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## Water Quality in a Small Tidal Creek: Parker Creek, Virginia

Carl F. Cerco

*Virginia Institute of Marine Science*

Albert Y. Kuo

*Virginia Institute of Marine Science*

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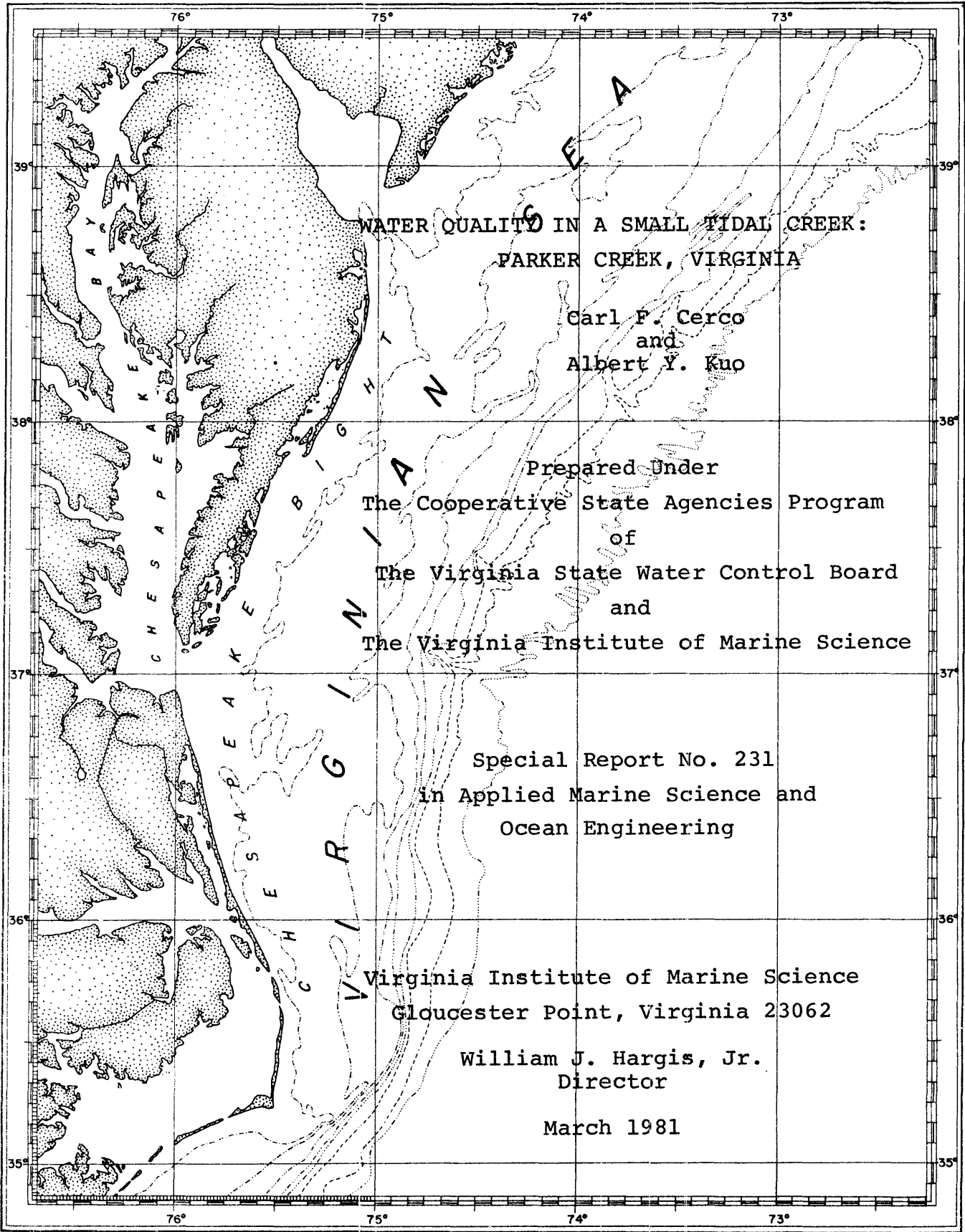
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WATER QUALITY IN A SMALL TIDAL CREEK:  
PARKER CREEK, VIRGINIA

Carl F. Cerco  
and  
Albert Y. Kuo

Prepared Under  
The Cooperative State Agencies Program  
of  
The Virginia State Water Control Board  
and  
The Virginia Institute of Marine Science

Special Report No. 231  
in Applied Marine Science and  
Ocean Engineering

Virginia Institute of Marine Science  
Gloucester Point, Virginia 23062

William J. Hargis, Jr.  
Director

March 1981

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Project Officers

Dale Jones  
Raymond Bowles

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## Abstract

Parker Creek is a branched tidal creek located on the Eastern Shore of Virginia. In its southern branch, the creek receives waste inputs from a poultry processing plant. A study has been conducted to determine the effects of these inputs and to formulate a mathematical model of the creek system suitable for water quality planning.

The model and field studies show the creek may be divided into two zones, an upstream zone dominated by freshwater flows and waste inputs, and a downstream zone dominated by conditions in adjacent Metomkin Bay. In the upstream zone of the waste-receiving branch, conditions of elevated nutrient and depressed dissolved oxygen concentrations exist. In the downstream zone, conditions are close to natural.

For purposes of comparison, surveys were conducted in three similar non-impacted tidal creeks and in Metomkin Bay. From a planning standpoint, the most significant result of these surveys is that violations of minimum dissolved oxygen standards may occur as a natural condition in tidal creeks.

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Keywords: Estuaries, Mathematical Models, Salt Marshes, Pollution, Virginia

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## Summary

System Characteristics - Parker Creek may be divided into two zones, an upstream regime characterized by a small volume and high ratio of runoff to tidal flow, and a downstream regime characterized by a large volume and low ratio of runoff to tidal flow. In the upstream regime, consisting of the headwaters and branches, conditions are dominated by the freshwater inputs and wasteflows. In the downstream regime, consisting of the main stem of the creek, conditions are dominated by the tidal influx from adjacent Metomkin Bay.

The downstream regime is characterized by relatively high oxygen concentrations and low nutrient levels. Conditions are comparable to those observed in similar natural creeks and are largely uninfluenced by wasteflows.

The upstream regime of the South Fork is characterized by depressed dissolved oxygen concentrations and elevated nutrient levels caused, in part, by wasteloading from above the fall-line. Ammonia, nitrate, and dissolved oxygen values in this portion of the creek are not comparable to the levels in similar natural creeks.

Dissolved Oxygen - Dissolved oxygen concentrations in Parker Creek frequently fall below 4 mg/l and may average less than 5 mg/l on a daily basis. Observations in unimpacted creeks suggest that D.O. concentrations below 5 mg/l are a natural occurrence. On the average, however, Parker

Creek is still depressed below natural D.O. levels, especially in the upstream portion of the South Fork.

The principal components of the Parker Creek D.O. deficit are benthic oxygen demand and wasteflows of ammonia. The benthic demand is influential throughout the creek while the nitrogenous oxygen demand is noticeable primarily in the South Fork.

Other Water Quality Parameters - Nitrate levels in Parker Creek are an order of magnitude or more greater than the levels in other creeks. Data are suggestive of elevated phosphorus concentrations as well. Parker Creek CBOD<sub>5</sub> and Total Suspended Solids levels are roughly equivalent or lower than concentrations observed in other creeks.

Benthic Oxygen Demand - Benthic oxygen demand in Parker Creek is highly variable but within the range observed in other creeks and in Metomkin Bay.

## Introduction

Parker Creek is a small tidal marsh-upland drainage system located on the Eastern Shore of Virginia. The creek is comprised of three forks, the South, Middle, and North Forks which join together to form the main stem which empties into Metomkin Bay, a delta bay separated from the Atlantic Ocean by a thin barrier island (Fig. 1). The upland drainage area of the creek is approximately 9.0 mi<sup>2</sup> and the total marsh area is 0.6 mi<sup>2</sup>. Distance from the mouth of the creek to the head of tide, the limit of the region of interest in this study, is approximately 3.0 miles along the South Fork, 2.4 miles along the North Fork and 2.2 miles along the Middle Fork.

The creek has been previously impacted by waste discharges from a chicken processing plant located at the headwaters of the South Fork. Conditions of depressed dissolved oxygen, accelerated eutrophication, and sludge deposits have been noted. (Va. SWCB, personal communication). At present, treatment facilities at the processing plant have been upgraded and waste discharges to the creek reduced. The creek has not recovered to expected levels, however, and depressed D.O. concentrations are still observed. Additional management efforts are hampered by lack of a means to predict the results of these efforts and by insufficient knowledge of

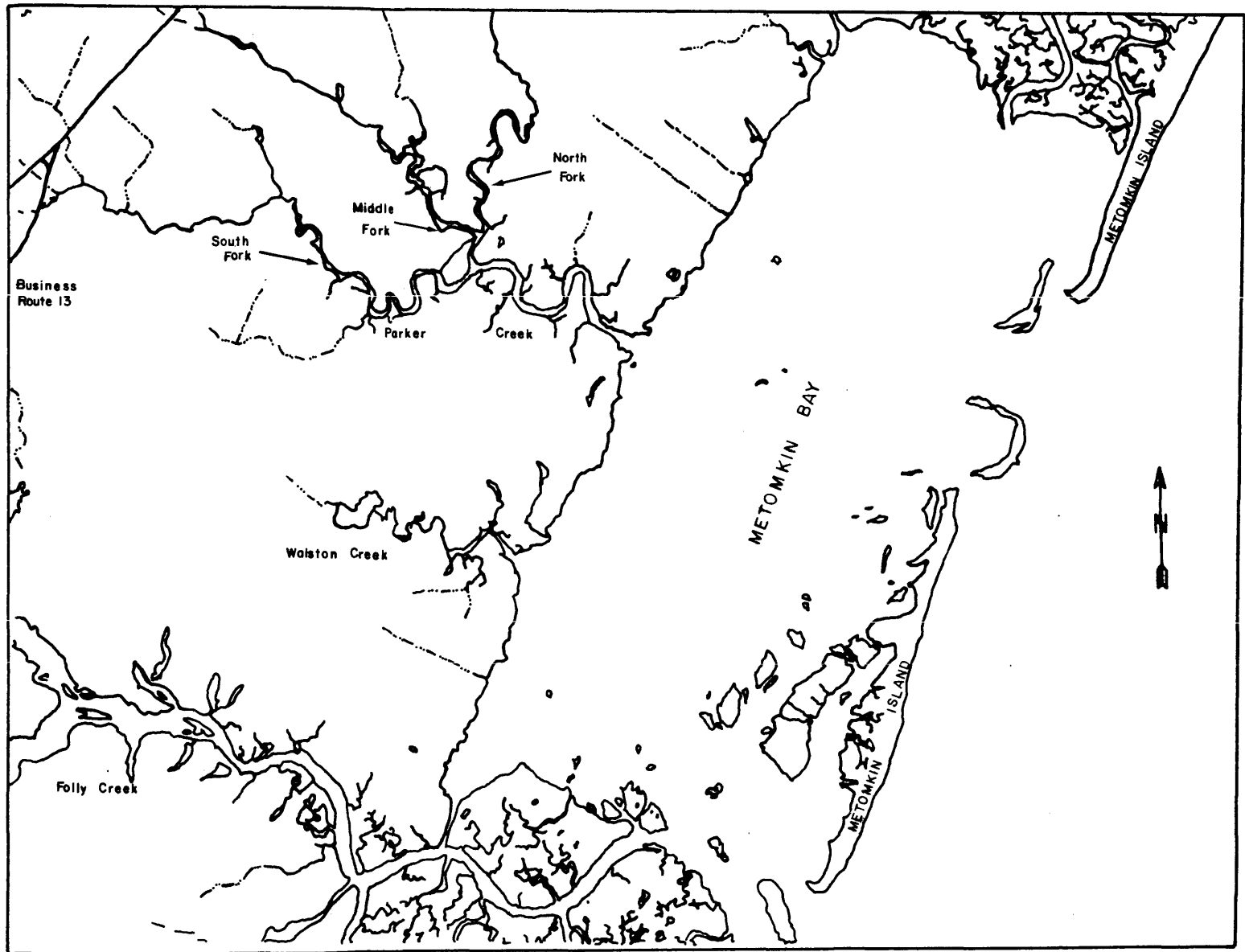


Figure 1. Parker Creek and Metomkin Bay.

the natural creek conditions towards which recovery steps are aimed.

This study has been conducted with two objectives - to develop a predictive model of water quality in the tidal section of Parker Creek and to compare the present conditions in the creek to several nearby non-impacted systems. Utilizing the results of the model, the factors which most influence water quality in the creek may be isolated and a rational management scheme may be formulated, based on the natural conditions observed in other streams. Details of the study are presented in succeeding chapters.

## Chapter 1

### Field Program

The field program in this study has been designed with two objectives: to obtain the physical and bio-geochemical data needed to develop, calibrate and verify a predictive water quality model of Parker Creek and to obtain comparative water quality data from several adjacent, similar creeks. A series of physical, intensive, and slack-water surveys were conducted to provide this data.

#### A. Physical Surveys

Physical surveys provide data about the physical characteristics of the system under study, e.g. drainage area, channel characteristics, and hydraulic data. Data obtained through physical surveys include:

1. Aerial Photographs - On August 24, 1978, a series of black-and-white infra-red aerial photographs were taken of Parker Creek and adjacent Metomkin Bay. Photos were taken at hourly intervals from low tide (approx. 0730) to high tide (approx. 1330) providing a progressive record of the tidal inundation of the creek. Identification of the submerged portions was facilitated by the reproduction, in infra-red, of water in black and vegetation in lighter shades approaching white (Fig. 2). Planimetry of the photographs provided data on the tidal prism of the creek and on the area of the marshes surrounding the water body.





Figure 2. Aerial infra-red photograph of Parker Creek.

2. Stream Transects - Measures of channel bathymetry were taken on August 21, 1978 at the locations shown in Figure 3. Data was obtained by drawing a recording fathometer across the stream surface from one side of the channel to the other during high tide resulting in a plot of channel depth vs. width. This data was then converted for use in the model into the geometric data presented in Table 1.

3. Tide Records - Two Fisher-Porter recording tide gauges, programmed to record stage level at six-minute intervals, were installed in the creek and operated from August 20 to August 24. One gauge was located at the mouth of the creek and the other was placed approximately half-way up the South Fork (Fig. 3). From this data, the tidal range in the creek (useful in calculating the tidal prism) was obtained and the stage at which water quality samples were withdrawn could be determined. A portion of the tidal record is reproduced as Figure 4.

4. Current Measurements - An Endeco Model 105 current meter was installed in the mouth of the channel and operated from 2200 hrs. on August 21 to 1430 hrs. on Aug. 24. By integrating the product of the current velocity and channel cross-section with respect to time, a measure of the tidal prism, independent of the aerial photos, was obtained. A portion of the current record is reproduced as Fig. 5.

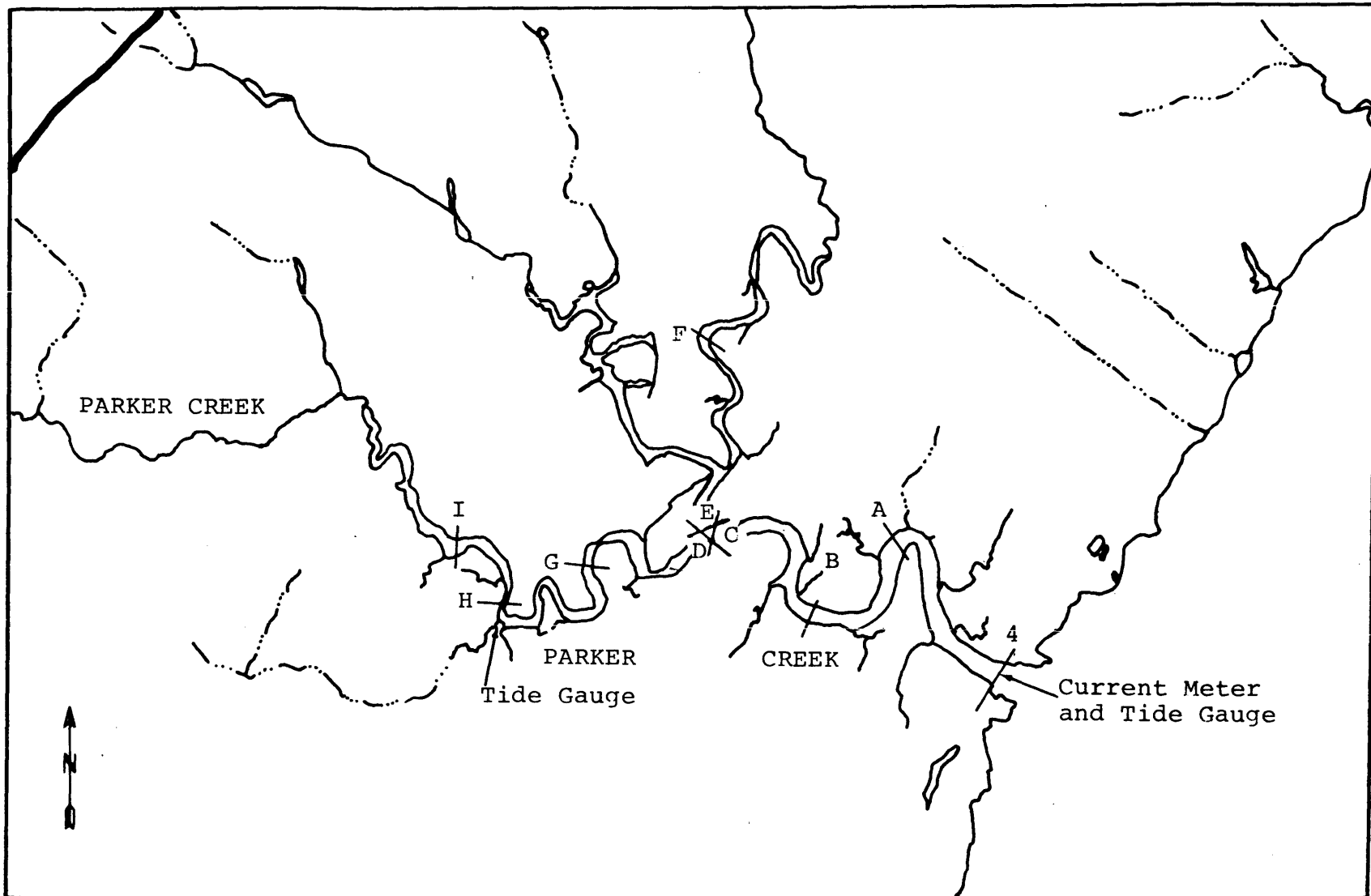


Figure 3. Location of survey transects, tide gauges, and current meter.

Table 1. Parker Creek Transect Dimensions

Transect	Distance (ft.)	High Tide		Low Tide	
		Area(ft <sup>2</sup> )	Width(ft.)	Area(ft <sup>2</sup> )	Width(ft.)
4	2371	626	174	181	113
A	1946	999	170	485	121
B	2128	883	162	392	107
C	122	682	149	229	92
D	2066	688	186	128	115
G	2858	233	67	47	40
H	1398	154	48	24	28
I		196	60	19	31
E	3161	542	135	148	82
F		143	43	20	26

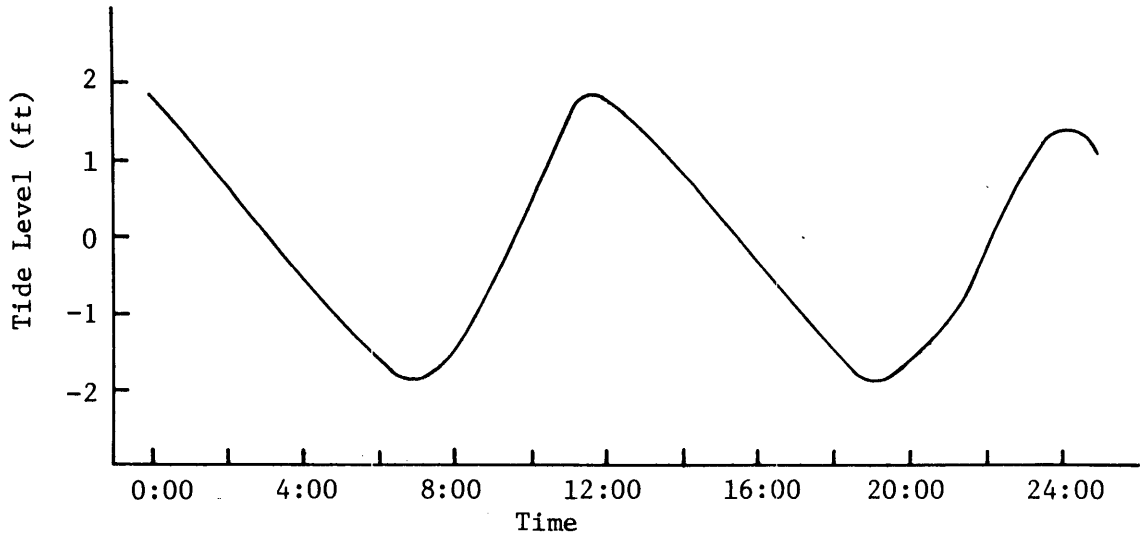


Figure 4. Tidal height at mouth of Parker Creek-Aug. 22, 1979.

