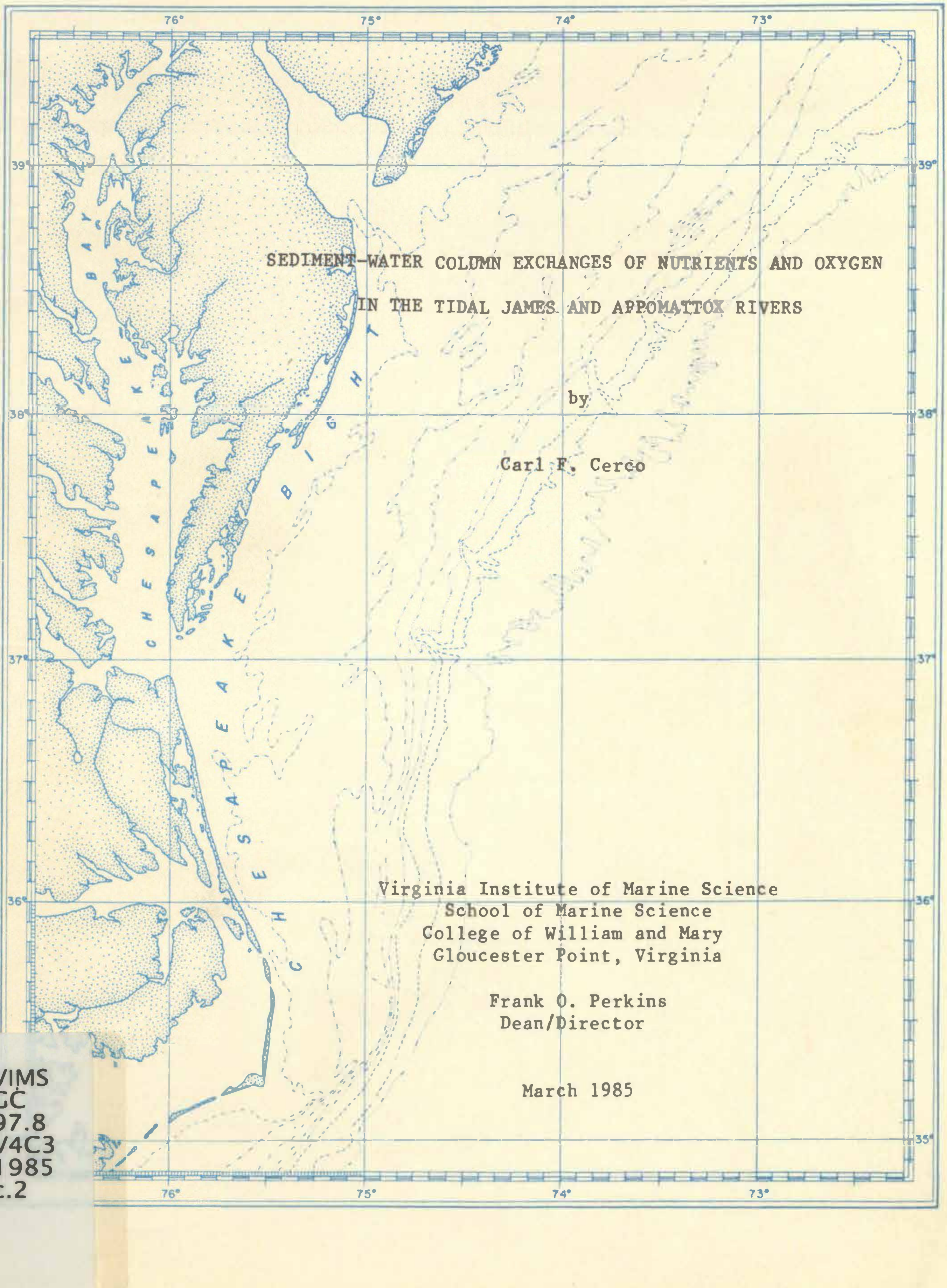
1985

Sediment-water column exchanges of nutrients and oxygen in the tidal James and Appomattox Rivers

Carl F. Cerco
Virginia Institute of Marine Science

KATOR



SEDIMENT-WATER COLUMN EXCHANGES OF NUTRIENTS AND OXYGEN IN THE TIDAL JAMES AND APPOMATTOX RIVERS

by

Carl F. Cerco

Virginia Institute of Marine Science
School of Marine Science
College of William and Mary
Gloucester Point, Virginia

Frank O. Perkins
Dean/Director

March 1985

TABLE OF CONTENTS

LIST OF FIGURES

Figure		Page

LIST OF TABLES

ABSTRACT

Fluxes between the sediments and overlying water of ammonium, nitrate, total phosphorus, ortho phosphorus, and dissolved oxygen have been measured in the tidal James and Appomattox Rivers, Va. A total of 68 nutrient flux measures, 203 oxygen flux measures, and 18 control measures were collected in the summer months, 1983 and 1984.

Ammonium is predominantly released from the sediments at a mean rate of 9.82 $mg/m^2/hr$. Nitrate is predominantly taken up by the sediments at a mean rate of 1.53 $mg/m^2/hr$. Total phosphorus is taken up by the sediments at a mean rate of 1.67 $mg/m^2/hr$. Ortho phosphorus may be taken up or released. Mean flux is an uptake of 0.75 $mg/m^2/hr$. Dissolved oxygen is taken up at a mean rate of 44 $mg/m^2/hr$.

The primary implication of this study for management is that the occurrence and rate of nitrification in the water column are obscured by the simultaneous sediment release of ammonium and uptake of nitrate. It is recommended that nitrification rates in an existing water-quality model of the James River be recalibrated following inclusion of the benthic nitrogen fluxes.

It is recommended that the sediment phosphorus fluxes observed be included in any future studies of algal eutrophication in the study system.

It is further recommended that the rates of sediment oxygen demand employed in the water-quality model of the James River be reexamined in light of new findings regarding the lack of influence of temperature and the existence of local extremes in oxygen demand.

ACKNOWLEDGEMENTS

This study would not have been possible without the contributions of a multitude of individuals. Among them were Cindy Bosco, Larry Gadbois and William Ihle who directed the field work, assisted by the specialists, technicians, mechanics, and aides of the Department of Physical Oceanography and Environmental Engineering.

Report preparation and artwork were ably accomplished by Shirley Crossley and Nancy Courtney.

Last but not least, the sponsorship of the Richmond Regional Planning District Commission is greatfully acknowledged.

Chapter I. Introduction

As the regulation of pollutant discharges to receiving waters becomes more stringent, attention is being devoted to alternate sources and sinks of substances deemed to be pollutants and of dissolved oxygen, a generalized indicator of the ´health´ of a water body. One alternative source/sink of importance is the flux of substances between the bottom sediments and the water column of estuarine systems. Knowledge of these fluxes is important both in understanding the factors which determine water quality and in applying mathematical water-quality models. Mathematical models must take into account all major sources and sinks of the substances modelled. If benthic fluxes are absent from the model, a significant process has been omitted and erroneous conclusions may be drawn from the model results.

This report presents the results of a study commissioned by the Richmond Regional Planning District Commission (RRPDC) to measure the flux of oxygen and nutrients between the bottom sediments and overlying water of the James and Appomattox Rivers, Va. The benthic-flux study is part of a larger project to apply mathematical models to the two rivers and to determine and maintain the water quality within the systems.

Benthic fluxes of ammonium nitrogen, nitrate+nitrite nitrogen, ortho phosphorus, total phosphorus, and dissolved oxygen (DO) have been measured. Ammonium is included for its role as an algal nutrient and because the oxidation of ammonium consumes dissolved oxygen through the nitrification process. In the absence of ammonium, nitrate+nitrite nitrogen may serve as an alternate algal nutrient. Therefore, the combined flux of these two nitrogen forms is measured as well. Phosphorus flux is measured because phosphorus is required, as well as nitrogen, for algal growth. Sediment fluxes of dissolved oxygen are measured since oxygen occupies a central role in determining the water quality of a system and because maintenance of dissolved oxygen concentration is a primary objective of management plans.

Chapter II. The Study Area

The study area consists of the portions of the James and Appomattox Rivers shown in Fig. 2-1. The tidal James extends from the mouth at Sewell´s Pt. (km 0), adjoining Chesapeake Bay, approximately 177 km upstream to the fall line at the City of Richmond. The study area extends only from km 69, downstream of the Chickahominy River mouth, to the fall line, however. Mean annual freshwater flow in the James is 215 m^3/sec although in the summer months flow is more typically in the range 35 to 75 m^3/sec. Mean tide range varies from 58 cm at the Chickahominy River mouth to 98 cm at Richmond. Salinity seldom intrudes upstream into the study area so the system can be considered essentially freshwater.

The Appomattox River is the major tributary of the tidal James. The tidal Appomattox joins the James at km 125 and extends upstream approximately 18 km to the fall line at the City of Petersburg. Mean annual freshwater flow in the Appomattox is 47 m^3/sec although summer flows are typically in the range 3 to 15 m^3/sec. Mean tide range in the river is approximately 84 cm.

The James and Appomattox Rivers can be conveniently divided into four subsections or reaches. These reaches are described in the remainder of this chapter.

A. Reach I

Reach I extends from the James River fall line down to km 145. Within this reach, the river is narrow and relatively deep. Total width is approximately 200 m and a navigational channel 5 to 7 m deep and 30 to 60 m wide is maintained. Thus, shoal areas are essentially absent. There are ox bows, however, at Farrar Island, Hatcher Island, and Jones Neck, which are largely stagnant due to dead ending or navigational cutoffs.

Reach I receives treated discharges from the Richmond STP (km 175), the Falling Creek STP (km 167) and the Proctors Creek STP (km 158). Several smaller industrial dischargers are also located within this reach and it is subject to pollutant loads, including Richmond combined-sewer overflows, from above the fall line.

The water within Reach I tends to be relatively high in nutrient concentration. Data collected by the RRPDC in the summer of 1983 (10) indicates ammonium concentrations in the range 0.3 to 0.7 mg/l are predominant. Nitrate nitrogen is typically in the range 0.4 to 0.7 mg/l and total phosphorus varies from approximately 0.2 to 0.5 mg/l.

Summer, 1983, observations indicate dissolved oxygen concentration in Reach I ranges from saturated, at the fall line, down to an approximately 5 mg/l minimum around km 161.

B. Reach II

Reach II extends from km 145 downstream to km 100. Within this reach the river opens up from the narrow channel just above Hopewell to a much broader expanse. Total width is roughly 1 to 2 km although narrower constrictions and wider embayments, as well as a single oxbow, Curles Neck, are present. Channel depth is 8 to 10 m and extensive shoals of less than 1 m depth exist, especially adjacent to and below Hopewell.

The primary discharge to Reach II is the Hopewell STP. Several industries discharge in Reach II as well, but the net contribution of these industries is small.

Ammonium concentrations in Reach II tend to be lower than in Reach I. During the summer, 1983, ammonium concentrations were in the 0 to 0.5 mg/l range. Nitrate concentrations were relatively high, however, ranging from 0.7 to 1.2 mg/l. Total phosphorus was generally between 0.05 and 0.15 mg/l. Dissolved oxygen observations were typically 6 mg/l or above although detailed monitoring did indicate excursions below 5 mg/l.

C. Reach III

The James River continues to grow wider within Reach III which extends from km 100 downstream to the limit of the study area at km 69. Total width ranges from 1 to 3.5 km although more narrow constrictions and wider embayments exist. Channel depth is approximately 10 m and shoal areas less than 1 meter deep occupy a much smaller fraction of the total width than in adjacent Reach II.

There are no significant point-source dischargers into Reach III and nutrient concentrations are lower than upstream. Ammonium nitrogen concentrations during summer, 1983, were generally below 0.1 mg/l and nitrate declined from 0.6 mg/l at the upstream end of the reach to 0.2 mg/l at the lower end. Total phosphorus was generally at or below 0.1 mg/l. Dissolved oxygen observations in Reach III were generally in the 5 to 7 mg/l range.

D. Reach IV

Reach IV is comprised of the tidal Appomattox River. The lower 5 km of the Appomattox resemble Reach I of the James in that a single channel approximately 200 m wide and 3 to 7 m deep exists. The river is physically much different above Point of Rocks, however, at which it splits into numerous shallow braided channels 1 to 2 m deep. Two primary channels are the North Channel which receives discharges from the Petersburg STP as well as freshwater flow from above the fall line and the South Channel which terminates at Petersburg and receives virtually no inflow.

Within the study region, summer, 1983, ammonium concentrations were approximately 0.5 mg/l. Nitrate concentrations ranged from 1 to 4 mg/l and total phosphorus varied widely from 0.1 to 0.7 mg/l. Dissolved oxygen was typically saturated or supersaturated and in the 7 to 13 mg/l range.

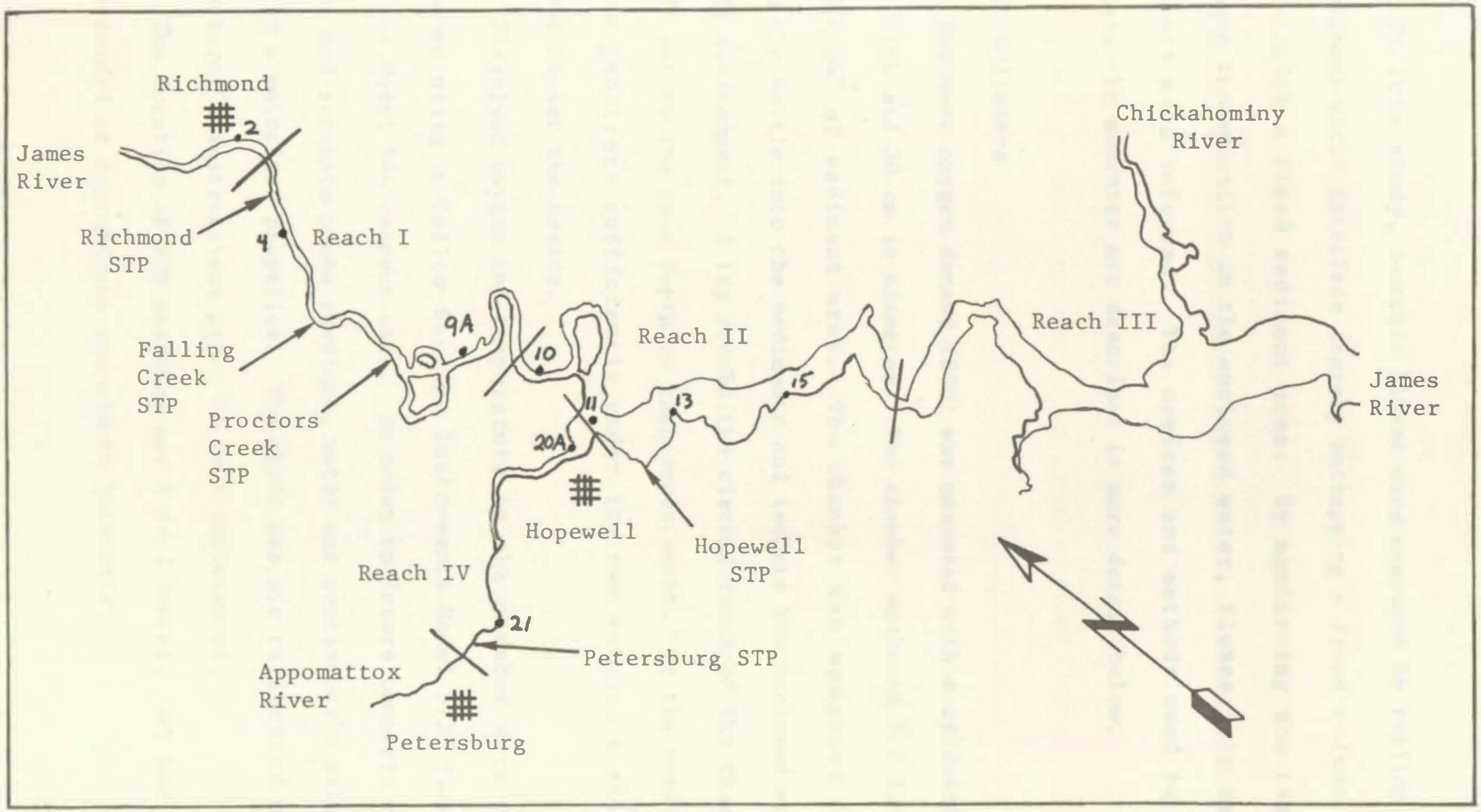


Figure 2-1. The Tidal James and Appomattox Rivers.

Chapter III. Methodology

In this study, benthic fluxes were measured by sealing a chamber to the sediment-water interface thereby entrapping a fixed volume of water in contact with a fixed sediment area. By monitoring the time course of substance concentration in the enclosed water, fluxes into or out of the sediments were inferred. The devices and methods used to collect and interpret the measures are described in more detail below.

A. SOD Cylinders

Sediment oxygen demand (SOD) was measured with a cylindrical chamber, 13 cm high and 30 cm in diameter. The chamber enclosed 9.2 liters of water and 707 cm^2 of sediment area. The chamber was weighted in order to partially settle into the sediments and isolate the enclosed water from the outside environment. A lip around the circumference of the chamber insured that it set to the same depth in each emplacement. In the event the chamber did not penetrate sufficiently under its own weight, a skin diver was employed to set the device.

Dissolved oxygen and temperature in the chamber were continuously monitored using a Yellow Springs Instruments Model 5739 dissolved oxygen probe and Model 54A readout unit. In order to insure complete mixing in the chamber and accurate probe readings, water was continuously stirred past the probe by a motorized propeller. The probe was air calibrated according to manufacturer´s instructions prior to each emplacement.

The duration of SOD measures was 1 to 2 hours. DO and temperature were recorded at approximate ten-minute intervals.

B. Nutrient Domes

Nutrient flux measures were collected using hemispherical dome-like chambers 46 cm in diameter and enclosing 25 liters of water and 1642 cm^2 sediment area. Water was circulated continuously, at a rate of 9 liters/minute, in the dome and through a closed loop to the estuary surface where samples were withdrawn for analysis.

As with the SOD cylinders, the dome was designed to partially penetrate the sediment surface and isolate the interior from the surroundings. A lip around the circumference of the dome prevented it from penetrating too deep when set under its own weight or by a diver.

As part of each dome emplacement, a known quantity of conservative fluorescent dye was injected into the dome at initiation of the measurement. Initial dilution of the dye provided an in-situ measure of dome volume (which may differ from the calculated displacement noted above) while the time series of dye concentration observed during the course of the measurement allowed calculation of the rate of diffusion of a conservative substance into the sediments and provided evidence of leaks between the dome contents and the surroundings.

Following positioning of the dome on the sediment surface, the dome was flushed with ambient water for fifteen minutes to remove sediment particles which may have been resuspended by the ´setting´ of the dome. Dye was next injected into the dome and sampled after five minutes of circulation in order to provide a volume measure. This 400 cm^3 sample was also analyzed for nutrients and dissolved oxygen in order to provide information on initial conditions in the dome. The time of this initial sampling was deemed hour zero of the dome emplacement. Commencing at hour one, five water samples were withdrawn at 1.5-hour intervals, providing a flux measure of seven hour's total duration. Ambient water equivalent to the sample volume withdrawn was allowed to enter the dome through a 'duckbill' valve. Ambient temperature was recorded at the initiation and completion of each dome emplacement.

C. Control Domes

Changes observed in substance concentration in the chambers are the sum of sediment-water exchange processes and of substance transformations within the water itself. In order to isolate the net effects of the sediment-water processes, transformations in the water must be measured separately and subtracted from the total apparent flux observed in the sediment chambers. Control domes were employed in order to measure those processes occurring solely in the water column.

The control domes were identical to the nutrient domes except that the bottom was sealed and not open to the sediments. Control domes were lowered to the river bottom by filling them with ambient water and were flushed, injected with dye, and sampled in the manner described for nutrient domes.

D. Sample Handling and Analysis

Samples for fluorescent dye analysis were withdrawn into 10 cm^3 cuvettes and analyzed at the site for dye concentration in a Turner Designs fluorometer.

Samples for dissolved oxygen analysis were withdrawn from the dome directly into 125 cm^3 glass bottles and fixed immediately with manganese sulfate solution and alkali-iodide-azide reagent. Samples were stored in the dark and returned to the lab within 12 hours for subsequent azide-modified iodiometric (Winkler) titration.(1)

Samples for nutrient analysis were withdrawn into a single 250 cm^3 Nalgene container and placed on ice in the dark for return to the laboratory within 12 hours. Upon return to the lab, a portion of the sample was suctioned through a 0.45 micron filter and split into subsamples for analysis of ammonium, nitrate+nitrite, and orthophosphorus. An unfiltered portion of the sample was retained for analysis of total phosphorus. Sample preservation (if necessary), storage, and holding time were all in accordance with EPA recommendations. (6)

Ammonium was analyzed via an automated phenate method (1) on a Technicon AAII autoanalyzer. The lowest standard analyzed via this method is 0.01 mg/l and recovery of a 0.2 mg/l spike is 106%.

Nitrate+nitrite was analyzed via the cadmium reduction method (1) on a Technicon AAII autoanalyzer. The lowest standard analyzed via this method is 0.01 mg/l and recovery of a 0.05 mg/l spike is 101%. N. B. Samples were analyzed for nitrate+nitrite nitrogen. It is assumed that nitrite accounts for a small fraction of the sum and therefore nitrate+nitrite will be referred to subsequently simply as nitrate.

Ortho phosphorus was analyzed via an ascorbic acid method (1) on a Bausch and Lomb Spectronic 20 spectrophotometer. The lowest standard analyzed via this method is 0.01 mg/l and recovery of a 0.05 mg/l spike is 95%.

Total phosphorus samples were first subjected to acid persulfate digestion and subsequently analyzed via an ascorbic acid method (1) on a Bausch and Lomb Spectronic 20 spectrophotometer. The lowest standard analyzed via this method is 0.01 mg/l and recovery of a 0.1 mg/l spike is 102%.

E. Calculation of Fluxes

Raw data from a chamber emplacement consisted of a time series of substance concentrations. Flux was computed from the time series via the relationship

$$F = \frac{(b_T - b_c)\ V}{A} \qquad (3\text{-}1)$$

in which

F = benthic flux ($M/L^2/T$)

b_T = slope of concentration vs. time curve in sediment chamber ($M/L^3/T$)

b_c = slope of concentration vs. time curve in control chamber ($M/L^3/T$)

V = volume of sediment chamber (L^3)

A = sediment area enclosed by chamber (L^2)

Methods of obtaining the slope for each device are described below:

1) SOD Cylinders - The slope of the concentration vs. time curve, b_T, was obtained by a least-squares fit of a straight line to the data. In some instances, dissolved oxygen exhibited a brief (0 to 10 minutes) precipitous decline followed by a less steep and more lengthy, linear decline. The initial decline of dissolved oxygen was attributed to disturbance of the sediments and, when evident, this non-linear behavior was omitted from the analysis. Data indicative of a reduction in oxygen demand due to oxygen depletion in the chamber were also omitted.

A typical time series of dissolved oxygen observations and the best-fit line are shown in Figure 3-1.

2) Nutrient and Control Domes - The slope of the concentration vs. time curve for each substance in the nutrient and control domes was obtained by a least-squares fit of a straight line to the observations. Observations in the latter portion of the emplacement were omitted if it was apparent the substance was depleted. Observations were also omitted if it appeared the occurrence of anoxic conditions in the dome affected the sediment-water flux rate. (As conditions in the dome approach anoxia, they no longer resemble the external environment and sediment-water fluxes of nitrogen and phosphorus may be altered from their ambient values.)

Typical time series of dye, ammonium, nitrate, ortho phosphorus, and dissolved oxygen are shown along with best-fit straight lines in Figures 3-2 to 3-6. Figure 3-5 indicates that only the first three ortho phosphorus observations were included in the flux calculation since dissolved oxygen became depleted after 2.5 hours. Figure 3-6 indicates that oxygen uptake was computed only during the period that oxygen was available.

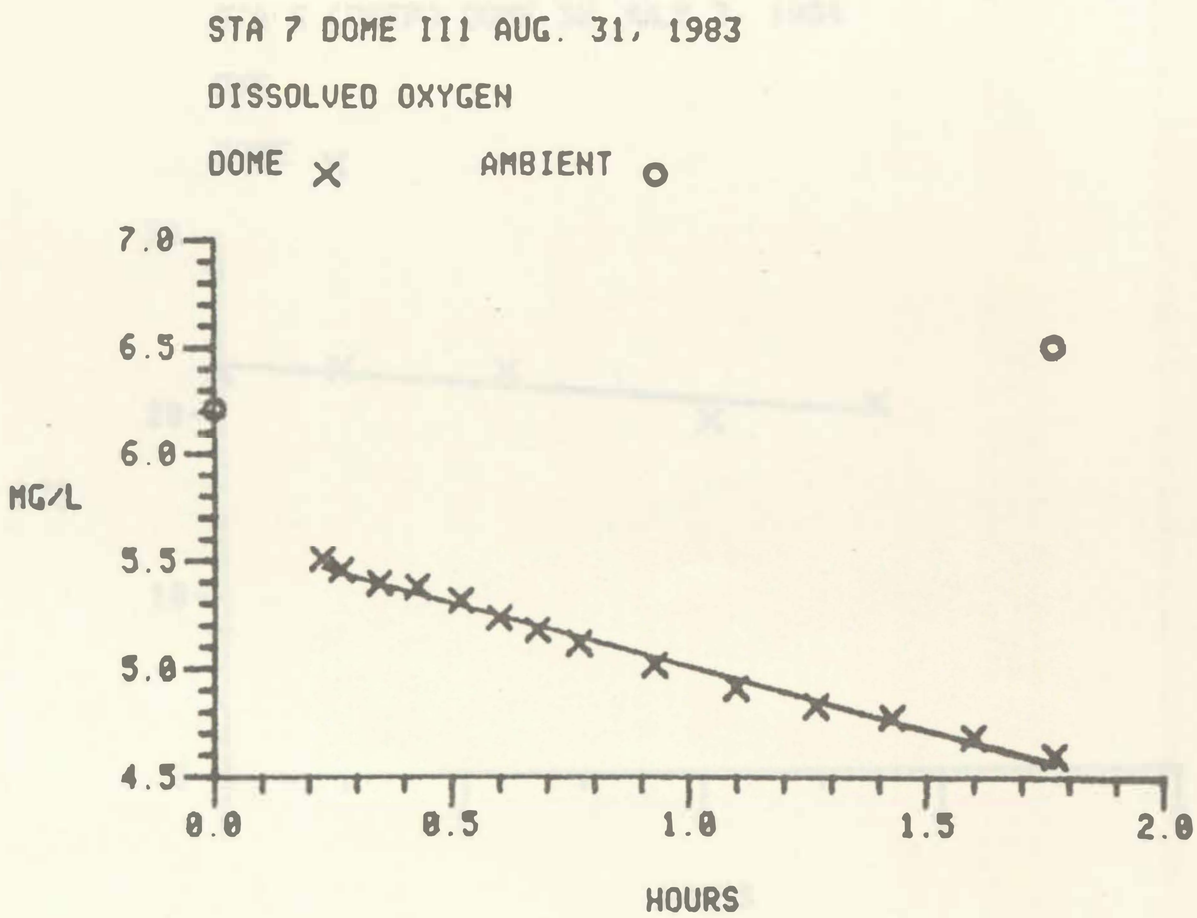


Figure 3-1. Time Series of Dissolved Oxygen in SOD Cylinder.

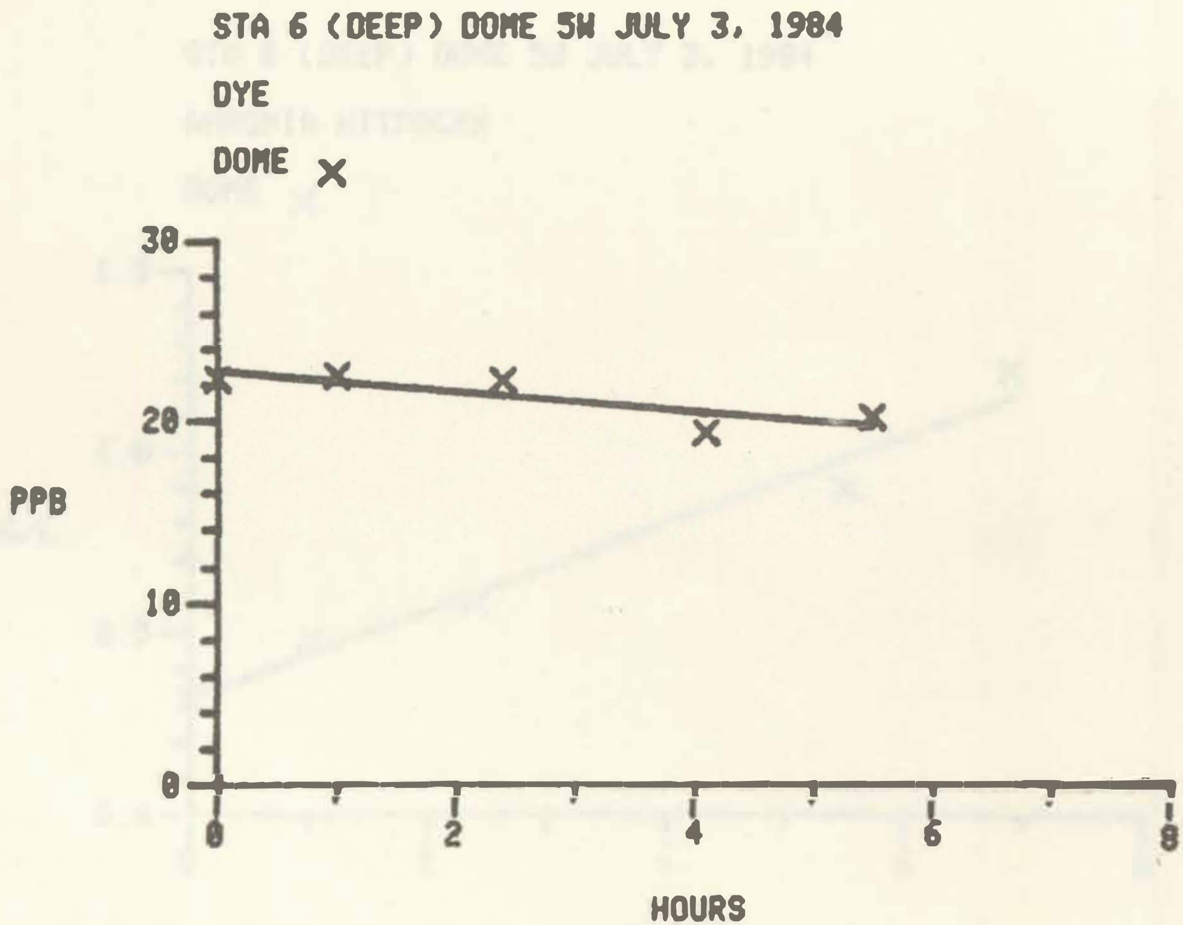


Figure 3-2. Times Series of Dye in Nutrient Dome.

