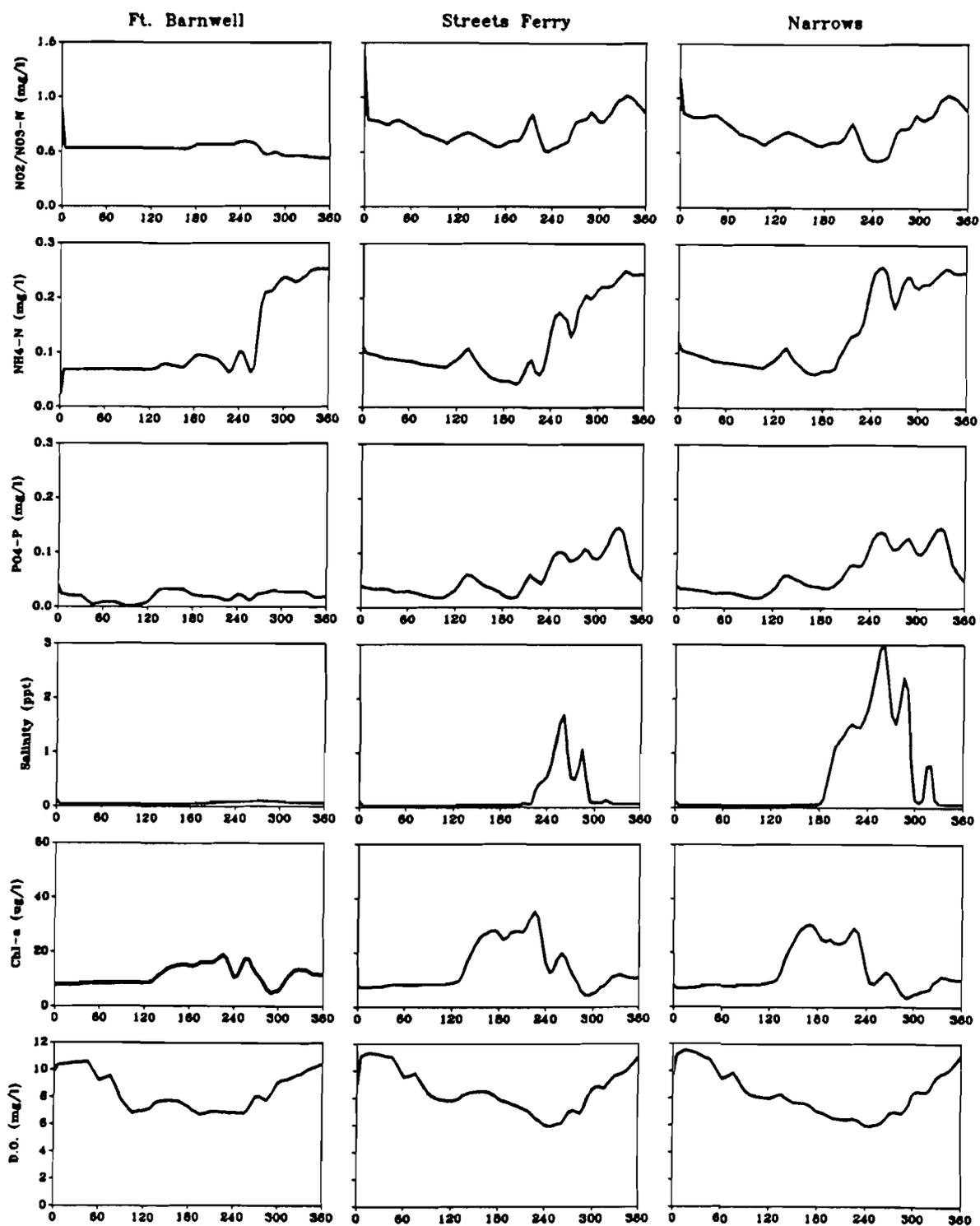


Figure II-6: Alternative 6 (0.5 mg/l P, 7 mg/l N).