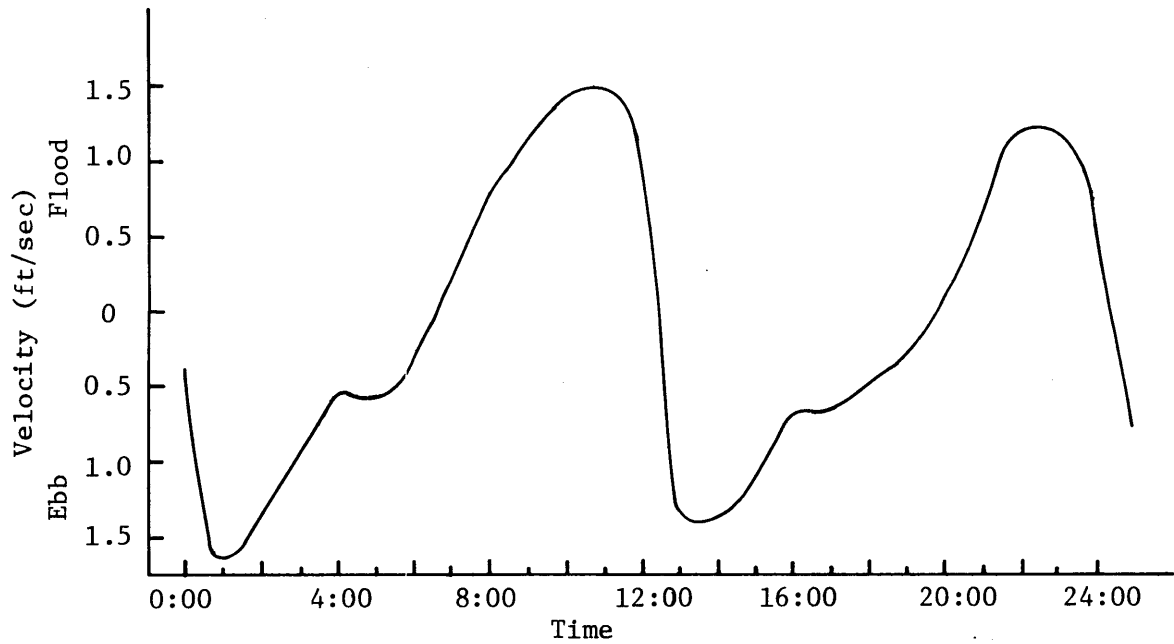


Figure 5. Current velocity at mouth of Parker Creek-Aug. 22, 1979.

## B. Intensive Water Quality Survey

An intensive water quality survey which provided the primary data set for this study was conducted in Parker Creek and Metomkin Bay from 2300 hrs. on Aug. 21 to 1400 hrs. on Aug. 24. Creek stations and Bay stations were sampled for consecutive twenty-five hour periods to provide water quality data for calibrating the proposed model and for determining the present condition of the creek. Twenty-five hour sampling periods allowed examination of both tidal and diurnal fluctuations within the system. Details of the creek survey are presented in subsequent paragraphs. A summary of the bay survey is presented in an appendix.

1. Sampling Stations - Six intensive stations were located on the tidal portion of Parker Creek (Fig. 6). Five stations were manned from the mouth of the creek to the head-of-tide of the South Fork, the branch of the creek which receives the waste discharges. A sixth station was located midway up the North Fork to assay the conditions in this segment of the creek.

2. Water Quality Parameters - At each station, samples were taken of the following parameters at the intervals shown:

- Total Kjeldahl Nitrogen (two hours)
- Ammonia Nitrogen (two hours)
- Nitrate + Nitrite Nitrogen (two hours)
- Total Phosphorus (two hours)
- CBOD<sub>5</sub> (one hour)

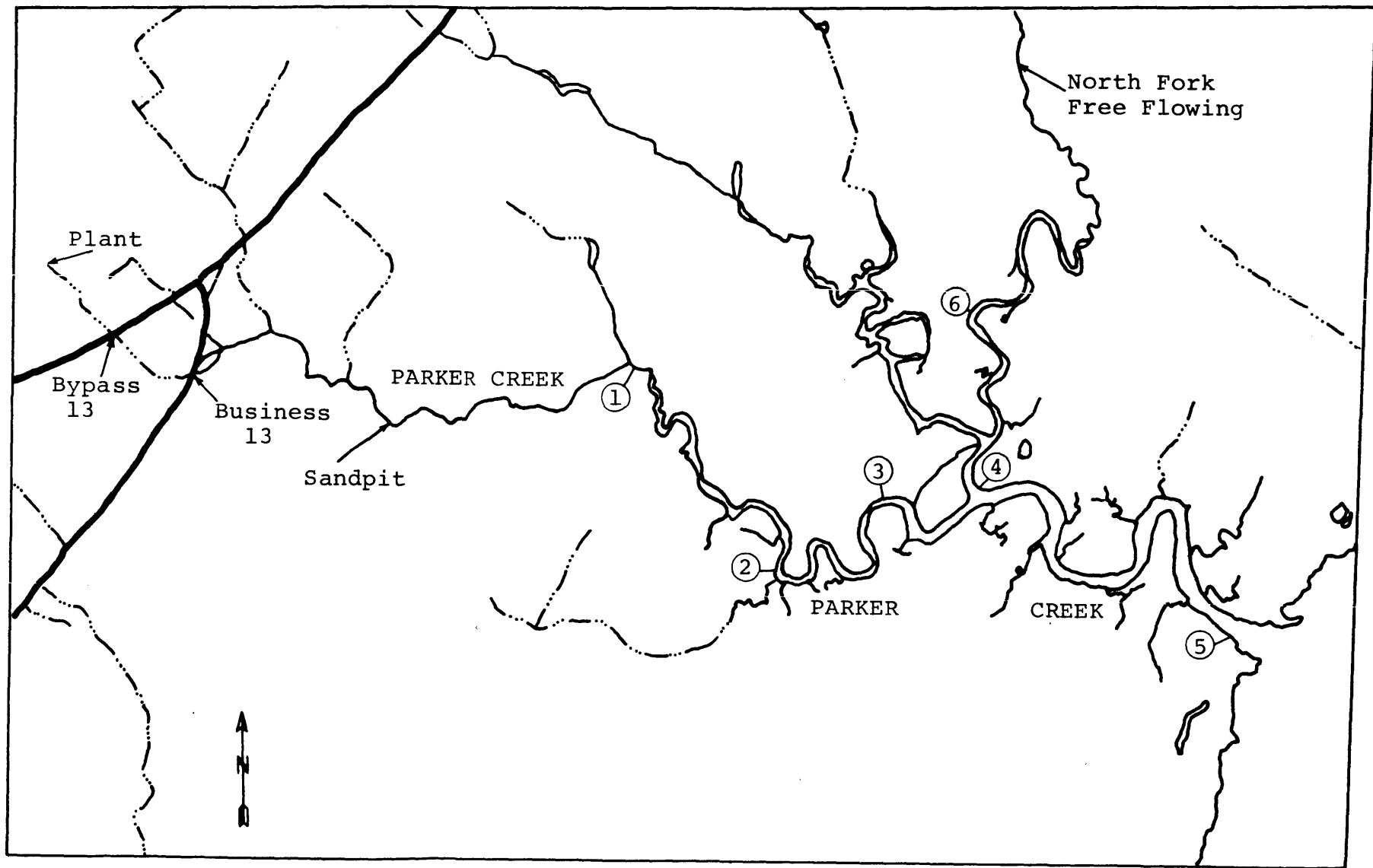


Figure 6. Intensive survey sample stations.

CBOD<sub>u</sub> (one sample)  
 Dissolved Oxygen (one hour)  
 Chlorophyll 'a' (one hour)  
 Salinity (one hour)  
 Temperature (one hour)

Five-day carbonaceous biochemical oxygen demand data (CBOD<sub>5</sub>) were scaled up to ultimate values (CBOD<sub>u</sub>) using the ratio of CBOD<sub>u</sub> to CBOD<sub>5</sub> derived from the average of the samples obtained at each station. This ratio is CBOD<sub>u</sub>/CBOD<sub>5</sub> = 2.6. A further correction was incorporated to allow for the planktonic biomass which contributed to the ultimate BOD of the sample. Final values of CBOD<sub>u</sub> were obtained via the relationship

$$\text{CBOD}_u = R * \text{CBOD}_5 - a_c * 2.67 * C \quad (1)$$

where

CBOD<sub>u</sub> = ultimate carbonaceous biochemical oxygen demand of sample

CBOD<sub>5</sub> = five-day carbonaceous biochemical oxygen demand of sample

R = ratio of CBOD<sub>u</sub>/CBOD<sub>5</sub> = 2.6

a<sub>n</sub> = ratio of carbon to chlorophyll in algal biomass = 0.025 mg/μgm (assumed)

C = chlorophyll 'a' concentration of sample

Values of organic nitrogen were obtained from TKN by subtracting the ammonia concentration and by correcting for the nitrogenous biomass of the phytoplankton entrapped in the sample. Final values of organic nitrogen were obtained via the relationship

$$\text{Org N} = \text{TKN} - \text{NH}_4 - a_n * C \quad (2)$$



where

Org N = organic nitrogen concentration of sample

TKN = total Kjeldahl nitrogen of sample

$\text{NH}_4$  = ammonia concentration of sample

$a_n$  = ratio of nitrogen to chlorophyll in algal biomass =  
0.005 mg/ $\mu\text{gm}$  (assumed)

A summary of the field data obtained is presented in Table 2.

3. Input Measurements - In addition to the intensive water quality stations, samples were withdrawn from the plant effluent and from four points above the tidal portion of the creek in order to determine the waste discharge and background inputs to the tidal system. These sample stations are shown in Fig. 6.

Two twenty-four hour composite samples were taken from the plant waste discharge - 0500 8/22 to 0500 8/23 and 0500 8/23 to 0500 8/24. Twice during this interval, the waste flow rate was measured by a Virginia State Water Control Board (SWCB) survey team permitting a quantification of the plant wasteloading.

The three remaining stations on the South Fork were sampled at four-hour intervals during the period from 0600 8/21 to 2200 8/22. Two flow measurements were also taken at each station. This data allowed a second calculation of the plant wasteload and provided information on the background loading and total input to the South Fork.

Table 2. Results of Intensive Water Quality Survey

Station	Org N mg/l	NH <sub>4</sub> mg/l	NO <sub>3</sub> + NO <sub>2</sub> mg/l	Tot P mg/l	Chl'a' µg/l	CBOD <sub>u</sub> mg/l	D.O. mg/l	Salinity ppt	Temp C°
1									
mean	0.86	15.6	44.9	0.20	7	2.7	3.8	0.7	-
range	0.03-1.17	1.1-19.4	34.8-54.9	0.11-0.28	1-60	1.7-7.6	2.5-4.9	0.5-6.2	
2									
mean	0.55	3.05	13.5	0.23	45	2.7	3.4	13.5	28.2
range	0.0-0.9	0.2-12.0	0.44-35.	0.14-0.48	15-71	1.6-16.9	1.3-7.6	4.3-30.9	25.1-31.9
3									
mean	0.55	3.25	5.2	0.23	28	4.4	3.0	19.8	-
range	0.0-1.07	0.05-16.	0.12-15.1	0.06-0.51	11-65	1.7-6.3	1.0-5.9	6.3-31.2	
4									
mean	0.44	2.69	3.4	0.18	17	4.6	3.7	32.7	21.4
range	0.0-0.76	0.03-17.4	0.07-10.4	0.11-0.35	4-28	1.6-11.4	1.5-5.4	22.1-40.9	17.0-23.6
5									
mean	0.40	0.23	0.40	0.13	11	4.5	4.4	39.4	21.5
range	0.0-0.64	0.05-0.68	0.01-1.71	0.04-0.25	3-29	2.1-9.6	0.7-6.2	33.1-42.0	18.1-23.8
6									
mean	0.59	0.43	5.6	0.17	16	3.9	3.8	18.0	-
range	0.0-1.1	0.1-1.13	0.18-38.1	0.06-0.35	6-41	1.8-9.2	1.4-6.0	4.7-31.1	

One water quality sample and flow measurement were taken in the free flowing stream immediately above the North Fork of the creek to provide information about the loading to this portion of the system. Results of the input measurements are presented in Table 3.

4. Additional Parameters - Measurements of two additional parameters, disk visibility and benthic oxygen demand, were also taken during and succeeding the intensive survey.

During the survey period, disk visibility in the creek averaged 0.2m. This parameter was converted to a light extinction coefficient, for use in the model, by the formula of Sverdrup et al. (1970)

$$k_e = \frac{1.7}{D_v} \quad (3)$$

where

$k_e$  = extinction coefficient ( $m^{-1}$ )

$D_v$  = disk visibility (m)

The extinction coefficient was next corrected for the phytoplankton concentration by the formula of Riley (1956)

$$k_e' = k_e - 0.0088 C - 0.054 C^{2/3} \quad (4)$$

where

$k_e'$  = non-phytoplankton related light extinction ( $m^{-1}$ )

$C$  = chlorophyll 'a' concentration ( $\mu g/l$ )

Light extinction in the Parker Creek system averages  $7.9 m^{-1}$ .

Table 3. Inputs to the Parker Creek System

Station	Flow	Distance from Tide-Line	Org N	NH <sub>4</sub>	NO <sub>2</sub> + NO <sub>3</sub>	Tot P	CBOD <sub>u</sub>	D.O.
	cfs	mi	mg/l (lb/day)	mg/l (lb/day)	mg/l (lb/day)	mg/l (lb/day)	mg/l (lb/day)	mg/l
Plant avg.conc. loading	3.7	1.76	0.25 (5.)	26.3 (525.)	77.5 (1546.)	0.37 (7.)	3.8 (76.)	5.4
Bypass 13 avg.conc. range loading	3.7	1.42	1.9 0.5-4.5 (38.)	25.3 22.0-27.0 (505.)	73.2 69.9-77.4 (1460.)	0.32 0.15-0.80 (6.)	3.4 1.0-7.2 (68.)	6.6 5.6-7.6
Bus. 13 avg.conc. range loading	3.7	1.25	0.4 0.0-1.5 (8.)	25.7 24.0-28.0 (513.)	75.9 67.4-79.9 (1514.)	0.31 0.19-0.40 (6.)	3.8 1.0-6.7 (76.)	6.6 5.2-7.3
Sand Pit avg.conc. range loading	3.7	0.95	0.7 0.0-4.5 (14.)	23.5 22.5-27.5 (481.)	69.6 64.8-77.4 (1426.)	0.23 0.20-0.30 (5.)	2.7 1.0-5.2 (55.)	6.9 6.6-7.2
North Fork conc. loading	2.1	0.38	0.6 (6.)	0.1 (1.)	6.0 (65.)	0.1 (1.)	2.0 (21.)	7.7

Benthic oxygen demand was measured during the August, 1978 survey at three locations shown in Fig. 7. In July, 1979, four additional creek stations and one repeat station were surveyed. Benthic oxygen demand measures, corrected to 20°C, are presented in Table 4.

Table 4. Benthic Oxygen Demand

Station	1	2	3	3*	4	5	6*	7*
Demand $\left( \frac{\text{mg D.O.}}{\text{m}^2\text{-day}} \right)$	0.9	3.3	1.3	1.0	2.7	1.8	2.2	4.8

\* 1978 value

#### C. Slack Water Survey

A less intensive slack water survey was conducted in Parker Creek on Sept. 13, 1978. The purpose of this survey was to collect additional data for verification of the predictive model. Samples were taken from the six creek stations at slack-before-flood (1300 hrs.) and slack-before-ebb (1900 hrs.). Results of the Sept. 13 slack-water survey are presented in Table 5.

#### D. Comparative Creek Surveys

As part of the effort to determine the natural conditions in Parker Creek in the absence of any waste-loading, a comparative survey was conducted in Parker Creek and in three similar creeks receiving no wasteflows (Fig. 8). The creeks selected were Bundick Creek, a tributary of Metomkin Bay, Gargathy Creek which feeds

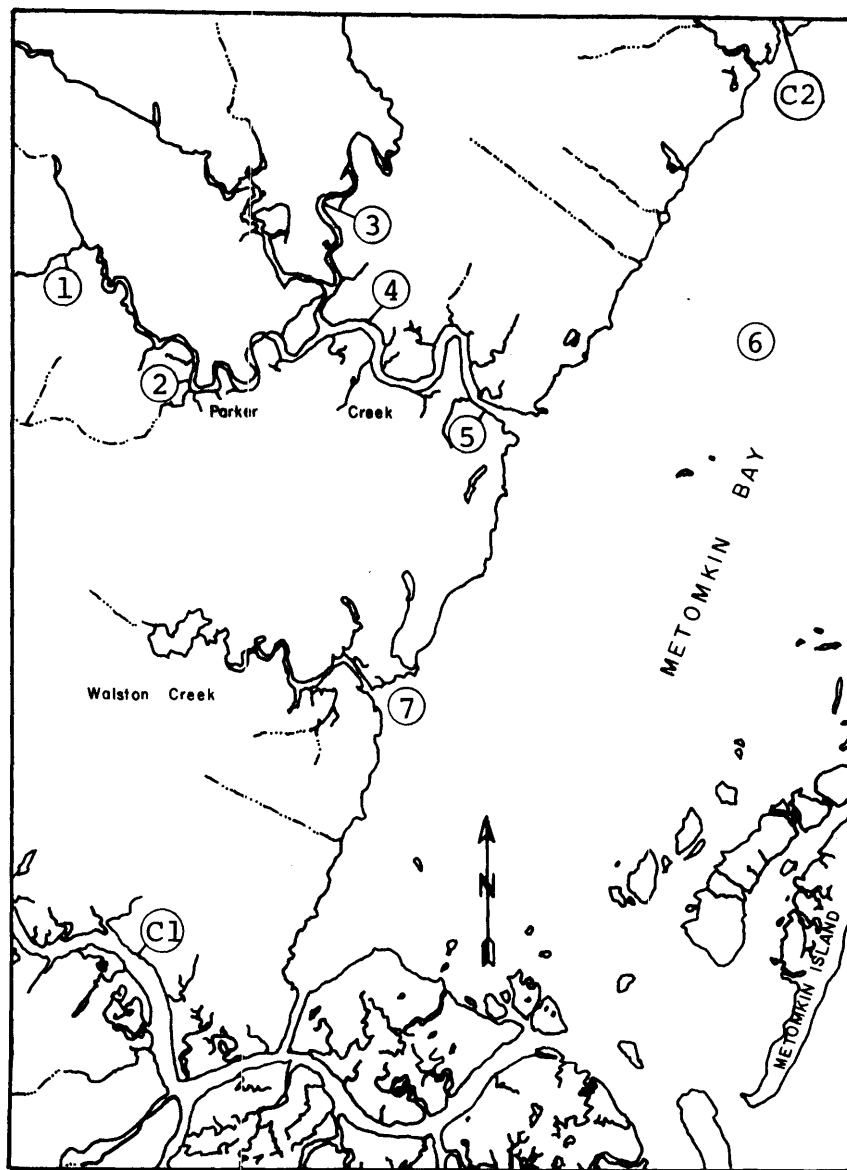


Figure 7. Benthic oxygen demand sample stations.

Table 5. Results of September 13 Slack Water Survey

Station	NO <sub>3</sub> + NO <sub>2</sub> mg/l	Tot P mg/l	Chl 'a' µg/l	CBOD <sub>u</sub> mg/l	D.O. mg/l	Salinity ppt	Temperature °C
1							
SBF		0.13	12.	13.0		0.5	22.
SBE	11.0	0.78		5.9		13.8	21.
2							
SBF			69.	7.4	4.8	2.0	22.
SBE	0.16	0.16	6.	3.9	6.6	31.0	22.
3							
SBF	8.0		77.		5.6	7.1	23.
SBE	0.10	0.09	5.	2.5	7.5	31.3	22.
4							
SBF	2.34	0.28	5.	9.3		13.9	23.
SBE	0.04	0.12	6.	2.6		31.3	22.
5							
SBF	1.05	0.16	5.	5.5		25.0	24.
SBE	0.04	0.12				31.2	23.
6							
SBF	3.36	0.33	85.	6.0	4.8	3.5	22.
SBE	0.07	0.88	6.	7.7	7.6	31.2	22.

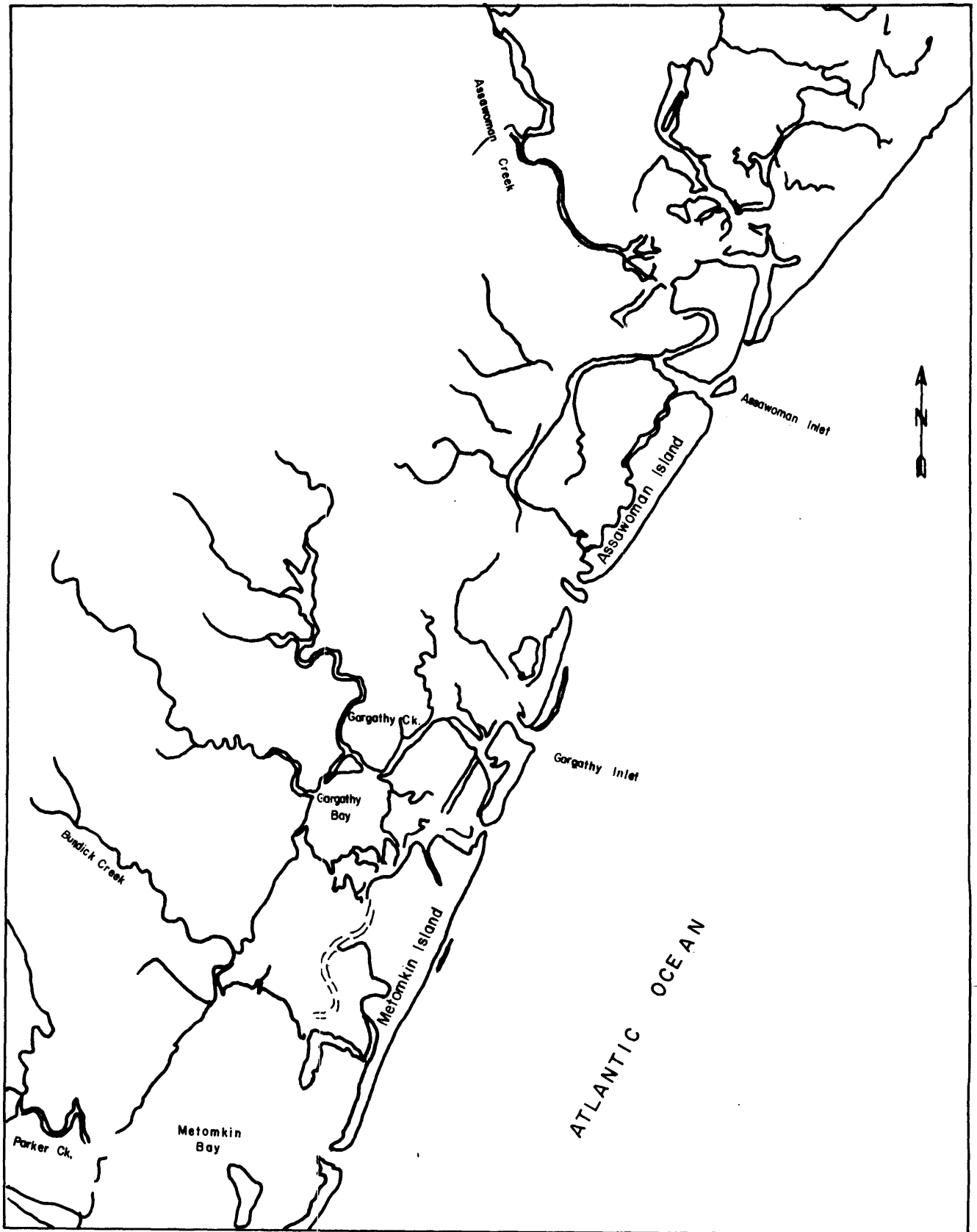


Figure 8. Locations of creeks surveyed during comparative study.