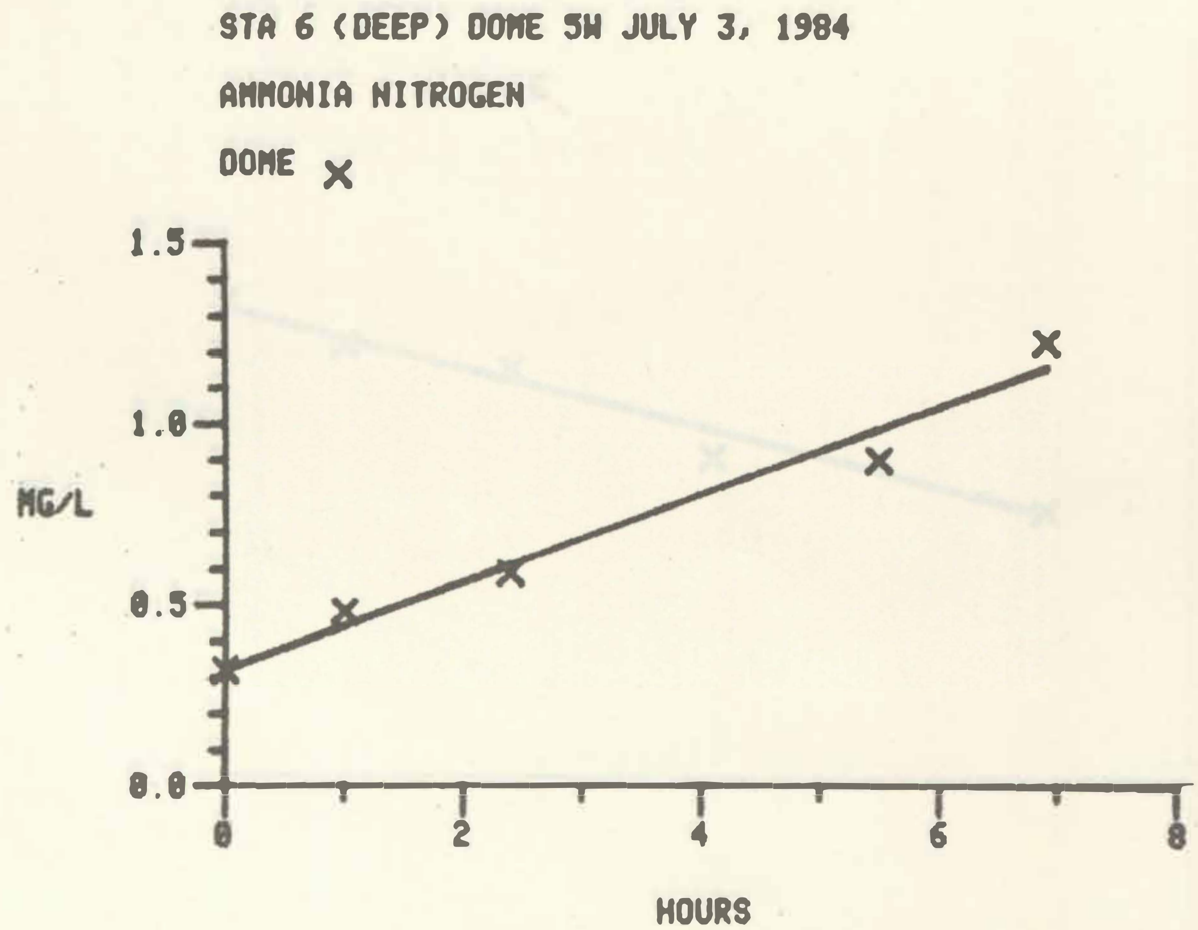


Figure 3-3. Time Series of Ammonium in Nutrient Dome.

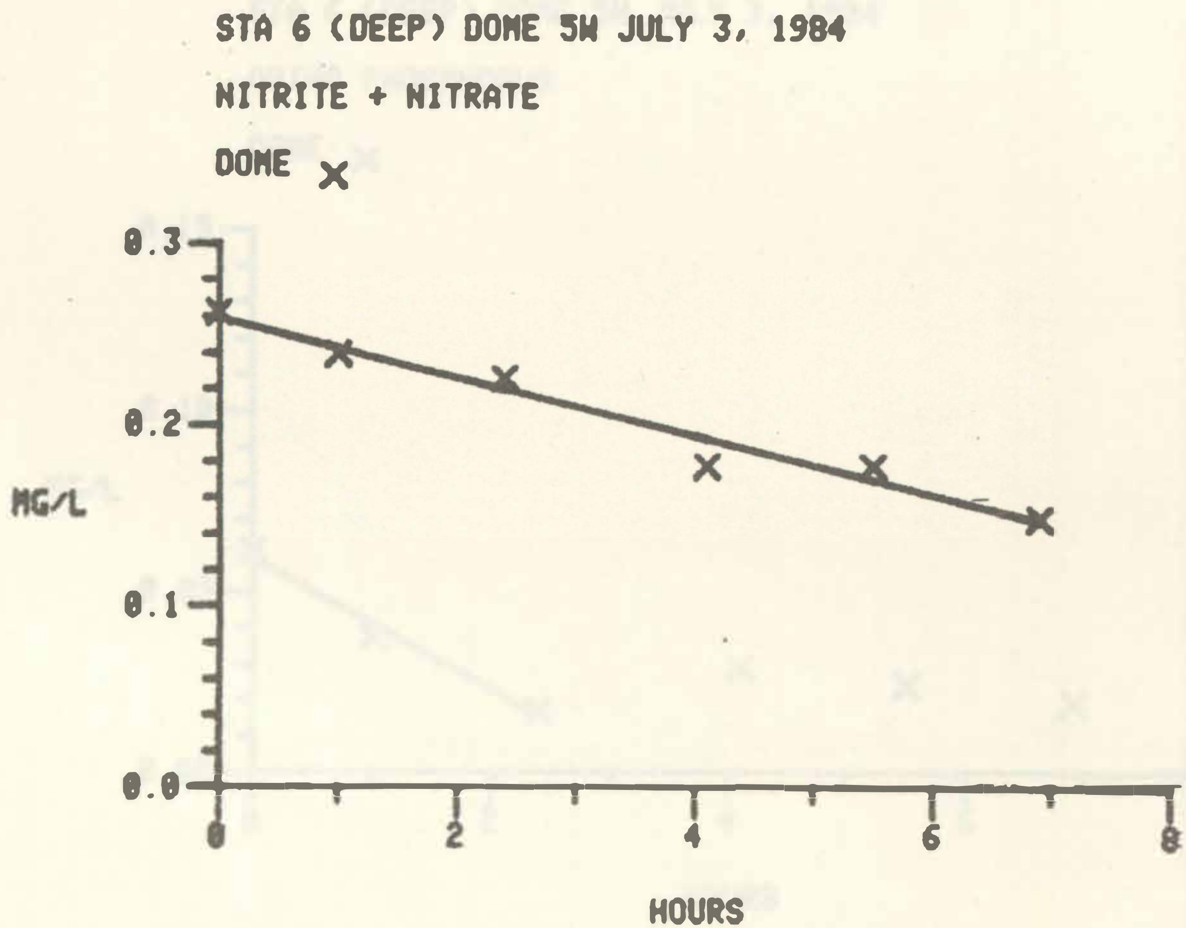


Figure 3-4. Time Series of Nitrate in Nutrient Dome.

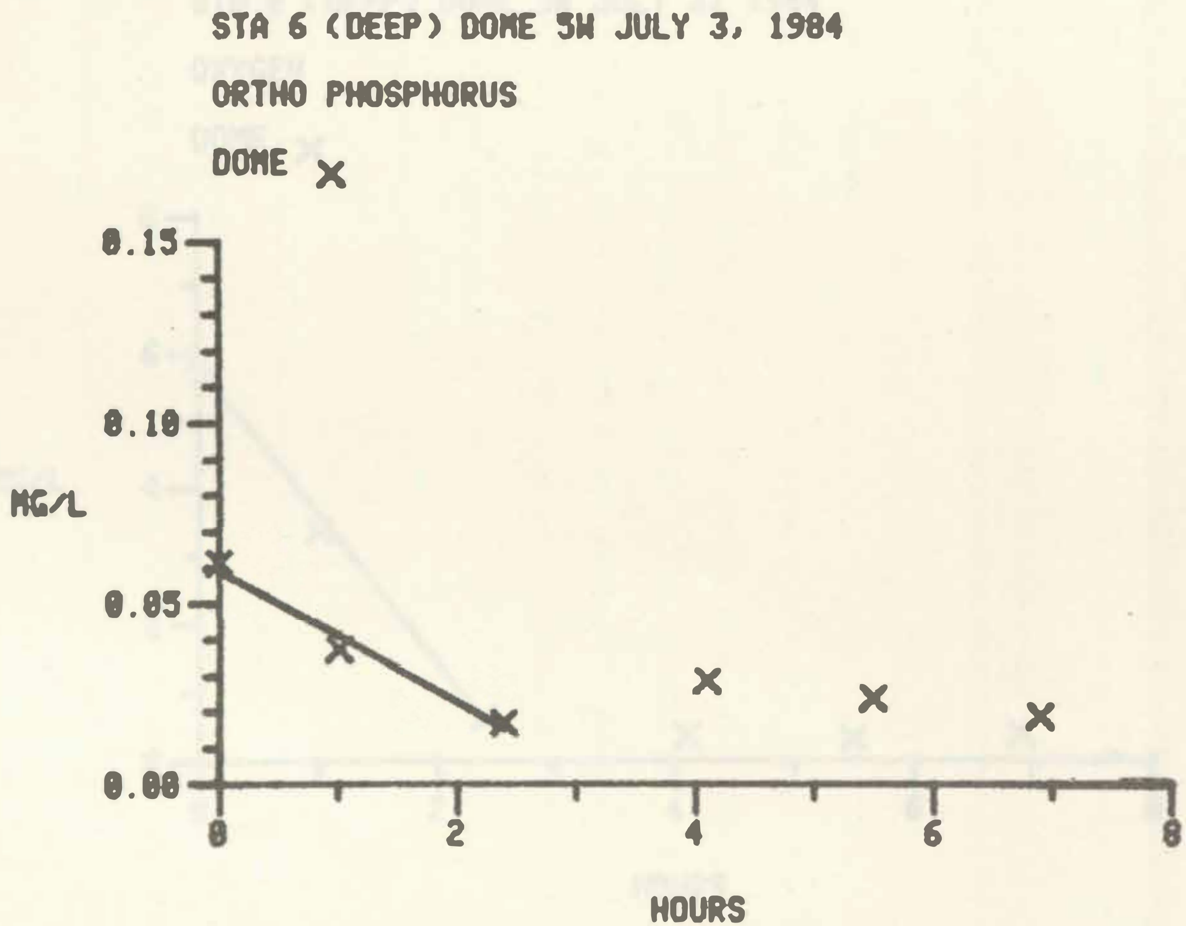


Figure 3-5. Time Series of Ortho Phosphorus in Nutrient Dome.

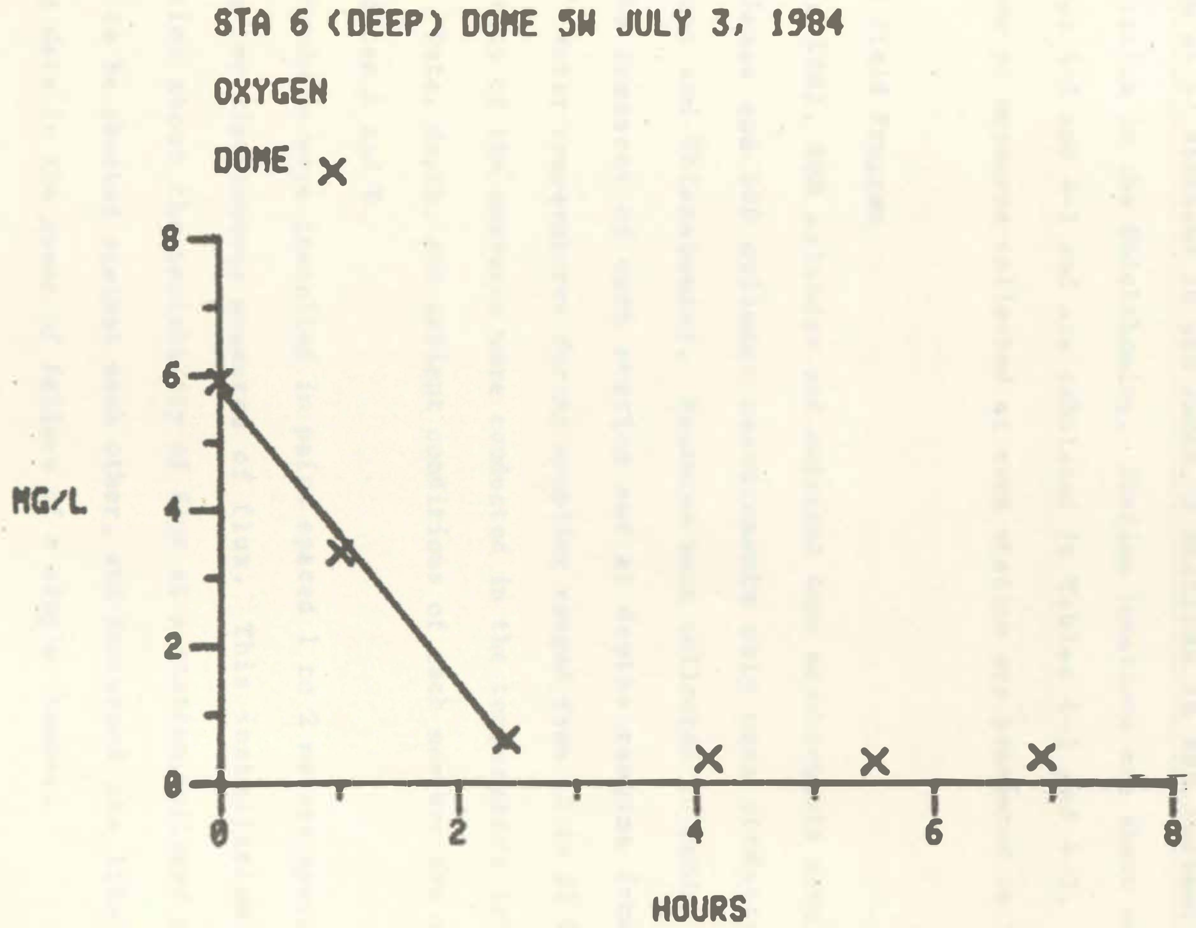


Figure 3-6. Time Series of Dissolved Oxygen in Nutrient Dome.

Chapter IV. Field Program

Sediment-water oxygen and nutrient flux measures were conducted during the months July to October 1983 and 1984. A total of 136 SOD cylinder measures, 68 nutrient dome measures and 18 control measures were collected at 17 stations in the James, 5 stations in the Appomattox and a single station in the Chickahominy. Station locations are shown on the maps on Figures 4-1 and 4-2 and are tabulated in Tables 4-1 and 4-2. The type and number of measures collected at each station are presented in Table 4-3.

A. 1983 Field Program

In 1983, SOD cylinder and nutrient dome measurements were conducted in the James and SOD cylinder measurements only were conducted in the Appomattox and Chickahominy. Measures were collected at random locations along the transect of each station and at depths ranging from 1 to 10 meters. Water temperatures during sampling ranged from 12 to 31 C although the majority of the measures were conducted in the temperature interval 18 to 30 C. Date, depth, and ambient conditions of each measure are summarized in Appendices A and B.

Chambers were installed in pairs spaced 1 to 2 meters apart and thus providing two simultaneous measures of flux. This installation provided information about the variability of flux at a station, allowed individual measures to be checked against each other, and increased the likelihood of obtaining data in the event of failure of a single chamber.

B. 1984 Field Program

In 1984, SOD cylinder and nutrient dome measurements were conducted in the James and Appomattox and SOD cylinder measurements only were conducted in the Chickahominy. Control domes were introduced in 1984 and used in conjunction with all nutrient dome measures. Water temperatures during sampling ranged from 18 to 28 C. Date, depth, and ambient conditions of each measure are summarized in Appendices A and B.

Analysis of 1983 results indicated large variability of flux at each station and suggested this variability might be related to the depth at which the sample was collected. To address the issue of the effect of depth on flux, the number of stations in the James were reduced but measurements were located more precisely in the transect of each station. Specifically, ′deep′ (5 to 6 m) and ′shallow′ (1 to 2 m) measures were conducted simultaneously. Sediment chambers were again installed in pairs and a single control was employed for each pair of nutrient domes. Thus, emplacements in the James consisted of two deep and two shallow SOD cylinders or two deep and two shallow nutrient domes employed simultaneously with one deep and one shallow control

The Appomattox River is too shallow for depth to play a dominant role in determining fluxes. Spatial variability of flux in the Appomattox was addressed by simultaneously measuring flux at the same depth (1 to 2 m) along the right and left sides of the channel. At Station 21, measures were alternated between the North and South channels as well. Thus, emplacements in the Appomattox consisted of two right and two left SOD cylinders or two right and two left nutrient domes employed simultaneously with one right and one left control.

Table 4-1. James River Sample Stations

Station	Description	Kilometer	Mile
3	Richmond I-95 crossing	177	110.0
4	Buoy 168, below Goode Creek	172	107.0
5	Buoy 166, below Deepwater Terminal	168	104.2
6	Buoy 165, at Falling Creek	166	103.2
7	Buoy 163, below Falling Creek	165	102.8
8	Buoy 157, below Kingsland Creek	160	99.3
9	Buoy 155, below Proctor´s Creek	157	97.8
10	Buoy 137, at Curles Neck	140	87.0
11	Buoy 120, confluence with Appomattox	126	78.1
12	City Point	125	77.7
13	Buoy 107, below Hopewell STP	121	75.0
14	Jordan Point	120	74.4
15	Buoy 91, near Herring Creek	110	68.1
16	Windmill Point	108	66.9
17	Buoy 74, near Brandon Point	90	55.9
18	Claremont	84	52.0
19	Swann´s Point, below Chickahominy River	69	42.9

Table 4-2. Appomattox and Chickahominy River Sample Stations

Station	Description	Kilometer	Mile
20	North Channel, at end of Conduit Road	11.8	7.3
21	North Channel, at conveyor crossing and below STP	15.5	9.6
21B	South Channel, at conveyor crossing	15.5	9.6
22	North Channel, above STP	17.5	10.9
23	Above Route 301 bridge	19.7	12.2
	Chickahominy		
25	Shipyard Landing	13.4	8.3

Table 4-3. Summary of Station and Type of Measurement

Station	SOD Cylinder 1983	SOD Cylinder 1984	Nutrient Dome 1983	Nutrient Dome 1984	Control 1984
3	4	4	1		
4	5	2	4		
5	3				
6	6		2	8	4
7	8		3		
8	3				
9	5				
10	4	5	2		
11	5		2		
12	3		4		
13	3		4	3	2
14	6			3	2
15	4	8			
16	6				
17	4	7			
18	4				
19	5		13	6	4
20	6			6	3
21	5	1		3	1
21B		1		4	2
22	3				
23	4	4			
25	4	4			

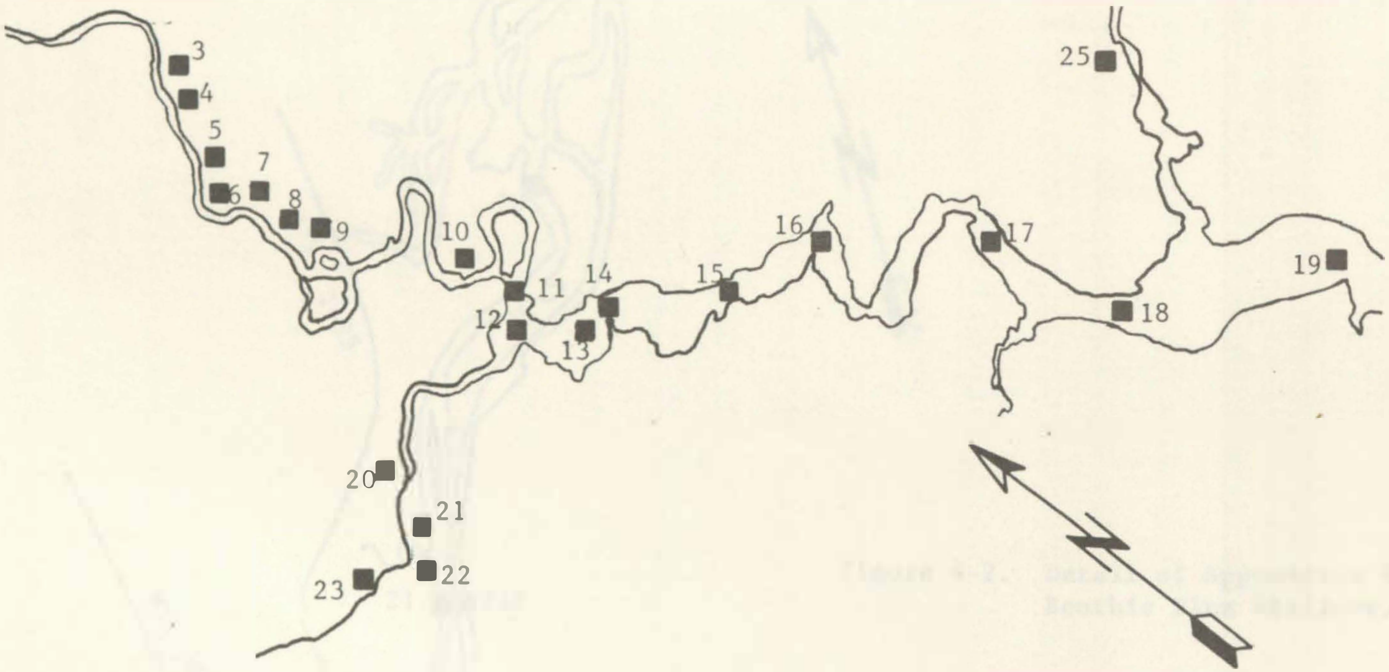


Figure 4-1. Benthic Flux Sample Stations.

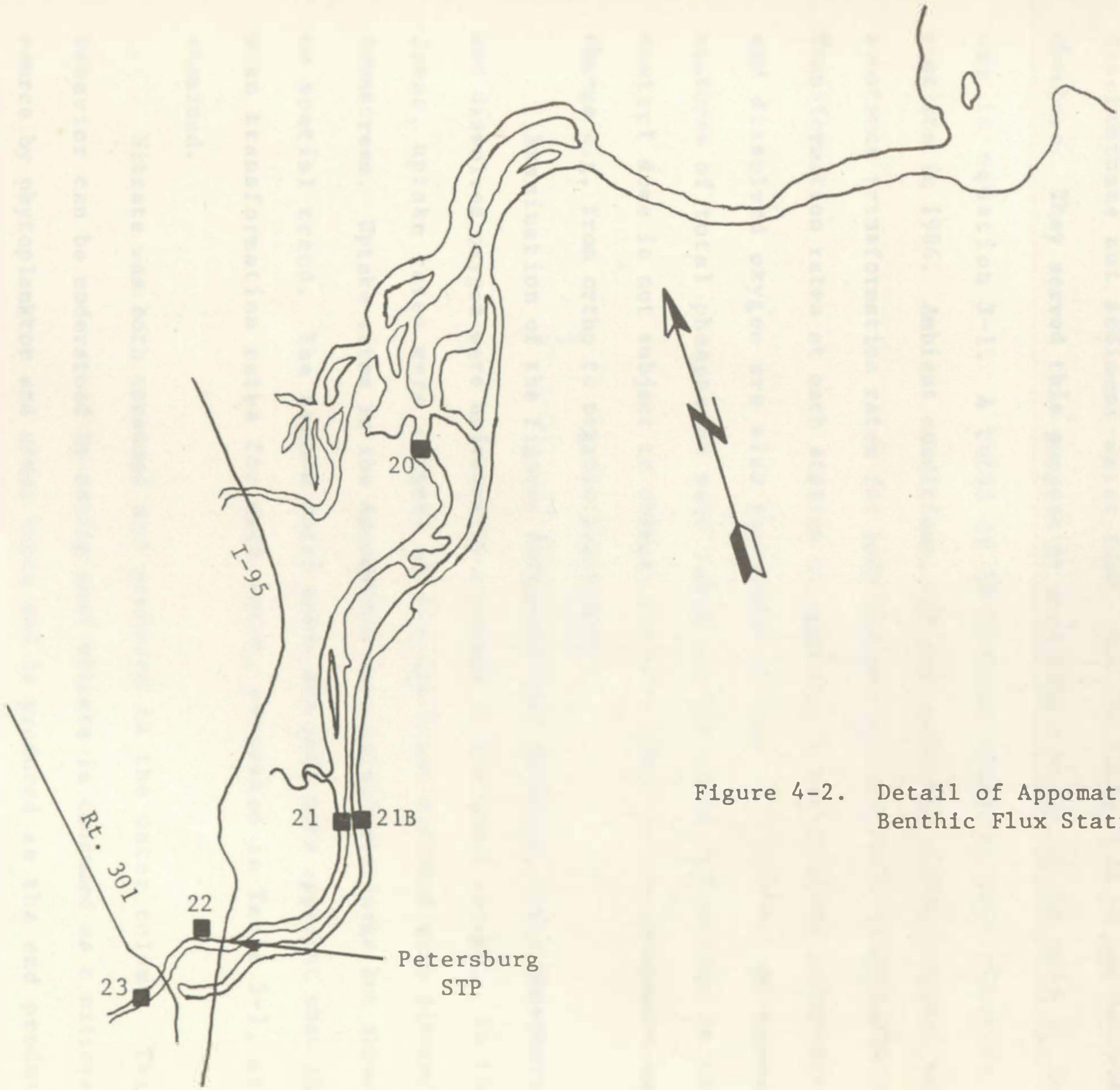


Figure 4-2. Detail of Appomattox River Benthic Flux Stations.

Chapter V. Results of Control Domes

Control domes measure the transformation of substances within the water column alone. They were employed primarily to provide data needed to discriminate net sediment-water flux from the total flux in the sediment chambers. They served this purpose by providing a value of the rate b_c for use in equation 3-1. A total of 18 control measures were taken at 7 stations in 1984. Ambient conditions, initial substance concentrations, and substance transformation rates for each measure are presented in Appendix C. Transformation rates at each station of ammonium, nitrate, ortho phosphorus and dissolved oxygen are also presented in Figs. 5-1 to 5-8. No control measures of total phosphorus were taken as the total phosphorus in the control dome is not subject to change; only the phase of the phosphorus may change e.g. from ortho to organic phosphorus.

Examination of the figures indicates that ammonium, ortho phosphorus and dissolved oxygen were universally consumed in the water column. In the James, uptake rates were largest at Station 6 and declined with distance downstream. Uptake rates in the Appomattox were relatively large but showed no spatial trend. The trends noted above are made more apparent when the mean transformation rates for each reach, presented in Table 5-1, are examined.

Nitrate was both consumed and produced in the water column. This behavior can be understood by noting that nitrate is consumed as a nitrogen source by phytoplankton and other biota and is produced as the end product of the nitrification reaction in which ammonium is converted to nitrate. Net consumption will be evident if biotic uptake occurs more rapidly than production by nitrification. Net production will be evident if nitrification proceeds at a faster rate than biotic uptake.

A. Relation of Transformations to Ambient Conditions and Location

Control measures were available for only a fraction of the sediment chamber emplacements. A means was necessary to estimate the water-column transformations in the sediment chamber emplacements for which control measures were not taken. Multiple linear regression was used to provide relationships which could be used to predict water column transformations in the absence of observations.

Regressions were based on the control dome observations which were available. A variety of additive and multiplicative relationships were tested in which substance concentrations, temperature, and station location were used as independent variables in the prediction of observed flux, the dependent variable. The relationships selected are presented below.

1) Ammonium - Ammonium uptake in the water column was calculated via the relationship

$$NH4FLX = 0.075\ NH4^{0.64} \quad \text{5-1}$$

in which

NH4FLX = rate of ammonium uptake (mg/1/hr)

NH4 = initial ammonium concentration in dome (mg/1)

This relationship is similar to first-order kinetics in that the rate of ammonium uptake is proportional to the amount available. Predicted ammonium uptake is plotted vs. observed uptake in Figure 5-9.

2) Nitrate - No single relationship was found suitable to describe nitrate flux in all reaches of the system. Instead, three relationships were employed

$NO3FLX = 4.43 \times 10^{-3}$ Reach I, II

$NO3FLX = -0.017 + 0.662\ NH4$ Reach III 5-2

$NO3FLX = 4.86 \times 10^{-4}$ Reach IV

in which

NO3FLX = Nitrate transformation rate (mg/l/hr). Positive rates indicate net production in the water column. Negative rates indicate net uptake.

The best predictors of nitrate transformations in Reaches I, II, and IV are simply the average of observations in those reaches. Nitrate transformations in Reach III are dependent upon the amount of ammonium available. Nitrate is consumed when the concentration of ammonium is low (NH4 < ~0.03mg/l). Nitrate is produced when the ammonium concentration is sufficient to act both as a nutrient source and as a substrate for nitrification.

Predicted nitrate transformations are plotted vs. observed in Figure 5-10.

3) Ortho Phosphorus - Ortho phosphorus uptake in the water column was calculated

$$PO4FLX = 0.039\ PO4^{0.79} \qquad 5\text{-}3$$

in which

PO4FLX = rate of ortho phosphorus uptake (mg/l/hr)

PO4 = initial ortho phosphorus concentration in dome (mg/l)

As with ammonium, the rate of phosphorus uptake is proportional to the quantity available. Predicted and observed phosphorus uptake rates are presented in Figure 5-11.

4) Dissolved Oxygen - Net dissolved oxygen consumption in the water column is determined by numerous factors including carbonaceous and nitrogenous biochemical oxygen demand, algal photosynthesis and respiration, and temperature. Of these factors, only temperature was consistently available for use as an independent variable in the calculation of water-column oxygen consumption in both the nutrient domes and SOD cylinders. Temperature alone proved to be a poor indicator of oxygen consumption, however. As a result, oxygen consumption in the water column was evaluated simply as the average consumption rate observed in each reach

DOFLX = 0.510	Reach I	
DOFLX = 0.337	Reach II	5-4
DOFLX = 0.294	Reach III	
DOFLX = 0.588	Reach IV	

in which

DOFLX = dissolved oxygen consumption in water column (mg/l/hr)

Predicted and observed dissolved oxygen consumption rates are presented in Figure 5-12. It can be seen there is a good deal of scatter about the diagonal line which indicates the ideal one-to-one correspondence of predictions and observations. Thus the correction for water-column respiration applied to individual observations of sediment oxygen demand may substantially overestimate or underestimate the actual water-column respiration. It is preferable to apply the correction to the mean of all SOD observations at a station or in a reach. In that case, the mean corrected sediment oxygen demand is considered to be representative of the actual mean demand at that station or in the reach.

In subsequent chapters of this report, it will be necessary to refer to individual oxygen demand measures in which case uncorrected measures will be reported. Oxygen demand measures which are not corrected for water-column respiration are referred to as "bottom respiration measures" in that they include the respiration in the sediments and in the water immediately overlying. The term "sediment oxygen demand" is reserved for measures which have been corrected for water-column respiration and will usually refer to the mean value at a station or reach.