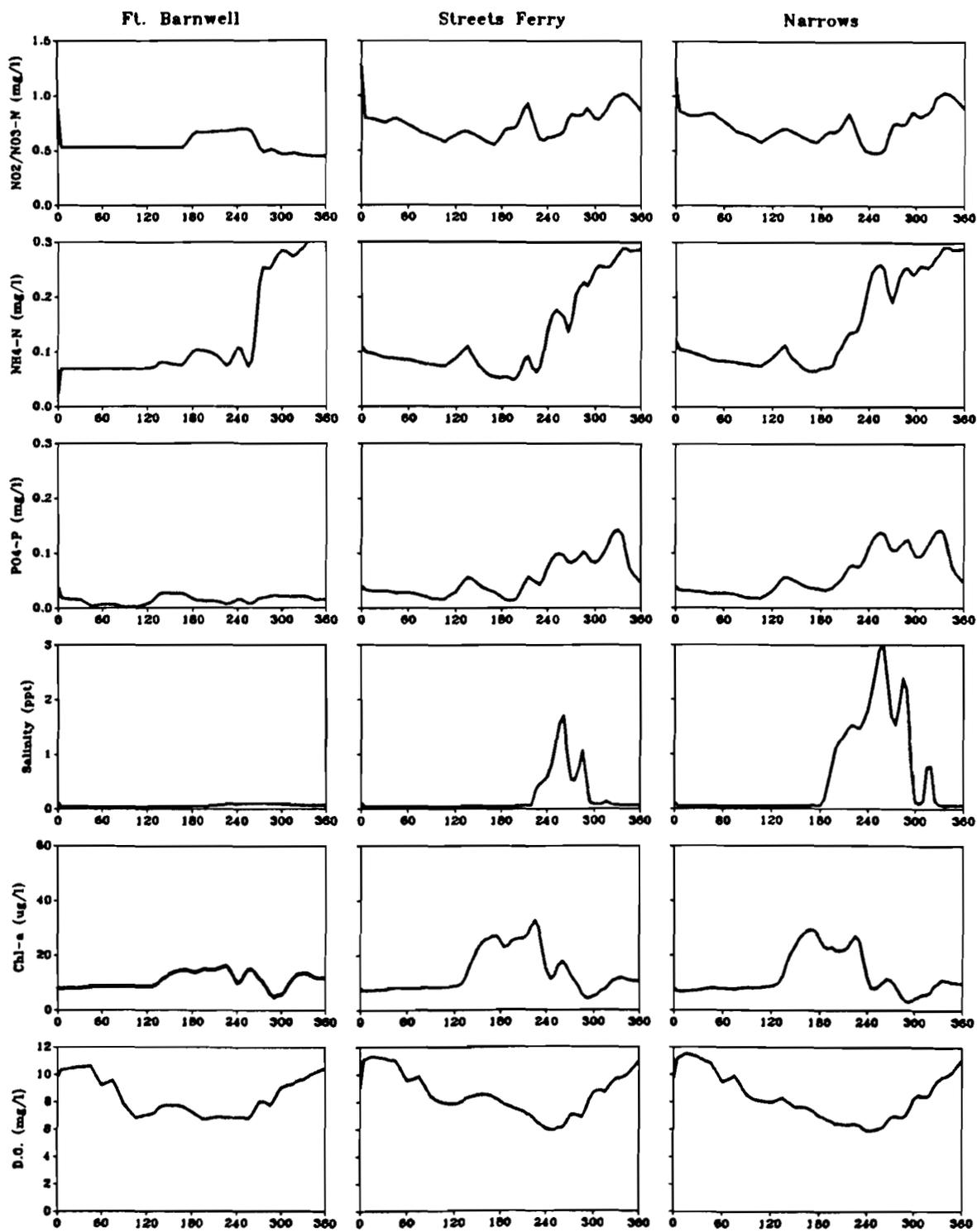


Figure II-7: Alternative 7 (0.2 mg/l P, 7 mg/l N).