Gargathy Bay, located immediately north of Metomkin Bay, and Assawoman Creek, situated south of Wallops Island.

Each of the four creeks was sampled on Sept. 21, 1978 at slack-before-flood (0730) and slack-before-ebb (1330). Sampling stations for Parker, Bundick, Gargathy, and Assawoman Creeks are shown in Figures 9-12 respectively. The parameters sampled are identical to those taken in the intensive survey except that no  $CBOD_u$  measures were taken and total suspended solids (TSS) were included. The results of the comparative survey are presented in Table 6.

1. Benthic Oxygen Demand - During the July 1979 benthic oxygen survey, two stations off Parker Creek were surveyed. Located on Folly Creek and Bundick Creek and designated C1 and C2, these stations are shown in Fig. 7. Corrected to  $20^{\circ}C$ , the benthic demands at stations C1 and C2 were  $1.0 \text{ gm/m}^2\text{-day}$  and  $2.8 \text{ gm/m}^2\text{-day}$ .

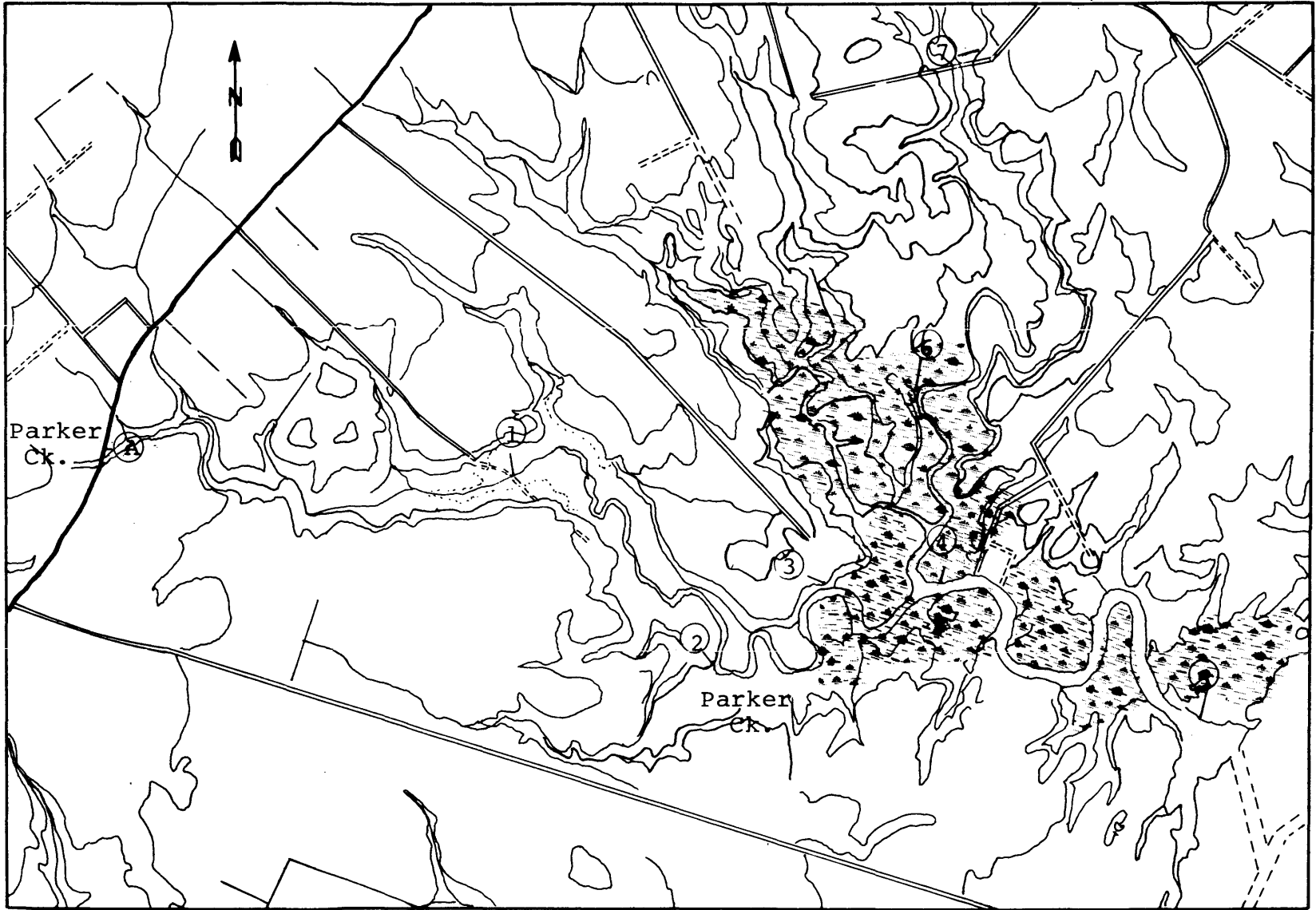


Figure 9. Parker Creek sample stations - Comparative Creek Study.

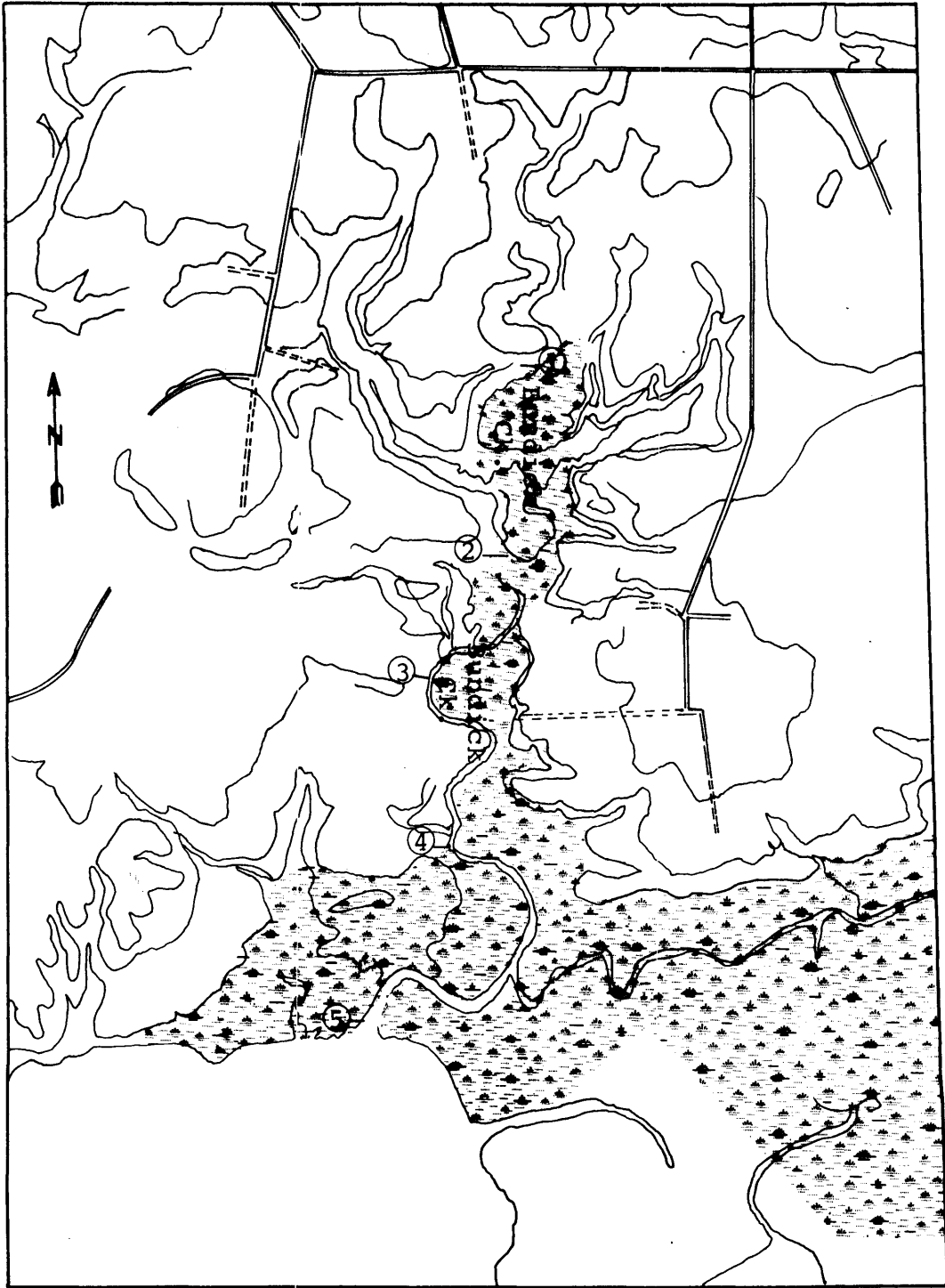


Figure 10. Bundick Creek sample stations - Comparative Creek Study.

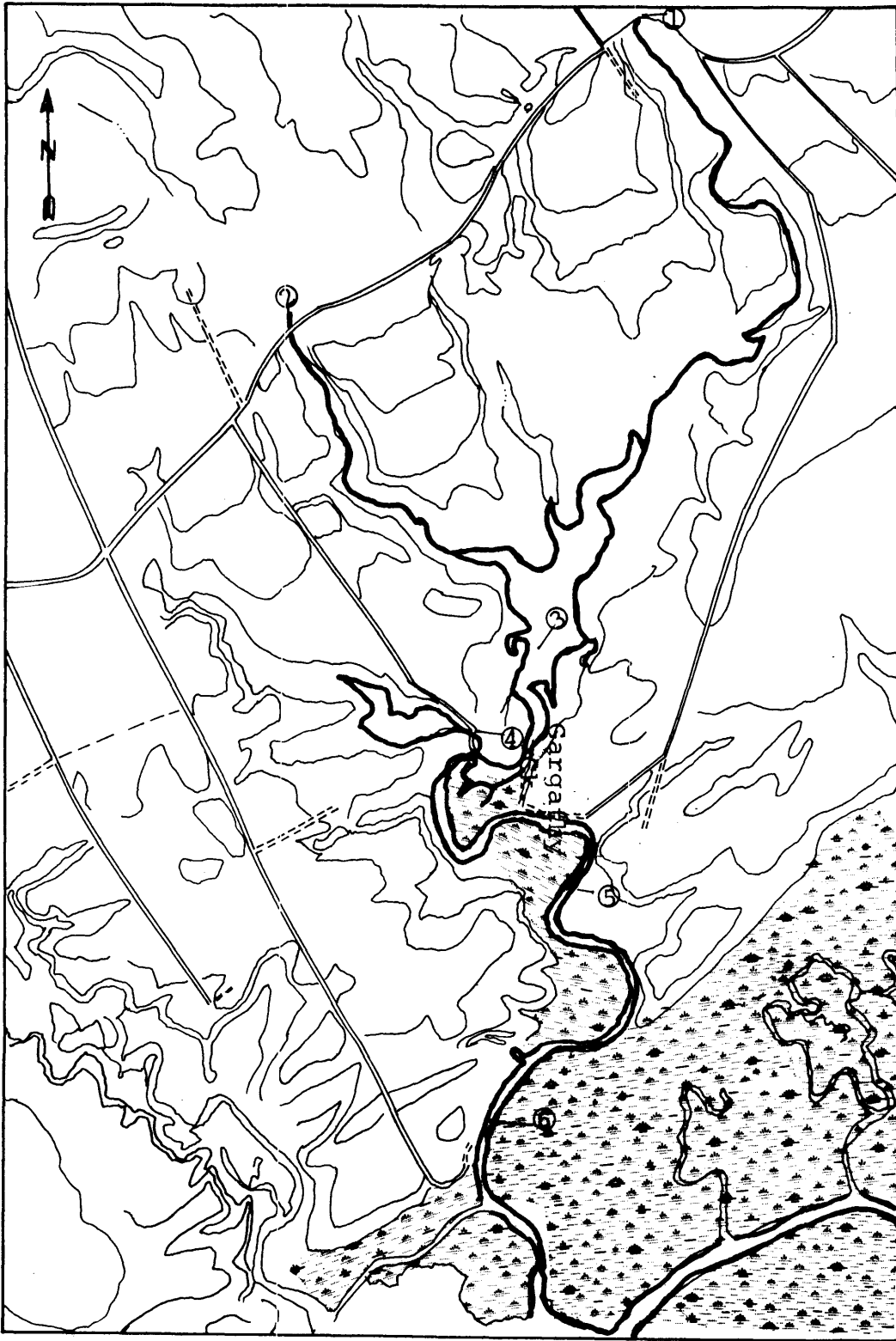


Figure 11. Gargathy Creek sample stations - Comparative Creek Study.

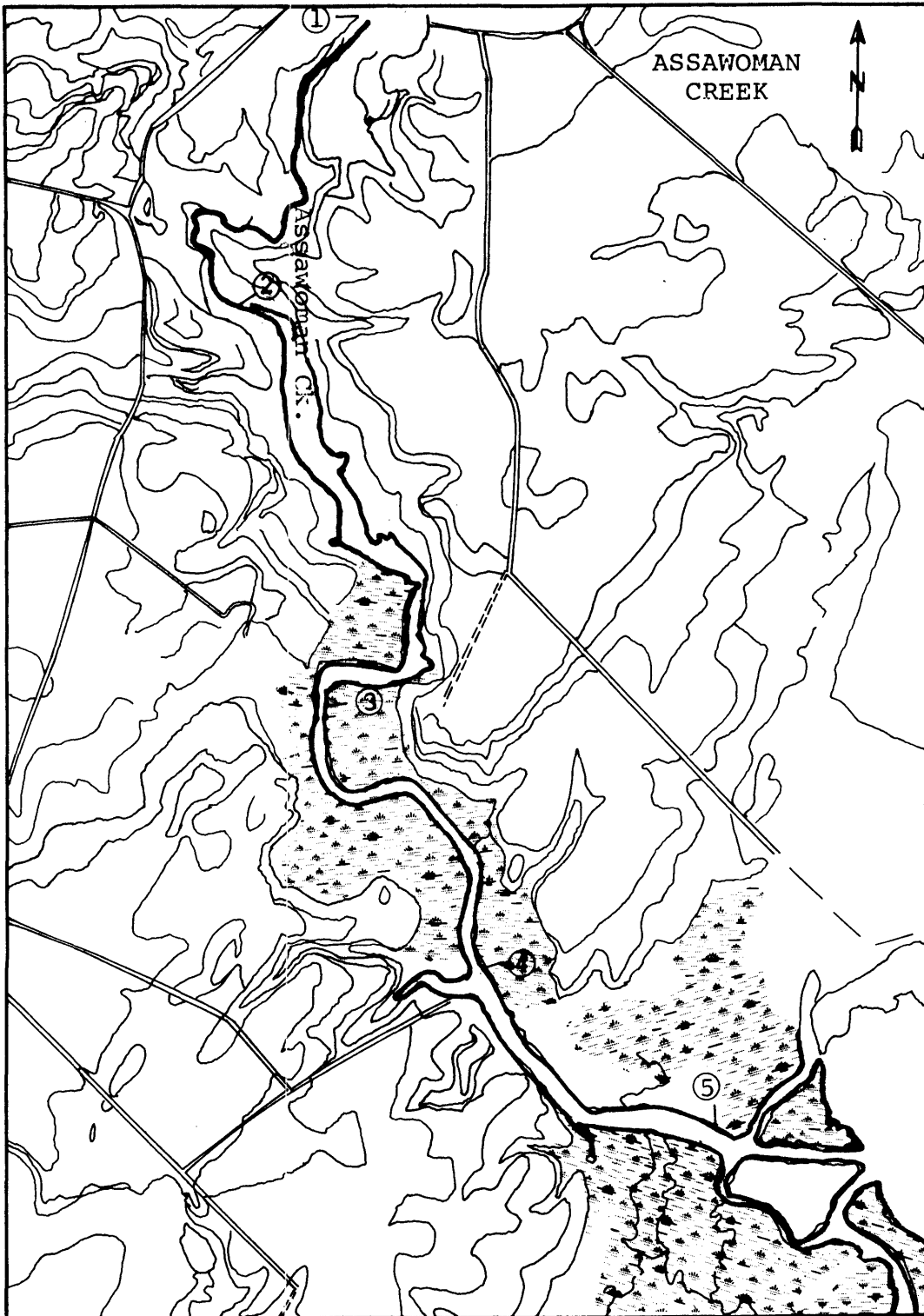


Figure 12. Assawoman Creek sample stations - Comparative Creek Study.

Table 6. Results of Comparative Survey

Station	Parker Creek		Bundick Creek		Gargathy Creek		Assawoman Creek		
	SBF	SBE	SBF	SBE	SBF	SBE	SBF	SBE	
A									
1				4.8			0.3	0.2	
2				<0.1*		1.8		0.5	Org. N
3					0.8	0.2	2.7	<0.1	(mg/l)
4			0.3	1.3		0.5		<0.1	
5			0.5	0.3	0.4		<0.1		
6									
7									
A									
1				0.8			<0.1	<0.1	
2				0.1		0.1		0.2	
3					0.3	0.1	<0.1	0.1	NH <sub>4</sub>
4			0.2	0.2		0.2		0.1	(mg/l)
5			0.1	<0.1	<0.1		0.1		
6									
7									
A	1.7	58.4							
1	4.5	28.4	0.12	0.53			1.60	1.48	
2	11.2	3.5		0.06	3.12	2.99			
3	13.5	0.3	0.60	0.03	0.26		0.13	0.01	NO <sub>3</sub> + NO <sub>2</sub>
4	3.9	0.2	0.42	0.11	0.38	0.02	0.01	0.01	(mg/l)
5	2.3	0.1	0.01	0.04	0.07	0.01	0.01	0.01	
6	3.5	0.5			0.41	0.01			
7	5.1	4.9							

\* < less than

Table 6 (Cont'd)

Station	Parker Creek		Bundick Creek		Gargathy Creek		Assawoman Creek		
	SBF	SBE	SBF	SBE	SBF	SBE	SBF	SBE	
A									
1			0.05	0.10			0.04	0.04	
2		0.32		0.13					
3		0.16	0.14	0.12			0.17	0.10	Total P
4	0.37	0.11	0.32	0.13	0.12	0.07	0.14	0.10	(mg/l)
5	0.21	0.09	0.11	0.11	0.10	0.10	0.18	0.14	
6	0.63	0.28				0.11			
7									
A	<1.	8.							
1	1.	3.	40.	19.	1.	<1.	<1.	<1.	
2	7.	6.	31.	7.	<1.	<1.	80.	7.	
3	7.	6.	11.	5.	11.	6.	46.	11.	Chl. 'a'
4	3.	5.	5.	6.	3.	8.	39.	6.	(µgm/l)
5	4.	6.	4.	10.	3.	5.	25.	11.	
6	4.	7.			2.	5.			
7	1.	2.							
A	2.0	1.0							
1	1.0	4.0	3.0	2.0	1.0	1.0	1.0	1.0	
2	1.0	1.5	2.0	1.0	1.0	1.0	5.5	7.5	
3	1.0	1.5	2.0	1.0	3.5	1.5	3.0	2.0	CBOD <sub>5</sub>
4	1.0	1.5	2.0	2.0	1.0	2.0	3.0	2.0	(mg/l)
5	1.0	2.0	1.0	2.0	2.0	2.0	2.5	1.5	
6	1.0	1.5			1.5	1.5			
7	1.0	1.0							

Table 6 (Cont'd)

Station	Parker Creek		Bundick Creek		Gargathy Creek		Assawoman Creek		
	SBF	SBE	SBF	SBE	SBF	SBE	SBF	SBE	
A	6.6	7.8							
1	3.7	4.4	7.1	8.5	8.2	8.2	8.8	7.9	
2	3.3	2.2	4.7	4.2	8.4	8.6	5.4	5.8	
3	5.4	2.5	5.3	3.0	3.8	6.6	5.2	8.2	D.O.
4	7.2	3.9	6.7	2.7	4.0	7.2	6.2	8.4	(mg/l)
5	7.1	3.3	7.1	4.4	5.2	7.3	6.0	8.3	
6	5.0	4.6			4.9	7.3			
7	4.2	8.2							
A	4.	6.							
1	<1.	8.	10.	21.	3.	<1.	4.	44.	
2	69.	59.	134.	55.	<1.	<1.	183.	48.	
3	24.	57.	100.	82.	57.	57.	49.	63.	TSS
4	35.	55.	408.	59.	97.	53.	53.	80.	(mg/l)
5	42.	46.	90.	70.	61.	111.	49.	50.	
6	91.	56.			58.	51.			
7	2.	2.							



Table 6 (Cont'd)

Station	Parker Creek		Bundick Creek		Gargathy Creek		Assawoman Creek		
	SBF	SBE	SBF	SBE	SBF	SBE	SBF	SBE	
A	0.	0.							
1	0.	0.	0.	6.4			0.	0.	
2	4.6	21.9	8.3	29.6	0.	0.	6.9	22.1	
3	8.8	30.2	15.0	30.3	25.6	30.7	0.	31.3	Salinity (ppt)
4		31.0	17.8	31.3	26.9	31.3	24.0	31.3	
5	5.0	30.8	31.0	30.7	29.4		26.3	31.4	
6	5.0	30.1			29.6	31.0			
7	0.	0.							
A	18.9	24.0							
1	17.0	21.1	22.8	23.1	18.0	20.0		19.0	
2	18.2	22.2	18.7	22.6	17.0	18.5	18.0	20.0	
3	19.6	21.7	20.1	22.5	22.0	25.0	20.0	21.0	
4	20.1	22.3	19.9	22.5	22.5	24.0	21.0	20.0	
5	21.2	22.5	21.0	22.5	22.5	24.0	20.0	20.0	
6	17.4	22.6			22.0	25.0			
7	15.4	20.6							

## Chapter 2

### The Mathematical Model - Formulation

Water quality in a tidal marsh system is the result of a complex series of biochemical substance transformations and physical transport processes. Nutrient exchanges between the surroundings and the water column and wasteload inputs exert additional influences on the system. Under these circumstances, it is difficult to predict the ultimate effect of changes in the use, wasteload or hydraulic characteristics of the water body. A mathematical model is useful in this instance both to aid in understanding of the system and to provide consistent, rational forecasts of the response of the system to changes in specified parameters.