Table 5-1. Mean Transformation Rates

Reach	NH4 µgm/l/hr	NO3 µgm/l/hr	PO4 µgm/l/hr	DO mg/l/hr
1	-39.2	5.62	-10.8	-0.510
2	-20.2	3.26	- 3.07	-0.337
3	- 4.0	-7.22	- 1.21	-0.294
4	-42.7	0.49	- 8.38	-0.588

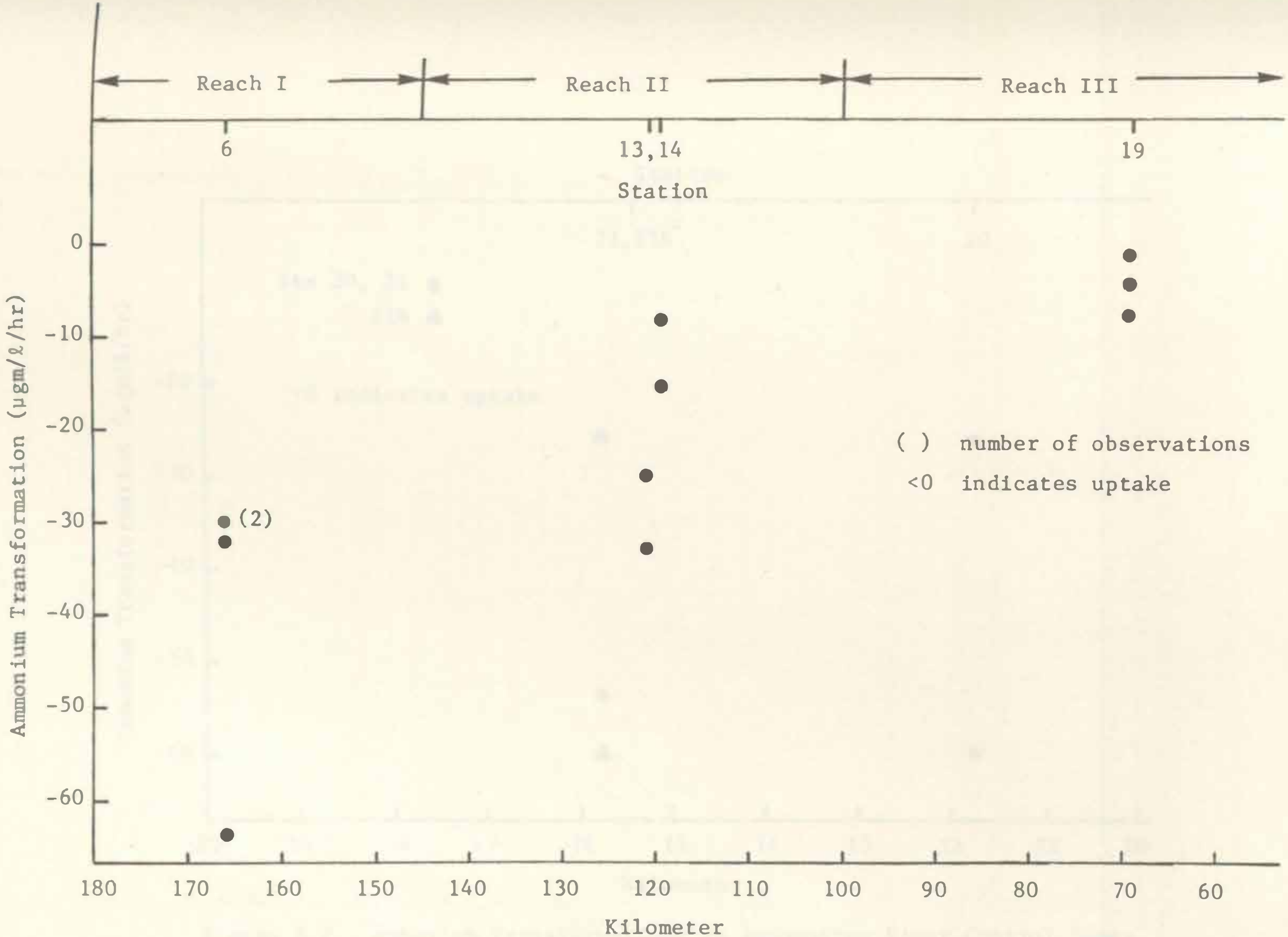


Figure 5-1. Ammonium Transformations in James River Control Domes.

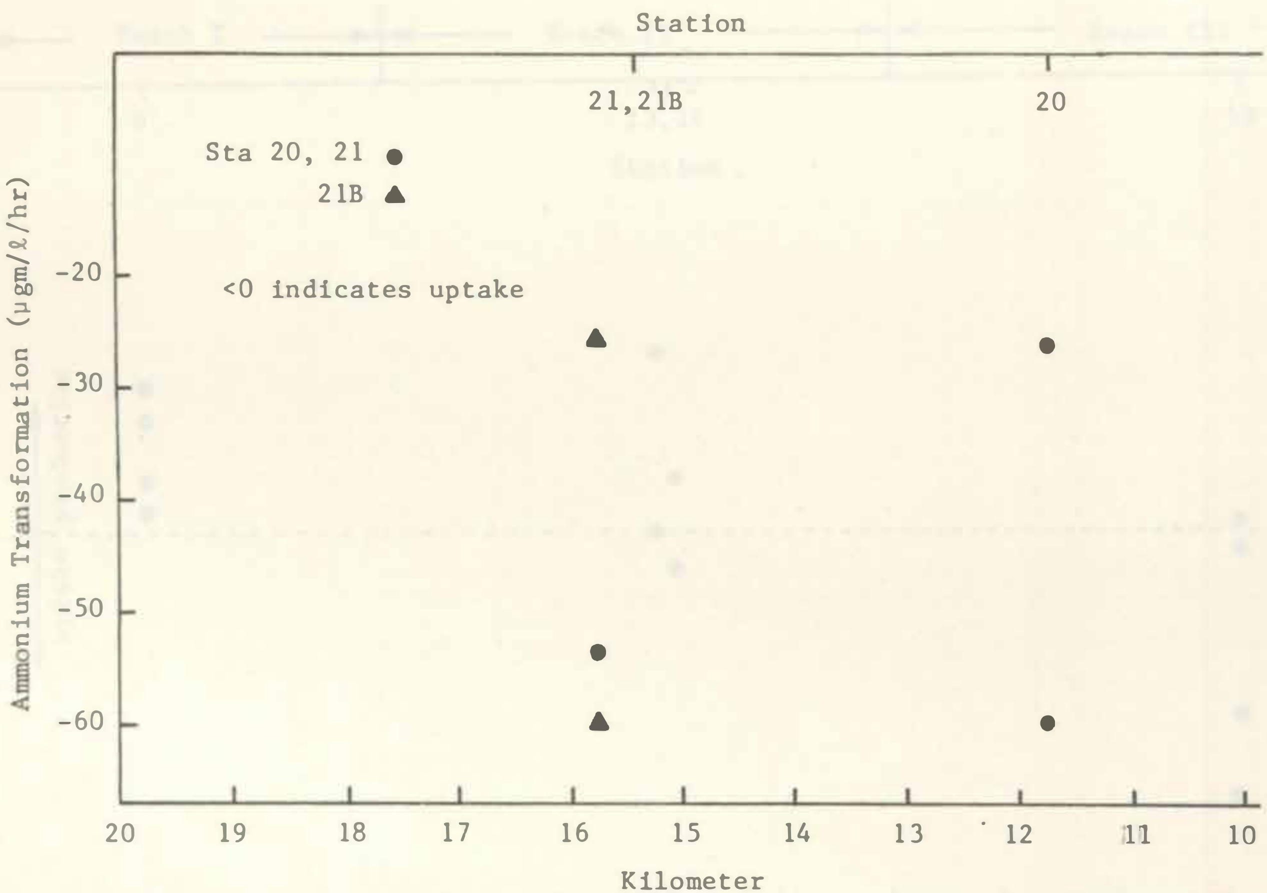


Figure 5-2. Ammonium Transformations in Appomattox River Control Domes.

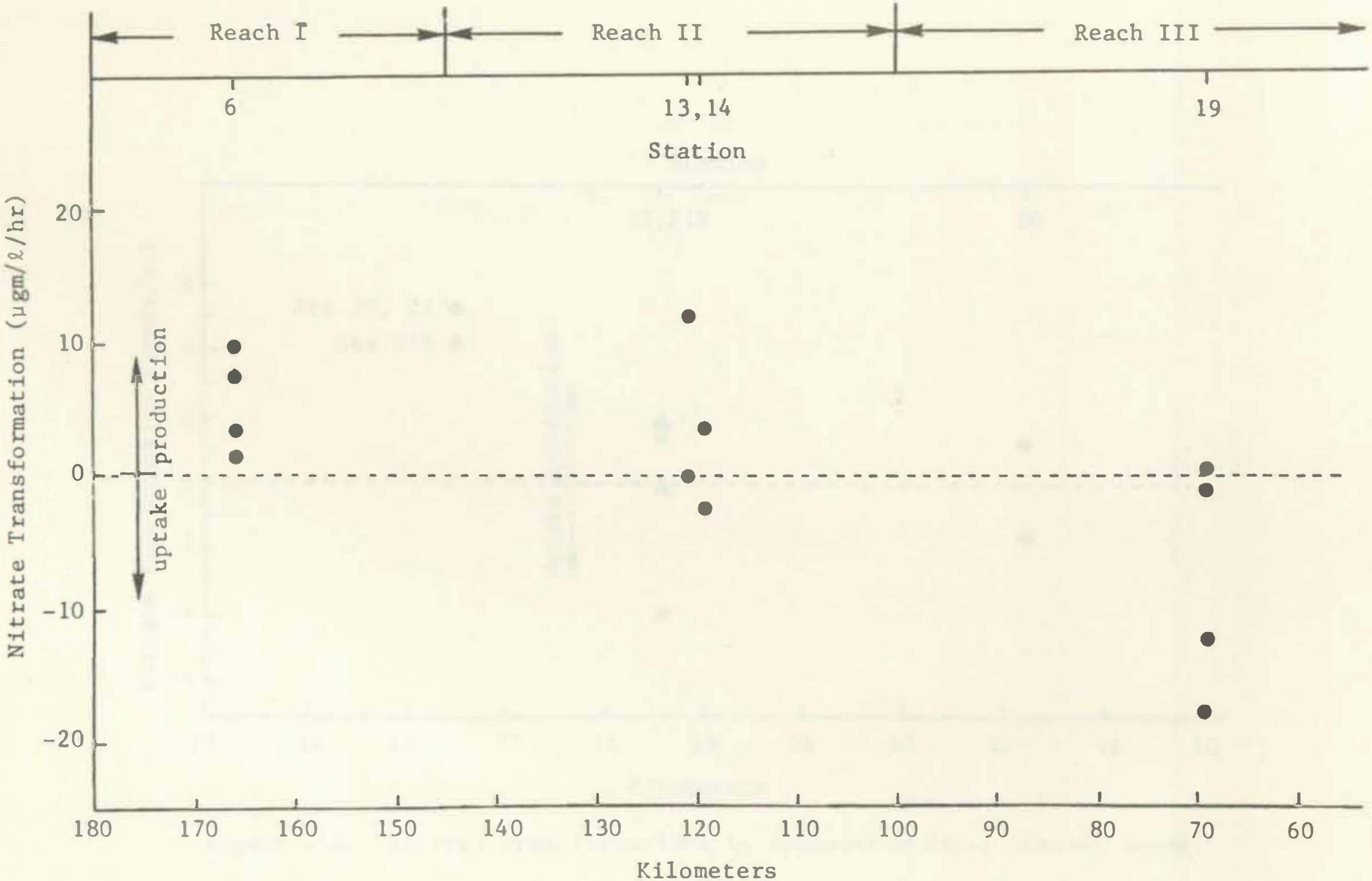


Figure 5-3. Nitrate Transformations in James River Control Domes.

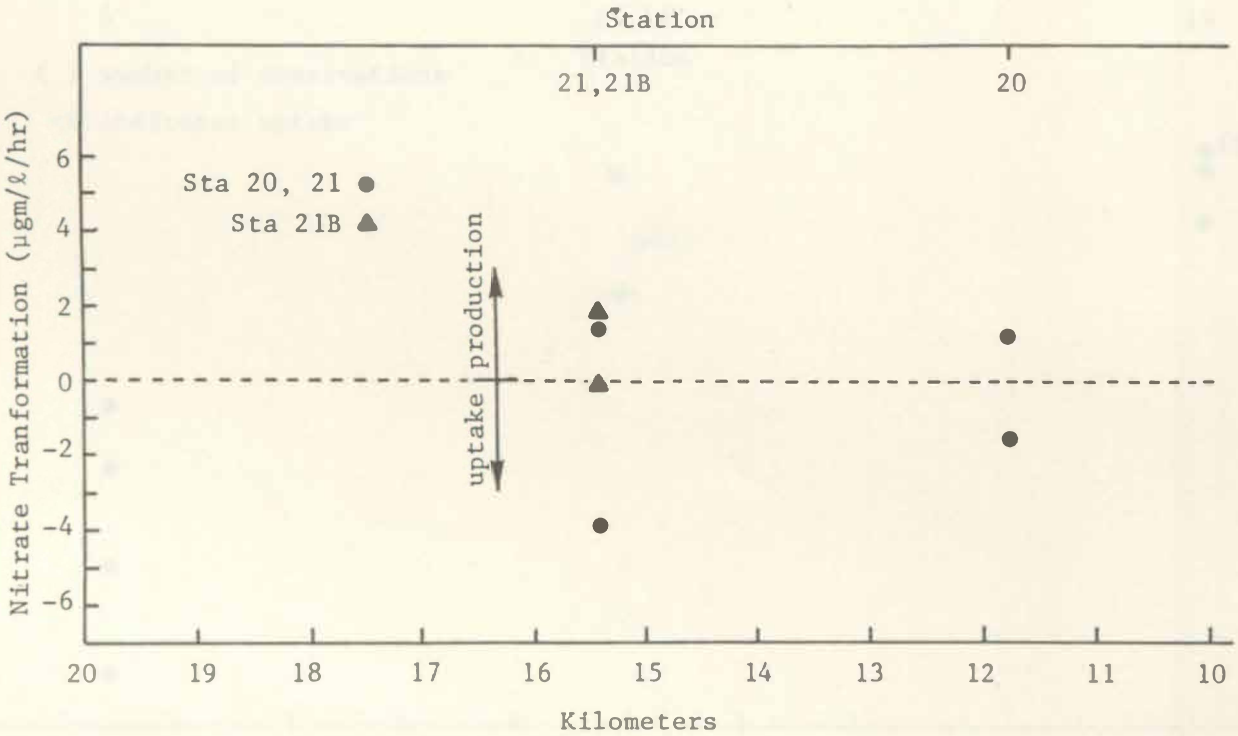


Figure 5-4. Nitrate Transformations in Appomattox River Control Domes.

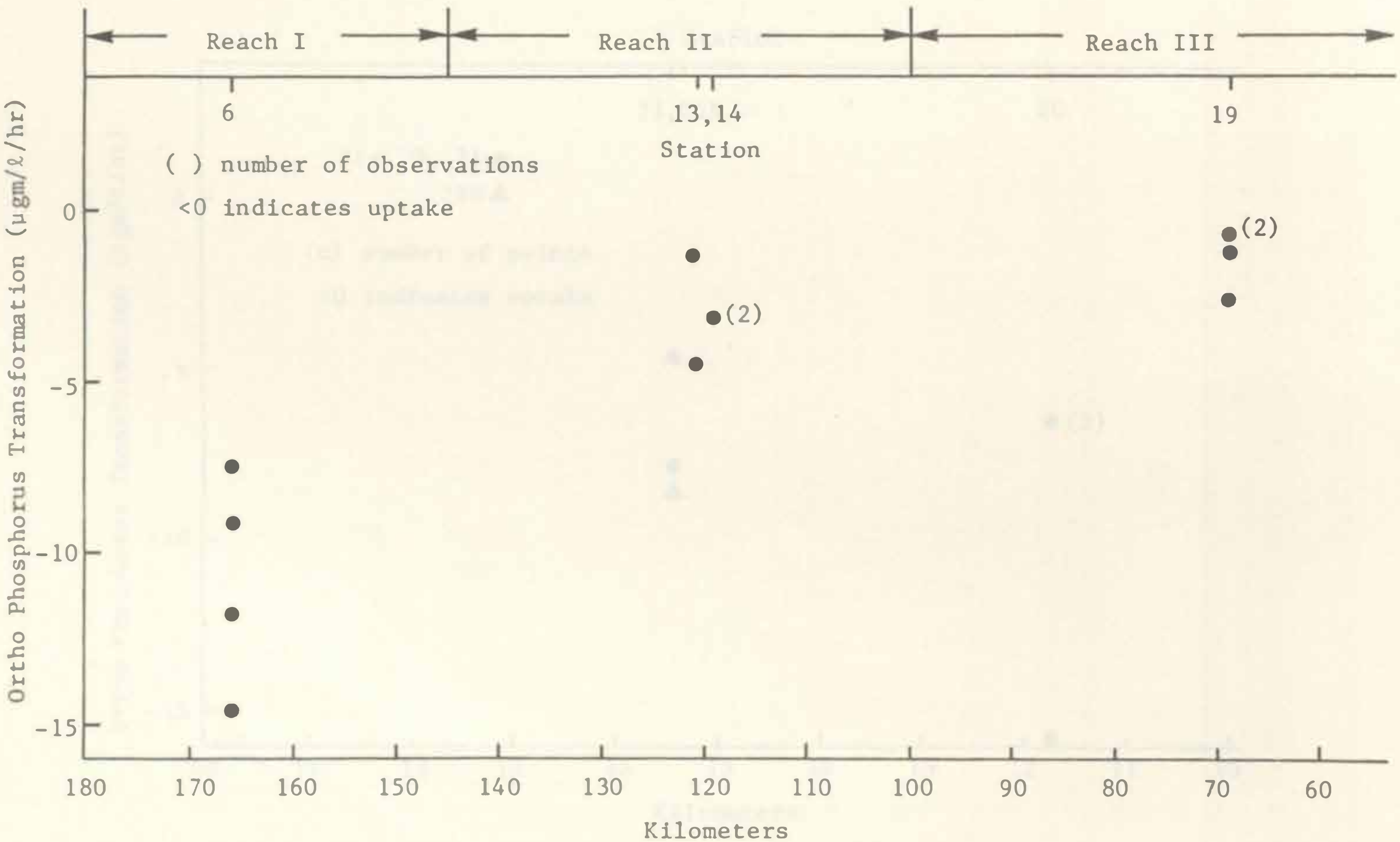


Figure 5-5. Ortho Phosphorus Transformations in James River Control Domes.

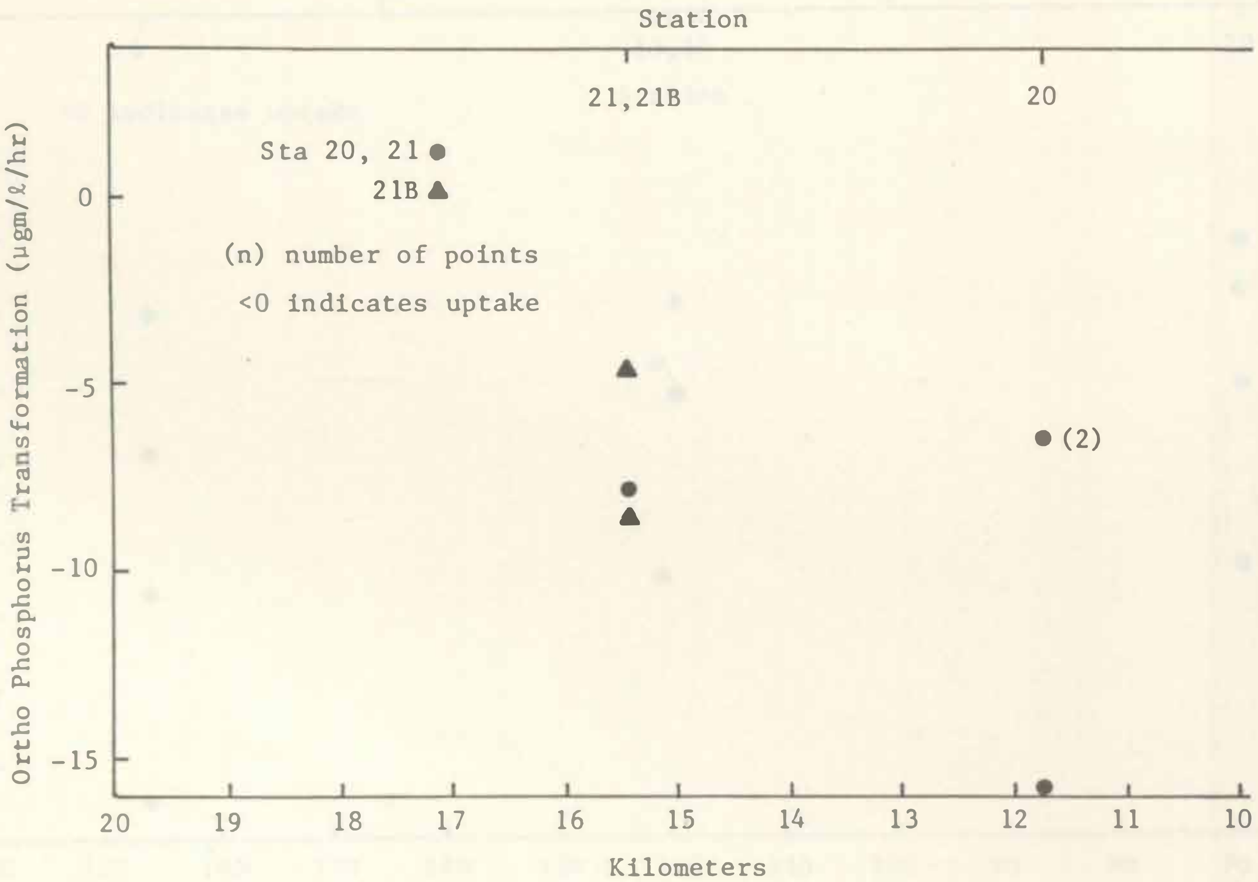


Figure 5-6. Ortho Phosphorus Transformations in Appomattox River Control Domes.

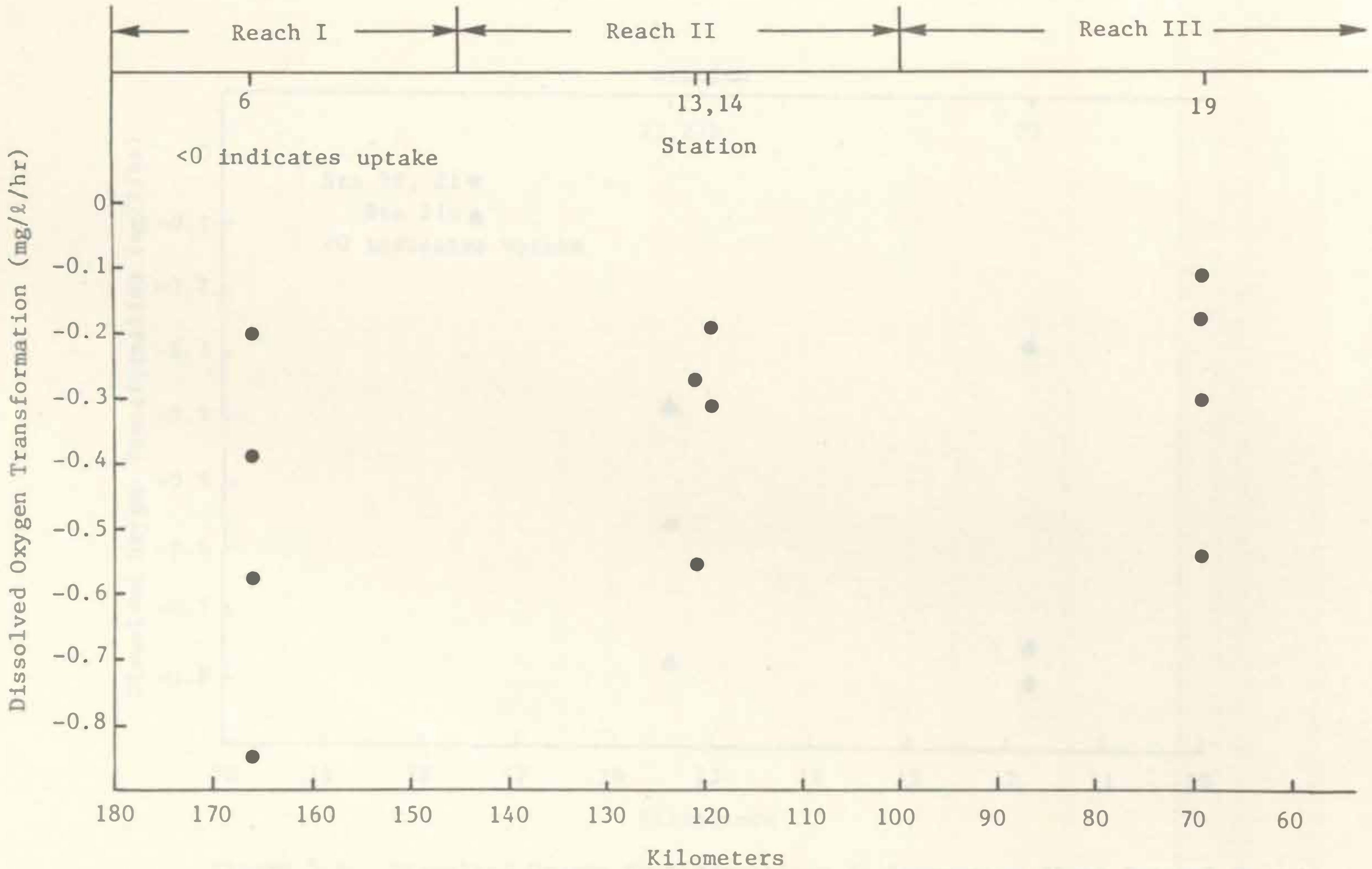


Figure 5-7. Dissolved Oxygen Transformation in James River Control Domes.

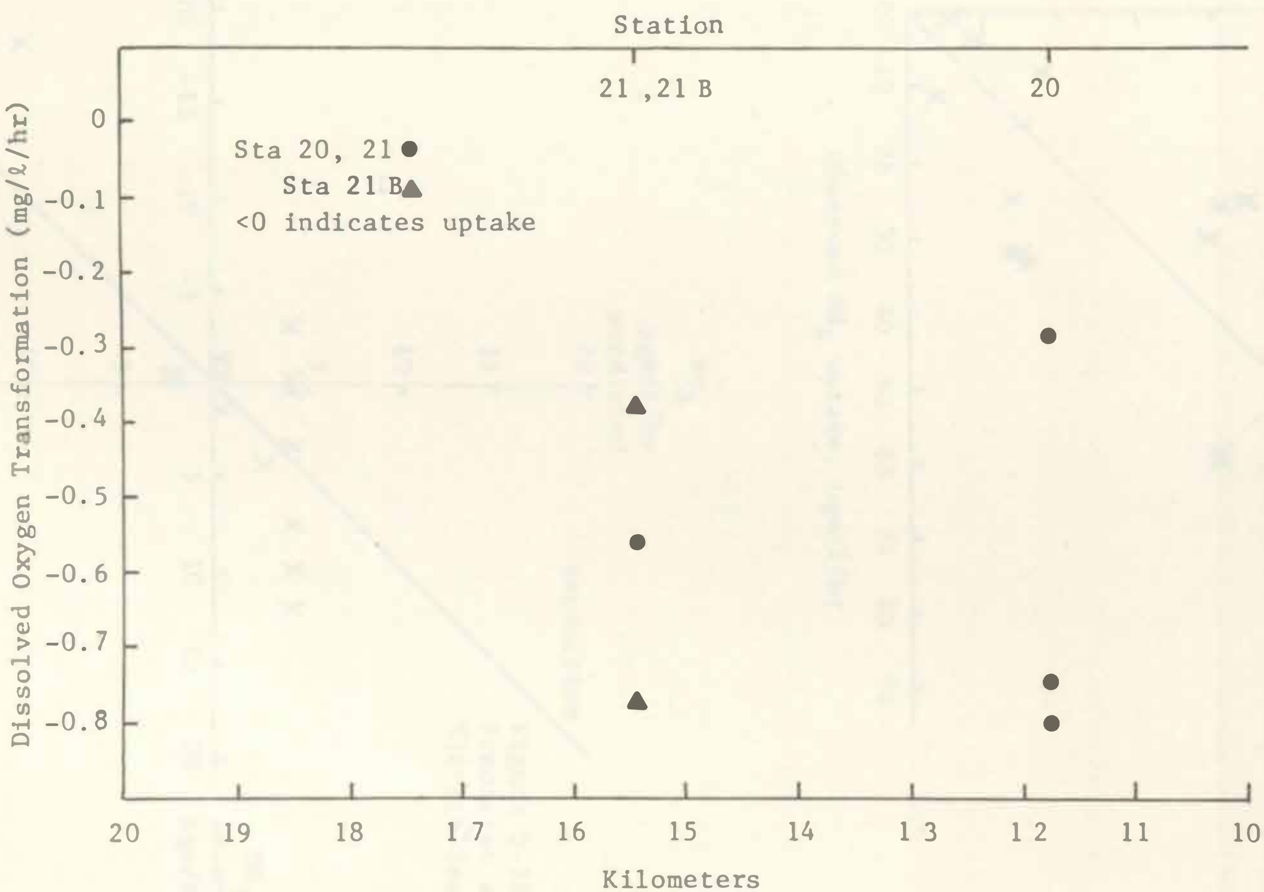


Figure 5-8. Dissolved Oxygen Transformations in Appomattox River Control Domes.

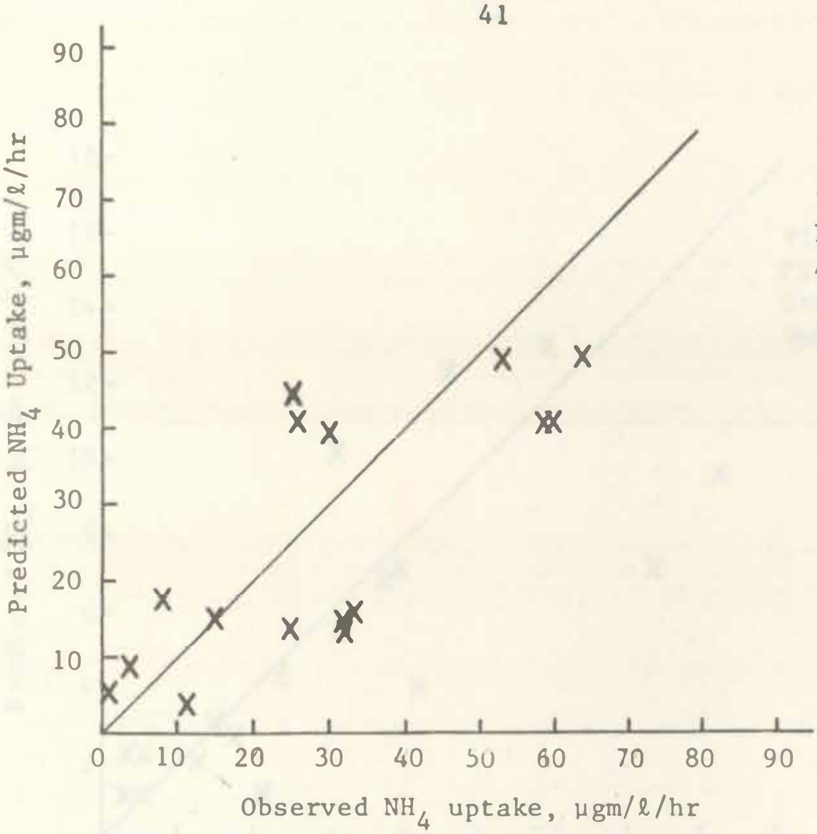


Figure 5-9.
Predicted and Observed Ammonium Uptake.