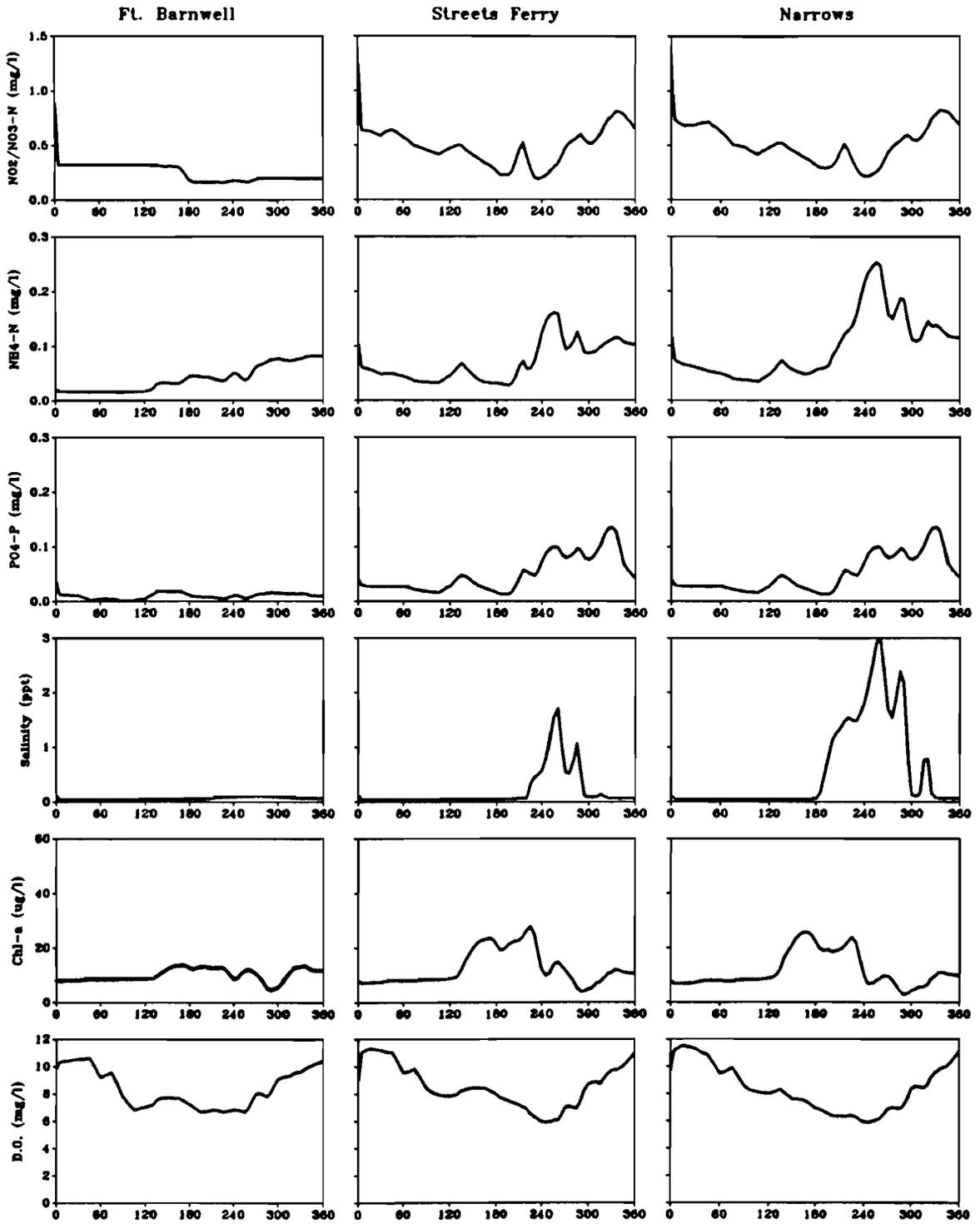


Figure II-8: Alternative 8 (0.2 mg/l P, 3 mg/l N. 30% reduction non-point N & P).