Mathematical models are generally based on the principal of conservation of mass. A complete model would couple the three-dimensional momentum and continuity equations describing mass transport in the system with a detailed description of the biochemical kinetics and sources and sinks of all dissolved constituents. Such a representation is neither mathematically feasible nor desirable. In practice, the modeller must decide which parameters are most important within the system and which are less so. He must isolate the dominant hydrodynamic terms, the dissolved constituents of interest, and the kinetic terms which influence these constituents and next must abstract these into a model consistent with

tractibility, economy, and desired results. The model developed in this manner for Parker Creek is described in the remainder of this chapter.

#### A. Hydrodynamic Representation

The hydrodynamic regime in Parker Creek is dominated by tidal transport. During each 12.4 hr. tidal cycle,  $9 \times 10^6 \text{ ft}^3$  of water are exchanged between the creek and the bay due to tidal flushing. During the same period, only about  $4 \times 10^5 \text{ ft}^3$  of fresh water enter the system. Thus a model based on substance transport by the tidal prism is appropriate. This model predicts the longitudinal distribution of conservative and nonconservative dissolved constituents during the period of high slack water (slack-before-ebb).

The rise and fall of the tide at the mouth of an estuary or coastal creek causes an exchange of water masses through the entrance. This results in the temporary storage of large amounts of sea water in the estuary during flood tide and the drainage of this water during ebb tide. This volume of water is known as the tidal prism. Since the water brought into the estuary on flood tide mixes with 'polluted' estuarine water, a portion of the pollutant mass in the estuary will be flushed out of the estuary on ebb tide. This kind of flushing mechanism due to the rise and fall of the tide is called tidal flushing.

Classical tidal prism theory was an early attempt to describe transport processes in an estuary. The theory assumed that mixing is complete throughout the entire estuary at high tide. Ketchum (1951) modified this tidal prism theory by dividing the estuary into segments, each of which is assumed to be completely mixed at high tide. The length of each segment is defined by the tidal excursion, the average distance travelled by a water particle on the flood tide, since this is the maximum length over which complete mixing can be assumed.

Some of the assumptions used by Ketchum are retained in this model. It is assumed that the estuary or coastal creek is in hydrodynamic equilibrium. That is, the freshwater inflow is constant and the net seaward transport of freshwater over a tidal cycle is equal to the volume of freshwater introduced by surface runoff during the same period. There is no net exchange of salt over a tidal cycle. This implies a balance between the inflow and outflow of sea water. The assumption that complete mixing is achieved within each segment having a length equal to or less than a tidal excursion also is retained.

1. Segmentation of Water Bodies - In the original (Ketchum's) approach, the segmentation of the estuary is started at the head of the estuary by defining the first segment as the one above which the tidal prism equals the river flow over a tidal cycle. In this study, a different

scheme developed by Kuo (1976) is utilized in which segmentation starts at the mouth of the estuary.

The water body outside of the mouth is denoted as the first segment (Figure 13). The adjacent segment within the estuary is indexed as segment number two, bounded by transects one and two. The first transect is across the mouth, the second transect is chosen such that a water particle will move from the first to the second transect over flood tide. Therefore, the tidal prism, or intertidal volume, upstream of the second transect must be big enough to accommodate the volume of water in segment two at low tide plus the total volume of freshwater inflow over flood tide, i.e.

$$P_2 = V_2 + R_2, \quad (5a)$$

or

$$V_2 = P_2 - R_2 \quad (5b)$$

where

$V_2$  = low tide volume of second segment

$P_2$  = tidal prism upstream of second transect

$R_2$  = volume of river water entering the water body upstream of the second transect during a half-tidal cycle

In general, a water particle at the (n-1)st transect at the beginning of flood tide should move to the nth transect at the end of flood tide. Thus,

$$P_n = V_n + R_n \quad (6)$$

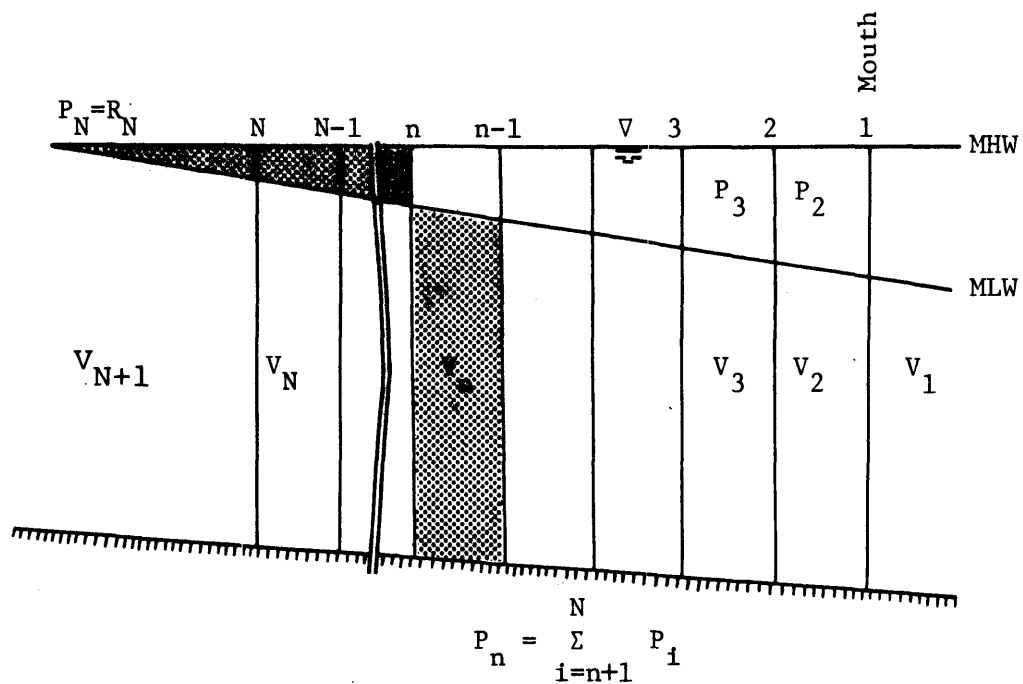


Figure 13. Segmentation of an estuary.

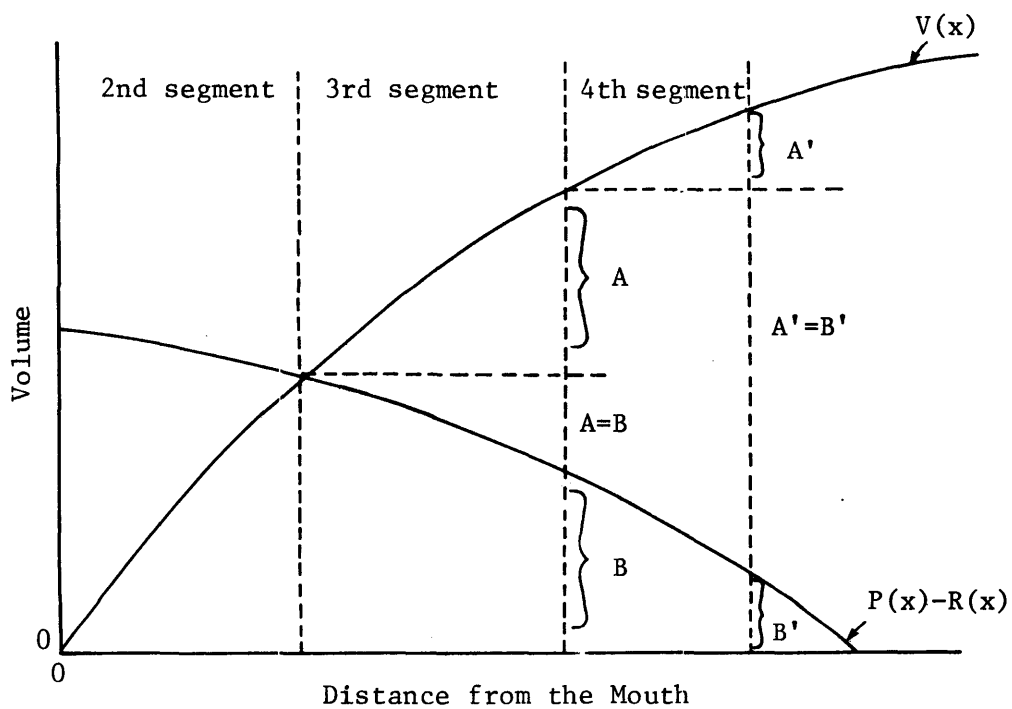


Figure 14. Determination of segment lengths.

or

$$\begin{aligned} V_n &= P_n - R_n \\ &= P_{n+1} + \rho_{n+1} - (R_{n+1} + r_{n+1}) \end{aligned} \quad (7)$$

or

$$V_n = V_{n+1} + \rho_{n+1} - r_{n+1} \quad (8)$$

where

$V_n$  = low tide volume of the nth segment

$P_n$  = tidal prism upstream of the nth transect

$R_n$  = total freshwater discharge above the  
nth transect over half a tidal cycle

$\rho_n$  = local tidal prism of the nth segment

$r_n$  = lateral freshwater input into the nth segment  
over half a tidal cycle

Equation (8) states that the low tide volume of a segment is equal to the high tide volume of its immediate landward segment less the lateral freshwater input into that segment.

It may be seen from equation (7) that  $V_n$  tends to zero as  $P_n$  decreases toward the head of the estuary. Therefore, an infinite number of segments will result unless a cut-off criterion is defined. The guideline utilized is to continue segmentation until  $P_{n+1} < 3R_{n+1}$ . Once this condition is reached, the remainder of the estuary is combined into one single segment, the Nth segment, as shown in Figure 13. The prism upstream of the Nth transect is equal to the upstream freshwater discharge, that is  $P_n = R_n$ . If there is no river flow, this method of segmentation is still valid except that the cutoff criterion

is never attained and the decision to cease segmentation is arbitrary.

The length of the Nth segment will be larger than the local tidal excursion and complete mixing cannot be achieved within this segment. The concentration predicted by the model for this segment still represents the average value of the segment, however.

2. Determination of Segment Lengths - Figure 14 shows for a hypothetical estuary the accumulated low tide volume,  $V(x)$ , and the difference between the tidal prism and the river flow upstream of a point,  $(P(x) - R(x))$ , plotted as a function of  $x$ , the distance from the mouth.  $V(x)$  is defined as the accumulated low tide volume from the mouth to any distance  $x$ .  $P(x)$  is defined as the intertidal volume upstream of a transect located at  $x$ .  $R(x)$  is defined as the freshwater input during a half tidal cycle, also upstream of a transect located at  $x$ .

Since each model segment length equals the local tidal excursion, the low tide volume of the first segment within the estuary should equal the intertidal volume minus the river flow over a half tidal cycle upstream of the segment's landward boundary. This point, where  $V(x) = (P(x) - R(x))$  can be determined graphically or by interpolation of a table of values of  $V(x)$  and  $(P(x) - R(x))$ .



The volume  $P_1$  represents the entire intertidal volume of the estuary. Similarly, the volume  $R_1$  represents the entire freshwater input into the estuary, including lateral inflow. These values are not used directly in the calculation, since the first low tide volume considered is  $V_2$ .  $V_1$  is a dummy volume, located outside the mouth. The initial segment, therefore, is indexed as segment two. Once the initial segment is determined, successive segmentation is shown in Figure 14. Segmentation continues until the boundary constraint previously mentioned is reached.

For an estuary with tributaries,  $P(x)$  is similarly defined, but it includes the intertidal volume of the tributaries as well.  $R(x)$  is defined such that the freshwater input from the tributaries is included. The value  $V(x)$  remains as the low tide volume along the main stem. These volumes are shown graphically in Figure 15. Once again, the initial segment is determined such that the low tide volume,  $V_2$ , is equal to the intertidal volume less the river flow upstream of that point. In a segment where a tributary comes in, the local low tide volume is equal to the tidal prism landward of the segment plus the prism less the river flow of the branch. Each of the tributaries may be segmented in the same way as the main stem.

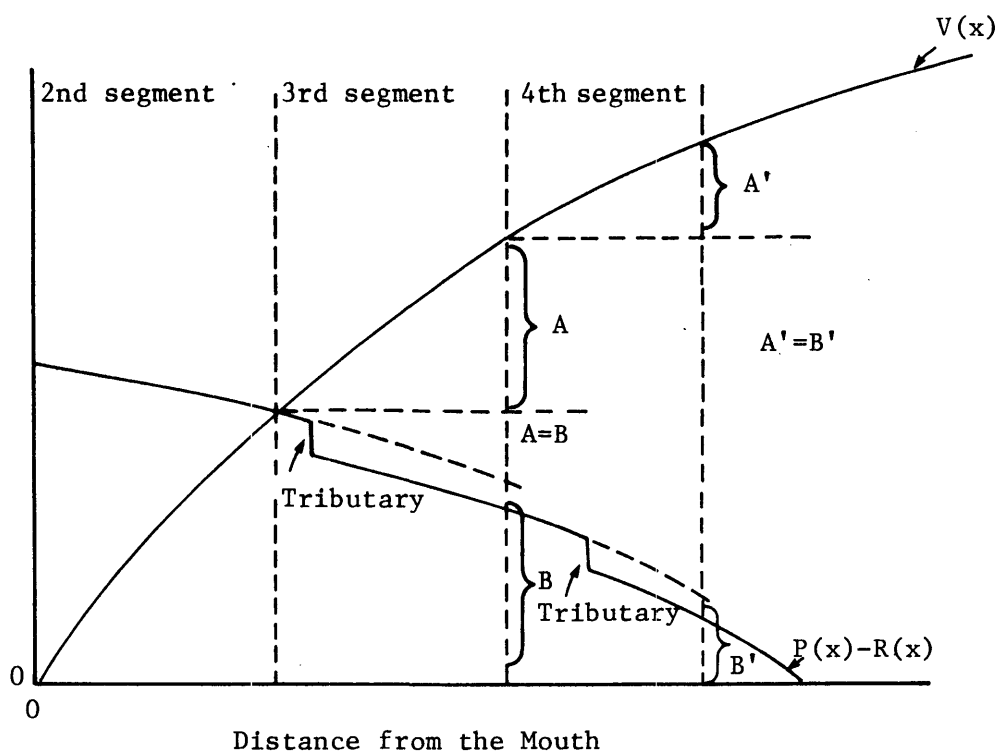


Figure 15. Determination of segment lengths in the presence of tributaries.

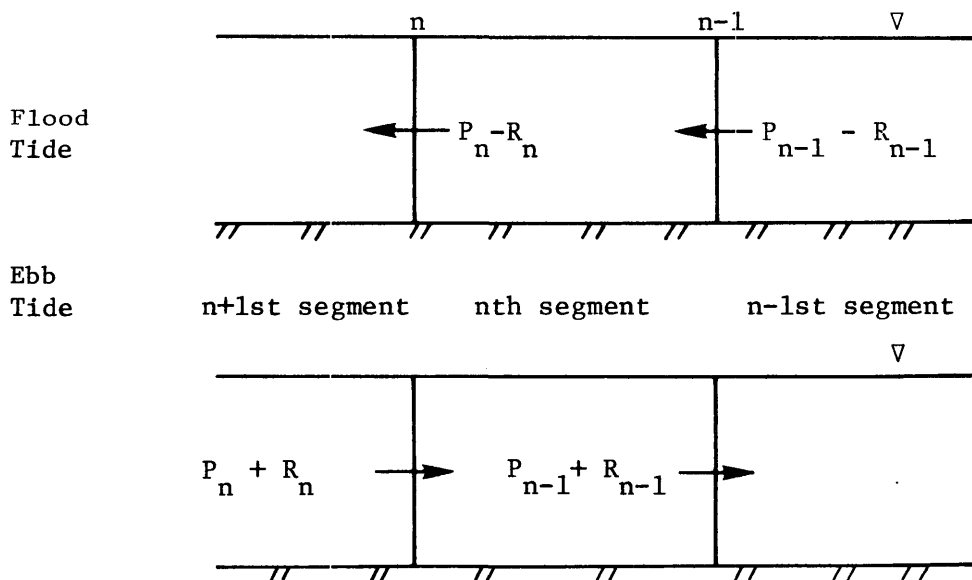


Figure 16. Flow across transects at flood and ebb tides.

## B. Calculation of the Concentration of a Conservative Substance

As the tide propagates upstream from the mouth of the water body, a volume of water equal to  $(P_{n-1} - R_{n-1})$  moves upstream across the  $(n-1)$ th transect and mixes with the water volume  $V_n$  present in the  $n$ th segment at low tide. Of this mixed water, the portion  $(P_n - R_n)$  moves upstream across the  $n$ th transect and is mixed with  $V_{n+1}$  and so forth. At the ebbing tide, the volume of water  $(P_n + R_n)$  moves downstream across the  $n$ th transect, pushing a volume  $(P_{n-1} + R_{n-1})$  across the  $(n-1)$ th transect, and so forth, thus completing tidal flushing. The flow across the transects bounding the  $n$ th segment is shown in Figure 16.

Except for the last transect, the water volume moving across the  $n$ th transect during ebb tide,  $(P_n + R_n)$ , may be separated into two parts. The first part is the water in the  $(n+1)$ th segment at high tide. This is

$$\begin{aligned} V_{n+1} + \rho_{n+1} &= P_{n+1} - R_{n+1} + \rho_{n+1} \\ &= P_n - R_{n+1} \end{aligned} \quad (9)$$

This volume has concentration  $C_{n+1}$  where  $C_{n+1}$  is the high tide concentration in the  $(n+1)$ th segment at the beginning of tidal cycle. The remainder of the water can be represented as

$$\begin{aligned} (P_n + R_n) - (V_{n+1} + \rho_{n+1}) & \quad (10) \\ &= P_n + R_n - (P_n - R_{n+1}) \\ &= R_n + R_{n+1} \end{aligned}$$

This volume,  $R_n + R_{n+1}$ , has the concentration  $C_{n+2}$  if

$$\begin{aligned} R_n + R_{n+1} &< V_{n+2} + \rho_{n+2} \\ &< P_{n+2} - R_{n+2} + \rho_{n+2} \\ &< P_{n+1} - R_{n+2} \end{aligned} \quad (11)$$

or  $P_{n+1} > R_n + R_{n+1} + R_{n+2}$

or approximately

$$P_{n+1} \geq 3R_{n+1} \quad (12)$$

This inequality is consistent with the guideline for stopping segmentation expressed in Section A of this chapter. This guideline results in computational efficiency since the concentration during ebb tide on any segment is restricted to dependence only on the concentrations in the next two segments immediately landward.

The mass transport into and out of the  $n$ th segment during ebb tide may now be expressed as

$$\begin{aligned} \text{mass in} &= \text{ETP}_n = \text{Ebb Tide Transport into the} \\ &\quad \text{nth Segment} \\ &= (P_n - R_{n+1}) C_{n+1} + (R_n + R_{n+1}) C_{n+2} \end{aligned} \quad (13)$$

$$\begin{aligned} \text{mass out} &= \text{ETP}_{n-1} = \text{Ebb Tide Transport out of} \\ &\quad \text{the nth Segment} \\ &= (P_{n-1} - R_n) C_n + (R_{n-1} + R_n) C_{n+1} \end{aligned} \quad (14)$$

The last,  $N$ th segment has a volume larger than that set by the criterion of segmentation. Therefore, the volume of water moving through the  $N$ th segment must be considered separately. The volume moving into the  $N$ th segment during ebb tide is equal to  $2R_N$ , the river flow over a tidal

cycle. This volume has concentration  $C_{N+1}$ . The volume leaving the segment during ebb tide is equal to  $P_{N-1} + R_{N-1}$  and has a concentration  $C_N$ . The mass transport into and out of the Nth segment during ebb tide may thus be expressed

$$\begin{aligned} \text{mass in} &= \text{ETP}_N = \text{Ebb Tide Transport into the} \\ &\quad \text{Nth Segment} \\ &= 2R_N C_{N+1} \end{aligned} \quad (15)$$

$$\begin{aligned} \text{mass out} &= \text{ETP}_{N-1} = \text{Ebb Tide Transport out of} \\ &\quad \text{the Nth Segment} \\ &= (P_{N-1} + R_{N-1}) C_N \end{aligned} \quad (16)$$

It is possible for some of the water that leaves a segment during ebb tide to return during the following flood tide. This is accounted for by defining a returning ratio,  $\alpha_n$ , such that  $100\alpha_n$  is the percentage of old water reentering through the nth transect at flood tide. The fraction of new water entering through the nth transect at flood tide may be expressed as  $(1-\alpha_n)$ .