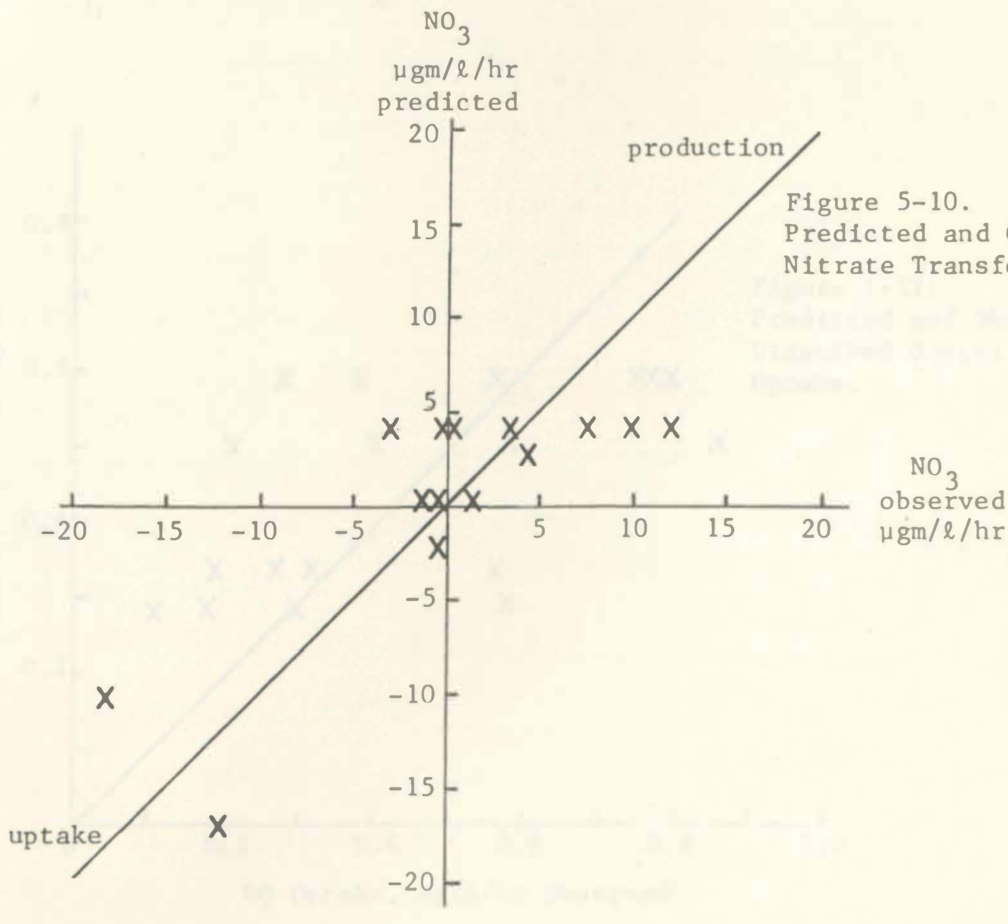


Figure 5-10.
Predicted and Observed Nitrate Transformations.

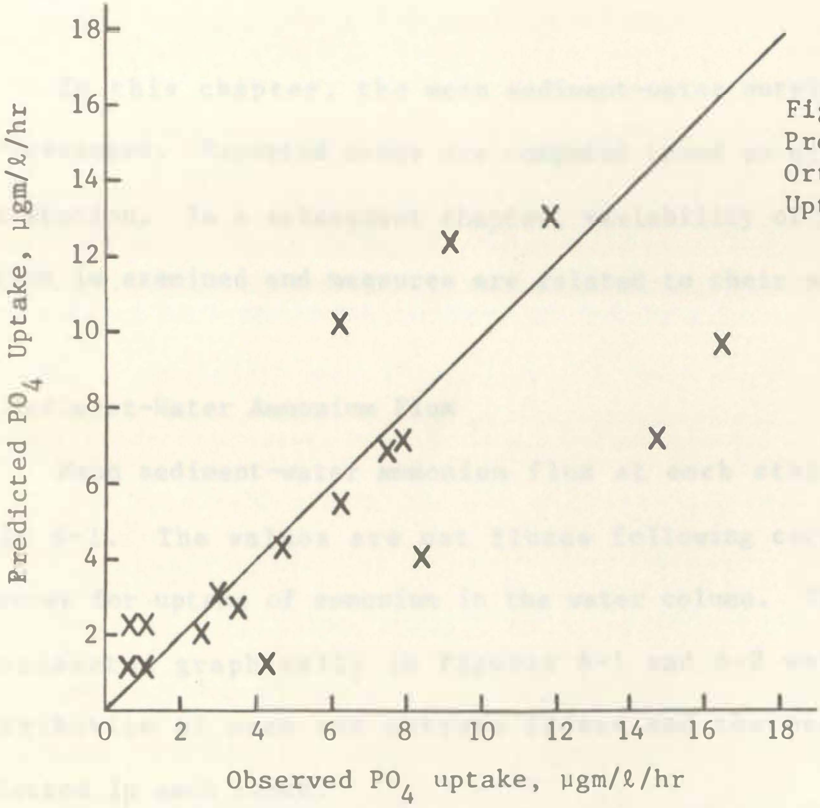


Figure 5-11.
Predicted and Observed
Ortho Phosphorus
Uptake.

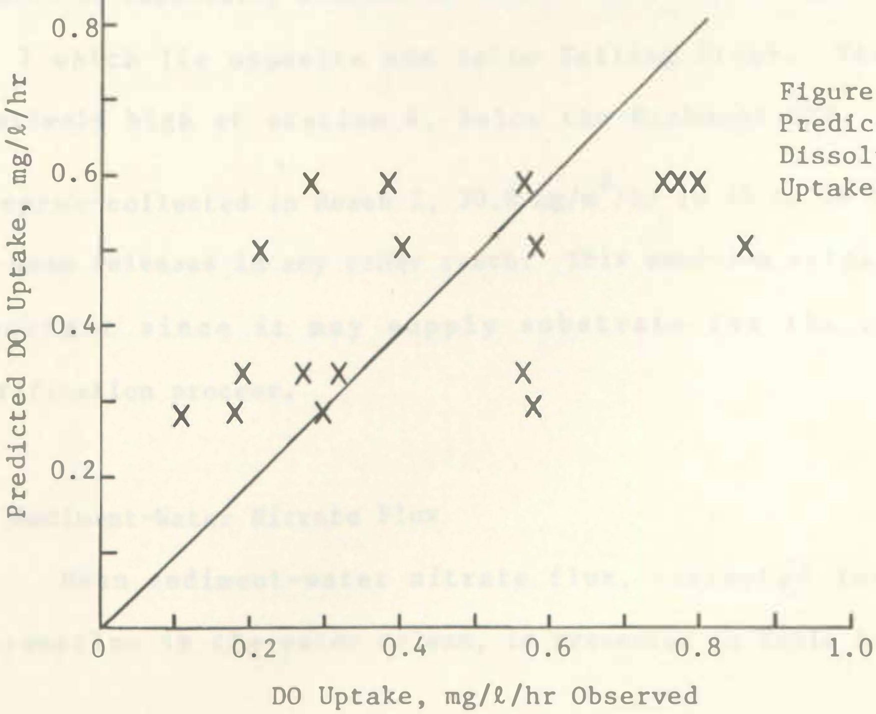


Figure 5-12.
Predicted and Observed
Dissolved Oxygen
Uptake.

Chapter VI. Results of Sediment Chambers

In this chapter, the mean sediment-water nutrient and oxygen fluxes are presented. Reported means are computed based on all measures collected at a station. In a subsequent chapter, variability of measurements within a station is examined and measures are related to their surroundings.

A. Sediment-Water Ammonium Flux

Mean sediment-water ammonium flux at each station is presented in Table 6-1. The values are net fluxes following correction of individual measures for uptake of ammonium in the water column. The same information is presented graphically in Figures 6-1 and 6-2 which show the spatial distribution of mean and extreme fluxes and the mean of all measures collected in each reach.

It can be seen that the majority of measures and the majority of stations demonstrate a net release of ammonium from the sediments. The release is especially evident in Reach I and, within Reach I, at stations 6 and 7 which lie opposite and below Falling Creek. The release is also relatively high at station 4, below the Richmond STP. The mean of all measures collected in Reach I, 30.8 $mg/m^2/hr$ is 15 to 26 times greater than the mean releases in any other reach. This ammonium release is especially important since it may supply substrate for the oxygen-demanding nitrification process.

B. Sediment-Water Nitrate Flux

Mean sediment-water nitrate flux, corrected for production or consumption in the water column, is presented in Table 6-1. Station means and extremes, and reach means are also shown in Figures 6-3 and 6-4. The majority of measures and the majority of stations demonstrate net uptake of nitrate by the sediments from the water column. In contrast to the ammonium flux, no distinct spatial trend in nitrate flux is evident. Mean uptake is in the range 0 to 5 mg/m^2/hr and one station, Station 19 in Reach III indicates a net sediment release of 0.4 mg/m^2/hr nitrate. Station 3 also suggests a negligibly small release but this result must be viewed with caution as it represents only a single observation.

The uptake of nitrate by the sediments may be construed as evidence of the denitrification process in which nitrate is reduced to a gaseous nitrogen form (7). The significance of this process to the system in question is that nitrate is the end product of the nitrification reaction. Production of nitrate in the water column has historically been viewed as partial evidence that nitrification is taking place (5). Consumption of nitrate by the sediments will act to conceal evidence of nitrification. Thus any determination of nitrification based on observations of nitrogen collected in the water column must take account of sediment-water fluxes or erroneous conclusions may be drawn.

C. Sediment-Water Ortho Phosphorus Flux

Mean sediment-water ortho phosphorus flux, corrected for consumption in the water column, is presented in Table 6-1. Station means and extremes and reach means are also shown in Figures 6-5 and 6-6.

The sediments tend to take up ortho phosphorus in Reach I, especially at Stations 6 and 7 in the vicinity of Falling Creek. This flux of ortho phosphorus into the sediments is likely due to sorption of ortho phosphorus onto mineral particles and subsequent settling, or to sorption of ortho phosphorus directly onto particles at the sediment-water interface. Downstream of Reach I and in the Appomattox River there is no distinct trend in ortho phosphorus flux. Stations may indicate mean release or consumption, generally at rates which are small in magnitude compared to those observed in Reach I. An exception is at Station 21 in which the largest ortho phosphorus releases in the system were consistently observed.

D. Sediment-Water Total Phosphorus Flux

Mean sediment-water total phosphorus flux is presented in Table 6-1. Total phosphorus flux measures were collected only in the James River and are not corrected for water column transformations. The correction is unnecessary since changes in total phosphorus in the water entrapped in the sediment domes must be due to exchange with the sediments. Station mean and extreme fluxes and reach means are also shown in Figure 6-7.

Total phosphorus fluxes are reflective of ortho phosphorus fluxes in that there is a tendency for sediment uptake in Reach I to be larger in magnitude than fluxes measured farther downstream. Mean uptake of total phosphorus in each reach also tends to be larger in magnitude than mean uptake of ortho phosphorus in the same reach. This enhanced flux of total phosphorus into the sediments is likely due to the settling of particulate phosphorus sorbed to mineral particles or bound up in organic detritus.

E. Sediment-Water Dissolved Oxygen Flux

Bottom respiration measures (which are not corrected for respiration in the water enclosed in the sediment chambers) are shown in Figures 6-8 and 6-9. The primary purpose of these figures is to illustrate the high degree of variability in bottom respiration. In view of this variability and of the lack of precision in the method used to correct the bottom respiration measures for water-column respiration, the analysis of individual sediment oxygen demand measures is of little significance. Rather, the mean bottom respiration at each station is corrected for the mean water-column respiration. The resultant mean sediment demand is presented in Table 6-1. Means at each station and reach are also shown in Figures 6-10 and 6-11. The left vertical axis is in units of $mg/m^2/hr$ consistent with the other fluxes reported in this study. The right vertical axis is in the conventional sediment oxygen demand units of $gm/m^2/day$.

No longitudinal trend in SOD is present in either the James or Appomattox Rivers although a high degree of spatial variability is evident. In Reach I, for example, SOD ranges from the minimum observed in the system, 0 $mg/m^2/hr$, at Station 5, to the maximum observations in the system, in excess of 70 $mg/m^2/hr$ at Stations 6 and 7, and back to a minimum of 0 $mg/m^2/hr$ at Station 8 in the space of 8 km. The origin of the spatial variability is not apparent. Large SOD measures do not appear to be associated with STP outfalls, however. Although SOD is a maximum at Stations 6 and 7 in the vicinity of Falling Creek, SOD is relatively low at Station 4, below the Richmond STP. In the Appomattox, SOD is greater at Station 22 above the Petersburg STP than at Station 21 below it.

When all SOD measures collected in a reach are averaged, it becomes apparent that sediment oxygen demand in all the reaches is roughly equivalent despite the differences in physical characteristics and wasteloading. Mean SOD in the system is 44 $mg/m^2/hr$ or approximately 1 $gm/m^2/day$.

Table 6-1. Mean Net Sediment-Water Fluxes

Station	NH4	NO3	PO4	Total P	DO
3	14.5	0.04	1.74	-1.96	-35.4
4	22.4	-1.26	-0.08	-3.23	-24.2
5					0
6	34.2	-2.48	-3.08	-3.88	-74.2
7	35.9	-2.56	-6.02	-6.42	-70.2
8					0
9					-28.7
10	- 0.64	-1.58	-0.80		-36.1
11	3.53	-2.09	0.20	-0.18	-33.9
12	3.46	-4.44	0.22	-0.47	-18.1
13	1.44	-4.08	-0.08	-0.60	-47.2
14	- 2.79	-1.14	-0.65		-50.9
15					-54.9
16					-71.3
17					-57.3
18					-49.5
19	1.90	0.43	0.14	-0.67	-42.3
20	1.87	-2.12	-1.39		-61.9
21	8.61	-0.10	3.40		-19.5
21B	- 2.94	-1.63	-1.24		-58.5
22					-64.2
23					-31.0
25					-20.0
Reach					
I	30.8	-2.08	-2.64	-4.19	-45.4
II	1.18	-3.17	-0.16	-0.46	-44.8
III	1.90	0.43	0.14	-0.67	-47.3
IV	1.97	-1.32	-0.24		-44.1
Grand Mean	9.82	- 1.53	-0.75	-1.67	-44.4

N.B. All measures in $mg/m^2/hr$

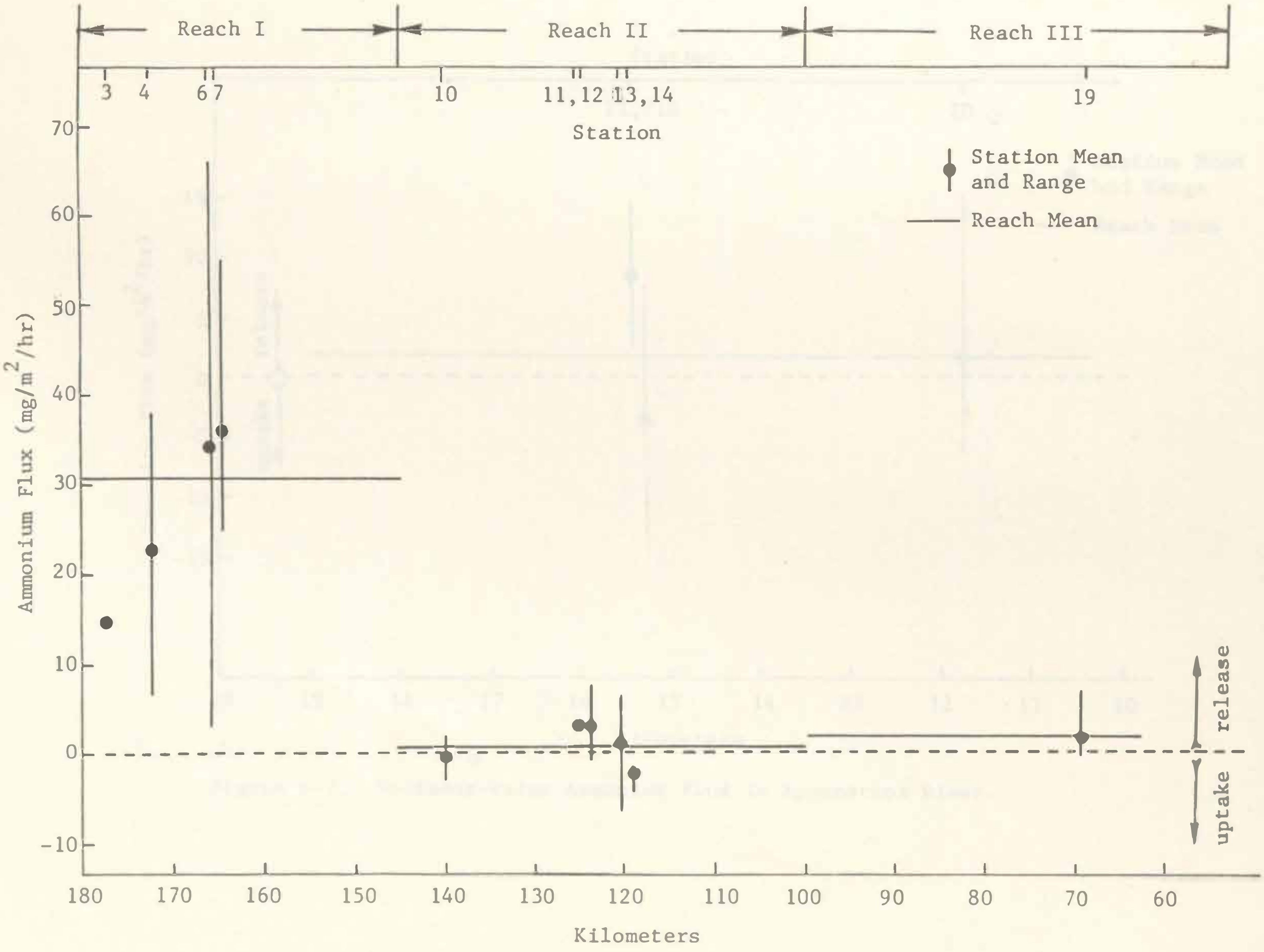


Figure 6-1. Sediment-Water Ammonium Flux in James River.

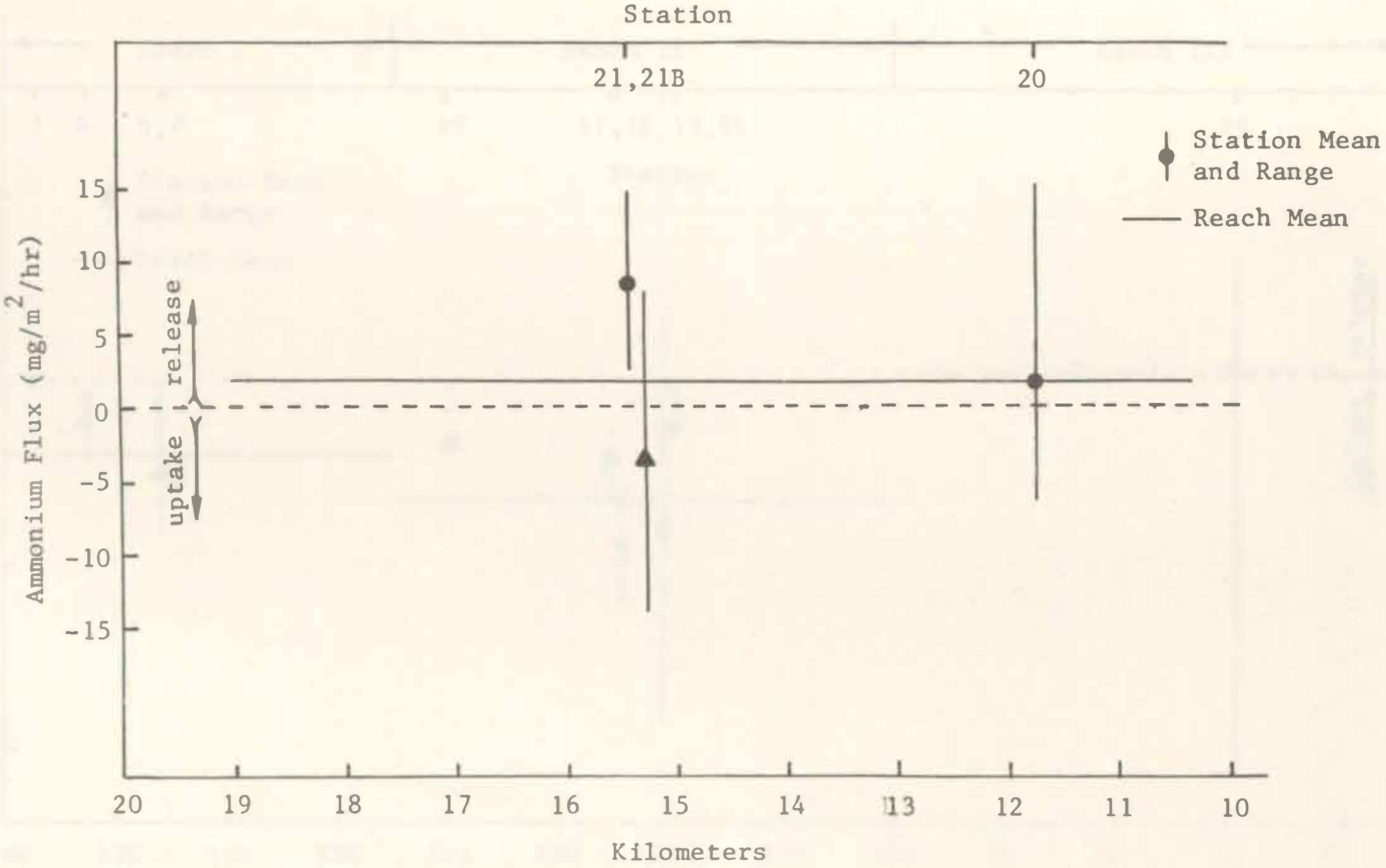


Figure 6-2. Sediment-Water Ammonium Flux in Appomattox River.

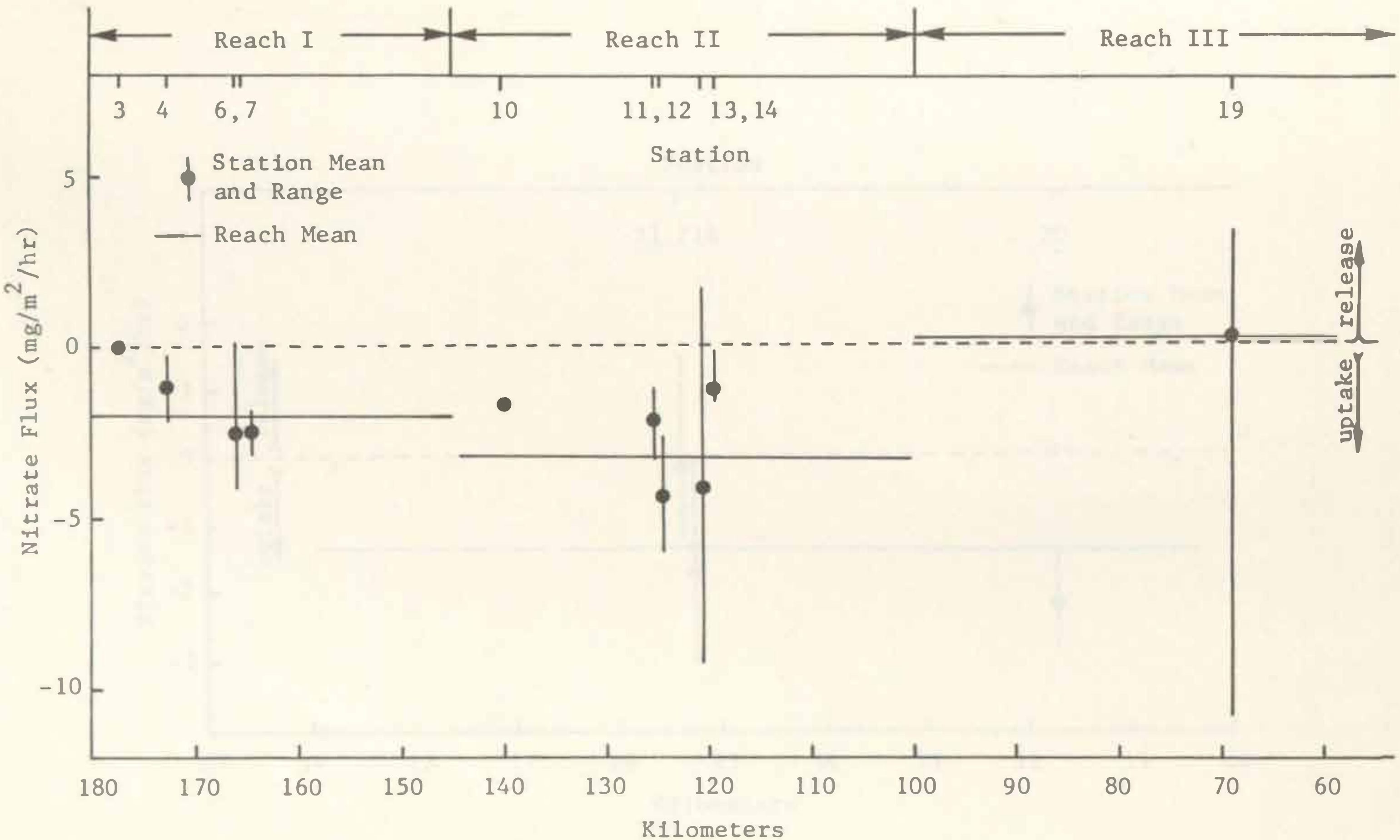


Figure 6-3. Sediment-Water Nitrate Flux in James River.

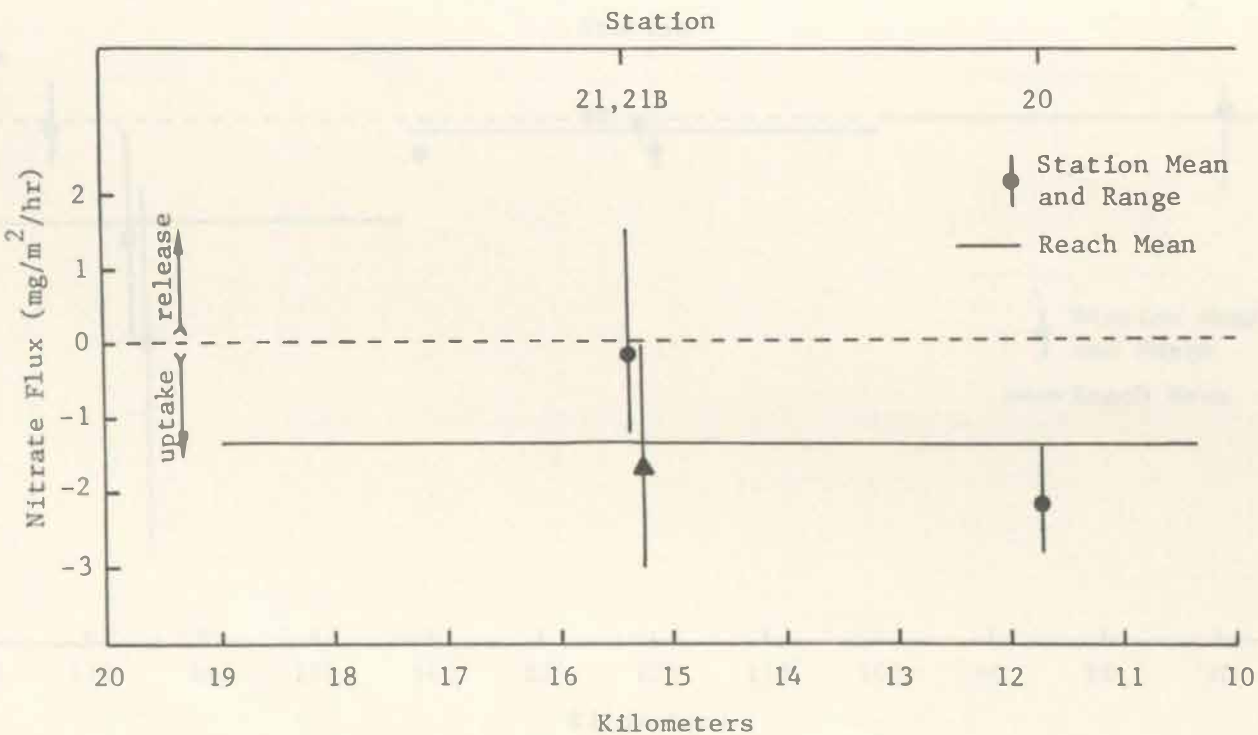


Figure 6-4. Sediment-Water Nitrate Flux in Appomattox River.

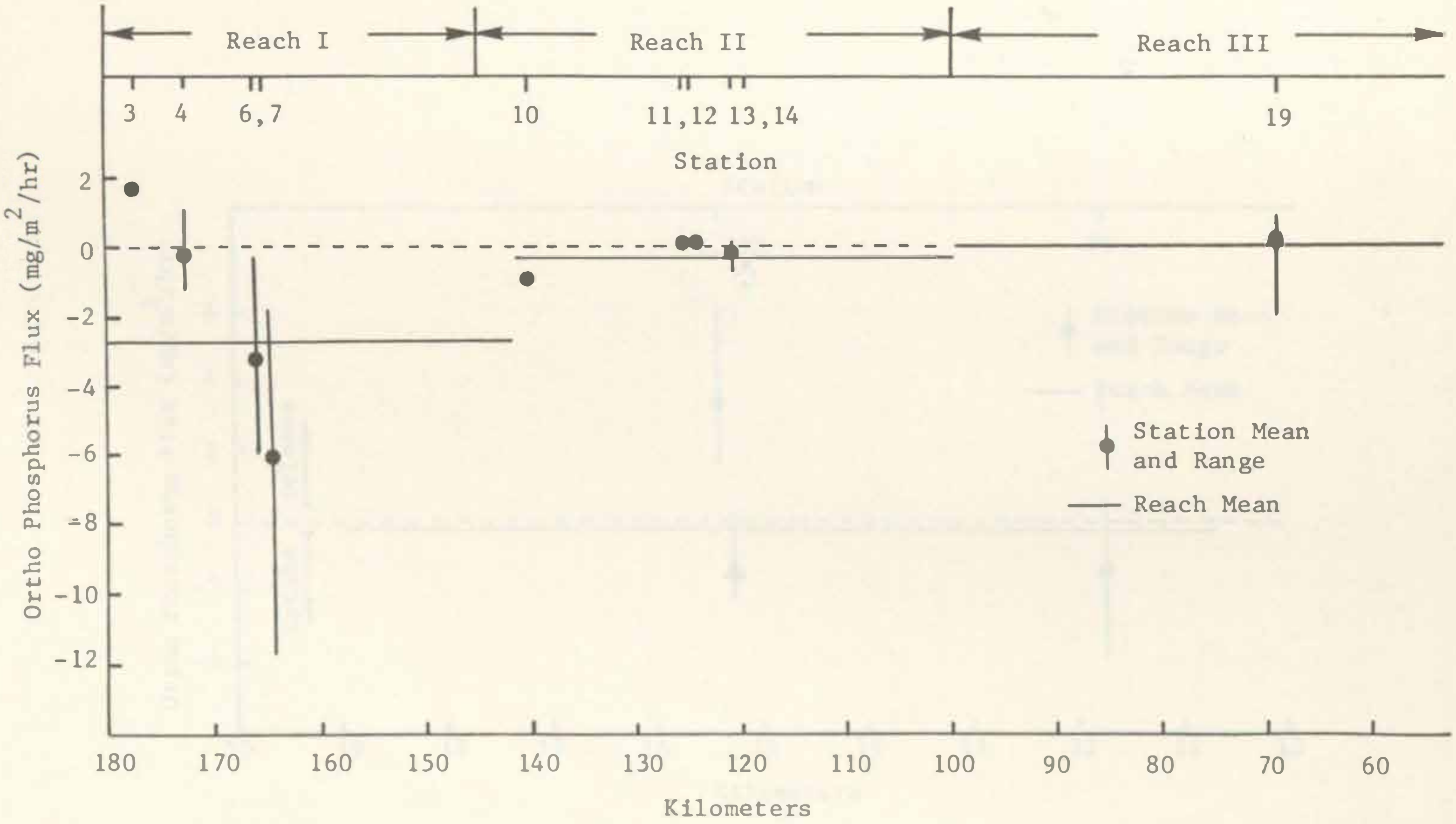


Figure 6-5. Sediment-Water Ortho Phosphorus Flux in James River.