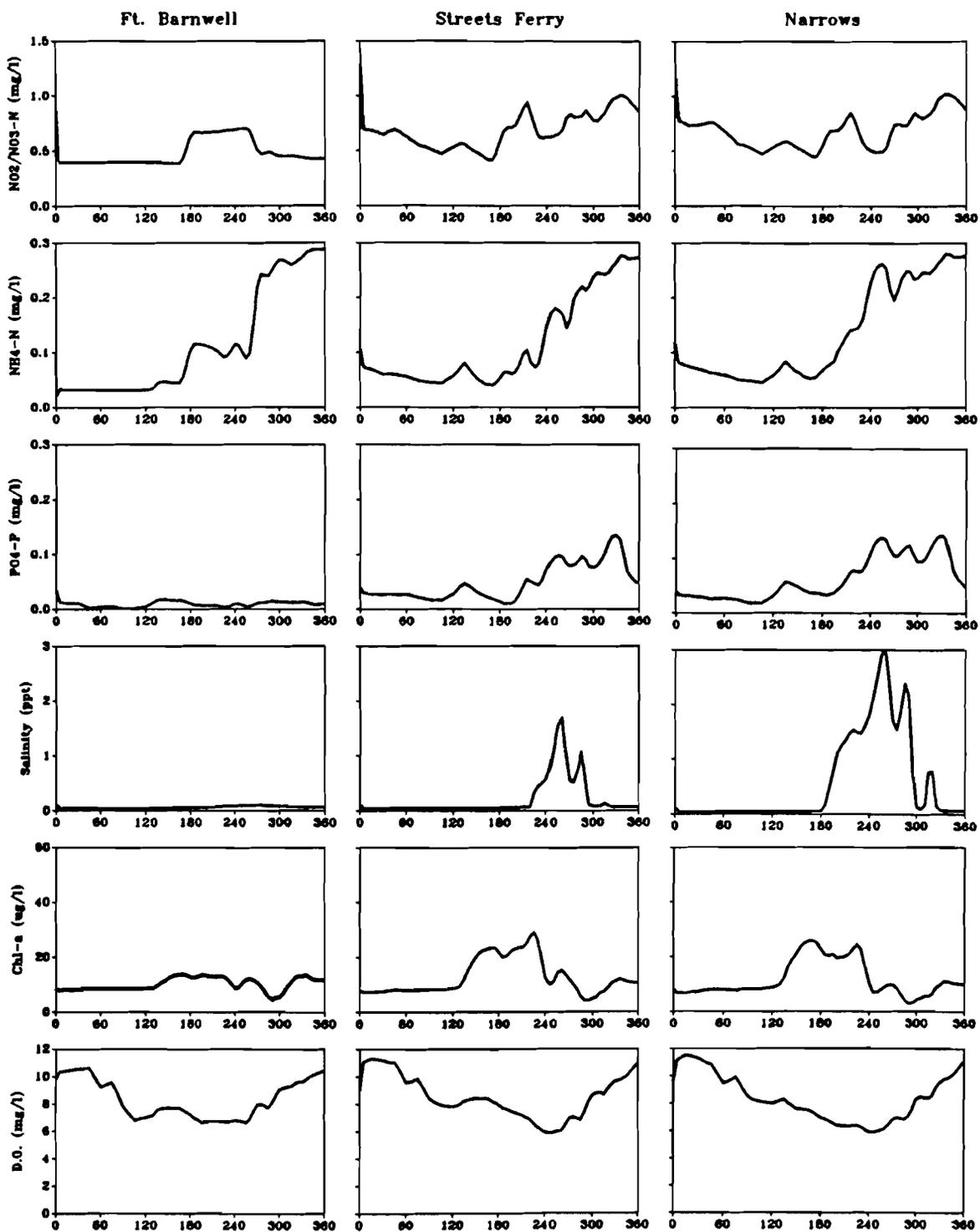


Figure II-9: Alternative 9 (0.2 mg/l P, 7 mg/l N, 30% reduction non-point N & P).