At flood tide, the volume  $(P_n - R_n)$  flowing through the nth transect has the concentration

$$\alpha_n C_{n+1} + (1 - \alpha_n) C2_n$$

where  $C2_n$  equals the high tide concentration at the end of tidal cycle. The mass transport into and out of the nth segment during flood tide may be expressed as

$$\begin{aligned} \text{mass in} &= \text{FTP}_{n-1} = \text{Flood Tide Transport into the} \\ &\quad \text{nth Segment} \\ &= \{ \alpha_{n-1} C_n + (1 - \alpha_{n-1}) C2_{n-1} \} (P_{n-1} - R_{n-1}) \end{aligned} \quad (17)$$

mass out =  $FTP_n$  = Flood Tide Transport out of  
the nth Segment

$$\{\alpha_n C_{n+1} + (1 - \alpha_n) C2_n\} (P_n - R_n) \quad (18)$$

The change of mass,  $\Delta m$ , with respect to time is

$$\frac{\Delta m}{\Delta t} = \text{sources} + (\text{mass in}) - (\text{mass out}) \quad (19)$$

In the present development, the change of mass in the nth segment over the entire tidal cycle can be represented as

$$(C2_n - C_n) (V_n + \rho_n) = \text{sources} + ETP_n - ETP_{n-1} + FTP_{n-1} - FTP_n \quad (20)$$

$$\begin{aligned} \text{or } (C2_n - C_n) (V_n + \rho_n) &= \text{sources} + ETP_n - ETP_{n-1} \\ &+ \{\alpha_{n-1} C_n + (1 - \alpha_{n-1}) C2_{n-1}\} (P_{n-1} - R_{n-1}) \\ &- \{\alpha_n C_{n+1} + (1 - \alpha_n) C2_n\} (P_n - R_n) \end{aligned} \quad (21)$$

Letting  $VH_n = V_n + \rho_n$ ,  $PRF_n = P_n - R_n$  and separating the contribution of mass by lateral inflow from the source term, the equation can then be solved for  $C2_n$ .

$$\begin{aligned} C2_n &= \left[ C_n + \frac{\text{sources}}{VH_n} + \frac{ETP_n - ETP_{n-1}}{VH_n} \right. \\ &+ \frac{PRF_{n-1}}{VH_n} \{\alpha_{n-1} C_n + (1 - \alpha_{n-1}) C2_{n-1}\} \\ &+ \left. \frac{PRF_n}{VH_n} (\alpha_n C_{n+1}) + \frac{2r_n BC_n}{VH_n} \right] \\ &\quad \Bigg/ \left\{ 1 + \frac{PRF_n}{VH_n} (1 - \alpha_n) \right\} \end{aligned} \quad (22)$$

where 'sources' represents the addition of mass due to wasteflows or non-point sources,  $2r_n \cdot BC_n$  represents mass

introduced from lateral inflows of fresh water, and  $BC_n$  is the concentration in the lateral inflow.

If  $N$  is the total number of segments,  $(N-1)$  equations will be obtained by writing equation (22) for  $n=2$  to  $N$ . The  $(N-1)$  equations may be solved for the  $(N-1)$  unknowns,  $C2_n$ , if the initial concentrations,  $C_n$  and two boundary conditions,  $C2_1$  and  $C_{N+1}$  are specified. The principal operation of the numerical computation is then to compute the concentrations in each segment at the first tidal cycle with a given or assumed initial concentration field at the zeroth tidal cycle. The computed concentration field at the first tidal cycle will then be used as the initial condition to compute the concentration field at the second tidal cycle, and so forth. Each computation cycle will advance time by the increment of one tidal cycle until a specified tidal cycle or equilibrium concentration field is reached. Within each computation cycle, the  $(N-1)$  equations are solved by successive substitution, since  $C2_{n-1}$  is the only unknown upon which  $C2_n$  depends.

### C. Calculation of the Concentrations of Nonconservative Substances

Equation (19) represents the rate of change of mass within a segment due to external sources and physical transport. For nonconservative substances, additional terms are required to simulate the chemical and biological

processes which may cause an increase or decrease in a particular substance within a segment. In general, equation (19) may be rewritten as

$$\frac{\Delta m}{\Delta t} = \text{sources} + (\text{mass in}) - (\text{mass out}) + B \quad (23)$$

where B represents chemical and biological transformations. In the present model, B is expressed explicitly in terms of concentrations of related substances at the beginning of a time step increment. Therefore, it does not introduce additional unknowns into equation (22).

The nonconservative substances considered in the present study include organic nitrogen, ammonia nitrogen, nitrate-nitrite nitrogen, organic phosphorus, inorganic phosphorus, phytoplankton (quantified as chlorophyll 'a'), carbonaceous biochemical oxygen demand, and dissolved oxygen. The interaction of the physical, chemical and biological processes among these parameters is shown in Figure 17. All chemical and biological processes are considered to act independently of the physical transport processes.

Given the initial conditions or calculated concentration fields at the slack-before-ebb (SBE) initiating a tidal cycle, the calculation of the concentrations at the succeeding SBE is performed in two steps. First, the concentration fields are calculated assuming that only the physical transport processes are in action. Secondly, the calculated concentration fields are adjusted for the relevant chemical and biological processes. The transpor-



tation portion of the calculation is identical to the procedure described in the preceding section for conservative substances. The kinetics portion consists of the addition and/or subtraction of the terms representing the chemical and biological transformations. These terms are obtained by the integration with time of the differential equations describing each constituent. The differential equations are derived by considering each model segment to be an independent, completely mixed system and are described below.

1. Phytoplankton Population, CH - The phytoplankton population, quantified as the concentration of chlorophyll 'a', occupies a central role in the schematic ecosystem of Fig. 17 and influences, to a greater or lesser extent, all of the remaining non-conservative dissolved constituents. The differential equation describing phytoplankton growth is

$$\frac{dCH}{dt} = CH \{G-R-P\} \quad (24)$$

where

CH = chlorophyll 'a' concentration ( $\mu\text{gm}/\ell$ )

G = growth rate of phytoplankton (1/day)

R = respiration rate of phytoplankton (1/day)

P = predation on phytoplankton by zooplankton (1/day)

Growth and respiration are dependent upon nutrient availability, ambient light, and temperature. The functional relationships used in the model generally follow the forms of DiToro et al (1971) and are as follows

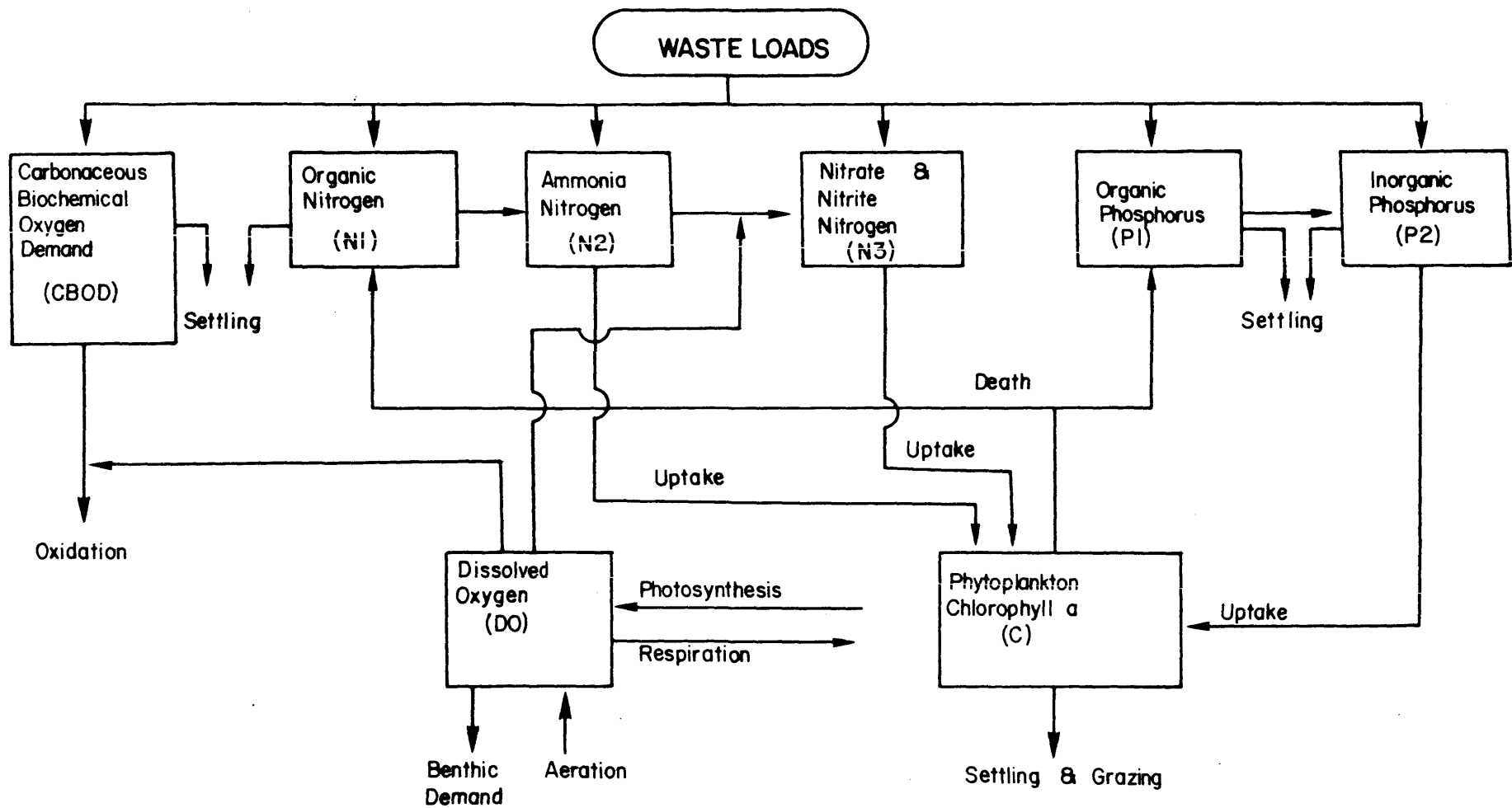


Figure 17. Schematic ecosystem.

Growth rate, G

$$G = k_{gr}^T \cdot I(I_a, I_s, k_e, CH, h) \cdot N(N_2, N_3, P_2) \quad (25)$$

temperature effect
light effect
nutrient effect

where

$$k_{gr} = \text{optimum growth rate (1/day/C}^\circ\text{)}$$

$$T = \text{temperature (C}^\circ\text{)}$$

I = attenuation of growth due to suboptimal lighting

N = effect on growth of nutrient availability

$$I = \frac{2.718f}{k_e h} (e^{-\alpha_1} - e^{-\alpha_0}) \quad (26a)$$

$$k_e = k_e' + 0.0088 \cdot CH + 0.054 \cdot CH^{0.66} \quad (26b)$$

$$\alpha_1 = \frac{I_a}{I_s} e^{-k_e h} \quad (26c)$$

$$\alpha_0 = \frac{I_a}{I_s} \quad (26d)$$

where

$k_e'$  = light extinction coefficient at zero chlorophyll concentration (1/meter)

$k_e$  = light extinction coefficient corrected for self-shading of plankton (1/meter)

$I_a$  = average incoming solar radiation (langleys/day)

$I_s$  = optimum light intensity

h = depth of water column

f = daylight fraction per 24 hours

The nutrient effect, N, is based on product Michaelis-Menton kinetics and is given by

$$N = \frac{N_2 + N_3}{K_{mn} + N_2 + N_3} \cdot \frac{P_2}{K_{mp} + P_2} \quad (27)$$

where

$N_2$  = ammonia concentration (mg/l)

$N_3$  = nitrate concentration (mg/l)

$P_2$  = orthophosphorus concentration (mg/l)

$K_{mn}$  = half-saturation concentration for inorganic nitrogen (mg/l)

$K_{mp}$  = half-saturation concentration for orthophosphorus (mg/l)

Respiration rate,  $R$

$$R = aT \quad (28)$$

where

$a$  = temperature dependence of respiration rate (1/day/ $C^\circ$ )

Predation rate,  $P$ .

$P$  should be dependent on the time-variable herbivore population which is in turn dependent upon the phytoplankton population. To avoid adding on additional trophic level to the model, however, a uniform rate of predation is assumed.

## 2. Organic Nitrogen, $N_1$

$$\frac{dN_1}{dt} = -\frac{K_{n12} T N_1}{K_{h12} + N_1} + a_n \{R + a_r * P\}CH \quad (29)$$

where

$K_{n12}$  = maximum hydrolysis rate of organic nitrogen to ammonia (mg/l/day/ $C^\circ$ )

$T$  = temperature ( $C^\circ$ )

$K_{h12}$  = half-saturation concentration for hydrolysis (mg/l)

$a_n$  = ratio of organic nitrogen to chlorophyll in phytoplankton (mg N/ $\mu$ gm Chl)

$a_r$  = proportion of consumed phytoplankton recycled by zooplankton (0.4 assumed)

## 3. Ammonia Nitrogen, N2

$$\frac{dN2}{dt} = -\frac{K_{n23} T N2}{K_{h23} + N2} + \frac{K_{n12} T N1}{K_{h12} + N1} - a_n \cdot G \cdot PR \cdot CH \quad (30)$$

where

$K_{n23}$  = maximum nitrification rate of ammonia to nitrate nitrogen (mg/l/day/C°)

T = temperature (C°)

$K_{h23}$  = half-saturation constant for nitrification (mg/l)

PR = preference of phytoplankton for ammonia or nitrate uptake

$$= \frac{N2}{N2 + K_{mn}} \quad \text{if ammonia is preferred}$$

$$= 1 - \frac{N3}{N3 + K_{mn}} \quad \text{if nitrate is preferred}$$

## 4. Nitrate Nitrogen, N3

$$\frac{dN3}{dt} = \frac{K_{n23} T N2}{K_{n23} + N2} - a_n \cdot G \cdot PR \cdot CH \quad (31)$$

where

$$PR = \frac{N3}{N3 + K_{mn}} \quad \text{if nitrate is preferred}$$

$$= 1 - \frac{N2}{N2 + K_{mn}} \quad \text{if ammonia is preferred}$$

## 5. Organic Phosphorus, P1

$$\frac{dP1}{dt} = -K_{p12} T P1 + a_p \cdot \{R + a_r P\} CH \quad (32)$$

where

$K_{p12}$  = first order hydrolysis rate of organic to inorganic phosphorus (1/day/C°)

$a_p$  = ratio of organic phosphorus to chlorophyll in phytoplankton (mgP/μgm Chl)

6. Inorganic (Ortho) Phosphorus, P<sub>2</sub>

$$\frac{dP_2}{dt} = K_{p12} T P_1 - a_p \cdot G \cdot CH \quad (33)$$

## 7. Carbonaceous Biochemical Oxygen Demand, CBOD

$$\frac{dCBOD}{dt} = -K_c \cdot CBOD + a_c \cdot a_{co} \cdot \{a_r P\} CH \quad (34a)$$

where

$K_c$  = first order decay rate of CBOD (1/day)

$a_c$  = ratio of carbon to chlorophyll in phytoplankton  
(mg C/ $\mu$ gm Chl)

$a_{co}$  = ratio of oxygen demand to organic carbon  
recycled = 2.67

The effect of temperature on  $K_c$  is given as

$$K_c = K_{c(20)} \cdot 1.047^{(T-20)} \quad (34b)$$

## 8. Dissolved Oxygen, DO

$$\begin{aligned} \frac{dDO}{dt} = & K_r (DO_s - DO) - K_c \cdot CBOD - a_{no} \left\{ \frac{K_{n23} T N_2}{K_{h23} + N_2} \right\} \\ & + a_{pr} \cdot a_c \{G-R\} \cdot CH - BEN \end{aligned} \quad (35a)$$

where

$K_r$  = reaeration rate (1/day)

$DO_s$  = saturation concentration of DO (mg/l)

$a_{no}$  = ratio of oxygen consumed per unit of ammonia  
nitrified = 4.33

$a_{pr}$  = ratio of oxygen to carbon produced/consumed  
during photosynthesis/respiration = 2.67

BEN = benthic oxygen demand (mg/l/day)

The reaeration rate,  $K_r$ , is further defined

(O'Connor and Dobbins; 1958).

$$K_r(20) = 12.4 u^{1/2} h^{-3/2} \quad (35b)$$

where

$K_r(20)$  = reaeration rate at 20°C

$u$  = mean cross sectional velocity (ft/sec)

$h$  = mean channel depth (ft)

The effect of temperature on the reaeration rate is (ASCE; 1961).

$$K_r = K_r(20) \cdot 1.024^{(T-20)} \quad (35c)$$

Saturation dissolved oxygen concentration,  $DO_s$ , is calculated as a function of water temperature and salinity from a polynomial fitted to the tables of Carritt and Green (1967).

$$DO_s = 14.6244 - 0.367134T + 0.0044972T^2 - 0.0966S + 0.00205TS + 0.0002739S^2 \quad (36)$$

where

$S$  = salinity (ppt)

Benthic oxygen demand,  $BEN$ , is measured in the field on a unit area basis (mg/day/m<sup>2</sup>). This value is changed internally in the model coding to a volumetric figure (mg/l/day). The effect of temperature on benthic oxygen demand is simulated (Thomann; 1972)

$$BEN = BEN_{(20)} \cdot 1.065^{(T-20)} \quad (37)$$

## Chapter 3

### The Mathematical Model - Application and Results

Utilization of the mathematical model requires the specification of three groups of parameters - physical parameters, input parameters, and calibration parameters. Physical parameters are measures such as channel width and depth which define the physical characteristics of the system. Input parameters are the variables upon which model predictions are based e.g. temperature or waste-loading. Calibration parameters are the biochemical rate constants and other unknowns which cannot be measured directly but must be derived through repeated adjustments until the model results agree satisfactorily with field data. Each of the parameters utilized in the model are described in the body of this chapter.

#### A. Physical Parameters

1. Tidal Prism - The tidal prism of an embayment may be defined as

$$TP = \int_{H_L}^{H_H} SA \, dh \quad (38)$$

where

TP = tidal prism ( $L^3$ )

SA = channel surface area ( $L^2$ )

$H_L$  = level of water surface at low tide (L)

$H_H$  = level of water surface at high tide (H)



Exact evaluation of this integral requires knowledge of the functional dependence of SA on h. In the absence of this function, the tidal prism may be approximated

$$TP \approx \overline{SA} \cdot \Delta h \quad (39)$$

where

$\overline{SA}$  = average channel surface area

$\Delta h$  = tide range

The tidal prism in Parker Creek is evaluated via Eq. 39. The average surface area, obtained through planimetry of aerial photographs, is  $2.58 \times 10^6 \text{ft}^2$ , and the tide range is 3.5 ft, resulting in a tidal prism of  $9.03 \times 10^6 \text{ft}^3$ .

This value may be verified independently through use of the current meter data. Assuming the freshwater input is negligible, the tidal prism may also be defined

$$TP = \int_{T_1}^{T_2} u \cdot A dt \quad (40)$$

where

$u$  = velocity at the mouth of the estuary (L/T)

$A$  = channel cross-sectional area at the mouth of the estuary ( $L^2$ )

$T_1$  = time of slack current

$T_2$  = time of succeeding slack current

Both the velocity and area are functions of time.

Assume these functions are sinusoidal and define

$$u = a \sin \left( \frac{2\pi}{T} \cdot t \right) \quad (41a)$$

$$A = b + \frac{c}{2} \cos \left( \frac{2\pi}{T} \cdot t \right) \quad (41b)$$

where

a = maximum velocity at mouth

b = average cross-sectional area

c = difference in cross sectional area between  
high and low tide

T = tidal period

Substituting 41 into 40 yields

$$\begin{aligned} TP &= \int_0^{T/2} \left\{ ab \sin \left( \frac{2\pi}{T} \cdot t \right) + \frac{ac}{2} \cos \left( \frac{2\pi}{T} \cdot t \right) \sin \left( \frac{2\pi}{T} \cdot t \right) \right\} dt \\ &= \frac{abT}{\pi} \end{aligned} \quad (42)$$

Noting that for Parker Creek, a = 5120 ft/hr., b = 404 ft<sup>2</sup>, and T = 12.4 hr. results in TP = 8.16 x 10<sup>6</sup> ft<sup>3</sup>. This agrees within 10% of the value obtained by the first method.

The value of the tidal prism as a function of distance was obtained by planimetering the aerial photos in small segments bounded by channel transects. The cumulative value of tidal prism, less freshwater inputs, is shown in Figure 18.

2. Low Tide Volume - The low tide volume of Parker Creek was obtained by correcting the surveyed channel cross-sections to the cross-sectional area at low tide and then multiplying the average value of adjacent transect areas by the distance between them. The cumulative value of low tide volume is shown in Figure 18.

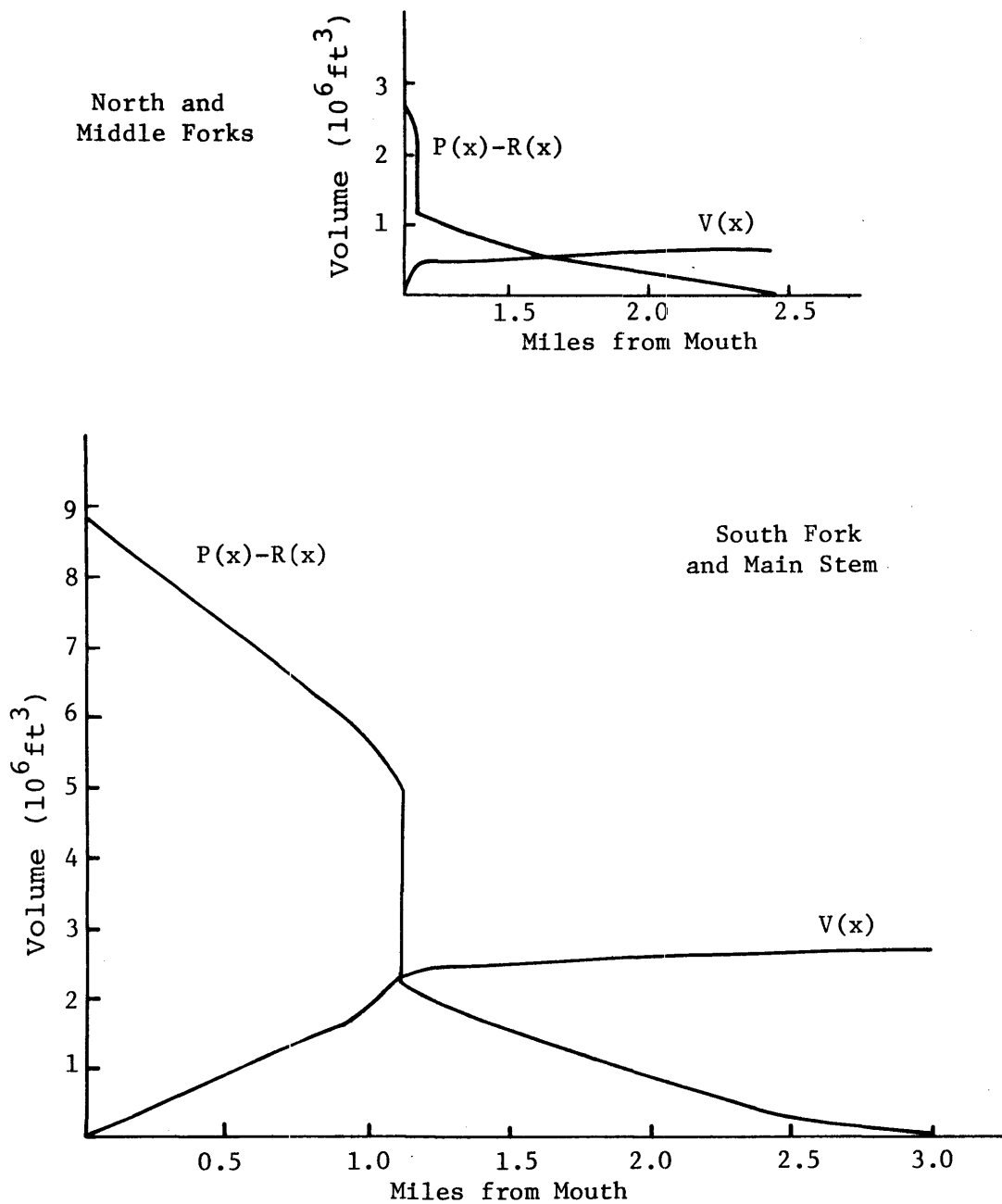


Figure 18. Tidal prism and low tide volume of Parker Creek.