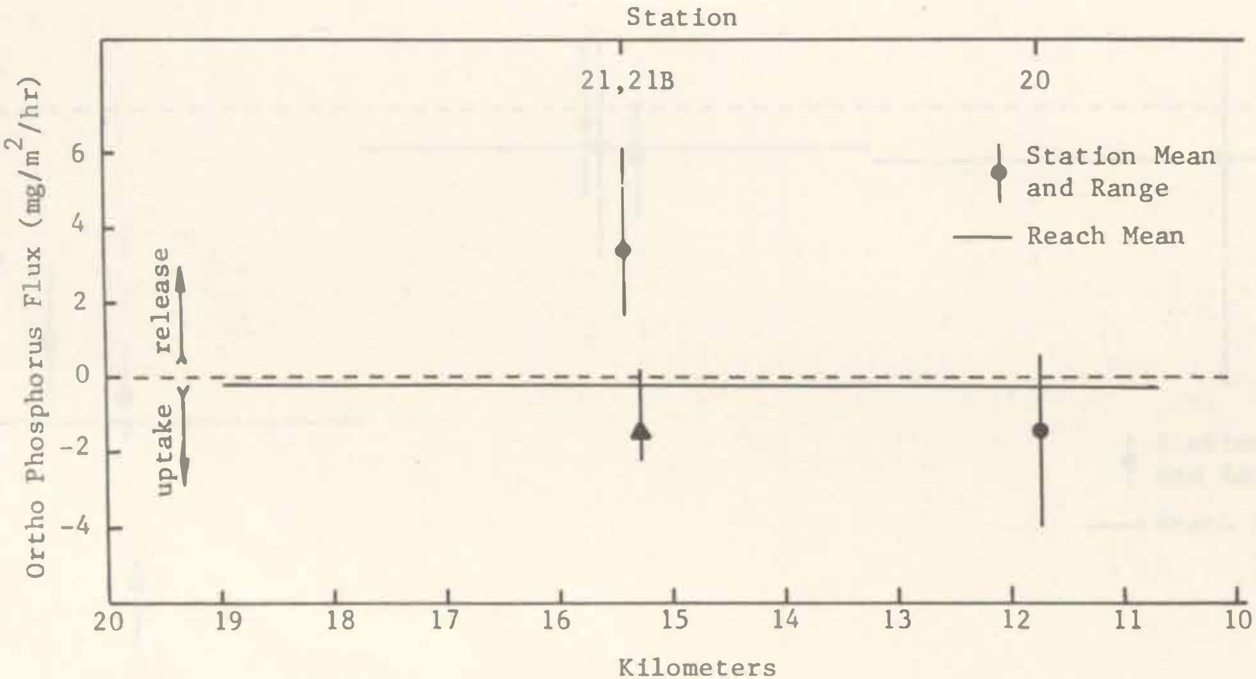


Figure 6-6. Sediment-Water Ortho Phosphorus Flux in Appomattox River.

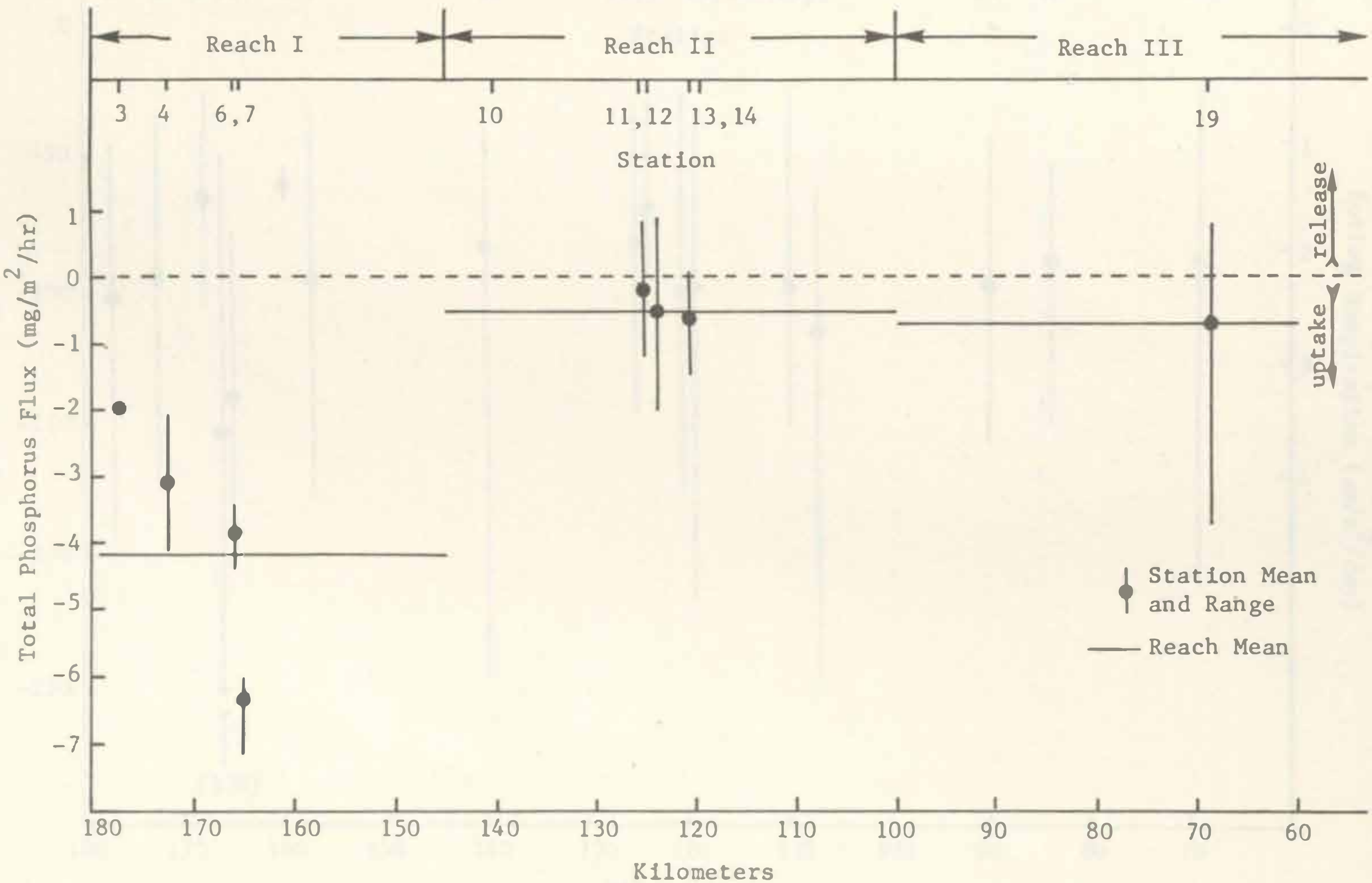


Figure 6-7. Sediment-Water Total Phosphorus Flux in James River.

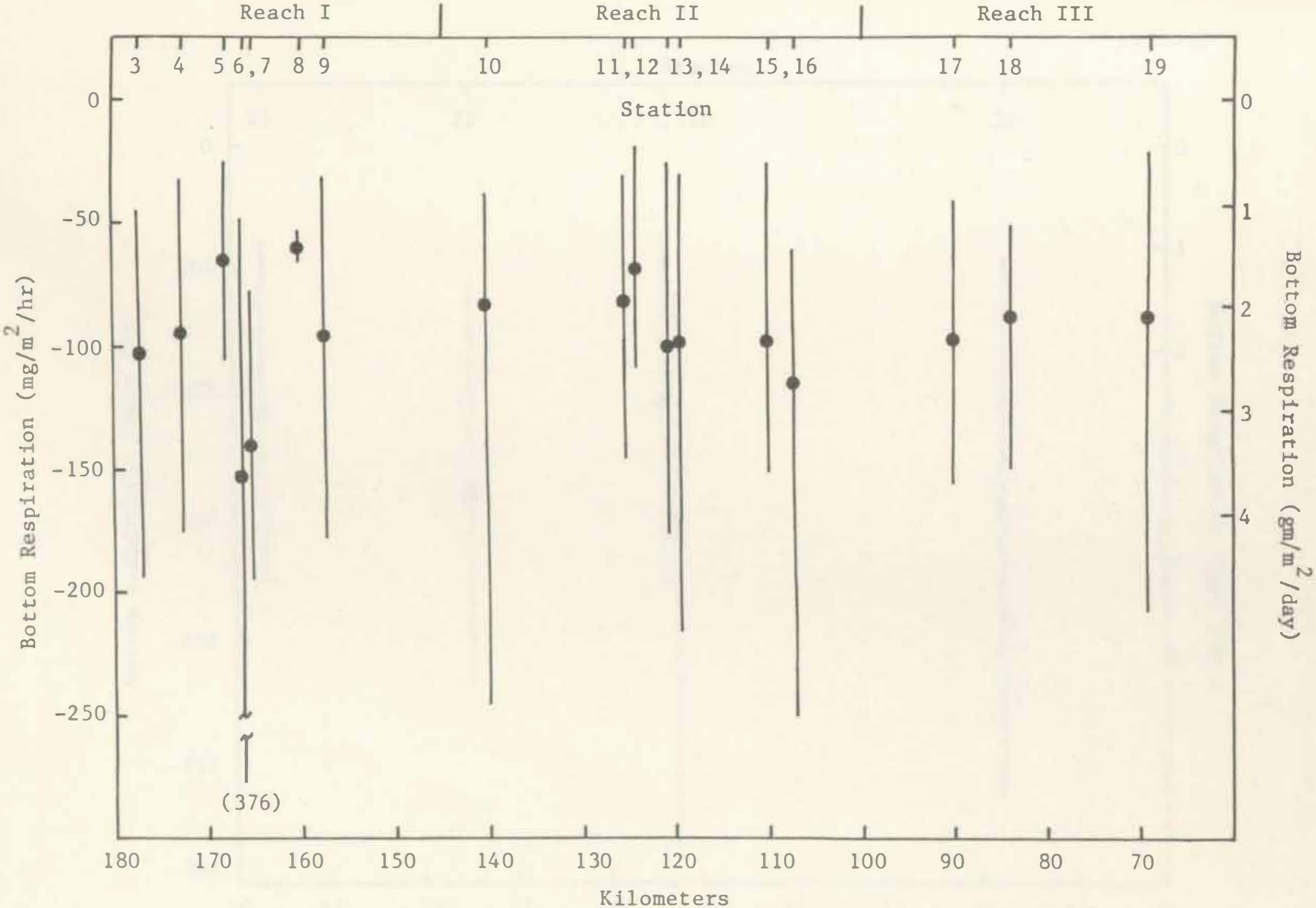


Figure 6-8. Bottom Respiration in James River.

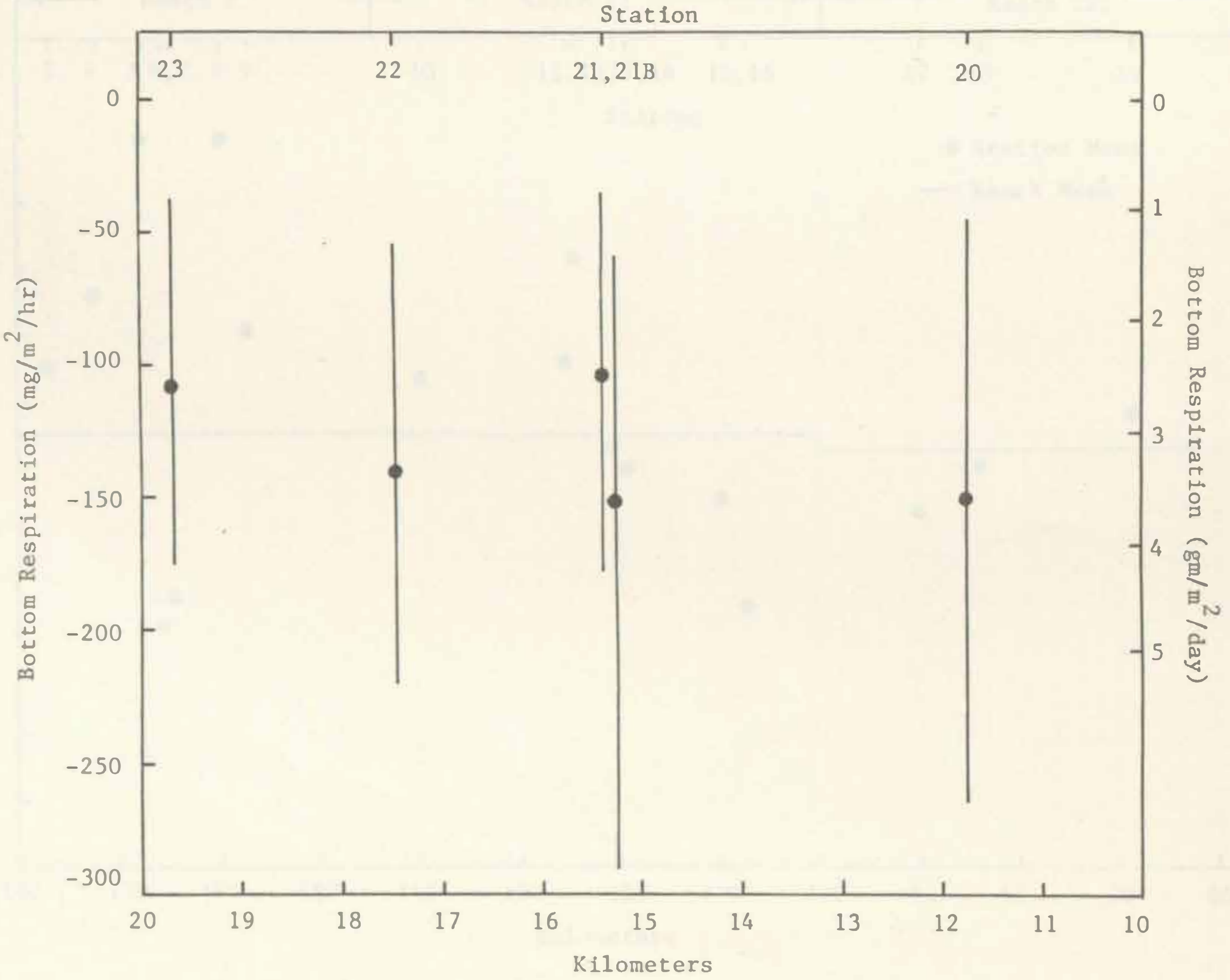


Figure 6-9. Bottom Respiration in Appomattox River.

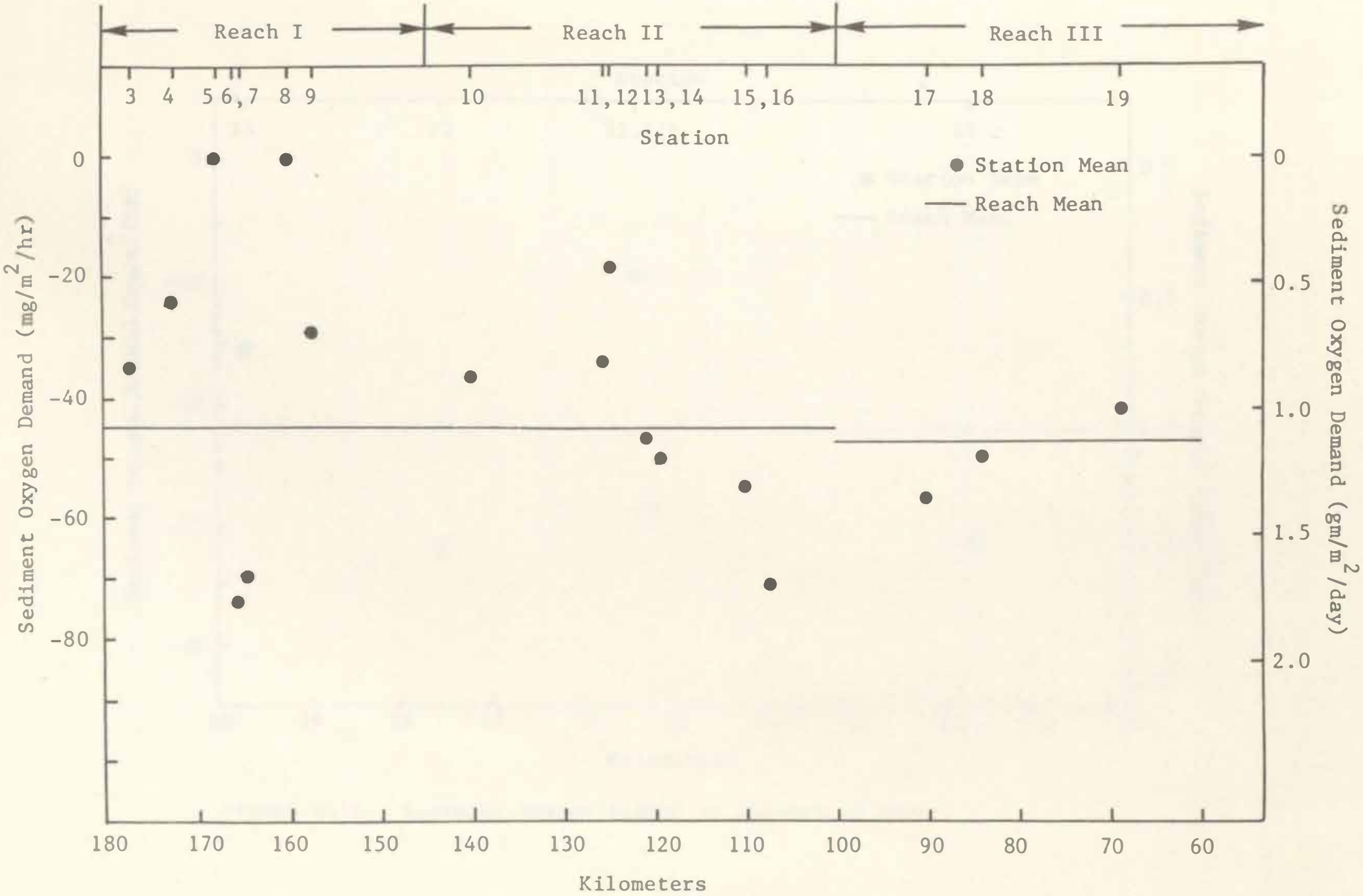


Figure 6-10. Sediment Oxygen Demand in James River.

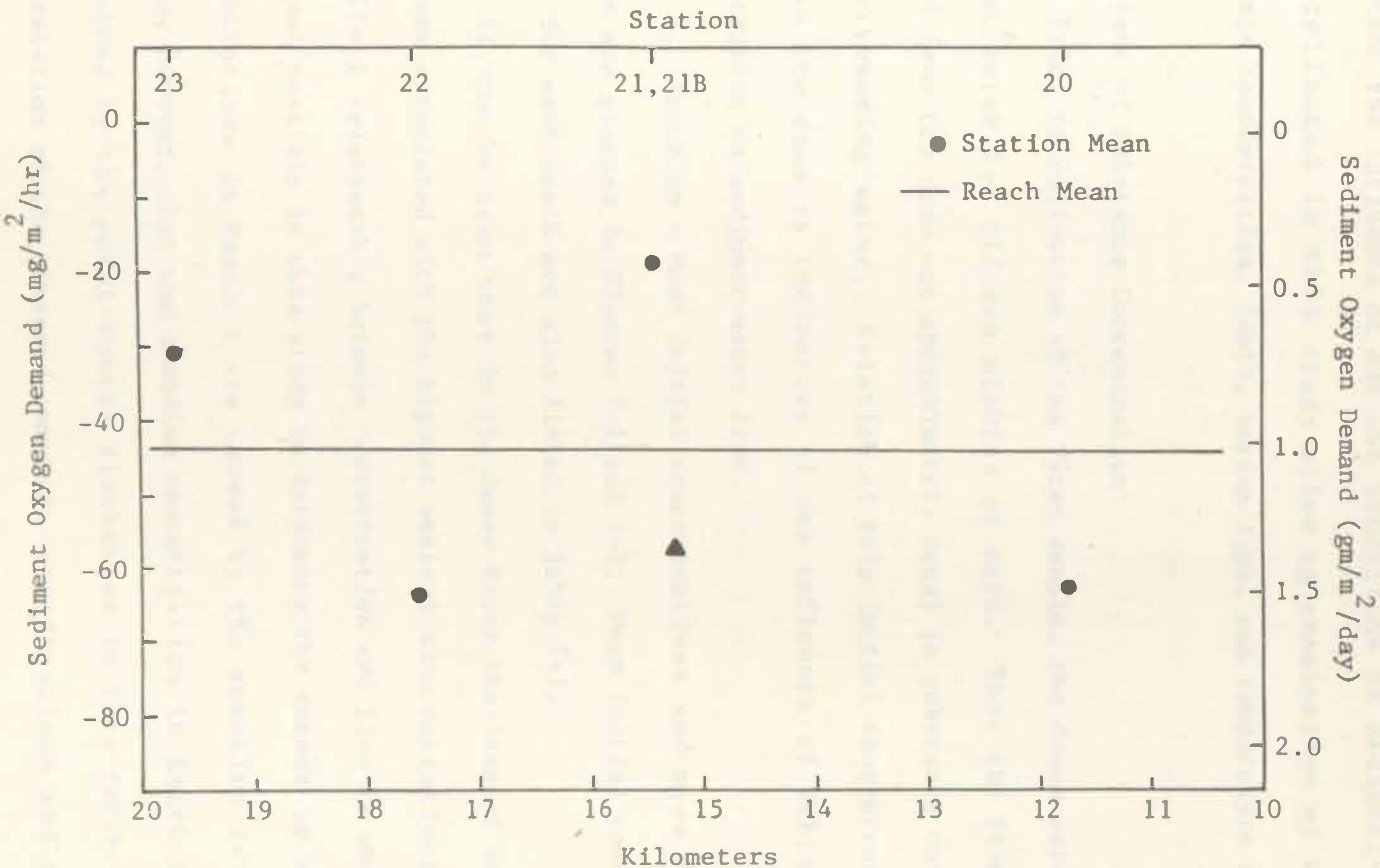


Figure 6-11. Sediment Oxygen Demand in Appomattox River.

Chapter VII. Relation of Fluxes to Their Environment

In order to manage and model water quality, it is useful to understand the influence of ambient conditions on sediment-water fluxes. Data collected in this study allow an examination of the effects of substance concentration, depth, bottom type, and temperature on the fluxes.

A. Effect of Substance Concentration

Prior to collection of the first sample, the domes were flushed with ambient water for fifteen minutes or more. Thus the first water sample removed from the dome was approximately equal in substance concentration to the surrounding water. Relation of this initial concentration to the net flux in the dome is indicative of the influence of ambient substance concentration on sediment-water flux.

1. Ammonium - Mean initial concentrations and mean fluxes at each station are plotted in Figures 7-1 and 7-2. Mean initial concentrations and fluxes for each reach are also listed in Table 7-1.

It can be seen that in the James River the largest ammonium release rates are associated with the highest ambient concentrations. The cause-and-effect relationship between concentration and flux is unclear, however. It is not possible in this study to determine the extent to which the high concentrations in Reach I are caused by the ammonium releases. It is certain, however, that the ammonium concentration in Reach I is partially determined by the point-source discharges in this reach. A qualitative interpretation of the observed ammonium concentrations and fluxes is that high concentrations are evidence of water which is impacted by waste discharges. These same impacted waters demonstrate a large benthic release of ammonium.

No relationship of concentration and flux is apparent in the limited spatial distribution of measures collected in the Appomattox. Reference to Table 7-1 indicates that release in the Appomattox is roughly equivalent to release in Reaches II and III of the James although mean concentration in the Appomattox is higher than in the lower reaches of the James. Thus the releases in the Appomattox are lower than would be expected if ammonium release were linearly proportional to ambient concentration.

2. Nitrate - Mean initial concentrations and mean fluxes at each station are plotted in Figures 7-3 and 7-4. Mean initial concentrations and fluxes for each reach are also listed in Table 7-1.

In Reach I of the James, it can be seen that the rate of nitrate removal increases as the nitrate concentration increases. The one-to-one correspondence is not evident in Reach II but both the highest concentrations and the highest removal rates occur in this reach. Reach III exhibits the lowest mean concentration in the James and a net release of nitrate. Thus the rate of nitrate removal is seen to be proportional to the quantity available. At very low concentrations, nitrate may be released from the sediments.

As with ammonium, no correspondence of flux and concentration is evident in the Appomattox. Mean concentrations in the Appomattox are roughly equivalent to Reach III of the James but the Appomattox shows a greater tendency for sediment uptake. An explanation of this phenomenon is that, in the absence of ammonium, nitrate is taken up as a nutrient by plankton and other biota in Reach III. Sufficient ammonium is available to supply biotic uptake in the Appomattox so nitrate is instead denitrified in the sediments.

3. Ortho Phosphorus - Mean initial concentrations and mean fluxes at each station are plotted in Figures 7-5 and 7-6. Mean initial concentrations and fluxes for each reach are also listed in Table 7-1.

It is immediately evident that the largest rates of ortho phosphorus uptake occur in Reach I of the James in which the greatest quantities of ortho phosphorus are available. In Reach II there is also evidence of a relationship between concentration and flux. Highest concentrations occur at Stations 10 and 14 which exhibit a small sediment uptake. Lower concentrations occur at Stations 11 to 13 which exhibit small releases of ortho phosphorus. The split between uptake and release occurs at approximately 0.03 mg/l ortho phosphorus. At higher concentrations sediments uptake ortho phosphorus. At lower concentrations sediments release ortho phosphorus. This relation holds true in Reach III in which mean initial ortho phosphorus concentration is 0.02 mg/l and in which a net release occurs.

In the Appomattox, concentrations at Stations 21B and 20 exceed 0.03 mg/l and the sediments take up ortho phosphorus. Station 21 exhibits an anomalous release of ortho phosphorus, however. A single anomalous release also occurred at Station 3 in the James. Thus the dependence of flux on concentration is useful as a guideline but is subject to exceptions.

4. Total Phosphorus - Mean initial concentrations and mean fluxes at each station are plotted in Figure 7-7. Mean initial concentrations and fluxes for each reach are also listed in Table 7-1.

As with ortho phosphorus, Reach I exhibits both the highest total phosphorus concentrations and the greatest rates of sediment uptake.

Concentrations and uptake rates are lesser in Reaches II and III. Thus the rate of total phosphorus uptake is proportional to the quantity of phosphorus available.

B. Effect of Depth

In 1983, samples were collected at random depths at each station. In 1984, systematic efforts were made to collect measures at two depths at each James River station sampled. As a result, data exists on which to base an examination of the effects of depth on the flux of ammonium, nitrate, and ortho phosphorus at four stations in the James.

To conduct the analysis, fluxes are classified as 'deep' (depth greater than two meters) or 'shallow' (depth less than or equal to two meters). The means of the deep and shallow measures at each station are presented in Table 7-2 and shown in the bar charts of Figure 7-8. It should be noted explicitly that the sample sizes are small, especially at Stations 13 and 14 for which only one shallow measure each is available. Still analysis suggests there is an effect of depth on sediment-water fluxes.

At Station 6, ammonium release and nitrate uptake are greater in the deep measures than in the shallow measures. Station 13 exhibits similar behavior. At station 14, the influence of depth on ammonium and nitrate fluxes is reversed. Ammonium release and nitrate uptake are greater in the shallow measures. Station 19 is consistent with Stations 6 and 13 in that ammonium release is greater in the deep measures than in the shallow measures. Nitrate is released in both the depths and shoals at approximately equal rates.

Ortho phosphorus is taken up more rapidly in the deep measures than the shallow measures at Stations 6 and 14. At Station 13, ortho phosphorus is taken up in the deep measures and released in the shallow measure. At Station 19, ortho phosphorus is released in both deep and shallow measures but the release rate is lower in the deep measures. Thus the deep sediments show a greater affinity for ortho phosphorus at all stations. Deep sediments take up ortho phosphorus at a faster rate than shallow sediments and, when release occurs, deep sediments release ortho phosphorus at a slower rate than shallow sediments.

Bottom respiration measures are used to examine the influence of depth on sediment oxygen demand. Bottom respiration measures are preferred for this purpose since they are more accurate than the corrected measures due to uncertainty in the correction term.

Due to the use of SOD cylinders, comparison of deep and shallow respiration measures are possible at more stations than nutrient flux measures. Preliminary analysis indicated there were stations at which respiration increased with depth and stations at which it decreased with depth. Averaging of deep and shallow measures in each reach produced a more clear trend, however, as shown in Table 7-3 and Figure 7-9. In all three reaches of the James, bottom respiration is larger at depths exceeding two meters than at depths less than two meters. The difference is relatively small in Reaches I and II, however, and the trend for respiration to increase with depth may be reversed at individual stations.

C. Effect of Bottom Composition

The nature of the bottom sediments is difficult to quantify although the bottom may be qualitatively described with terms such as ´muddy´, ´sandy´, or ´clay-like´. An illustration of the potential influence of bottom composition on sediment-water fluxes is gained by examination of the measures collected at Station 21B in the Appomattox River on July 6, 1984. Flux measures were collected in two domes each on the left and right hand sides of the channel at the same depth, approximately 1.5 m. Average fluxes on the two sides are presented in Table 7-4 and Figure 7-10.

It can be seen there was a distinct difference in the fluxes on the two sides of the channel. The left side took up nitrate, ortho phosphorus, and dissolved oxygen at a faster rate than the right side and the left side took up ammonium while the right side released this substance. The differences in fluxes are attributed to a difference in bottom types. The left side of the channel was sandy while the right side was muddy.

The influence of bottom composition illustrated here is extreme. Still, it cautions against collecting measures at only a single location and against placing too much reliance on individual flux measures.

D. Influence of Temperature on Respiration

It has been shown that substance concentration, depth, and bottom composition all influence sediment-water fluxes. In view of these influences, it is difficult to isolate the effects of temperature from a small number of samples. The most promising data base is comprised of the bottom respiration measures. There are more of these measures (203) at a greater range of temperatures (12 to 31 C) than any other flux measures.

Bottom respiration is plotted as a function of temperature in Figure 7-11. Data points represent the mean of all observations at that temperature. Respiration measures are uncorrected for water-column respiration and are combined from all reaches and depths.

No dependence of bottom respiration on temperature is evident. Analyses of respiration in each reach and at individual depths also evidences no dependence of respiration on temperature. Although it is clearly known that temperature influences microbial processes such as respiration, other deterministic and random factors active in the environment render the effect of temperature impossible to perceive in a limited range of field observations. The implication of this analysis is to caution against the application of simplistic exponential relationships in an attempt to predict the effect of temperature on sediment-water fluxes.