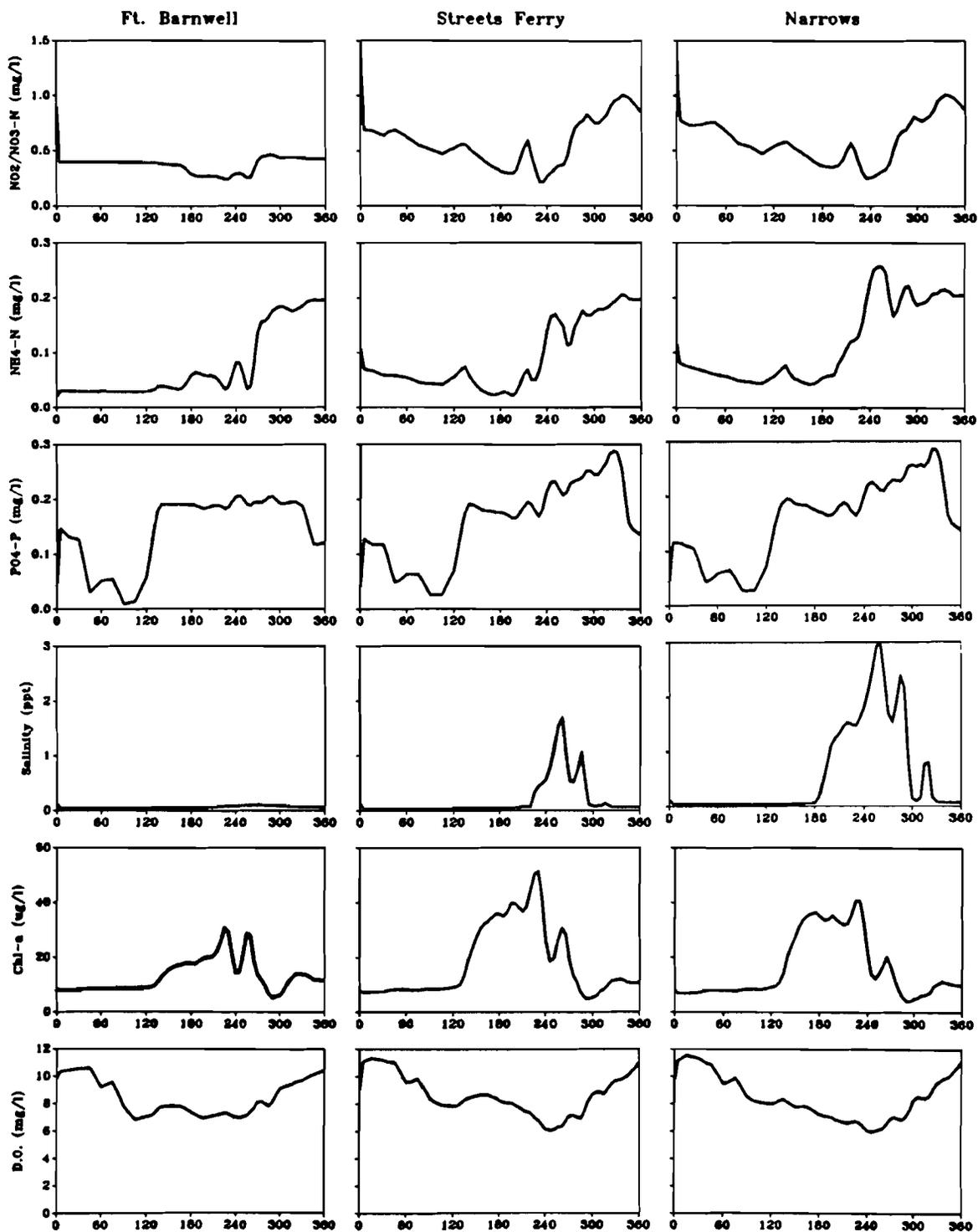


Figure II-10: Alternative 10 (6 mg/l P, 7 mg/l N, 30% reduction non-point N & P).

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