3. Freshwater Input - Freshwater inputs,  $R$ , utilized for segmenting the model were as follows:

South Fork	$R = 5.5$ cfs (SWCB survey)
North Fork	$R = 2.0$ cfs (SWCB survey)
Middle Fork	$R = 2.0$ cfs (assumed)

4. Model Segmentation - Segmentation of Parker Creek was conducted according to the criteria outlined in Chapter 2 via computerized interpolation of tables of cumulative volume and tidal prism. The segmentation is shown in Figure 19 and the parameters for each segment are presented in Table 7.

5. Segment Depths - Segment depths, determined as the average depth of the two transects bordering each segment, are presented in Table 7.

6. Returning Ratio - The returning ratio,  $\alpha$ , was arbitrarily set to 0.1. Sensitivity to this parameter is small.

#### B. Input Parameters

1. External Loading - External nutrient and pollutant loads are introduced to Parker Creek through the headwaters of the South, Middle, and North Forks. Inputs to the South Fork are primarily process wastes while inputs to the Middle and North Forks are natural, background loadings. During the August 1978 intensive survey parameter concentrations and streamflow rates were measured at the sand pit station, 0.95 miles above the tide-line of the South Fork, and at a

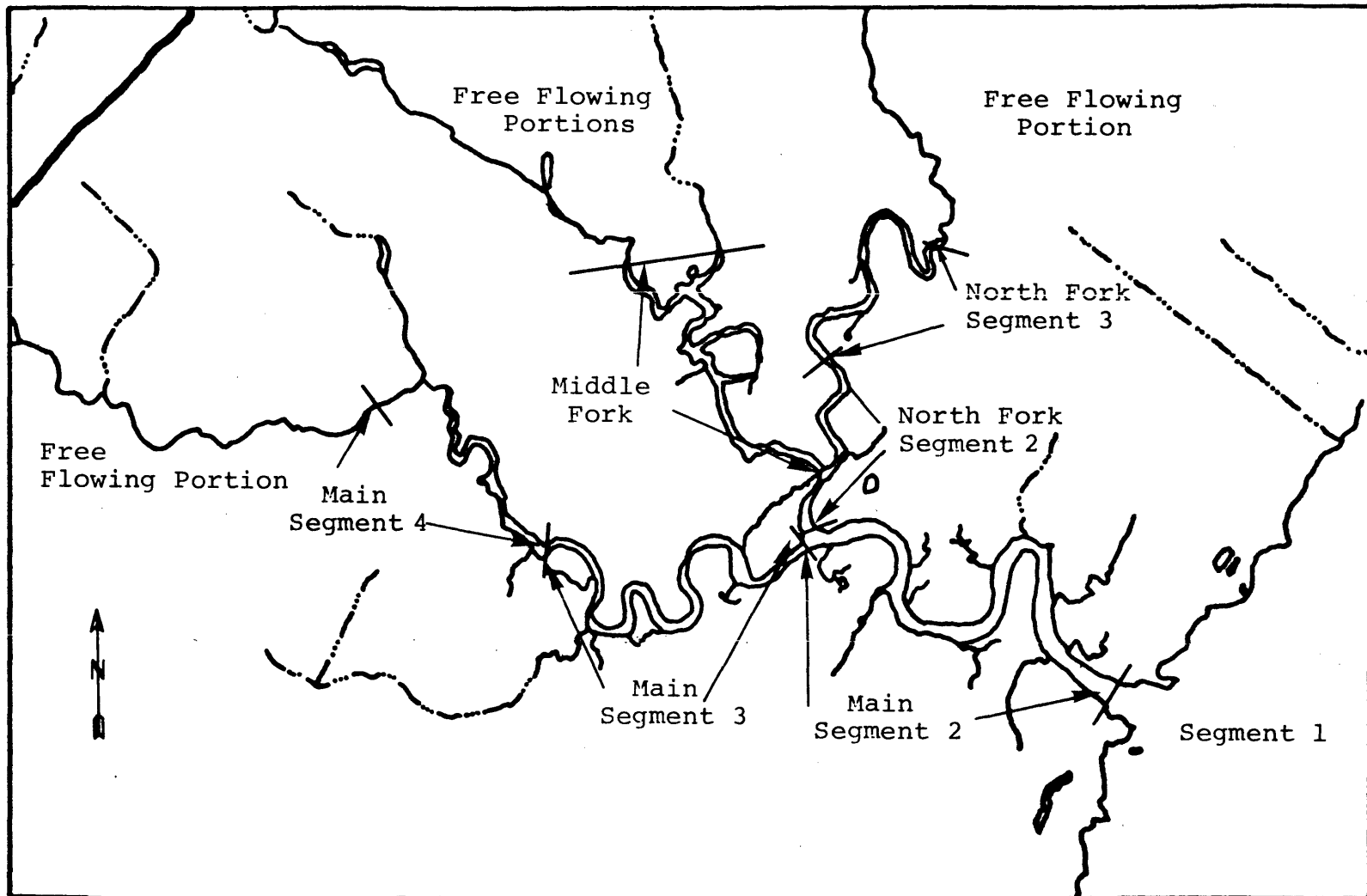


Figure 19. Segmentation of Parker Creek.

Table 7. Geometry of Model Segments

Segment	Length (ft)	High Tide Volume ( $10^6\text{ft}^3$ )	Average Depth (ft)
Main 2	6442	9.03	3.9
Main 3	6600	2.59	2.2
Main 4	2798	0.25	1.5
North Fork 2	2798	2.76	2.0
North Fork 3	3643	0.62	1.5

point 0.38 miles above the tide-line of the North Fork (Table 3). These measurements permitted calculation, for use in the model, of the pollutant and nutrient masses entering these two branches from the headwaters. The loading of the Middle Fork was assumed to be equivalent to that of the North Fork.

2. Solar Radiation - An average value of 500 langleys/day was assumed.

3. Benthic Oxygen Demand - Benthic oxygen demand was measured at five locations in the Creek (Table 4). An average  $2.0 \text{ gm/m}^2/\text{day}$  at  $20^\circ\text{C}$  was utilized in the model.

4. Light Extinction - An average value of  $7.9/\text{m}$  was used.

5. Upstream Boundary Conditions - As defined in the model formulation, upstream boundary conditions are the parameter concentrations of the freshwater inflows to the system. Since these parameters are already explicitly accounted for as external mass loads to the extreme upstream model segments, all upstream boundary conditions are set to zero except dissolved oxygen concentration. The upstream D.O. boundary is  $7.5 \text{ mg/l}$  for the South Fork and  $7.9 \text{ mg/l}$  for the North and Middle Forks.

6. Downstream Boundary Conditions - In a tidal flushing model, the downstream boundary condition for each parameter is the concentration at the mouth of the estuary

at high tide. Boundary values utilized in the model are determined as the average of the high-tide concentrations measured during the August and September 1978 surveys. These concentrations are given in Table 8.

Table 8. Downstream Boundary Conditions

Org. N	NH <sub>4</sub>	NO <sub>3</sub>	Tot. P	Chl. 'a'	CBOD <sub>u</sub>	D.O.	Salinity
mg/l	mg/l	mg/l	mg/l	µg/l	mg/l	mg/l	ppt
0.4	0.1	0.07	0.13	8.0	4.7	5.7	37.0

7. Temperature - The temperature is set at the average value measured during the August and September 1978 surveys - 22.1°C.

#### C. Calibration Parameters

Calibration parameters are those quantities required by the model which cannot be measured or evaluated directly. They are instead obtained through the calibration procedure. Model calibration is a recursive process in which the model is utilized to predict a set of previously measured field conditions based on a set of simultaneously evaluated inputs. The calibration parameters are adjusted in successive runs, within reasonable limits, until agreement is reached between the model predictions and the field data. To insure the validity of the model, additional verification of these calibrated parameters against more than one set of field data is desirable.



1. Phytoplankton Related Parameters - The parameters utilized in modelling the phytoplankton population (Eq. 24-28) and in relating the chlorophyll 'a' concentration to associated constituents (eq. 29, 32, 34a) are presented in Table 9.

Table 9. Phytoplankton Related Parameters

$k_{gr}$ 1/day/C <sup>o</sup>	$I_s$ langleys/day	$K_{mn}$ mg N/l	$K_{mp}$ mg P/l	$a$ 1/day/C <sup>o</sup>	$P$
0.11	250.	0.025	0.005	0.005	0.1
$a_n$ mg N/ $\mu$ g Chl	$a_p$ mg P/ $\mu$ gm Chl	$a_c$ mg C/ $\mu$ gm Chl			
0.01	0.0005	0.025			

2. Nutrient Transfer and Decay Coefficients - The rate constants utilized in evaluating hydrolysis (Eq. 29, 32), nitrification (Eq. 30), and CBOD decay (Eq. 34a) are presented in Table 10.

Table 10. Nutrient Transfer and Decay Coefficients

$K_{n12}$ mg/l/day/C <sup>o</sup>	$K_{h12}$ mg/l	$K_{n23}$ mg/l/day/C <sup>o</sup>	$K_{h23}$ mg/l	$K_{p12}$ 1/day/C <sup>o</sup>	$K_{c(20)}$ 1/day
0.035	1.0	0.035	1.0	0.008	0.25

3. Nutrient and Organics Exchange Rates - The exchange of nutrients and organic constituents between the water column and the adjacent marsh and bed sediments is a major factor in determining water quality in a system such as

Parker Creek. As utilized in this study, the exchange rates occupy a position mid-way between input and calibration parameters. They are input parameters in that the quantity of constituents entering or leaving the system via exchange processes can be directly evaluated as the difference between the amount entering from the headwaters and the amount leaving the mouth. The exact pathways of nutrient exchanges and the ultimate fate of substances removed from the water column are unknown, however, and must be estimated by the calibration procedure.

The amount of each dissolved constituent entering the system is known from measurements taken during the intensive survey (Table 3). The quantity leaving the system may be obtained by integrating with respect to time the product of the volumetric flow rate and constituent concentration measured at the mouth of the creek.

$$F = \int_{T_1}^{T_2} Q \cdot C \, dt \quad (43)$$

where

F = mass flux of constituent over a tidal cycle (M)

Q = volumetric flow rate ( $L^3/T$ )

C = constituent of concentration ( $M/L^3$ )

$T_1$  = starting time of tidal cycle

$T_2$  = completion time of tidal cycle

Since the concentration,  $C$ , is known only at discrete intervals, Eq. 43 is approximated

$$F = \sum_{i=1}^n Q_i C_i \Delta t \quad (44)$$

where

$Q_i$  = volumetric flow rate centered on time interval  $i$

$C_i$  = concentration measured at the center of interval  $i$

$\Delta t$  = time interval between measurements

Exact quantification of mass fluxes in a reversing flow such as at the mouth of a tidal marsh requires an extensive series of measurements and analysis of the errors inherent due to measurement limitations and to spatial and temporal correlations in the flow and concentration (Boon, 1978). A program of this nature is beyond the scope of this study. An approximation of the error incurred in flux estimations via Eq. 44 can be obtained through use of a salt balance, however.

Salt is considered a conservative substance; it is neither produced nor consumed in the marsh. Thus the estimated quantity of salt entering the marsh on the flood tide should exactly equal the quantity estimated to leave on the ebb tide. Any discrepancy may be assigned to sampling and other errors. The relative difference in the amount of salt entering and leaving the marsh sets a lower bound on the measurement errors of other, non-conservative substances. If the relative difference in the salt fluxes

is equal to or greater than the difference in the fluxes of another constituent, this apparent constituent flux may be due to measurement errors alone. If the relative difference in the constituent fluxes entering and leaving the marsh is much greater than the differences in the salt fluxes, however, there is good evidence to suggest the constituent actually is being produced or consumed in the marsh.

The quantities of each constituent estimated to enter and leave through the mouth of Parker Creek in each of the two tidal cycles sampled during the intensive survey are shown in Table 11 along with the relative difference in these fluxes. It can be seen that within the rough error limits set by salinity, there are significant fluxes, measured at the mouth, of organic nitrogen (2 cycles), ammonia (1 cycle) and nitrate (1 cycle).

Mass transformations within the Parker Creek System can be obtained as the difference between the quantity introduced at the headwaters and the quantity leaving through the mouth, as shown in Table 12. It can be seen that approximately 394 lbs. of  $\text{NH}_4$  and 1457 lbs. of  $\text{NO}_3$  were transformed within or otherwise removed from the water column per day during the survey. At the same time, approximately 234 lbs of organic nitrogen were produced, resulting in the net removal from the water column of 1617 lb/day of nitrogen.

Table 11. Mass Fluxes at the Mouth of Parker Creek

	Salt	Org N	NH <sub>4</sub>	NO <sub>3</sub>	Tot P	CBOD <sub>u</sub>
Cycle 1						
flood (lb)	2.07x10 <sup>7</sup>	156	59	189	43	2641
ebb (lb)	2.34x10 <sup>7</sup>	326	148	195	47	2368
% difference	6%	35%	43%	2%	4%	5%
Cycle 2						
flood (lb)	2.23x10 <sup>7</sup>	129	140	167	65	3126
ebb (lb)	2.43x10 <sup>7</sup>	219	142	266	77	3138
% difference	4%	26%	<1%	23%	8%	<1%

Table 12. Mass Transformations Within Parker Creek

	Org N	NH <sub>4</sub>	NO <sub>3</sub>
Introduced through Headwaters	26	483	1556
Leaving through Mouth	260	89	99
<u>Difference</u>	<u>-234</u>	<u>394</u>	<u>1457</u>

As noted previously, while the approximate quantities of nutrients and organics transformed and exchanged can be evaluated, the pathways and rates of change can only be included in the model via the calibration process.

Figure 20 shows a simplified nitrogen cycle for Parker Creek. It can be seen that the primary transformation pathway for organic nitrogen is hydrolysis to ammonia. The hydrolysis rate may be estimated on the basis of known rates in similar systems and refined via calibration with the field data.

Ammonia, in turn, may nitrify to nitrate, may diffuse into the sediments, or may undergo uptake by phytoplankton,

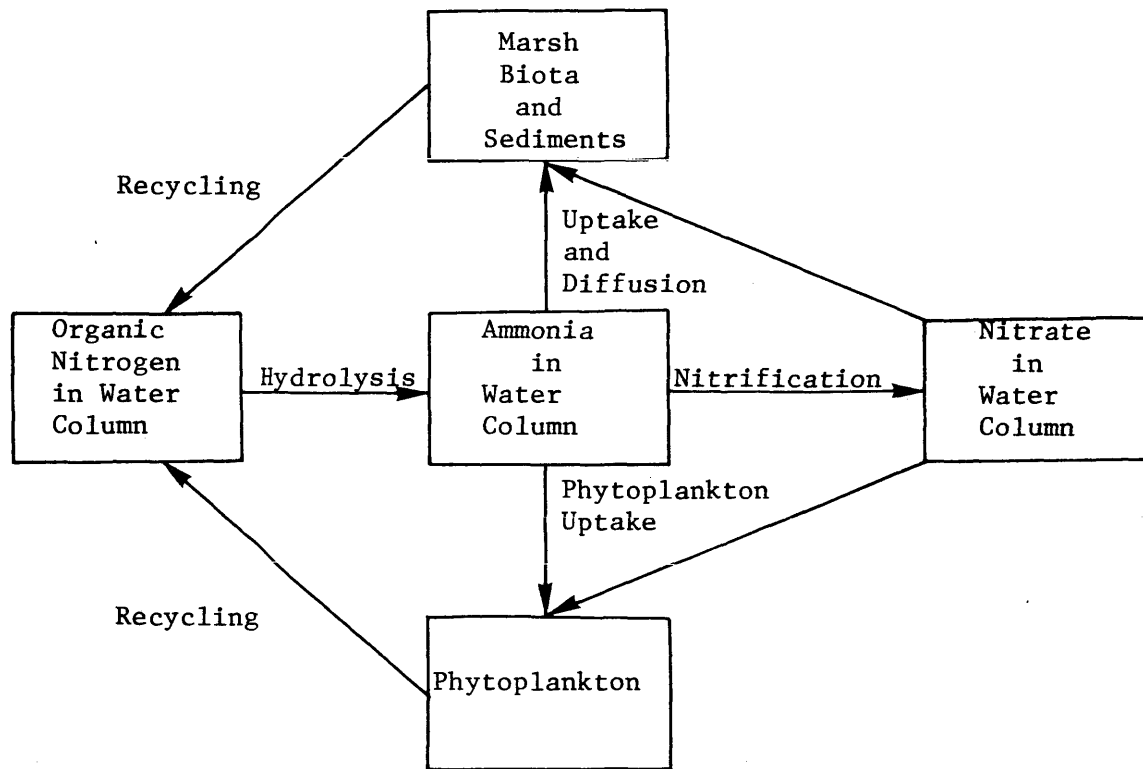


Figure 20. Simplified nitrogen cycle.

vascular plants, and other marsh organisms. Nitrification and phytoplankton uptake are functionally included in the model and may be evaluated. The remaining sinks of ammonia are not explicitly included but may be simulated by removing a specified quantity from the water column at each time step.

Nitrate may undergo uptake by phytoplankton, vascular plants and other organisms, may diffuse into the sediments, and may be denitrified to gaseous nitrogen forms. Of these sinks, only phytoplankton uptake is functionally included in the model. The remainder must be accounted for via a removal process similar to that of ammonia.

A portion of the mineral nitrogen uptake by marsh and planktonic organisms is returned to the water column in the form of organic nitrogen. Of this recycling, only excretion and death of planktonic organisms are functionally represented. The remaining sources of organic nitrogen must be included by adding organic nitrogen to the water column at each time step.

A summary of the calibration procedure for nutrient and organic exchanges is to remove from each model segment amounts of mineral nitrogen (ammonia and nitrate) simulating uptake by marsh organisms and other sinks and to add to each segment organic nitrogen simulating recycling by marsh organisms. The quantities removed and added must be consistent both with the measured fluxes (Table 12) and with

the field data observed during the intensive survey. These quantities, obtained via calibration, are presented in Table 13. Note that negative quantities indicate removal from the water column and that 1563 lb/day of nitrogen are removed from the water column, roughly consistent with the total value from Table 12. Inputs of phosphorus were obtained by assuming a 6:1 ratio of nitrogen to phosphorus in organic matter and were found to improve the model results.

Table 13. Mass Exchanges Between Water Column and Surroundings

Segment	Org N lb/day	NH <sub>4</sub> lb/day	NO <sub>3</sub> lb/day	Tot P lb/day
Main 2	50	-90	-550	8
Main 3	30	-90	-550	5
Main 4	15	-30	-300	2
NF 2	15	0	-25	2
NF 3	12	0	-50	2
	<u>122</u>	<u>-210</u>	<u>-1475</u>	<u>19</u>

#### D. Model Results

The results of the model, compared to the field data collected during the August and September surveys are shown in Figs. 21-28 for salinity, organic nitrogen, ammonia, nitrate, total phosphorus, chlorophyll 'a', CBOD<sub>u</sub> and dissolved oxygen, respectively. Primary calibration is against the data collected during the August intensive survey. For this survey, the range of the field data over two tidal cycles is shown, as well as the values at slack-before-ebb for which the model prediction is valid. Additional verification is provided by the slack-before-ebb data collected during the September slack water surveys, shown on the same graphs.