Table 7-1. Mean Initial Concentrations and Fluxes

	Reach I	Reach II	Reach III	Reach IV
Ammonium				
Concentration	0.69	0.13	0.02	0.42
Flux	30.8	1.18	1.90	1.97
Nitrate				
Concentration	0.42	0.91	0.18	0.20
Flux	-2.08	-3.17	0.43	-1.32
Ortho Phosphorus				
Concentration	0.27	0.03	0.02	0.10
Flux	-2.64	-0.16	0.14	-0.24
Total Phosphorus				
Concentration	0.46	0.15	0.08	
Flux	-4.19	-0.46	-0.67	

N.B. All fluxes in $mg/m^2/hr$
All concentrations in mg/l

Table 7-2. Deep and Shallow Sediment-Water Fluxes

	Ammonium	Nitrate	Ortho Phosphorus
Station 6			
Shallow (4)	20.6	-1.20	-2.77
Deep (6)	43.2	-3.34	-3.28
Station 13			
Shallow (1)	0.57	-3.38	0.19
Deep (6)	1.58	-4.20	-0.13
Station 14			
Shallow (1)	-2.18	-1.50	-0.11
Deep (2)	-3.09	-0.96	-0.92
Station 19			
Shallow (4)	0.60	0.45	0.22
Deep (14)	2.27	0.43	0.12

N.B. All fluxes in $mg/m^2/hr$
( ) indicates number of observations
Shallow: depth < 2 m
Deep: depth > 2 m

Table 7-3. Deep and Shallow Bottom Respiration Measures

	Reach I	Reach II	Reach III
Bottom Respiration			
Shallow	-100 (17)	-81 (9)	-57 (7)
Deep	-123 (41)	-94 (53)	-98 (32)

N.B. Bottom respiration in $mg/m^2/hr$
Not corrected for water-column respiration
( ) indicates number of observations

Table 7-4. Flux at Station 21B. July 6, 1984

	Left (Sandy)	Right (Muddy)
Ammonium	-11.6	5.7
Nitrate	-2.90	-0.36
Ortho Phosphorus	-1.57	-0.91
Bottom Respiration	-161	-67

N.B. All fluxes in $mg/m^2/hr$

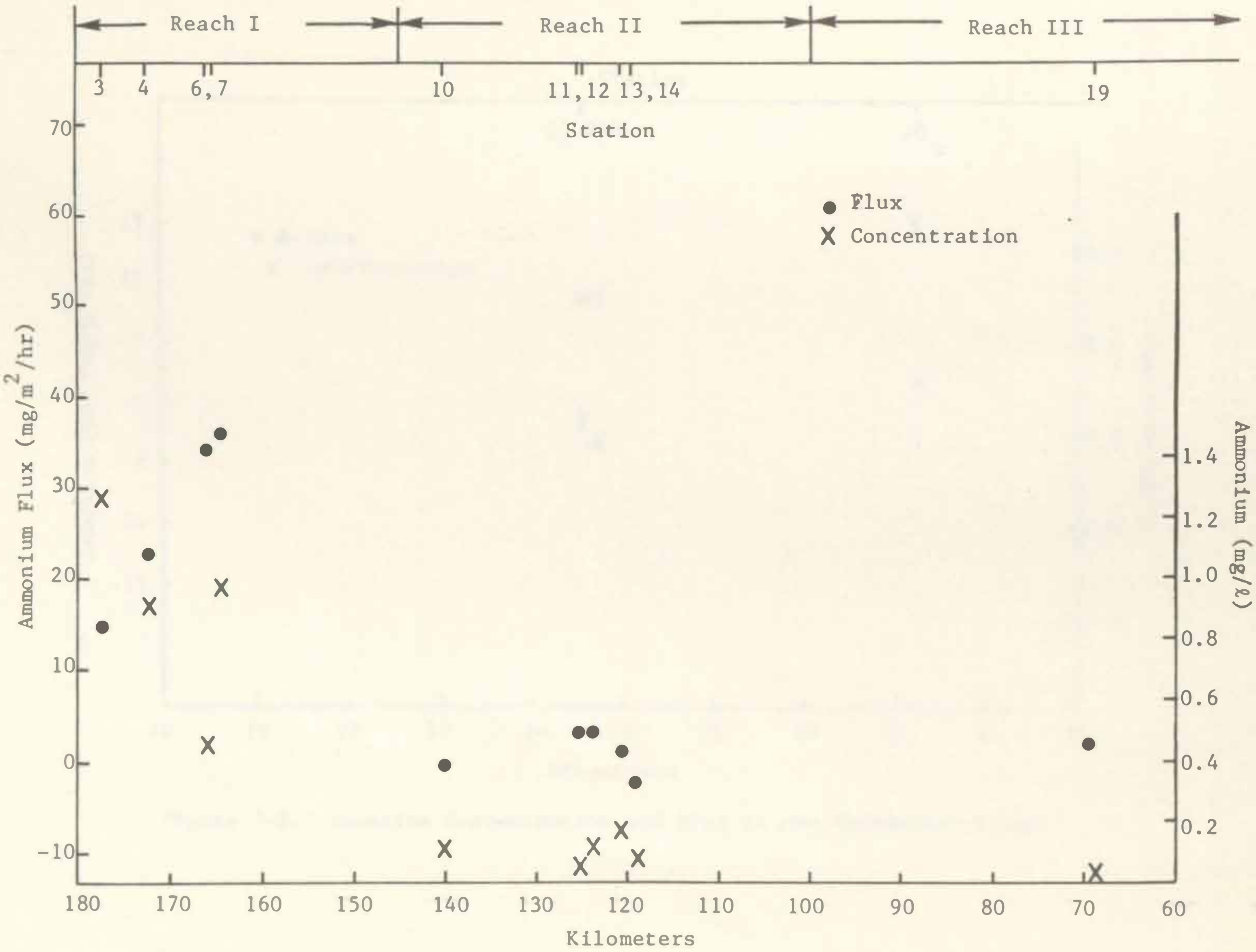


Figure 7-1. Ammonium Concentration and Flux in the James River.

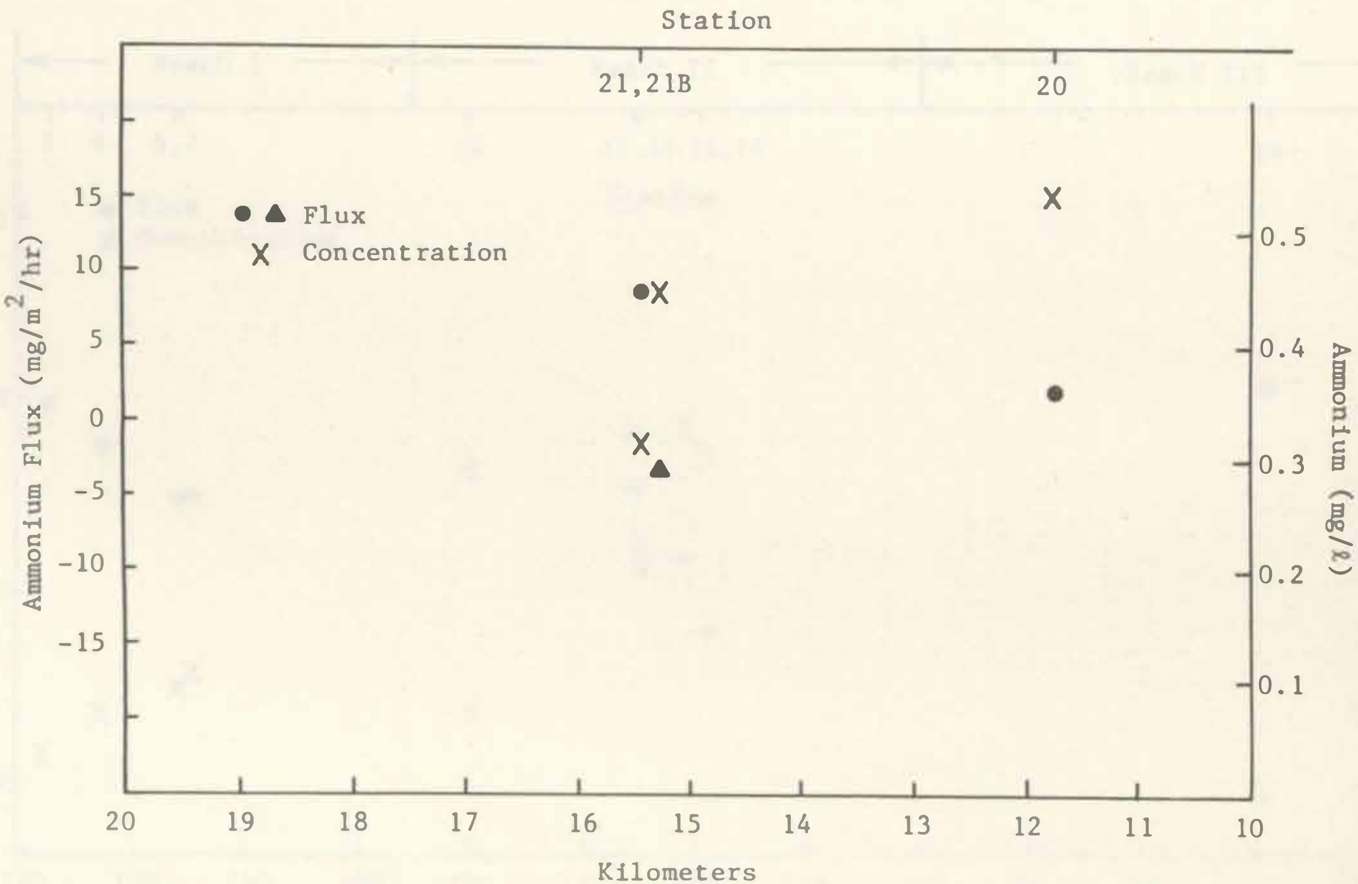


Figure 7-2. Ammonium Concentration and Flux in the Appomattox River.

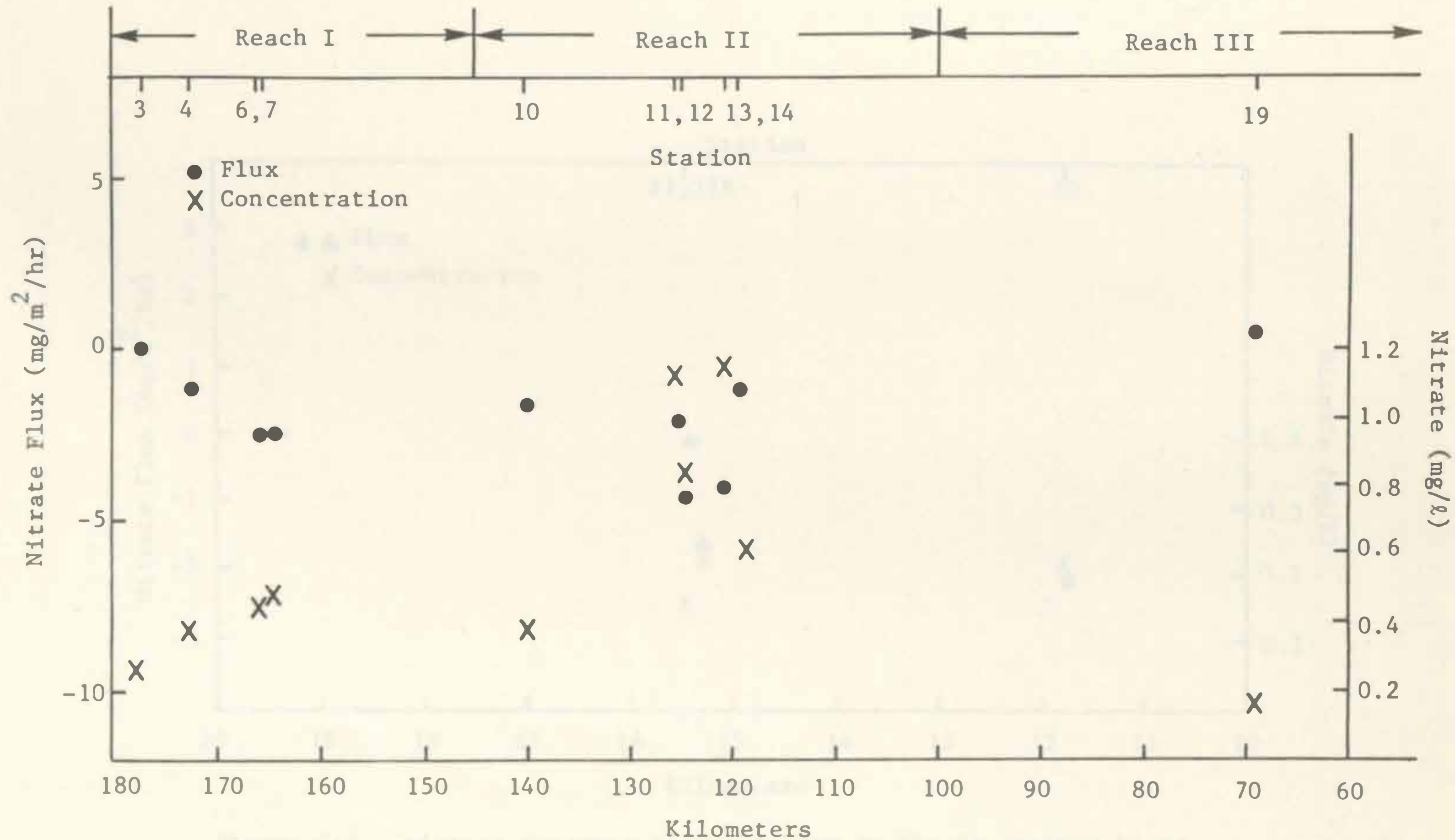


Figure 7-3. Nitrate Concentrations and Flux in the James River.

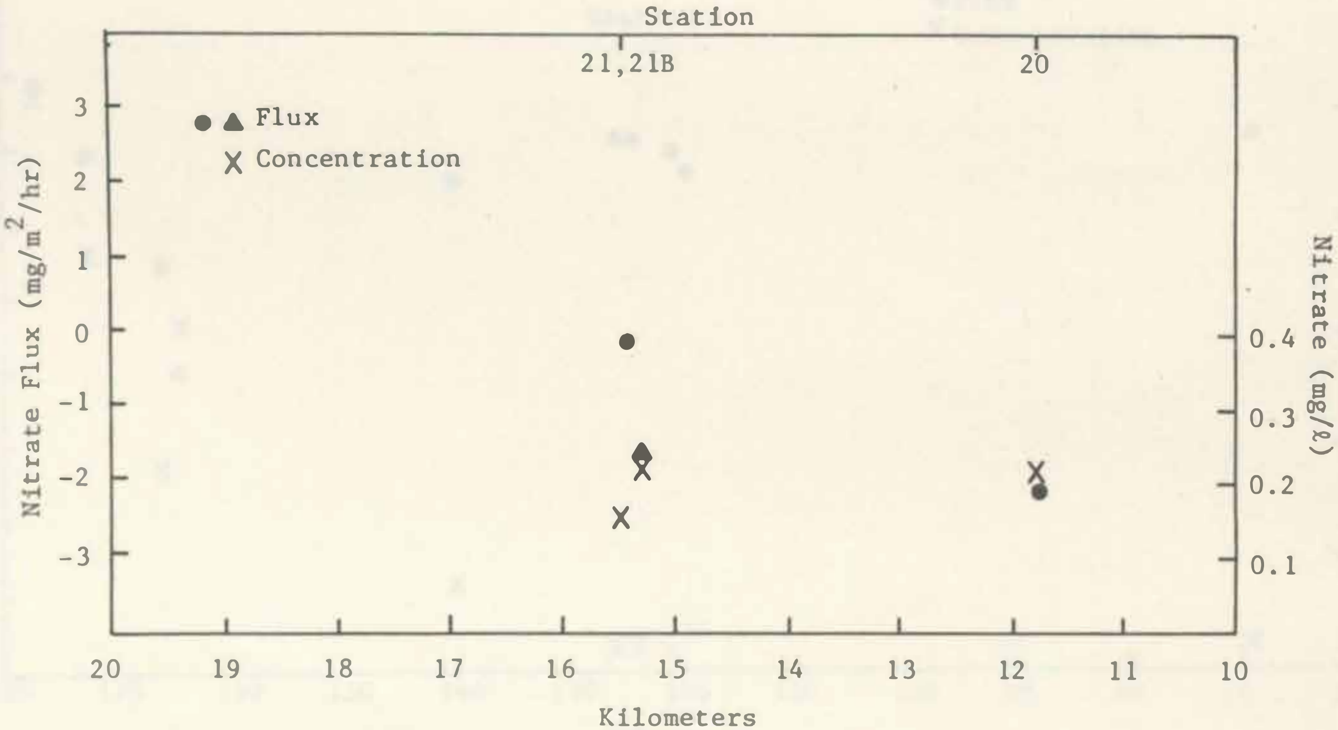


Figure 7-4. Nitrate Concentration and Flux in the Appomattox River.

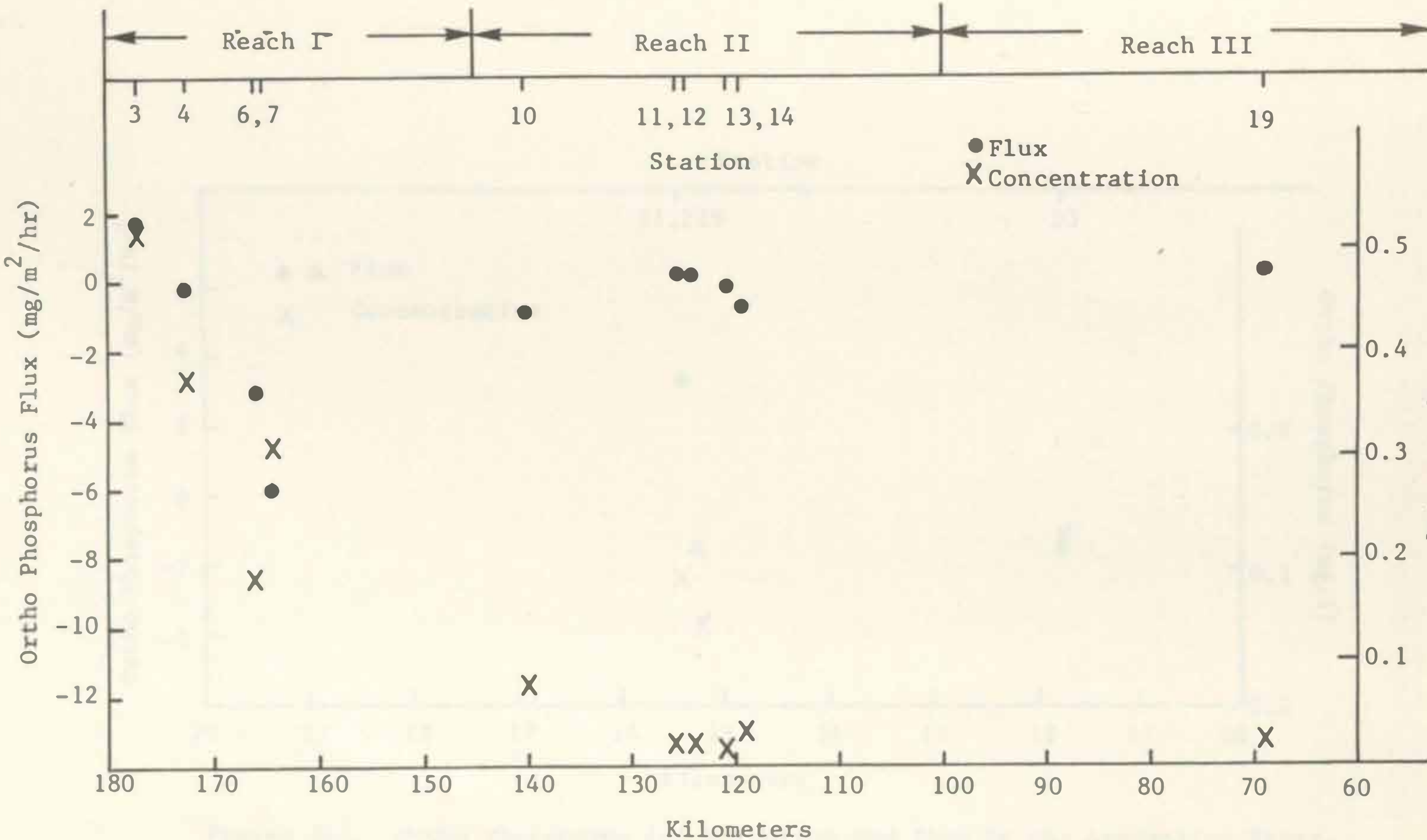


Figure 7-5. Ortho Phosphorus Concentration and Flux in the James River.

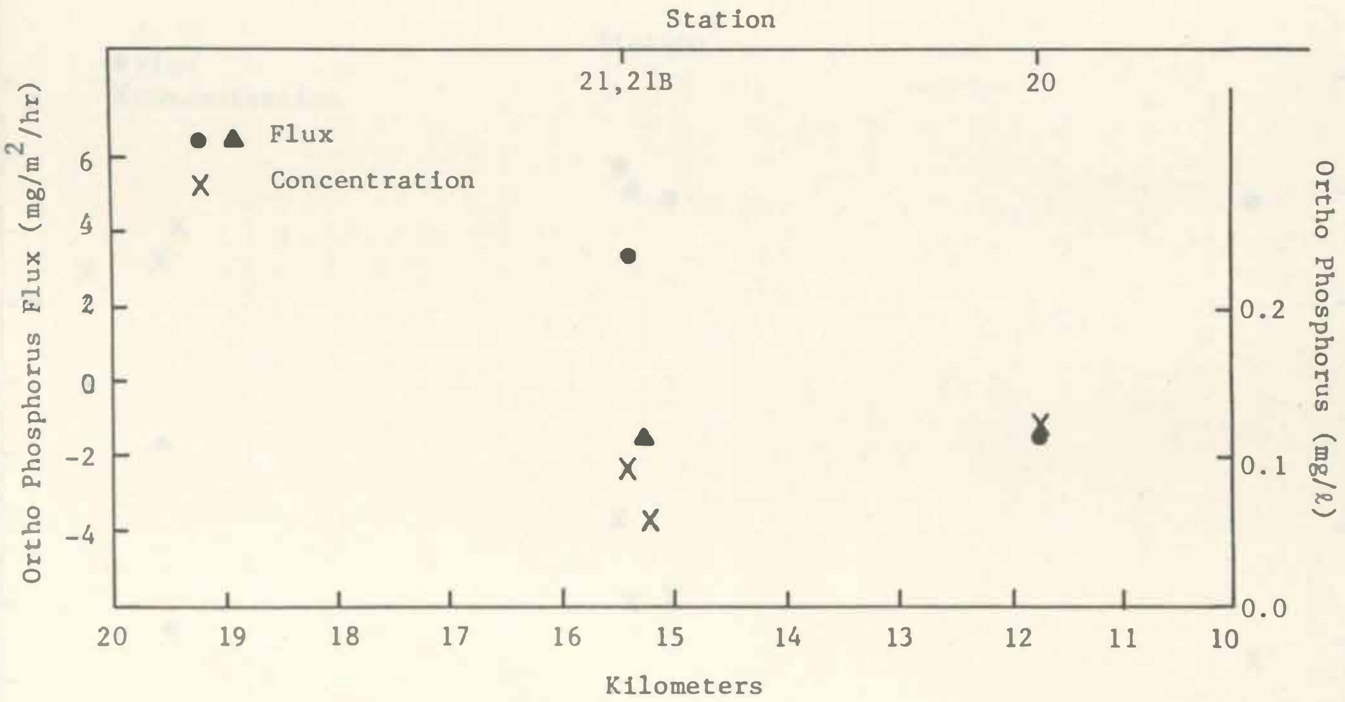


Figure 7-6. Ortho Phosphorus Concentration and Flux in the Appomattox River.

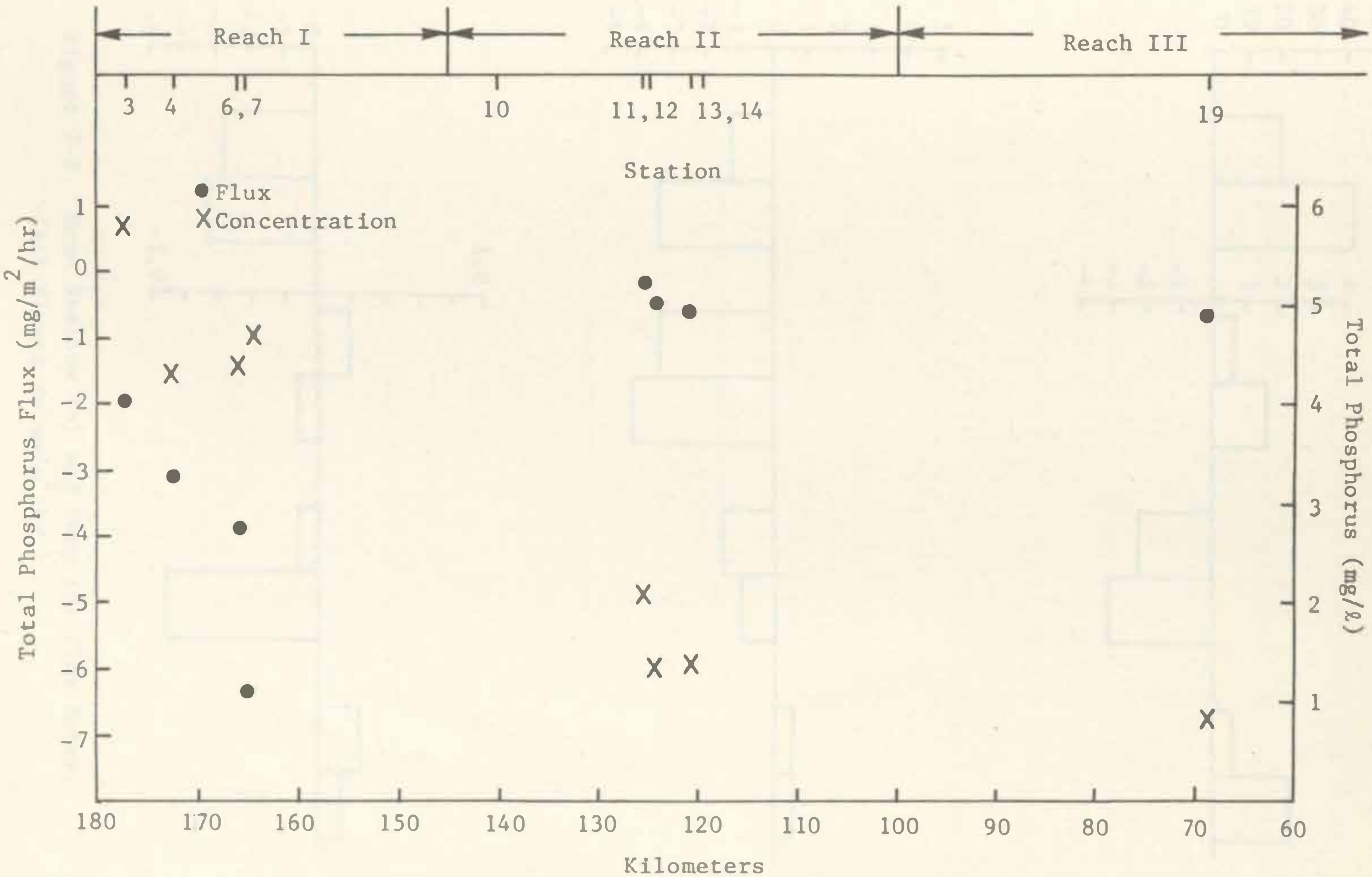


Figure 7-7. Total Phosphorus Concentration and Flux in the James River.

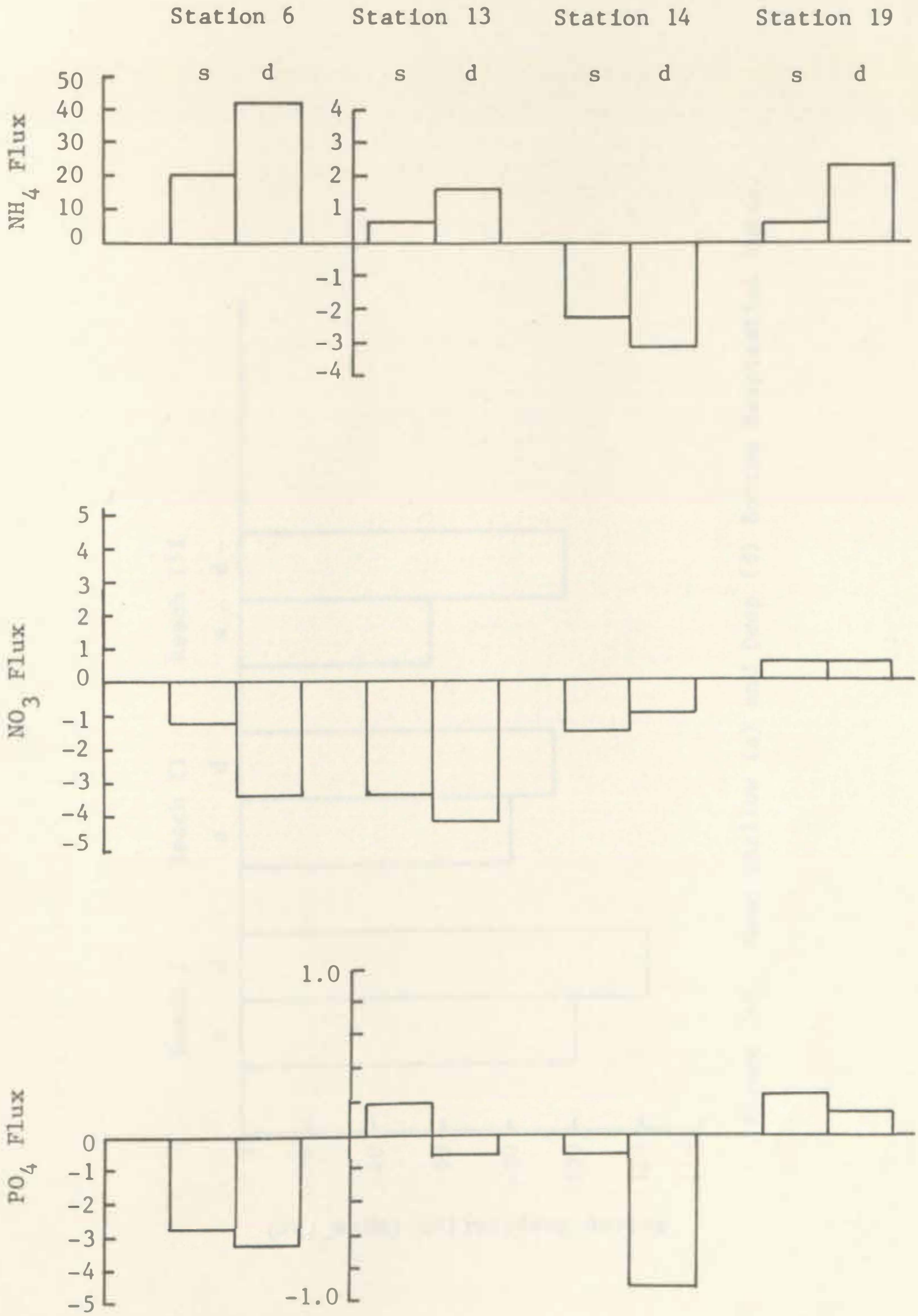


Figure 7-8. Mean Shallow (s) and Deep (d) Flux Rates. (All fluxes in $mg/m^2/hr$.)

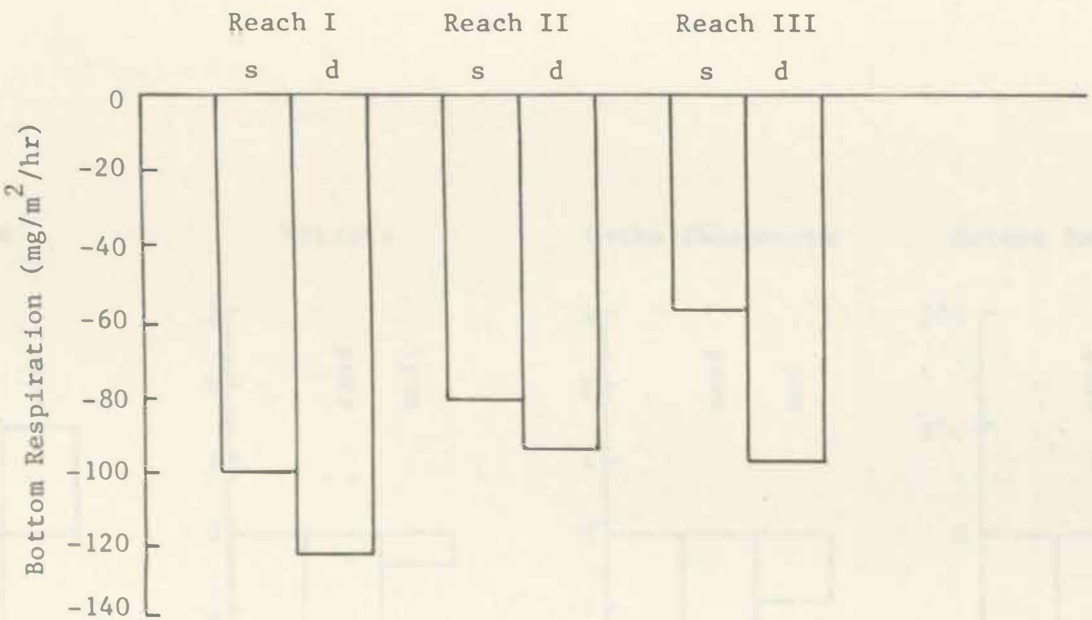


Figure 7-9. Mean Shallow (s) and Deep (d) Bottom Respiration Rates.