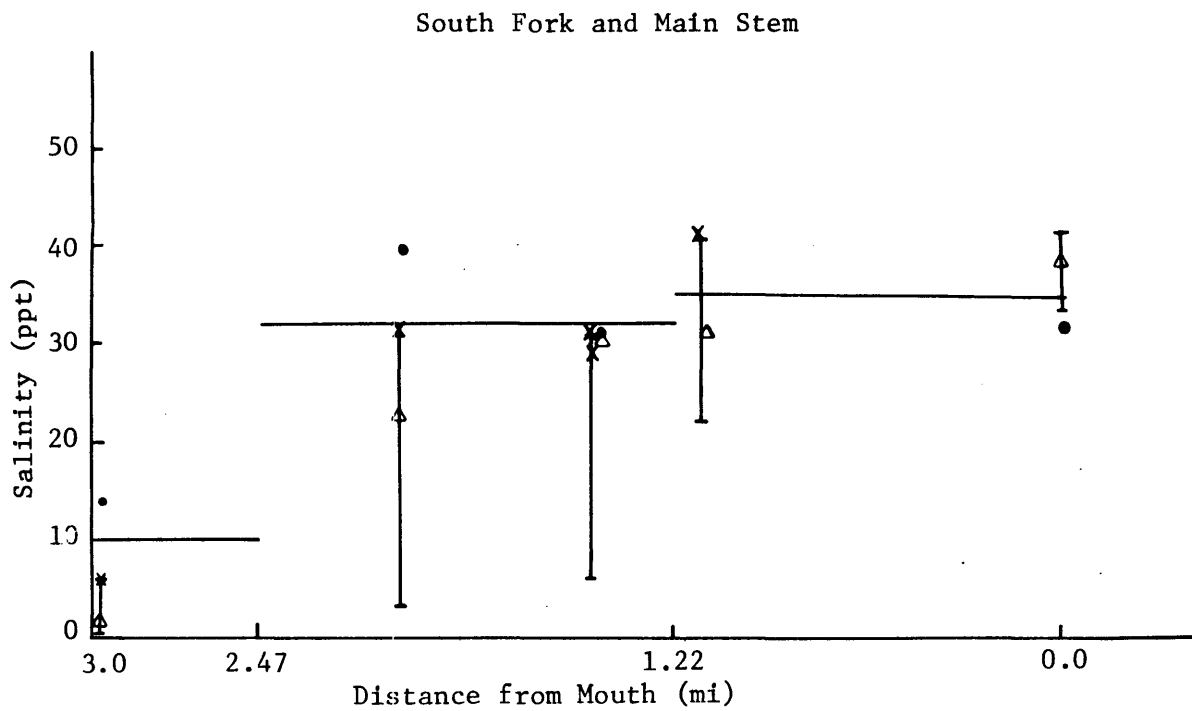
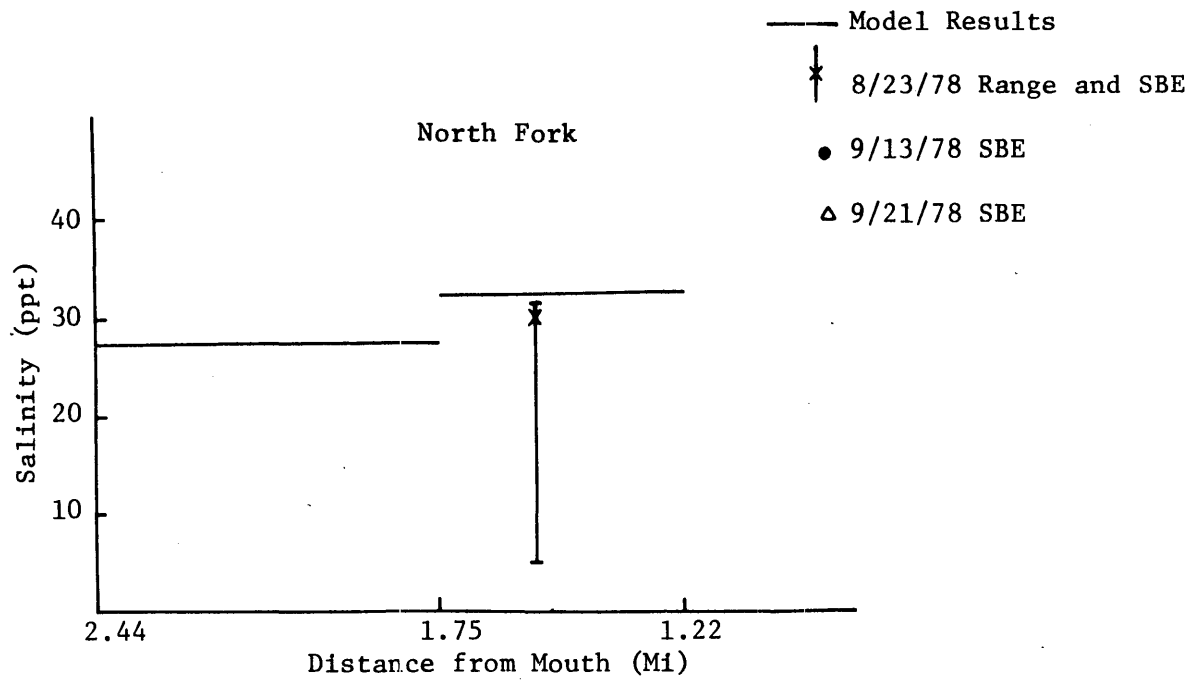


Figure 21. Salinity calibration and verification.

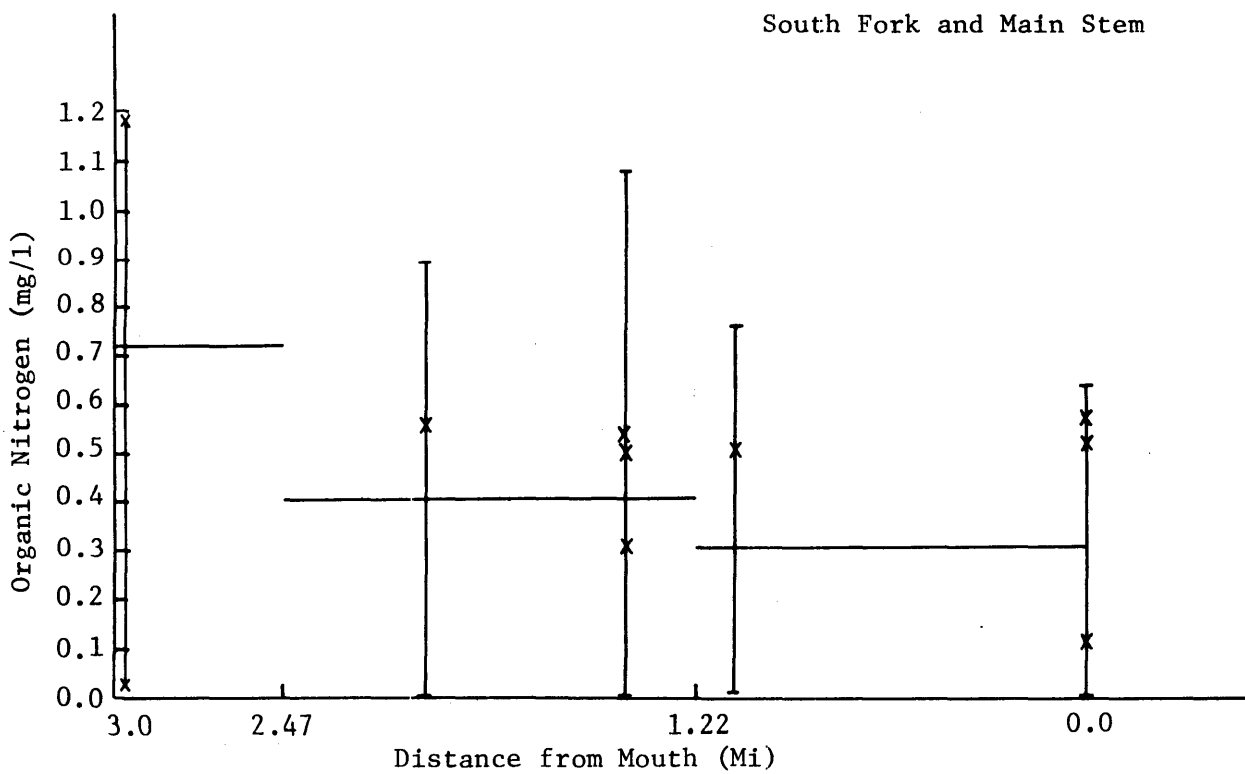
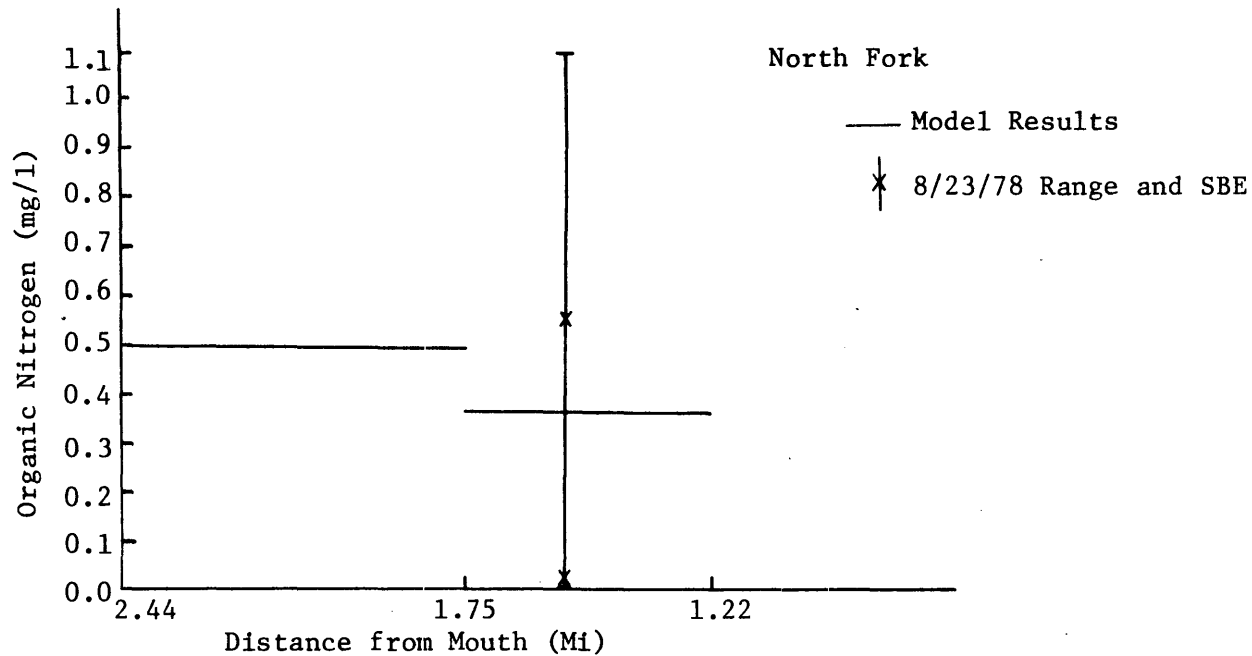


Figure 22.. Organic nitrogen calibration.

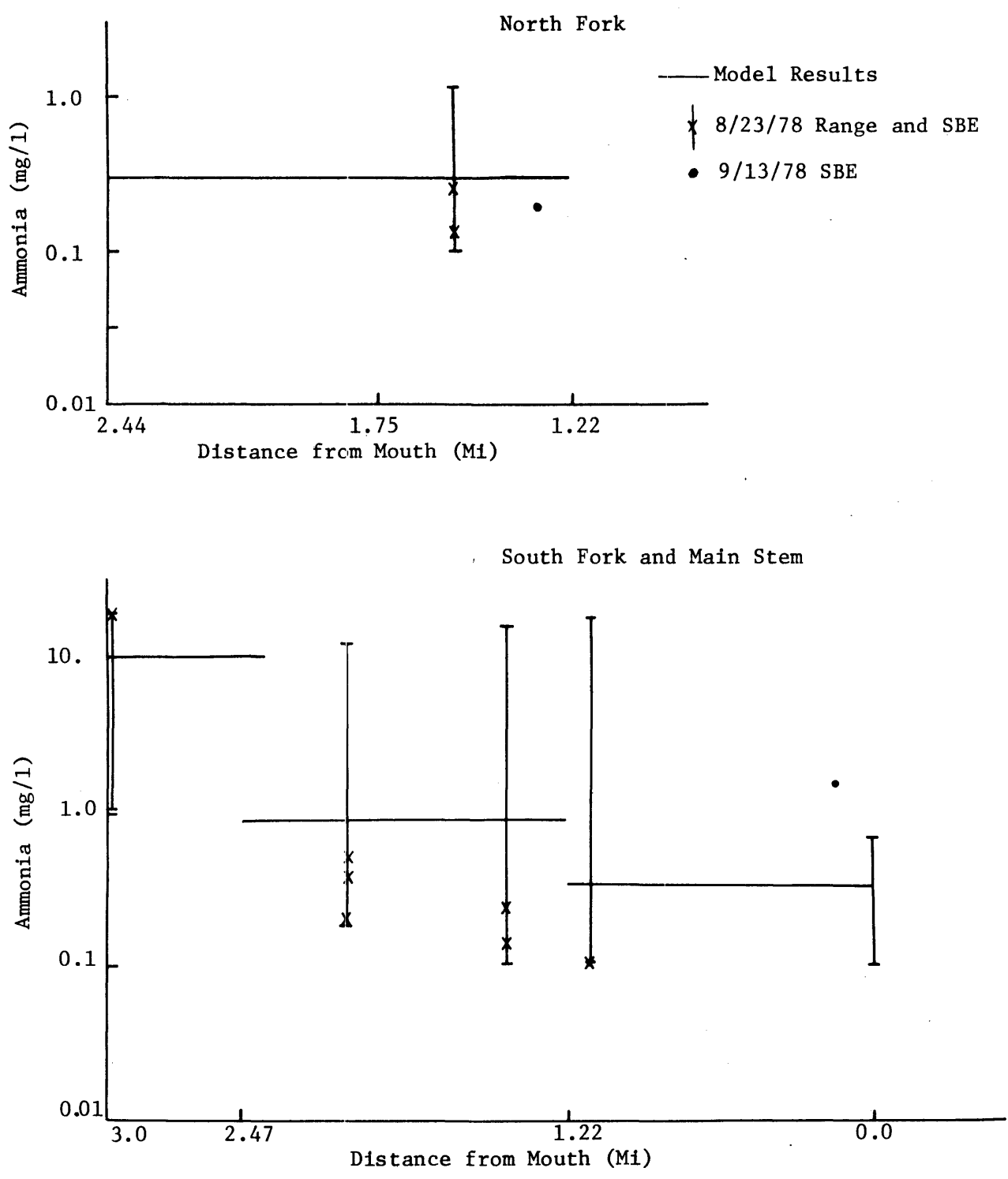


Figure 23. Ammonia calibration and verification.

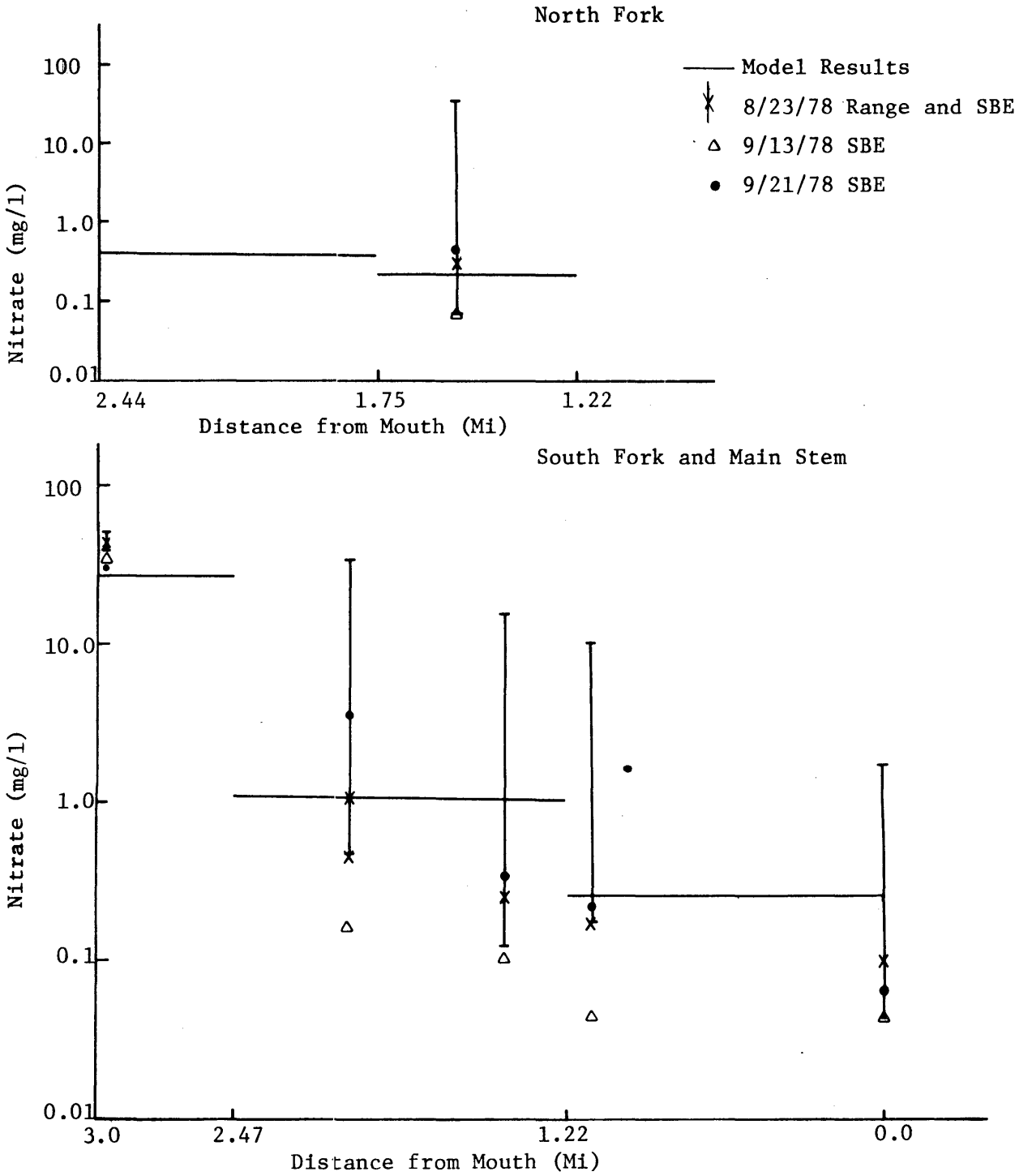


Figure 24. Nitrate Calibration and Verification.

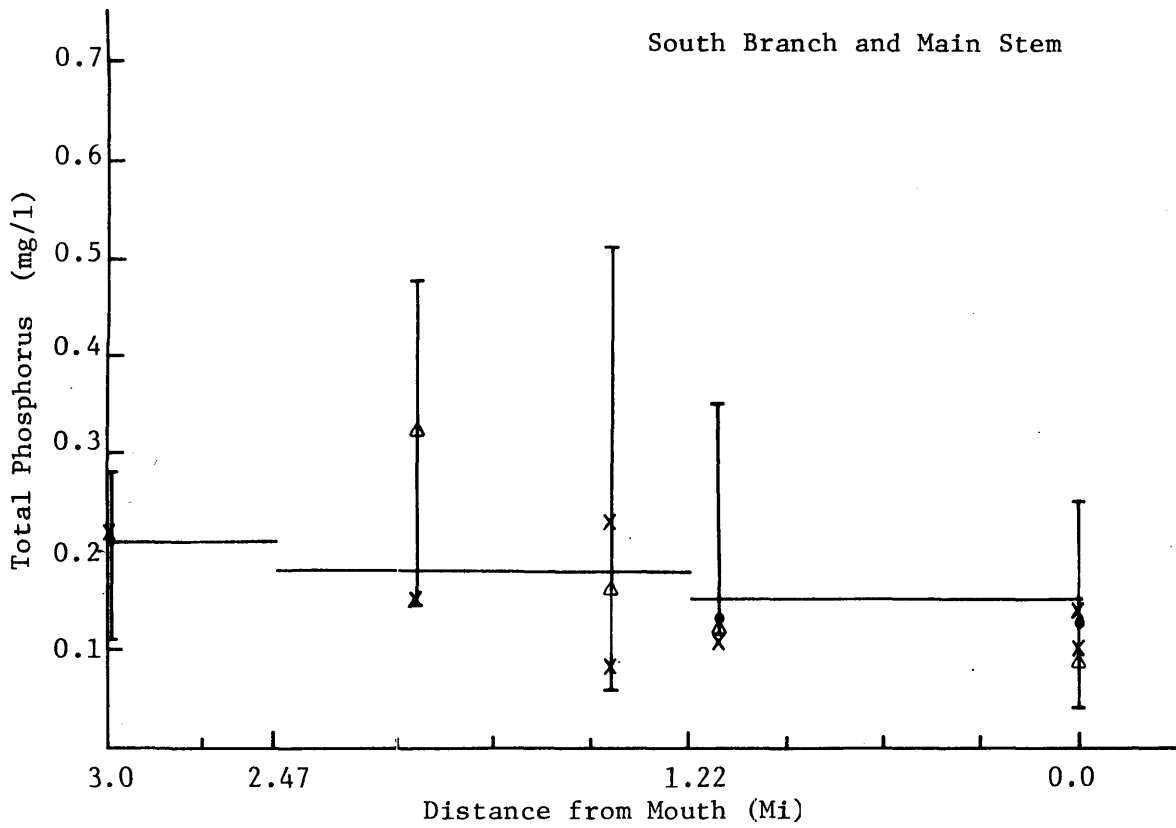
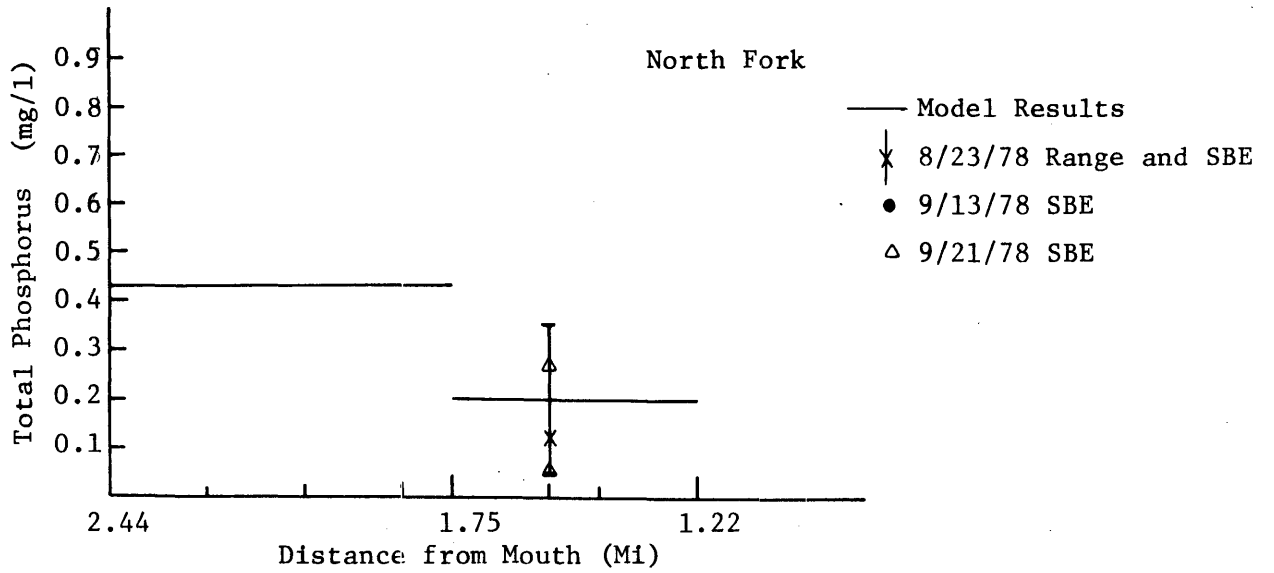


Figure 25. Phosphorus calibration and verification.