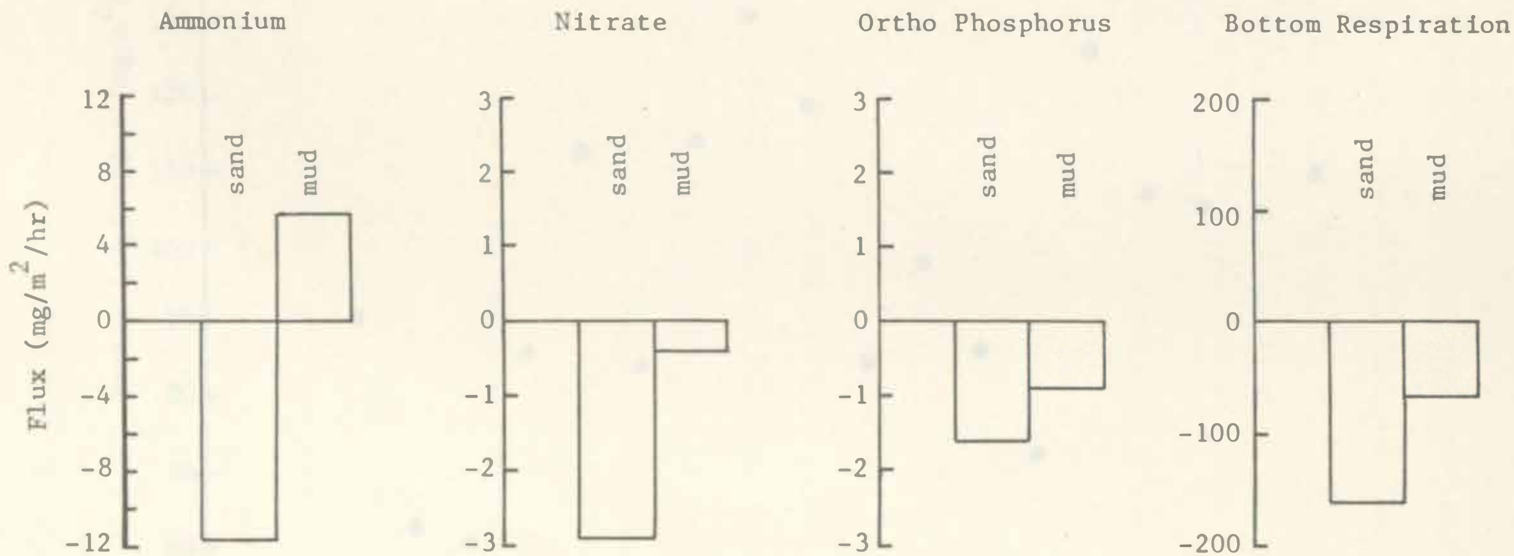


Figure 7-10. Influence of Bottom Composition on Flux Rate.

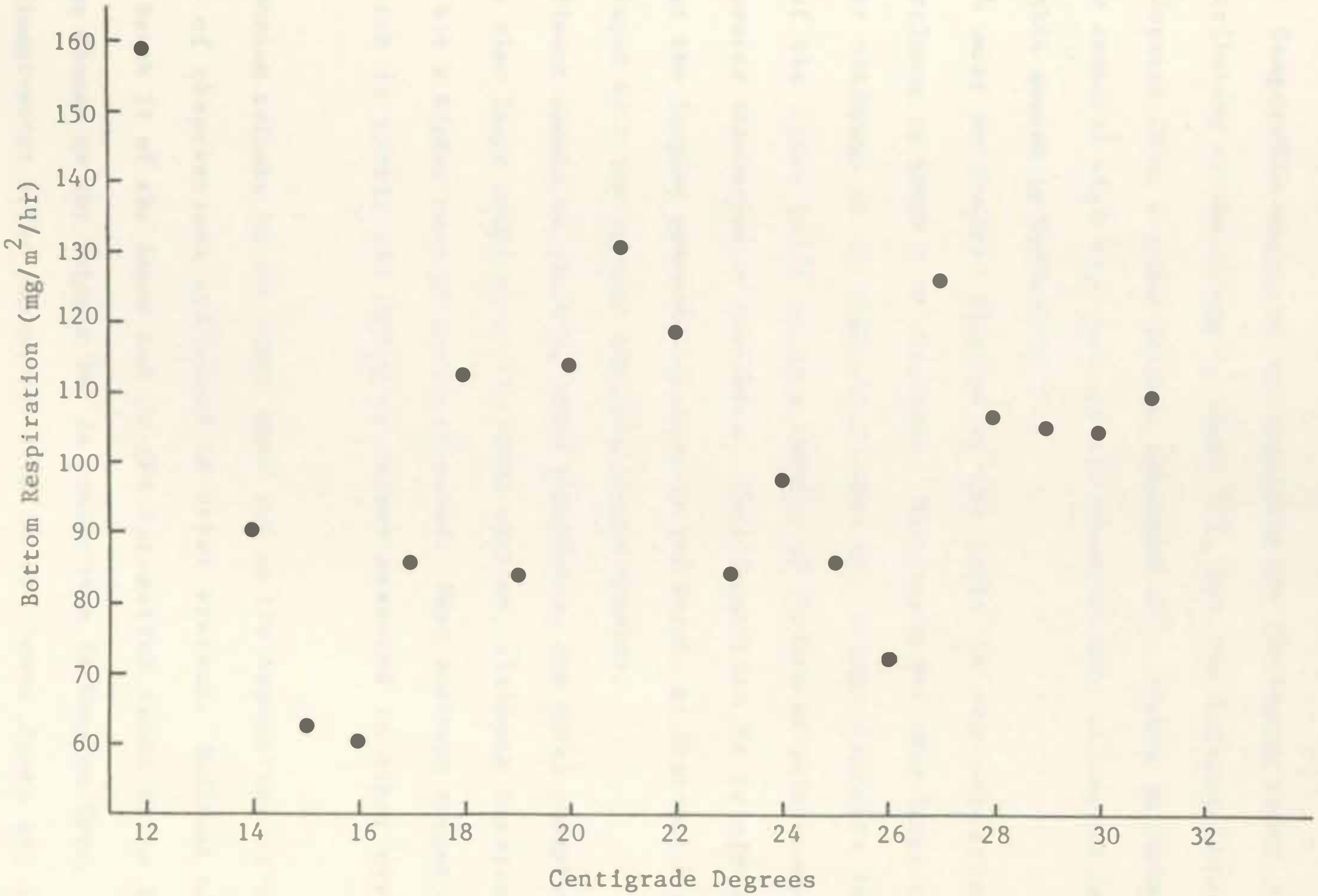


Figure 7-11. Influence of Temperature on Bottom Respiration.

Chapter VIII. Comparisons With Other Systems

It is useful to compare the measures collected in this study with measures of sediment-water fluxes collected in other tidal, freshwater systems. Comparable measures are available for the Chowan River, a North Carolina tributary of the Albemarle Sound (9), for the Potomac River (2), and for Gunston Cove, a tidal Potomac Embayment (4). Fluxes in these three system are compared with the mean of all observations collected in each Reach of this system in Table 8-1.

The most noticeable feature of the table is the extraordinary ammonium release in Reach I of the James. The reason for this large release is unclear although it is suggested there are sludge deposits in this portion of the river built up as a results of decades of point-source and nonpoint-source discharges to the Reach. This suggestion is reinforced by noting that the largest ammonium releases in the Reach, at Stations 6 and 7, are associated with the largest sediment oxygen demands.

Sediment uptake of nitrate, ortho phosphorus, and total phosphorus in Reach I is also large compared to the other systems, although Gunston Cove does exhibit a higher rate of denitrification. Mean sediment oxygen demand in the Reach is within the range of values measured in other systems, however.

Ammonium release in the lower James and in the Appomattox is within the range of observations collected in other systems. Sediment nitrate uptake in Reach II of the James and in the Appomattox tends to be larger than in the Chowan or the Potomac but is lesser than in Gunston Cove.

Sediment-water ortho phosphorus flux in the lower James and in the Appomattox is of the magnitude observed in the other systems although portions of the James and Appomattox exhibit a greater tendency for sediment uptake than the other systems. Sediment uptake of total phosphorus in the lower James is approximately equivalent to sediment uptake of total phosphorus in Gunston Cove.

Sediment oxygen demand in the lower James and in the Appomattox is within the range observed in the Chowan and Potomac Rivers and in Gunston Cove.

Table 8-1. Comparison of Sediment-Water Fluxes in Four Systems

	Ammonium	Nitrate	Ortho P	Total P	SOD
Reach I	30.8	-2.08	-2.64	-4.19	-45.4
Reach II	1.18	-3.17	-0.16	-0.46	-44.8
Reach III	1.90	0.43	0.14	-0.67	-47.3
Reach IV	1.97	-1.32	-0.24		-44.1
Chowan[1]	1.28	0.02	0.13		-22.3
Gunston[2]	9.27	-10.4	0	-0.65	-96.3
Potomac[3]	3.97	-0.21	0.26		-108

All fluxes in $mg/m^2/hr$

1) Reported mean of June 1980 measures

2) Laboratory measures at 25 C, 8 mg/l dissolved oxygen

3) NH4 and PO4 are mean reported values for tidal river.
NO3 and SOD from Station V26
Study conducted August, 1979

Chapter IX. Management Implications

The primary purpose of this study was to collect information useful in the management and modelling of water quality in the tidal James and Appomattox Rivers. Results have several implications for management of the two systems.

A. Occurrence of Nitrification

Based on observations collected in July, 1976, and in September, 1978, it has been stated that nitrification does not occur in the James River between Richmond and the Appomattox confluence (8). Sediment-water flux data noted herein indicate that statement needs to be reexamined.

Classically, nitrification is inferred by a decrease in ammonium concentration as a function of distance downstream of a point source and by a concurrent increase in nitrate concentration (11). If ammonium does not decrease and/or if nitrate does not increase, it may be inferred that nitrification is not occurring. Benthic fluxes of ammonium and nitrate act to obscure the classic evidence of nitrification in the upper tidal James, however.

Ammonium is released by bottom sediments in Reach I of the James. Thus the transformation of ammonium to nitrate in the water column is obscured by simultaneous release of ammonium from the sediments.

Nitrate is generally taken up by bottom sediments in the James River, most likely through the process of denitrification. Moreover, the rate of uptake is proportional to the quantity available. Thus, the end product indicative of nitrification is disappearing into the sediments. The more rapidly the end product is produced, the more rapidly it disappears. The occurrence of denitrification in the tidal James has been previously suggested and the need to include this process in models of the system has been noted (3).

Nitrification rates are generally obtained by ´calibrating´ predictive models to observations. In view of the findings noted above, existing models of the upper tidal James must be recalibrated following inclusions of benthic nitrogen fluxes and the occurrence of nitrification must be reassessed.

B. Sediment Oxygen Demand

Sediment oxygen demand in the James and Appomattox Rivers is highly variable in location and time but averages approximately 1 gm/m^2/day. This finding indicates that the model previously applied to the tidal James (8) has underestimated SOD in some reaches and overestimated it in others.

The model employs a base SOD rate of 0.5 gm/m^2/day, at 20 C, between Richmond and the Appomattox confluence. The amount by which SOD is underestimated in this reach depends on the temperature specified in the model simulation since the base SOD is adjusted upwards as a function of temperature. At 30 C, for example, the base rate of 0.5 gm/m^2/day is adjusted upward to 0.94 gm/m^2/day which is fair agreement with the mean of the observations.

Downstream of the Appomattox confluence, the model employs a base SOD rate of 1.0 gm/m^2/day at 20 C. This rate is corrected upwards for temperatures in excess of 20 C. Data collected in this study, however, indicate the rate of 1.0 gm/m^2/day is predominant at temperatures of 27 to 31 C. Thus, sediment oxygen demand has been overestimated downstream of the

Appomattox confluence at temperatures in the range 25 to 30 C usually employed in water-quality simulations.

The net effect of discrepancies in predicted and observed SOD on model predictions of dissolved oxygen in the James River cannot be derived in this study but should be investigated. In addition, the influence of locally high or non-existent SOD should be examined. That is, it needs to be determined if SOD within a reach should be averaged, for model purposes, or if SOD should be treated as variable on a length scale of the same order as the model segmentation.

C. Sediment-Water Phosphorus Fluxes

Total phosphorus is generally lost to the James River sediments. Ortho phosphorus is also lost to the sediments when water-column concentrations are relatively high but may be regenerated from the sediments when concentrations are below approximately 0.03 mg/l. In the Appomattox, ortho phosphorus may be lost to the sediments or regenerated depending on station location and bottom type (Total phosphorus fluxes were not measured in the Appomattox but it is apparent that ortho phosphorus cannot be released unless some form of phosphorus is first settling to the bottom). Since phosphorus is recognized as a significant and sometimes limiting algal nutrient in tidal freshwater, careful accounting of sediment-water phosphorus exchanges must be included in any future studies of eutrophication in the tidal James and Appomattox Rivers.

D. Recommendations for Model Implementation

Results of this study indicate that benthic fluxes are a significant factor in the nutrient and dissolved oxygen budgets of the tidal James and

Appomattox Rivers. Mass balances cannot be accomplished and correct model calibrations cannot be attained without inclusion of these fluxes.

1. Effect of Temperature - It has been previously noted that no influence of temperature on bottom respiration is evident and it has been recommended that no deterministic relationship of SOD to temperature be included in the model. Since approximately half of the SOD measures in this study were collected at temperatures of 27 to 31 C, the use of representative measures directly in the model insures that SOD will be correctly represented at critical water-quality temperatures.

The recommendation of omission of temperature dependence holds, as well, for the inclusion of benthic nutrient fluxes in any model of the James or Appomattox. It is preferable to use an average value than to falsely assume that temporal changes in bottom flux can be predicted simply and exactly as a function of temperature.

2. Prediction of Sediment-Water Fluxes - The state-of-the-art of water-quality modelling does not permit, at this time, the deterministic modelling of sediment-water fluxes. Nevertheless, data presented herein indicate the fluxes of some substances may be predicted based on conditions in the water column.

Both nitrate and total phosphorus are lost to the sediments at a rate proportional to the amount available. This phenomenon suggests that a first-order loss mechanism is appropriate to model the fluxes of these two substances to the sediments. In instances when ortho phosphorus is lost to the sediments, a first-order loss mechanism is appropriate as well. If this loss mechanism is adopted, then care should be taken to insure that predicted flux of these substances is in the range of the observations.

Ammonium release has been associated with the concentration of ammonium in the overlying water but this concentration cannot be used in the prediction of sediment-water flux. It is recommended that ammonium flux be treated as a constant at any location but variation due to location must be specified.

References

(1) American Public Health Association. 1976. **Standard Methods for the Examination of Water and Wastewater.** Fourteenth Edition. American Public Health Association. Washington, D. C.

(2) Callender, E., and Hammond, D. E. 1982. ´Nutrient Exchange Across the Sediment-Water Interface in the Potomac River Estuary´. Estuarine, Coastal and Shelf Science. Vol. 15, pp. 395-413.

(3) Cerco, C. F. 1981. ´Nitrification in the Upper Tidal James River´ in **Estuaries and Nutrients.** Neilson and Cronin eds. Humana Press.

(4) Cerco, C. F. 1985. ´Effect of Temperature and Dissolved Oxygen on Benthic Nutrient Flux´. Research in progress.

(5) Courchaine, R. J. 1968. ´Significance of Nitrification in Stream Analysis - Effects on the Oxygen Balance´. Journal of Water Pollution Control Federation. Vol. 40, pp. 835-847.

(6) E. P. A. 1981. ´Required Containers, Preservation Techniques and Holding Times´. Final Draft Amendment to 40 CFR Part 136. U. S. Environmental Protection Agency, Region III, Philadelphia, Pa.

(7) Faust, S. D., and Aly, O. M. 1981. **Chemistry of Natural Waters.** Ann Arbor Science Publishers, Inc.

(8) Hydroscience, Inc. 1979. ´Water Quality Analysis of the Upper Tidal James River´. Hydroscience Incorporated. Westwood, N. J.

(9) Kuenzler, E. J., Stone, C. L. and Albert, D. B. 1982. ´Phytoplankton Uptake and Sediment Release of Nitrogen and Phosphorus in the Chowan River, North Carolina.´ Report UNC-WRRI-82-186. Water Resources Research Institute of the University of North Carolina. Raleigh, N. C.

(10) Occoquan Watershed Monitoring Laboratory. 1984. ´Water Quality Review and Analysis Richmond-Crater James River Water Quality Monitoring Program´. Department of Civil Engineering, Virginia Polytechnic Institute and State University.

(11) Thomann, R. V. 1972. **Systems Analysis and Water Quality Management.** Environmental Research and Applications, Inc. Fig. 6-12, p. 156.

Appendix A. SOD Cylinder Measurements

Flux in $mg/m^2/hr$

Total flux is benthic respiration

Net flux is benthic respiration minus mean water-column respiration

STATION 3 830811 2.0 METERS 29.7 CENT.
DO (MG/L) 7.1 FLUX TOTAL -45.0 NET 20.8

STATION 3 830811 2.0 METERS 29.7 CENT.
DO (MG/L) 6.2 FLUX TOTAL -133.3 NET -67.5

STATION 3 831119 2.0 METERS 17.5 CENT.
DO (MG/L) 9.4 FLUX TOTAL -79.6 NET -13.8

STATION 3 831119 2.0 METERS 17.5 CENT.
DO (MG/L) 9.0 FLUX TOTAL -113.8 NET -47.9

STATION 3 840719 2.0 METERS 28.5 CENT.
DO (MG/L) 7.9 FLUX TOTAL -78.8 NET -12.9

STATION 3 840719 2.0 METERS 28.5 CENT.
DO (MG/L) 6.9 FLUX TOTAL -195.0 NET -129.2

STATION 3 840921 2.0 METERS 23.3 CENT.
DO (MG/L) 9.7 FLUX TOTAL -150.8 NET -85.0

STATION 3 840921 2.0 METERS 23.3 CENT.
DO (MG/L) 12.2 FLUX TOTAL -55.8 NET 10.0

STATION 4 830811 5.0 METERS 29.5 CENT.
DO (MG/L) 7.4 FLUX TOTAL -32.1 NET 33.7

STATION 4 830830 6.0 METERS 28.4 CENT.
DO (MG/L) 5.6 FLUX TOTAL -58.3 NET 7.5

STATION 4 831019 5.0 METERS 19.0 CENT.
DO (MG/L) 8.1 FLUX TOTAL -119.6 NET -53.8

STATION 4 831028 5.0 METERS 11.6 CENT.
DO (MG/L) 10.4 FLUX TOTAL -164.6 NET -98.8

STATION 4 831028 5.0 METERS 11.6 CENT.
DO (MG/L) 9.8 FLUX TOTAL -175.8 NET -110.0

STATION 4 840719 6.0 METERS 27.1 CENT.
DO (MG/L) 7.7 FLUX TOTAL -44.6 NET 21.2

STATION 4 840918 2.0 METERS 22.2 CENT.
DO (MG/L) 8.3 FLUX TOTAL -93.3 NET -27.5

STATION 5 830811 4.0 METERS 30.0 CENT.
DO (MG/L) 5.5 FLUX TOTAL -105.4 NET -39.6

STATION 5 830830 4.0 METERS 28.0 CENT.
DO (MG/L) 5.1 FLUX TOTAL -25.8 NET 40.0

```
STATION    5   830830    4.0 METERS    28.0 CENT.
DO (MG/L)  5.2   FLUX TOTAL  -58.3  NET     7.5

STATION    5   831019    4.0 METERS    17.5 CENT.
DO (MG/L)  8.5   FLUX TOTAL  -65.8  NET     0.0

STATION    6   830810    4.0 METERS    30.0 CENT.
DO (MG/L)  2.7   FLUX TOTAL -103.8  NET   -37.9

STATION    6   830810    4.0 METERS    30.0 CENT.
DO (MG/L)  3.5   FLUX TOTAL -210.4  NET -144.6

STATION    6   830830    6.0 METERS    28.2 CENT.
DO (MG/L)  5.2   FLUX TOTAL -178.8  NET -112.9

STATION    6   830830    6.0 METERS    28.2 CENT.
DO (MG/L)  5.1   FLUX TOTAL -163.8  NET   -97.9

STATION    6   831019    6.0 METERS    19.0 CENT.
DO (MG/L)  8.0   FLUX TOTAL  -57.5  NET     8.3

STATION    6   831019    6.0 METERS    19.0 CENT.
DO (MG/L)  7.2   FLUX TOTAL  -98.8  NET   -32.9

STATION    7   830811    5.2 METERS    30.0 CENT.
DO (MG/L)  4.6   FLUX TOTAL -192.5  NET -126.7

STATION    7   830811    5.2 METERS    30.0 CENT.
DO (MG/L)  4.1   FLUX TOTAL -190.4  NET -124.6

STATION    7   830831    4.0 METERS    28.8 CENT.
DO (MG/L)  5.5   FLUX TOTAL  -76.7  NET   -10.8

STATION    7   830831    4.0 METERS    28.8 CENT.
DO (MG/L)  6.2   FLUX TOTAL -100.8  NET   -35.0

STATION    7   831017    5.2 METERS    18.5 CENT.
DO (MG/L)  8.2   FLUX TOTAL -154.2  NET   -88.3

STATION    7   831017    5.2 METERS    18.5 CENT.
DO (MG/L)  8.1   FLUX TOTAL -147.9  NET   -82.1

STATION    7   831028    5.2 METERS    12.5 CENT.
DO (MG/L) 10.2   FLUX TOTAL -148.3  NET   -82.5

STATION    7   831028    5.2 METERS    12.5 CENT.
DO (MG/L)  9.4   FLUX TOTAL -146.7  NET   -80.8

STATION    8   830831    5.0 METERS    29.5 CENT.
DO (MG/L)  5.9   FLUX TOTAL  -63.8  NET     2.1
```

STATION 8 831017 2.0 METERS 19.5 CENT.
DO (MG/L) 6.6 FLUX TOTAL -59.6 NET 6.2

STATION 8 831017 2.0 METERS 19.5 CENT.
DO (MG/L) 6.7 FLUX TOTAL -53.3 NET 12.5

STATION 9 830810 8.0 METERS 30.0 CENT.
DO (MG/L) 6.1 FLUX TOTAL -45.8 NET 20.0

STATION 9 830810 8.0 METERS 30.0 CENT.
DO (MG/L) 5.1 FLUX TOTAL -30.8 NET 35.0

STATION 9 830831 1.0 METERS 31.0 CENT.
DO (MG/L) 6.1 FLUX TOTAL -140.0 NET -74.2

STATION 9 830831 1.0 METERS 31.0 CENT.
DO (MG/L) 5.8 FLUX TOTAL -78.3 NET -12.5

STATION 9 831028 8.0 METERS 14.5 CENT.
DO (MG/L) 8.9 FLUX TOTAL -177.5 NET -111.7

STATION 10 830804 6.0 METERS 29.0 CENT.
DO (MG/L) 6.1 FLUX TOTAL -48.8 NET -5.4

STATION 10 831017 6.0 METERS 20.5 CENT.
DO (MG/L) 7.2 FLUX TOTAL -56.7 NET -13.3

STATION 10 831017 5.0 METERS 20.5 CENT.
DO (MG/L) 7.3 FLUX TOTAL -37.1 NET 6.2

STATION 10 831005 6.0 METERS 21.5 CENT.
DO (MG/L) 7.9 FLUX TOTAL -245.0 NET -201.7

STATION 10 840730 2.0 METERS 26.5 CENT.
DO (MG/L) 6.8 FLUX TOTAL -50.8 NET -7.5

STATION 10 840730 2.0 METERS 26.5 CENT.
DO (MG/L) 6.8 FLUX TOTAL -60.8 NET -17.5

STATION 10 840730 10.0 METERS 26.2 CENT.
DO (MG/L) 6.5 FLUX TOTAL -44.2 NET -0.8

STATION 10 840912 1.5 METERS 26.2 CENT.
DO (MG/L) 7.7 FLUX TOTAL -66.7 NET -23.3

STATION 10 840912 5.0 METERS 28.1 CENT.
DO (MG/L) 8.0 FLUX TOTAL -64.2 NET -20.8

STATION 11 830804 4.0 METERS 29.5 CENT.
DO (MG/L) 6.4 FLUX TOTAL -95.0 NET -51.7

STATION 11 830901 3.0 METERS 28.0 CENT.
DO (MG/L) 4.3 FLUX TOTAL -115.0 NET -71.7

STATION 11 830901 3.0 METERS 28.0 CENT.
DO (MG/L) 4.3 FLUX TOTAL -143.8 NET -100.4

STATION 11 831026 4.0 METERS 14.0 CENT.
DO (MG/L) 8.8 FLUX TOTAL -29.6 NET 13.7

STATION 11 831026 4.0 METERS 14.0 CENT.
DO (MG/L) 8.4 FLUX TOTAL -63.8 NET -20.4

STATION 12 830901 2.0 METERS 27.7 CENT.
DO (MG/L) 7.5 FLUX TOTAL -108.3 NET -65.0

STATION 12 830901 2.0 METERS 27.7 CENT.
DO (MG/L) 7.5 FLUX TOTAL -61.3 NET -17.9

STATION 12 831005 5.2 METERS 22.0 CENT.
DO (MG/L) 9.2 FLUX TOTAL -75.0 NET -31.7

STATION 13 830803 8.0 METERS 28.0 CENT.
DO (MG/L) 5.0 FLUX TOTAL -175.0 NET -131.7

STATION 13 830901 5.0 METERS 28.0 CENT.
DO (MG/L) 5.6 FLUX TOTAL -92.9 NET -49.6

STATION 13 831005 8.0 METERS 21.2 CENT.
DO (MG/L) 8.1 FLUX TOTAL -92.5 NET -49.2

STATION 14 830803 9.0 METERS 28.0 CENT.
DO (MG/L) 5.9 FLUX TOTAL -72.1 NET -28.8

STATION 14 830803 9.0 METERS 28.0 CENT.
DO (MG/L) 5.8 FLUX TOTAL -59.6 NET -16.3

STATION 14 831005 5.0 METERS 20.8 CENT.
DO (MG/L) 7.5 FLUX TOTAL -73.3 NET -30.0

STATION 14 831005 5.0 METERS 20.8 CENT.
DO (MG/L) 7.5 FLUX TOTAL -114.2 NET -70.8

STATION 14 831026 6.0 METERS 15.5 CENT.
DO (MG/L) 7.7 FLUX TOTAL -30.4 NET 12.9

STATION 14 831026 6.0 METERS 15.5 CENT.
DO (MG/L) 7.6 FLUX TOTAL -36.7 NET 6.7

STATION 15 830804 7.0 METERS 28.0 CENT.
DO (MG/L) 5.6 FLUX TOTAL -135.8 NET -92.5

```
STATION  15   831005   6.7 METERS   19.9 CENT.
DO (MG/L)  7.2  FLUX TOTAL  -25.0  NET   18.3

STATION  15   831026   3.3 METERS   16.0 CENT.
DO (MG/L)  6.9  FLUX TOTAL  -47.5  NET   -4.2

STATION  15   831026   3.3 METERS   16.0 CENT.
DO (MG/L)  6.9  FLUX TOTAL  -46.7  NET   -3.3

STATION  15   840717   1.5 METERS   28.1 CENT.
DO (MG/L)  6.9  FLUX TOTAL  -91.7  NET  -48.3

STATION  15   840717   1.5 METERS   28.1 CENT.
DO (MG/L)  7.1  FLUX TOTAL  -82.1  NET  -38.8

STATION  15   840717   5.0 METERS   28.3 CENT.
DO (MG/L)  4.9  FLUX TOTAL -149.6  NET -106.3

STATION  15   840717   5.0 METERS   28.3 CENT.
DO (MG/L)  5.9  FLUX TOTAL -132.9  NET  -89.6

STATION  15   840921   3.0 METERS   22.4 CENT.
DO (MG/L)  8.0  FLUX TOTAL  -97.9  NET  -54.6

STATION  15   840921   3.0 METERS   22.4 CENT.
DO (MG/L)  8.5  FLUX TOTAL -122.1  NET  -78.8

STATION  15   840921   6.0 METERS   22.7 CENT.
DO (MG/L)  6.9  FLUX TOTAL -134.2  NET  -90.8

STATION  15   840921   6.0 METERS   22.7 CENT.
DO (MG/L)  7.5  FLUX TOTAL -113.3  NET  -70.0

STATION  16   830803   7.0 METERS   28.2 CENT.
DO (MG/L)  5.4  FLUX TOTAL  -59.6  NET  -16.3

STATION  16   830803   7.0 METERS   28.2 CENT.
DO (MG/L)  5.6  FLUX TOTAL  -71.7  NET  -28.3

STATION  16   831013   7.0 METERS   20.0 CENT.
DO (MG/L)  6.7  FLUX TOTAL -250.8  NET -207.5

STATION  16   831013   7.0 METERS   20.0 CENT.
DO (MG/L)  6.8  FLUX TOTAL -119.2  NET  -75.8

STATION  16   831026   7.0 METERS   16.0 CENT.
DO (MG/L)  6.4  FLUX TOTAL  -75.0  NET  -31.7

STATION  16   831026   7.0 METERS   16.0 CENT.
DO (MG/L)  6.0  FLUX TOTAL -111.3  NET  -67.9
```

```
STATION  17   830809   9.3 METERS   29.0 CENT.
DO (MG/L)  6.4  FLUX TOTAL -154.2  NET -116.3

STATION  17   830809   9.3 METERS   29.0 CENT.
DO (MG/L)  5.5  FLUX TOTAL -117.9  NET  -80.0

STATION  17   830908   9.3 METERS   28.0 CENT.
DO (MG/L)  4.5  FLUX TOTAL -136.7  NET  -98.8

STATION  17   831028   6.0 METERS   15.0 CENT.
DO (MG/L)  7.2  FLUX TOTAL -129.6  NET  -91.7

STATION  17   840726   2.0 METERS   27.3 CENT.
DO (MG/L)  6.3  FLUX TOTAL  -41.3  NET   -3.3

STATION  17   840726  10.0 METERS   27.3 CENT.
DO (MG/L)  6.4  FLUX TOTAL  -92.5  NET  -54.6

STATION  17   840726  10.0 METERS   27.3 CENT.
DO (MG/L)  6.5  FLUX TOTAL -134.6  NET  -96.7

STATION  17   841008   1.5 METERS   18.4 CENT.
DO (MG/L)  8.4  FLUX TOTAL  -64.2  NET  -26.3

STATION  17   841008   1.5 METERS   18.4 CENT.
DO (MG/L)  8.8  FLUX TOTAL  -39.2  NET   -1.3

STATION  17   841008   8.0 METERS   18.5 CENT.
DO (MG/L)  7.9  FLUX TOTAL  -76.3  NET  -38.3

STATION  17   841008   8.0 METERS   18.5 CENT.
DO (MG/L)  8.5  FLUX TOTAL  -60.8  NET  -22.9

STATION  18   830809   6.0 METERS   29.0 CENT.
DO (MG/L)  6.2  FLUX TOTAL -148.3  NET -110.4

STATION  18   830908   6.0 METERS   28.0 CENT.
DO (MG/L)  6.5  FLUX TOTAL  -97.5  NET  -59.6

STATION  18   831028   6.0 METERS   16.0 CENT.
DO (MG/L)  7.2  FLUX TOTAL  -51.3  NET  -13.3

STATION  18   831028   6.0 METERS   16.0 CENT.
DO (MG/L)  7.7  FLUX TOTAL  -52.5  NET  -14.6

STATION  19   830809   4.5 METERS   28.5 CENT.
DO (MG/L)  5.5  FLUX TOTAL -135.0  NET  -97.1

STATION  19   830809   4.5 METERS   28.5 CENT.
DO (MG/L)  5.3  FLUX TOTAL -127.1  NET  -89.2
```

STATION 19 830913 5.0 METERS 27.8 CENT.
DO (MG/L) 6.7 FLUX TOTAL -73.3 NET -35.4

STATION 19 831004 4.0 METERS 19.0 CENT.
DO (MG/L) 6.6 FLUX TOTAL -43.3 NET -5.4

STATION 19 831004 4.0 METERS 19.0 CENT.
DO (MG/L) 6.9 FLUX TOTAL -49.6 NET -11.7

STATION 20 830824 3.8 METERS 29.5 CENT.
DO (MG/L) 10.1 FLUX TOTAL -225.0 NET -149.2

STATION 20 830824 3.8 METERS 29.5 CENT.
DO (MG/L) 11.5 FLUX TOTAL -119.2 NET -43.3

STATION 20 831003 3.8 METERS 18.9 CENT.
DO (MG/L) 11.8 FLUX TOTAL -104.2 NET -28.3

STATION 20 831025 3.8 METERS 15.5 CENT.
DO (MG/L) 6.8 FLUX TOTAL -44.6 NET 31.2

STATION 20 831025 3.8 METERS 15.5 CENT.
DO (MG/L) 6.3 FLUX TOTAL -67.1 NET 8.8

STATION 21 830824 2.0 METERS 29.0 CENT.
DO (MG/L) 4.8 FLUX TOTAL -85.0 NET -9.2

STATION 21 831003 2.0 METERS 19.0 CENT.
DO (MG/L) 7.4 FLUX TOTAL -139.6 NET -63.8

STATION 21 831003 2.0 METERS 19.0 CENT.
DO (MG/L) 7.0 FLUX TOTAL -128.8 NET -52.9

STATION 21 831025 2.0 METERS 18.1 CENT.
DO (MG/L) 8.9 FLUX TOTAL -34.2 NET 41.7

STATION 21 831025 2.0 METERS 18.1 CENT.
DO (MG/L) 8.5 FLUX TOTAL -56.7 NET 19.2

STATION 21 840725 1.5 METERS 27.6 CENT.
DO (MG/L) 7.8 FLUX TOTAL -52.9 NET 22.9

STATION 21B 840911 2.0 METERS 24.4 CENT.
DO (MG/L) 9.0 FLUX TOTAL -107.1 NET -31.3

STATION 22 831003 1.7 METERS 19.0 CENT.
DO (MG/L) 8.1 FLUX TOTAL -55.8 NET 20.0

STATION 22 831003 1.7 METERS 19.0 CENT.
DO (MG/L) 8.1 FLUX TOTAL -145.0 NET -69.2

STATION 22 831025 1.7 METERS 18.0 CENT.
DO (MG/L) 8.7 FLUX TOTAL -219.2 NET -143.3

STATION 23 830824 1.5 METERS 28.3 CENT.
DO (MG/L) 6.4 FLUX TOTAL -69.6 NET 6.2

STATION 23 830824 1.5 METERS 28.3 CENT.
DO (MG/L) 6.5 FLUX TOTAL -67.1 NET 8.8

STATION 23 831025 1.5 METERS 16.3 CENT.
DO (MG/L) 9.2 FLUX TOTAL -36.7 NET 39.2

STATION 23 831025 1.5 METERS 16.3 CENT.
DO (MG/L) 9.1 FLUX TOTAL -57.1 NET 18.8

STATION 23 840725 1.0 METERS 27.2 CENT.
DO (MG/L) 8.1 FLUX TOTAL -174.2 NET -98.3

STATION 23 840725 1.0 METERS 27.2 CENT.
DO (MG/L) 7.4 FLUX TOTAL -159.6 NET -83.8

STATION 23 840911 2.0 METERS 24.3 CENT.
DO (MG/L) 7.9 FLUX TOTAL -127.9 NET -52.1

STATION 23 840911 2.0 METERS 24.3 CENT.
DO (MG/L) 7.7 FLUX TOTAL -162.9 NET -87.1

STATION 25 830809 7.0 METERS 29.6 CENT.
DO (MG/L) 6.5 FLUX TOTAL -74.6 NET -36.7

STATION 25 830809 7.0 METERS 29.6 CENT.
DO (MG/L) 6.0 FLUX TOTAL -27.5 NET 10.4

STATION 25 830913 7.0 METERS 27.1 CENT.
DO (MG/L) 7.0 FLUX TOTAL -33.8 NET 4.2

STATION 25 831004 1.0 METERS 19.1 CENT.
DO (MG/L) 7.9 FLUX TOTAL -35.8 NET 2.1

STATION 25 840905 2.0 METERS 25.9 CENT.
DO (MG/L) 6.4 FLUX TOTAL -121.7 NET -83.8

STATION 25 840905 2.0 METERS 25.9 CENT.
DO (MG/L) 6.9 FLUX TOTAL -74.2 NET -36.3

STATION 25 840905 4.0 METERS 25.5 CENT.
DO (MG/L) 5.7 FLUX TOTAL -56.3 NET -18.3

STATION 25 840905 4.0 METERS 25.5 CENT.
DO (MG/L) 6.4 FLUX TOTAL -39.2 NET -1.3

Appendix B. Nutrient Dome Measures

Concentration in mg/l

Flux in $mg/m^2/hr$

Negative fluxes indicate sediment uptake

Total flux is combined sediment flux and water-column transformation

Net flux is sediment flux after correction for water-column transformation

Missing data indicated by 999

STATION 3 830920 5.5 METERS 27.0 CENT.

	NH4	NO3	PO4	TOT P	DO
CONC.	1.270	0.280	0.519	0.582	7.41
TOTAL FLUX	-0.02	0.77	-2.090	-1.960	-77.00
NET FLUX	14.47	0.04	1.741	-1.960	7.00

STATION 4 830822 7.0 METERS 28.0 CENT.

	NH4	NO3	PO4	TOT P	DO
CONC.	0.685	0.322	0.332	0.368	7.40
TOTAL FLUX	20.40	0.19	-3.330	-2.090	-81.00
NET FLUX	30.13	-0.54	-0.641	-2.090	3.00

STATION 4 830822 7.0 METERS 28.0 CENT.

	NH4	NO3	PO4	TOT P	DO
CONC.	0.920	0.347	0.284	0.376	6.85
TOTAL FLUX	26.40	-1.45	-3.620	-4.060	-128.00
NET FLUX	38.17	-2.18	-1.244	-4.060	-44.00

STATION 4 830920 5.8 METERS 27.0 CENT.

	NH4	NO3	PO4	TOT P	DO
CONC.	1.070	0.400	0.443	0.516	8.14
TOTAL FLUX	-6.08	0.43	-2.890	-3.970	999.00
NET FLUX	6.89	-0.30	0.489	-3.970	999.00

STATION 4 830920 5.8 METERS 27.0 CENT.

	NH4	NO3	PO4	TOT P	DO
CONC.	0.910	0.420	0.424	0.466	7.68
TOTAL FLUX	2.56	-1.29	-2.200	-2.800	-57.00
NET FLUX	14.25	-2.02	1.064	-2.800	27.00

STATION 6 830920 7.8 METERS 27.0 CENT.

	NH4	NO3	PO4	TOT P	DO
CONC.	0.690	0.640	0.361	0.434	8.57
TOTAL FLUX	35.70	-2.78	-4.950	-3.400	-139.00
NET FLUX	45.48	-3.51	-2.076	-3.400	-55.00

STATION 6 830920 5.8 METERS 27.0 CENT.

	NH4	NO3	PO4	TOT P	DO
CONC.	0.700	0.660	0.378	0.448	8.89
TOTAL FLUX	32.10	-3.10	-8.910	-4.350	-179.00
NET FLUX	41.97	-3.83	-5.930	-4.350	-95.00

STATION 6 840703 1.0 METERS 28.0 CENT.

	NH4	NO3	PO4	TOT P	DO
CONC.	0.090	0.196	0.104	999.000	6.20
TOTAL FLUX	0.69	0.90	-1.940	999.000	-47.00
NET FLUX	3.32	0.17	-0.868	999.000	37.00

STATION 6	840703	1.0 METERS	28.0 CENT.		
	NH4	NO3	PO4	TOT P	DO
CONC.	0.120	0.189	0.102	999.000	6.20
TOTAL FLUX	2.89	0.28	-1.250	999.000	-75.00
NET FLUX	6.06	-0.45	-0.194	999.000	9.00

STATION 6	840703	5.0 METERS	28.0 CENT.		
	NH4	NO3	PO4	TOT P	DO
CONC.	0.320	0.262	0.061	999.000	5.92
TOTAL FLUX	19.00	-2.69	-3.110	999.000	-376.00
NET FLUX	24.96	-3.42	-2.407	999.000	-292.00

STATION 6	840703	5.0 METERS	28.0 CENT.		
	NH4	NO3	PO4	TOT P	DO
CONC.	0.680	0.228	0.056	999.000	5.84
TOTAL FLUX	56.30	-1.30	-1.560	999.000	-233.00
NET FLUX	65.99	-2.03	-0.903	999.000	-149.00

STATION 6	840917	2.0 METERS	22.0 CENT.		
	NH4	NO3	PO4	TOT P	DO
CONC.	0.480	0.535	0.195	999.000	7.04
TOTAL FLUX	17.30	-0.56	-5.900	999.000	-100.00
NET FLUX	25.04	-1.29	-4.136	999.000	-16.00

STATION 6	840917	2.0 METERS	22.0 CENT.		
	NH4	NO3	PO4	TOT P	DO
CONC.	0.485	0.530	0.197	999.000	7.02
TOTAL FLUX	40.20	-2.49	-7.680	999.000	-216.00
NET FLUX	47.99	-3.22	-5.901	999.000	-132.00

STATION 6	840918	5.0 METERS	22.0 CENT.		
	NH4	NO3	PO4	TOT P	DO
CONC.	0.437	0.549	0.189	999.000	7.52
TOTAL FLUX	27.30	-2.35	-5.620	999.000	-171.00
NET FLUX	34.59	-3.08	-3.899	999.000	-87.00

STATION 6	840918	5.0 METERS	22.0 CENT.		
	NH4	NO3	PO4	TOT P	DO
CONC.	0.576	0.567	0.193	999.000	7.32
TOTAL FLUX	37.70	-3.41	-6.230	999.000	-74.00
NET FLUX	46.41	-4.14	-4.480	999.000	10.00

STATION 7	830822	6.0 METERS	28.0 CENT.		
	NH4	NO3	PO4	TOT P	DO
CONC.	1.230	0.367	0.294	0.406	5.67
TOTAL FLUX	13.20	-2.41	-14.100	-7.180	-152.00
NET FLUX	27.39	-3.14	-11.658	-7.180	-68.00

STATION 7 830822 6.0 METERS 28.0 CENT.

	NH4	NO3	PO4	TOT P	DO
CONC.	0.920	0.353	0.258	0.446	5.67
TOTAL FLUX	13.20	-1.06	-3.930	-5.960	-145.00
NET FLUX	24.97	-1.79	-1.728	-5.960	-61.00

STATION 7 830920 7.5 METERS 27.0 CENT.

	NH4	NO3	PO4	TOT P	DO
CONC.	0.800	0.680	0.380	0.565	7.51
TOTAL FLUX	44.70	-2.02	-7.660	-6.130	-97.00
NET FLUX	55.46	-2.75	-4.667	-6.130	-13.00

STATION 10 830818 4.5 METERS 28.5 CENT.

	NH4	NO3	PO4	TOT P	DO
CONC.	0.107	0.358	0.067	0.188	6.42
TOTAL FLUX	-0.81	-0.83	-1.400	999.000	-104.00
NET FLUX	2.13	-1.56	-0.643	999.000	-48.50

STATION 10 830818 4.5 METERS 28.5 CENT.

	NH4	NO3	PO4	TOT P	DO
CONC.	0.114	0.387	0.065	0.170	6.34
TOTAL FLUX	-6.48	-0.86	-1.700	999.000	-120.00
NET FLUX	-3.41	-1.59	-0.961	999.000	-64.50

STATION 11 831006 5.0 METERS 23.0 CENT.

	NH4	NO3	PO4	TOT P	DO
CONC.	0.040	1.100	0.027	0.171	7.17
TOTAL FLUX	2.37	-0.42	-0.040	0.820	-56.00
NET FLUX	3.93	-1.15	0.329	0.820	-0.50

STATION 11 831006 5.0 METERS 23.0 CENT.

	NH4	NO3	PO4	TOT P	DO
CONC.	0.020	1.130	0.022	0.239	7.09
TOTAL FLUX	2.12	-2.29	-0.240	-1.170	-62.00
NET FLUX	3.12	-3.02	0.073	-1.170	-6.50

STATION 12 830818 8.3 METERS 28.0 CENT.

	NH4	NO3	PO4	TOT P	DO
CONC.	0.097	0.392	0.033	0.160	6.67
TOTAL FLUX	5.36	-1.80	-0.070	-0.960	-50.00
NET FLUX	8.12	-2.53	0.362	-0.960	5.50

STATION 12 830818 8.3 METERS 28.0 CENT.

	NH4	NO3	PO4	TOT P	DO
CONC.	0.074	0.406	0.035	0.126	6.69
TOTAL FLUX	2.94	-2.71	-0.250	0.880	-62.00
NET FLUX	5.26	-3.44	0.203	0.880	-6.50

STATION 12	830915	3.5 METERS	28.0 CENT.		
	NH4	NO3	PO4	TOT P	DO
CONC.	0.260	1.460	0.021	0.093	5.99
TOTAL FLUX	-5.79	-5.22	-0.110	0.180	-18.00
NET FLUX	-0.57	-5.95	0.192	0.180	37.50

STATION 12	831013	4.2 METERS	20.0 CENT.		
	NH4	NO3	PO4	TOT P	DO
CONC.	0.020	1.150	0.008	0.162	6.91
TOTAL FLUX	0.01	-5.10	-0.030	-1.960	-104.00
NET FLUX	1.01	-5.83	0.111	-1.960	-48.50

STATION 13	830915	3.0 METERS	28.0 CENT.		
	NH4	NO3	PO4	TOT P	DO
CONC.	0.400	1.350	0.021	0.130	6.14
TOTAL FLUX	-3.11	-0.74	-0.680	-0.570	-120.00
NET FLUX	3.77	-1.47	-0.378	-0.570	-64.50

STATION 13	831013	8.1 METERS	20.0 CENT.		
	NH4	NO3	PO4	TOT P	DO
CONC.	0.240	1.540	0.017	0.141	7.27
TOTAL FLUX	2.32	-7.09	-0.040	-1.420	-73.00
NET FLUX	7.27	-7.82	0.216	-1.420	-17.50

STATION 13	831013	8.1 METERS	20.0 CENT.		
	NH4	NO3	PO4	TOT P	DO
CONC.	0.250	1.540	0.019	0.141	6.16
TOTAL FLUX	-3.32	2.45	-0.190	0.100	-25.00
NET FLUX	1.77	1.72	0.089	0.100	30.50

STATION 13	831013	3.9 METERS	20.0 CENT.		
	NH4	NO3	PO4	TOT P	DO
CONC.	0.120	1.510	0.017	0.133	7.07
TOTAL FLUX	-3.23	-0.56	-0.280	-0.490	-72.00
NET FLUX	-0.06	-1.29	-0.024	-0.490	-16.50

STATION 13	840705	1.8 METERS	28.0 CENT.		
	NH4	NO3	PO4	TOT P	DO
CONC.	0.090	0.728	0.012	999.000	6.65
TOTAL FLUX	-2.06	-2.65	0.000	999.000	-80.00
NET FLUX	0.57	-3.38	0.194	999.000	-24.50

STATION 13	840705	3.7 METERS	28.0 CENT.		
	NH4	NO3	PO4	TOT P	DO
CONC.	0.120	0.686	0.019	999.000	6.45
TOTAL FLUX	-2.53	-6.27	-0.330	999.000	-148.00
NET FLUX	0.64	-7.00	-0.051	999.000	-92.50

STATION 13 840705 3.7 METERS 28.0 CENT.

	NH4	NO3	PO4	TOT P	DO
CONC.	0.090	0.747	0.016	999.000	6.63
TOTAL FLUX	-6.53	-8.59	-0.830	999.000	-112.00
NET FLUX	-3.90	-9.32	-0.586	999.000	-56.50

STATION 14 841011 2.0 METERS 18.5 CENT.

	NH4	NO3	PO4	TOT P	DO
CONC.	0.063	0.620	0.031	999.000	8.69
TOTAL FLUX	-4.28	-0.77	-0.520	999.000	-125.00
NET FLUX	-2.19	-1.50	-0.109	999.000	-69.50

STATION 14 841011 5.0 METERS 18.5 CENT.

	NH4	NO3	PO4	TOT P	DO
CONC.	0.092	0.594	0.034	999.000	7.64
TOTAL FLUX	-6.96	-1.10	-1.590	999.000	-216.00
NET FLUX	-4.29	-1.83	-1.148	999.000	-160.50

STATION 14 841011 5.0 METERS 18.5 CENT.

	NH4	NO3	PO4	TOT P	DO
CONC.	0.106	0.606	0.037	999.000	9.23
TOTAL FLUX	-4.81	0.64	-1.170	999.000	-157.00
NET FLUX	-1.88	-0.09	-0.697	999.000	-101.50

STATION 19 830816 2.5 METERS 28.5 CENT.

	NH4	NO3	PO4	TOT P	DO
CONC.	0.022	0.111	0.025	0.113	5.98
TOTAL FLUX	-0.41	-2.05	-2.290	0.230	-140.00
NET FLUX	0.65	-0.85	-1.943	0.230	-91.50

STATION 19 830816 2.5 METERS 28.5 CENT.

	NH4	NO3	PO4	TOT P	DO
CONC.	0.002	0.092	0.024	0.072	6.20
TOTAL FLUX	1.46	-0.07	-0.460	-1.380	-107.00
NET FLUX	1.69	3.31	-0.124	-1.380	-58.50

STATION 19 830816 2.5 METERS 28.5 CENT.

	NH4	NO3	PO4	TOT P	DO
CONC.	0.019	0.087	0.022	0.092	6.00
TOTAL FLUX	0.19	-0.30	0.000	-1.200	-105.00
NET FLUX	1.16	1.23	0.313	-1.200	-56.50

STATION 19 830816 2.5 METERS 28.5 CENT.

	NH4	NO3	PO4	TOT P	DO
CONC.	0.032	0.083	0.025	0.032	6.02
TOTAL FLUX	-1.49	-0.08	-0.410	-1.440	-106.00
NET FLUX	-0.14	0.03	-0.063	-1.440	-57.50

STATION 19 830816 7.0 METERS 28.0 CENT.

	NH4	NO3	PO4	TOT P	DO
CONC.	0.012	0.092	0.020	0.064	6.56
TOTAL FLUX	1.14	-0.72	0.000	-0.200	-20.00
NET FLUX	1.86	1.57	0.291	-0.200	28.50

STATION 19 830913 2.5 METERS 27.5 CENT.

	NH4	NO3	PO4	TOT P	DO
CONC.	0.010	0.120	0.026	0.076	6.85
TOTAL FLUX	0.46	0.36	-0.430	-0.640	-118.00
NET FLUX	1.10	2.87	-0.072	-0.640	-69.50

STATION 19 830913 2.5 METERS 27.5 CENT.

	NH4	NO3	PO4	TOT P	DO
CONC.	0.010	0.100	0.027	0.169	6.06
TOTAL FLUX	-0.13	-1.05	-0.490	-3.700	-134.00
NET FLUX	0.51	1.46	-0.121	-3.700	-85.50

STATION 19 830913 7.1 METERS 27.5 CENT.

	NH4	NO3	PO4	TOT P	DO
CONC.	0.010	0.060	0.027	0.070	6.77
TOTAL FLUX	1.60	1.20	0.620	-0.170	-65.00
NET FLUX	2.24	3.71	0.989	-0.170	-16.50

STATION 19 830913 7.1 METERS 27.5 CENT.

	NH4	NO3	PO4	TOT P	DO
CONC.	0.020	0.120	0.035	0.070	6.83
TOTAL FLUX	2.56	0.16	0.400	0.830	-149.00
NET FLUX	3.56	1.58	0.853	0.830	-100.50

STATION 19 831004 3.2 METERS 24.0 CENT.

	NH4	NO3	PO4	TOT P	DO
CONC.	0.050	0.240	0.024	0.081	7.21
TOTAL FLUX	6.69	-0.20	0.210	0.410	-41.00
NET FLUX	8.49	-2.05	0.546	0.410	7.50

STATION 19 831004 3.2 METERS 24.0 CENT.

	NH4	NO3	PO4	TOT P	DO
CONC.	0.030	0.250	0.025	0.069	7.31
TOTAL FLUX	2.99	-0.10	0.170	-0.200	-50.00
NET FLUX	4.29	0.23	0.517	-0.200	-1.50

STATION 19 831004 6.9 METERS 23.5 CENT.

	NH4	NO3	PO4	TOT P	DO
CONC.	0.020	0.240	0.024	0.067	7.31
TOTAL FLUX	1.32	0.00	0.130	-0.470	-52.00
NET FLUX	2.32	1.42	0.466	-0.470	-3.50

STATION 19 831004 6.9 METERS 23.5 CENT.

	NH4	NO3	PO4	TOT P	DO
CONC.	0.030	0.023	0.025	0.124	7.65
TOTAL FLUX	2.30	0.00	0.270	-0.800	-50.00
NET FLUX	3.60	0.33	0.617	-0.800	-1.50

STATION 19 840702 1.5 METERS 26.0 CENT.

	NH4	NO3	PO4	TOT P	DO
CONC.	0.004	0.327	0.010	999.000	8.32
TOTAL FLUX	0.52	2.39	0.260	999.000	-65.00
NET FLUX	0.87	5.55	0.428	999.000	-16.50

STATION 19 840702 1.5 METERS 26.0 CENT.

	NH4	NO3	PO4	TOT P	DO
CONC.	0.035	0.357	0.018	999.000	7.58
TOTAL FLUX	-1.48	-0.24	-0.030	999.000	-64.00
NET FLUX	-0.05	-0.45	0.237	999.000	-15.50

STATION 19 840702 5.0 METERS 26.0 CENT.

	NH4	NO3	PO4	TOT P	DO
CONC.	0.007	0.477	0.025	999.000	6.22
TOTAL FLUX	999.00	-2.10	-0.180	999.000	-100.00
NET FLUX	999.00	0.74	0.167	999.000	-51.50

STATION 19 840906 2.0 METERS 24.6 CENT.

	NH4	NO3	PO4	TOT P	DO
CONC.	0.036	0.231	0.024	999.000	6.68
TOTAL FLUX	-0.55	-1.54	-0.310	999.000	-44.00
NET FLUX	0.91	-1.86	0.026	999.000	4.50

STATION 19 840906 2.0 METERS 24.6 CENT.

	NH4	NO3	PO4	TOT P	DO
CONC.	0.033	0.236	0.026	999.000	6.98
TOTAL FLUX	-0.72	-1.43	-0.150	999.000	-80.00
NET FLUX	0.66	-1.43	0.208	999.000	-31.50

STATION 19 840906 5.0 METERS 24.6 CENT.

	NH4	NO3	PO4	TOT P	DO
CONC.	0.019	0.233	0.030	999.000	7.10
TOTAL FLUX	-0.48	-10.70	-1.060	999.000	-208.00
NET FLUX	0.49	-9.17	-0.659	999.000	-159.50

STATION 20 840709 1.5 METERS 27.0 CENT.

	NH4	NO3	PO4	TOT P	DO
CONC.	0.420	0.234	0.167	999.000	5.21
TOTAL FLUX	-13.20	-2.68	-5.620	999.000	-266.00
NET FLUX	-6.10	-2.76	-4.059	999.000	-169.00

STATION 20	840709	1.5 METERS	27.0 CENT.		
	NH4	NO3	PO4	TOT P	DO
CONC.	0.580	0.201	0.144	999.000	4.48
TOTAL FLUX	-12.50	-2.17	-5.040	999.000	-231.00
NET FLUX	-3.75	-2.25	-3.652	999.000	-134.00

STATION 20	840709	1.5 METERS	27.0 CENT.		
	NH4	NO3	PO4	TOT P	DO
CONC.	0.600	0.238	0.136	999.000	5.25
TOTAL FLUX	6.52	-1.27	-0.310	999.000	-69.00
NET FLUX	15.46	-1.35	1.016	999.000	28.00

STATION 20	840925	2.0 METERS	20.0 CENT.		
	NH4	NO3	PO4	TOT P	DO
CONC.	999.000	999.000	0.087	999.000	5.39
TOTAL FLUX	999.00	999.00	-3.220	999.000	-216.00
NET FLUX	999.00	999.00	-2.289	999.000	-119.00

STATION 20	840925	2.0 METERS	20.0 CENT.		
	NH4	NO3	PO4	TOT P	DO
CONC.	999.000	999.000	0.126	999.000	5.77
TOTAL FLUX	999.00	999.00	-0.500	999.000	-158.00
NET FLUX	999.00	999.00	0.748	999.000	-61.00

STATION 20	840925	1.5 METERS	20.0 CENT.		
	NH4	NO3	PO4	TOT P	DO
CONC.	999.000	999.000	0.071	999.000	6.16
TOTAL FLUX	999.00	999.00	-0.900	999.000	-142.00
NET FLUX	999.00	999.00	-0.107	999.000	-45.00

STATION 21	840924	2.0 METERS	20.0 CENT.		
	NH4	NO3	PO4	TOT P	DO
CONC.	0.362	0.155	0.077	999.000	6.07
TOTAL FLUX	-3.20	-1.06	0.710	999.000	-145.00
NET FLUX	3.26	-1.14	1.555	999.000	-48.00

STATION 21	840924	2.0 METERS	20.0 CENT.		
	NH4	NO3	PO4	TOT P	DO
CONC.	0.230	0.164	0.062	999.000	6.85
TOTAL FLUX	2.94	-0.65	1.880	999.000	-103.00
NET FLUX	7.76	-0.73	2.592	999.000	-6.00

STATION 21	840924	2.5 METERS	20.0 CENT.		
	NH4	NO3	PO4	TOT P	DO
CONC.	0.341	0.135	0.141	999.000	6.91
TOTAL FLUX	8.61	1.65	4.690	999.000	-176.00
NET FLUX	14.82	1.57	6.055	999.000	-79.00

STATION 21B	840706	1.5 METERS	27.0 CENT.		
	NH4	NO3	PO4	TOT P	DO
CONC.	0.410	0.212	0.048	999.000	6.02
TOTAL FLUX	-21.10	-2.93	-2.790	999.000	-290.00
NET FLUX	-14.11	-3.01	-2.209	999.000	-193.00

STATION 21B	840706	1.5 METERS	27.0 CENT.		
	NH4	NO3	PO4	TOT P	DO
CONC.	0.420	0.219	0.048	999.000	5.68
TOTAL FLUX	-16.10	-2.71	-1.510	999.000	-225.00
NET FLUX	-9.00	-2.79	-0.929	999.000	-128.00

STATION 21B	840706	1.5 METERS	27.0 CENT.		
	NH4	NO3	PO4	TOT P	DO
CONC.	0.460	0.255	0.058	999.000	6.44
TOTAL FLUX	-3.96	0.17	-2.630	999.000	-59.00
NET FLUX	3.57	0.09	-1.955	999.000	38.00

STATION 21B	840706	1.5 METERS	27.0 CENT.		
	NH4	NO3	PO4	TOT P	DO
CONC.	0.450	0.221	0.073	999.000	6.75
TOTAL FLUX	0.33	-0.72	-0.680	999.000	-75.00
NET FLUX	7.76	-0.80	0.130	999.000	22.00

Appendix C. Control Dome Measures

Concentration in mg/l

Flux in ugm/l/hr

Negative flux indicates water-column uptake

Missing data indicated by 999.

STATION 6 840703 1.0 METERS 28.0 CENT.

	NH4	NO3	PO4	TOT P	DO
CONC.	0.070	0.189	0.111	999.000	6.44
TOTAL FLUX	-30.84	7.65	-7.527	999.000	-0.40

STATION 6 840703 5.0 METERS 28.0 CENT.

	NH4	NO3	PO4	TOT P	DO
CONC.	0.080	0.251	0.117	999.000	7.60
TOTAL FLUX	-32.05	1.34	-14.689	999.000	-0.86

STATION 6 840917 2.0 METERS 22.0 CENT.

	NH4	NO3	PO4	TOT P	DO
CONC.	0.373	0.488	0.234	999.000	7.04
TOTAL FLUX	-30.05	3.58	-9.044	999.000	-0.21

STATION 6 840918 5.0 METERS 22.0 CENT.

	NH4	NO3	PO4	TOT P	DO
CONC.	0.544	0.697	0.251	999.000	8.06
TOTAL FLUX	-63.74	9.89	-11.776	999.000	-0.58

STATION 13 840705 1.8 METERS 28.0 CENT.

	NH4	NO3	PO4	TOT P	DO
CONC.	0.090	0.649	0.011	999.000	6.81
TOTAL FLUX	-33.02	0.00	-1.153	999.000	-0.27

STATION 13 840705 3.7 METERS 28.0 CENT.

	NH4	NO3	PO4	TOT P	DO
CONC.	0.070	0.631	0.014	999.000	6.63
TOTAL FLUX	-25.13	11.96	-4.370	999.000	-0.56

STATION 14 841011 2.0 METERS 18.5 CENT.

	NH4	NO3	PO4	TOT P	DO
CONC.	0.082	0.648	0.035	999.000	9.05
TOTAL FLUX	-14.75	-2.55	-3.642	999.000	-0.20

STATION 14 841011 5.0 METERS 18.5 CENT.

	NH4	NO3	PO4	TOT P	DO
CONC.	0.109	0.625	0.042	999.000	9.72
TOTAL FLUX	-7.95	3.58	-3.096	999.000	-0.32

STATION 19 840702 1.5 METERS 26.0 CENT.

	NH4	NO3	PO4	TOT P	DO
CONC.	0.011	0.329	0.011	999.000	8.14
TOTAL FLUX	-11.23	-18.15	-0.607	999.000	-0.58

STATION 19 840702 5.0 METERS 26.0 CENT.

	NH4	NO3	PO4	TOT P	DO
CONC.	0.000	0.467	0.023	999.000	6.44
TOTAL FLUX	999.00	-14.02	-2.549	999.000	-0.30

STATION 19 840906 2.0 METERS 24.6 CENT.

	NH4	NO3	PO4	TOT P	DO
CONC.	0.030	0.204	0.025	999.000	6.90
TOTAL FLUX	-3.82	4.61	-1.032	999.000	-0.18

STATION 19 840906 5.0 METERS 24.6 CENT.

	NH4	NO3	PO4	TOT P	DO
CONC.	0.023	0.210	0.027	999.000	7.55
TOTAL FLUX	-1.15	-1.34	-0.607	999.000	-0.12

STATION 20 840709 1.5 METERS 27.0 CENT.

	NH4	NO3	PO4	TOT P	DO
CONC.	0.400	0.238	0.175	999.000	6.04
TOTAL FLUX	-58.82	1.15	-16.693	999.000	-0.80

STATION 20 840709 1.5 METERS 27.0 CENT.

	NH4	NO3	PO4	TOT P	DO
CONC.	0.410	0.243	0.185	999.000	5.51
TOTAL FLUX	-26.28	-1.58	-6.313	999.000	-0.28

STATION 20 840925 1.5 METERS 20.0 CENT.

	NH4	NO3	PO4	TOT P	DO
CONC.	999.000	999.000	0.082	999.000	6.30
TOTAL FLUX	999.00	999.00	-6.313	999.000	-0.75

STATION 21 840924 2.5 METERS 20.0 CENT.

	NH4	NO3	PO4	TOT P	DO
CONC.	0.568	0.169	0.118	999.000	7.34
TOTAL FLUX	-43.58	1.27	-7.891	999.000	-0.56

STATION 21B 840706 1.5 METERS 27.0 CENT.

	NH4	NO3	PO4	TOT P	DO
CONC.	0.390	0.193	0.056	999.000	6.12
TOTAL FLUX	-59.55	1.58	-8.437	999.000	-0.77

STATION 21B 840706 1.5 METERS 27.0 CENT.

	NH4	NO3	PO4	TOT P	DO
CONC.	0.440	0.214	0.063	999.000	6.73
TOTAL FLUX	-25.07	0.00	-4.674	999.000	-0.38