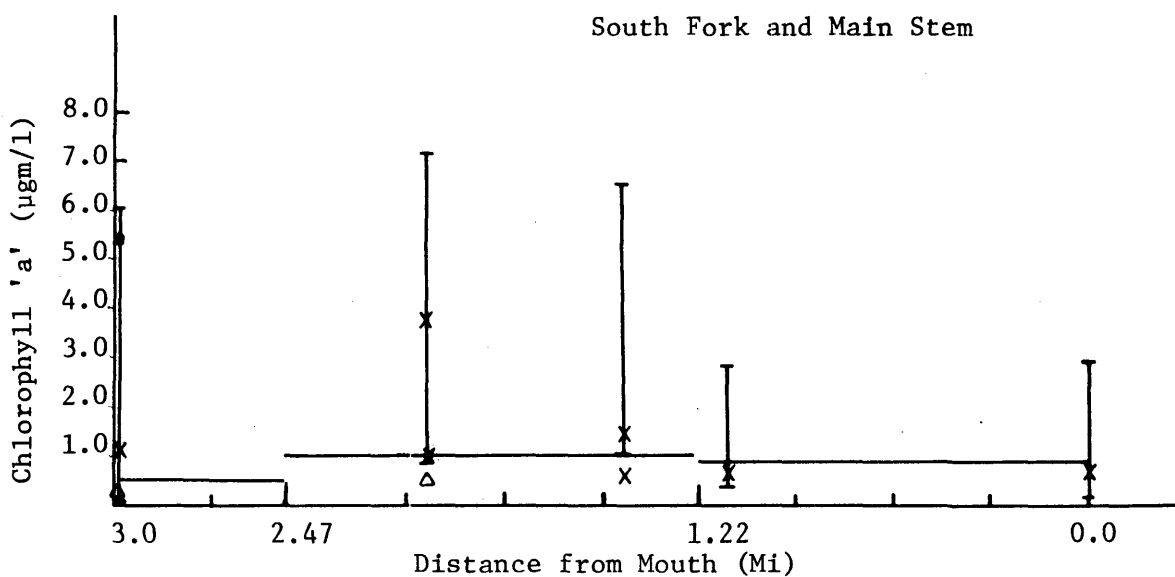
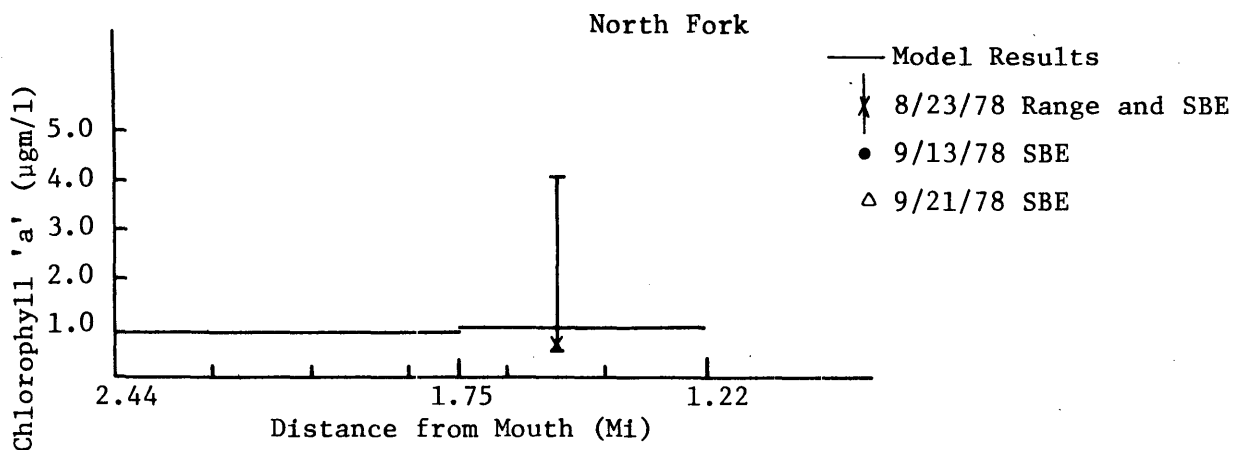


Figure 26. Chlorophyll calibration and verification.

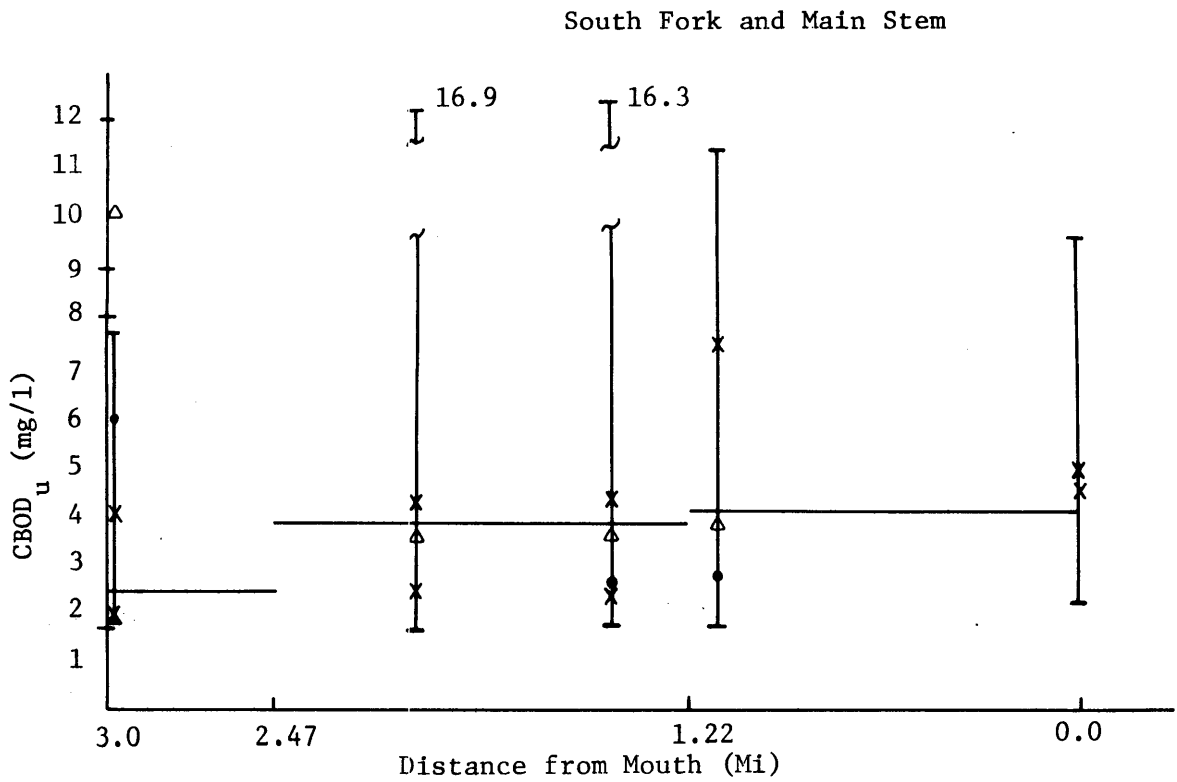
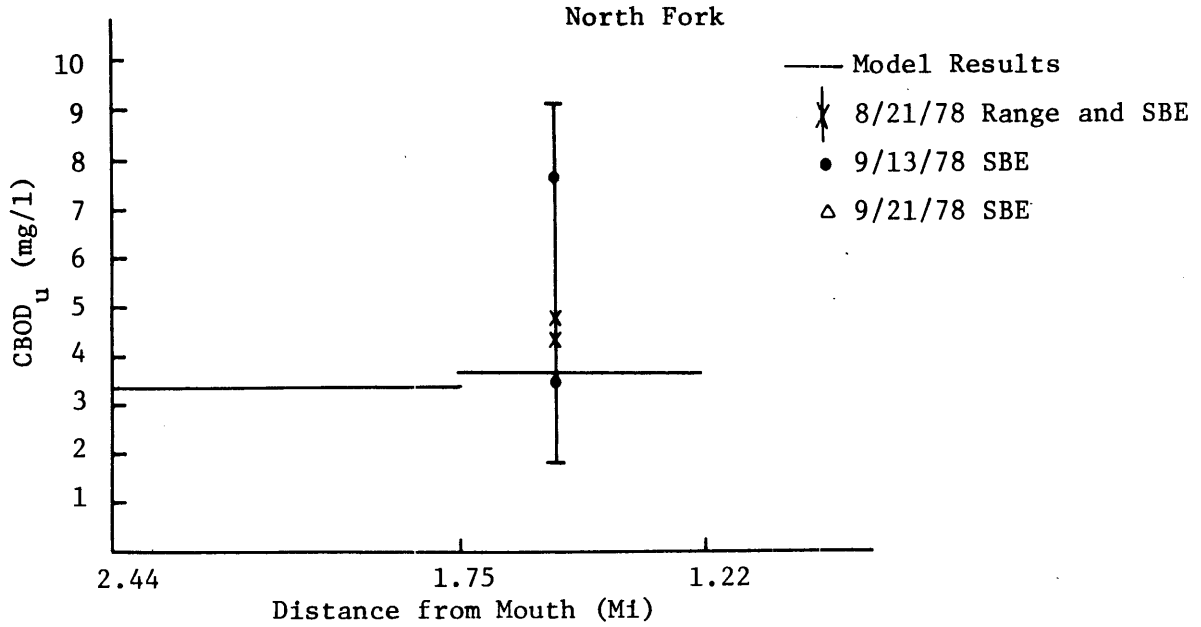


Figure 27. CBOD calibration.

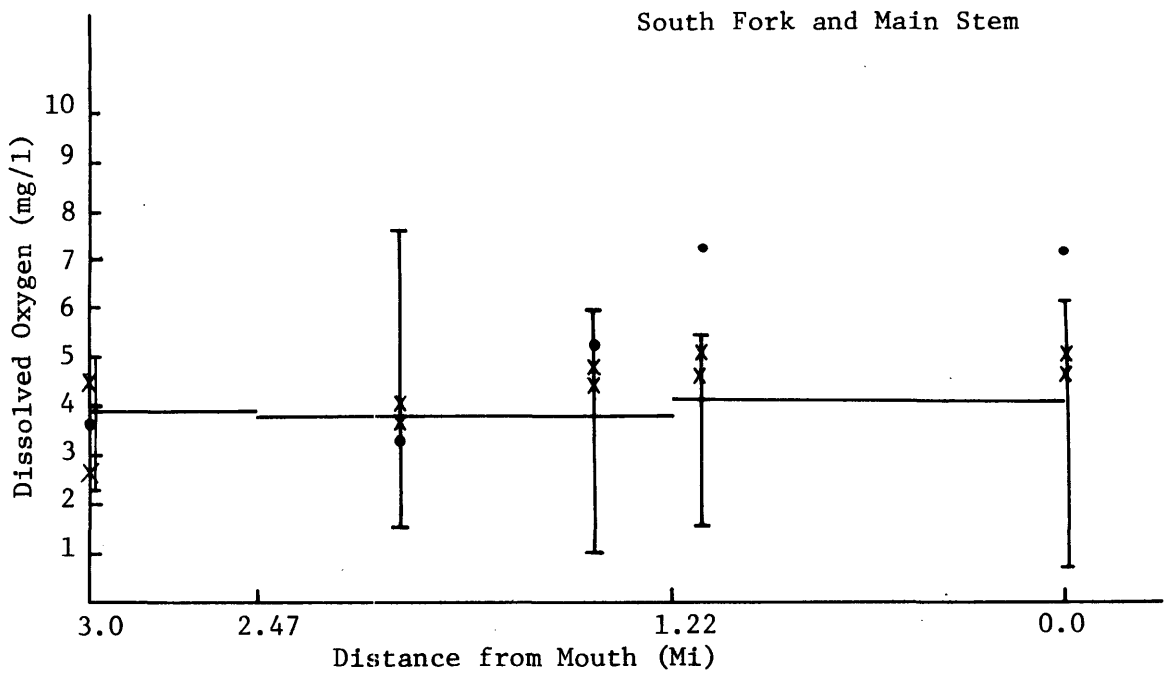
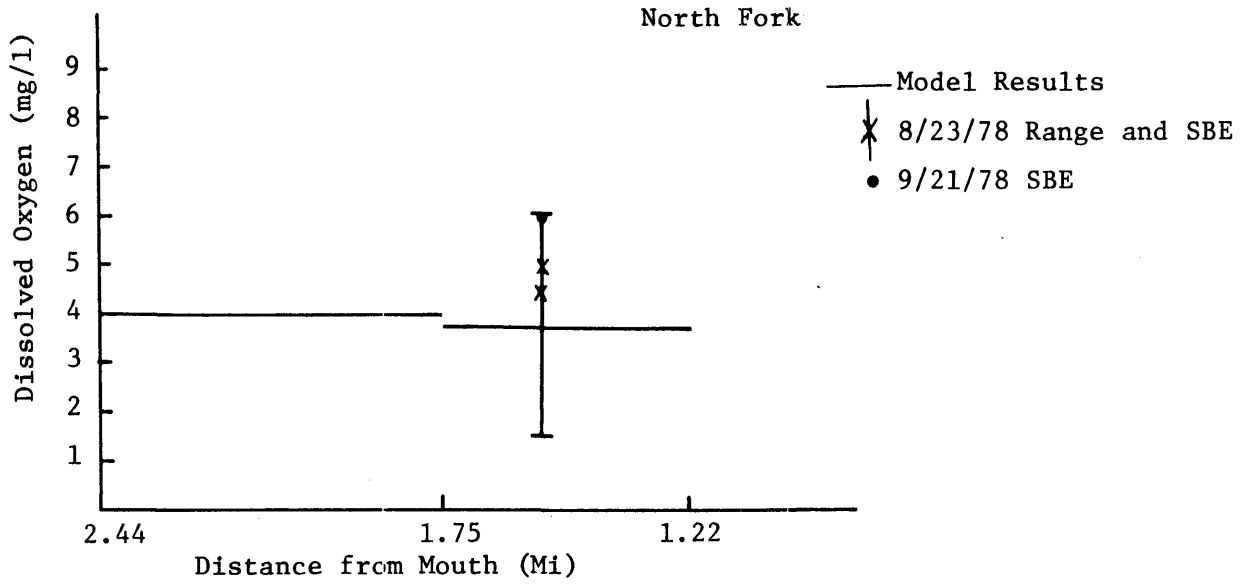


Figure 28. Dissolved oxygen calibration and verification.



## Chapter 4

### Sensitivity Analysis

Sensitivity analysis is the process by which the effect on the model predictions of variations in calibration and input parameters is ascertained. By determining the relative effect on model predictions of a specific parameter change, the modeller can determine which parameters require careful attention in their evaluation and which require less rigorous approximation. Sensitivity analysis also allows the modeller to judge the effects of his assumptions and to weigh the confidence placed in the model results.

This form of analysis is useful not only in model evaluation, however. It is also a tool by which the influence on the prototype of various factors such as pollutant inputs may be discerned and it may be used as a device for evaluating the effect of alternative management schemes before they are implemented.

The sensitivity analysis presented herein is directed primarily towards evaluating the influence of various parameters on the dissolved oxygen (D.O.) concentration. Parameters which were selected include the return ratio,  $\alpha$ , the CBOD decay rate,  $K_c$ , the organic nitrogen hydrolysis rate,  $K_{n12}$ , the ammonia nitrification rate,  $K_{n23}$ , the upstream and downstream CBOD and DO boundary conditions, the point source inputs to the South Fork, the nonpoint exchange rates, and the benthic oxygen demand. The influence of each of these factors is detailed in the subsequent sections of this chapter.

### A. Return Ratio

The return ratio,  $\alpha$ , is a measure of the fraction of dissolved constituents which return to an embayment on the flood tide after being flushed by the preceding ebb. A value of  $\alpha=0.1$  was selected for use based on experience in similar systems. To test the effect of this selection, the model was run with  $\alpha=0.0$  and  $\alpha=0.5$ . The results for salinity and D.O. are shown in Figs. 29a and 29b. Decreasing  $\alpha$  to 0.0 has essentially no influence on the model results. Increasing  $\alpha$  to 0.5, an unrealistically high value, decreases the salinity throughout the creek by 2 to 5 ppt but changes D.O. only by 0.3 mg/l or less. Thus the sensitivity of the model predictions to  $\alpha$  is small.

### B. CBOD Decay Rate

The CBOD decay rate,  $K_c$ , is the rate at which organic material is heterotrophically oxidized in the creek. This oxidation may provide a significant contribution to the observed D.O. deficit. To determine the effect of utilizing a  $K_c$  value other than the calibration value of 0.25/day, model runs were made with  $K_c$  varied by  $\pm 25\%$ . The resulting CBOD and D.O. concentrations are shown in Figs. 30a and 30b. Varying  $K_c$  by 25% results in a net change in CBOD of 0.3 mg/l or less and in a net change in D.O. of 0.2 mg/l or less.

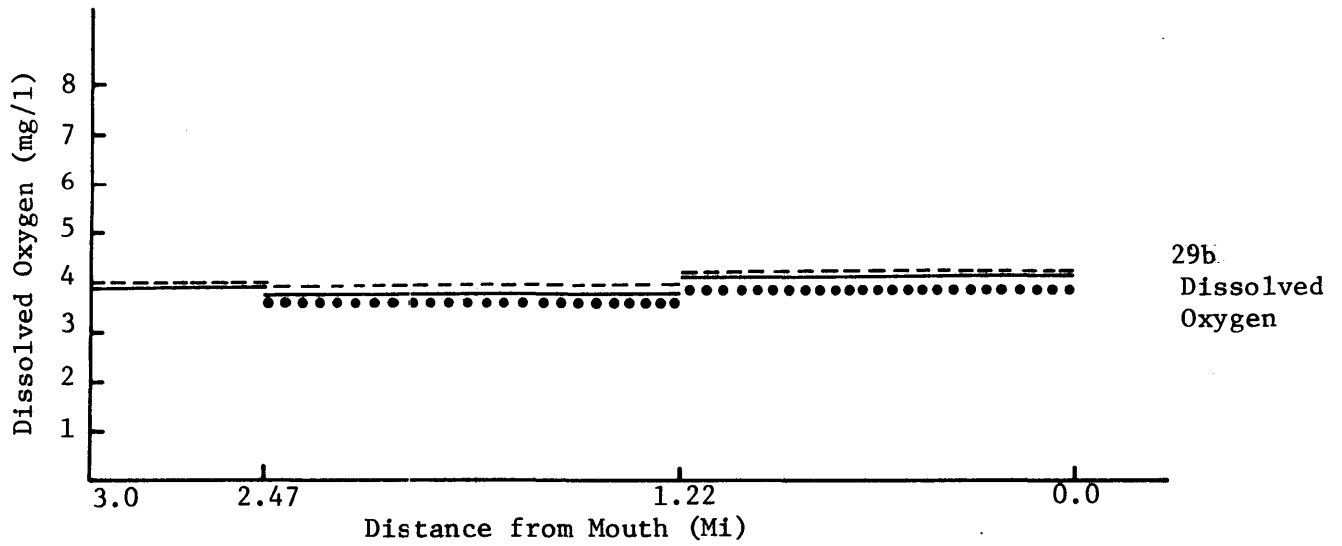
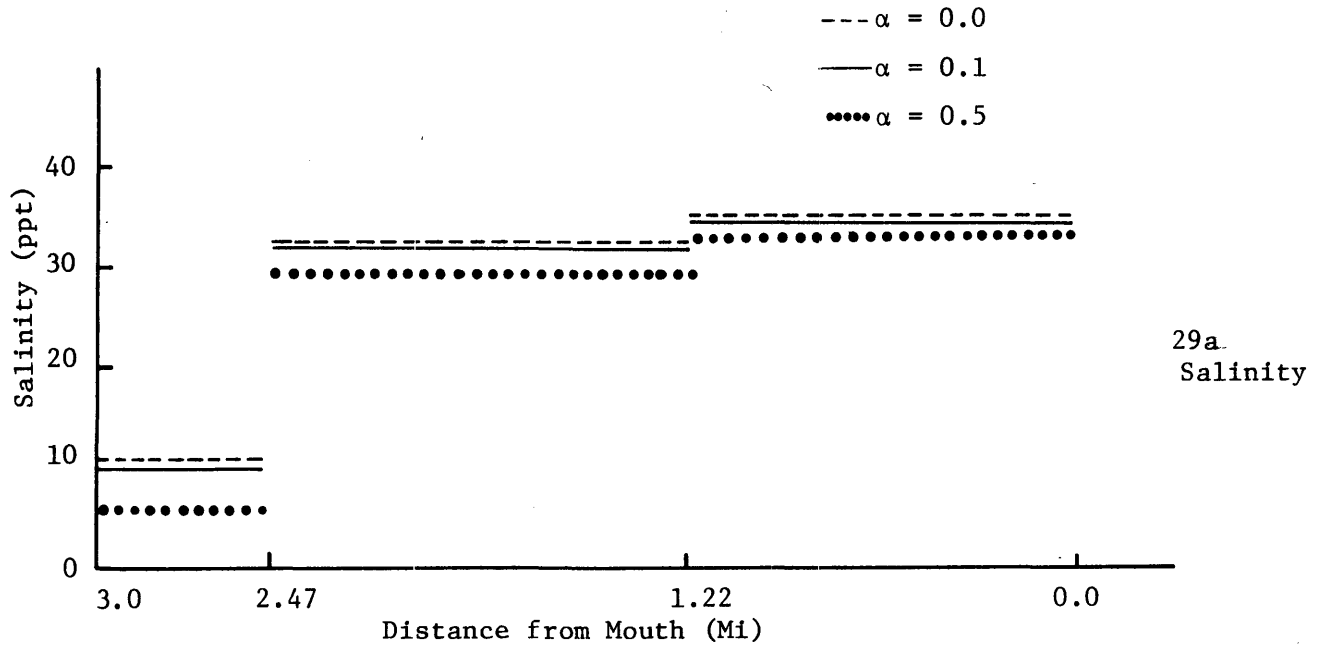


Figure 29. Sensitivity to return ratio,  $\alpha$ .

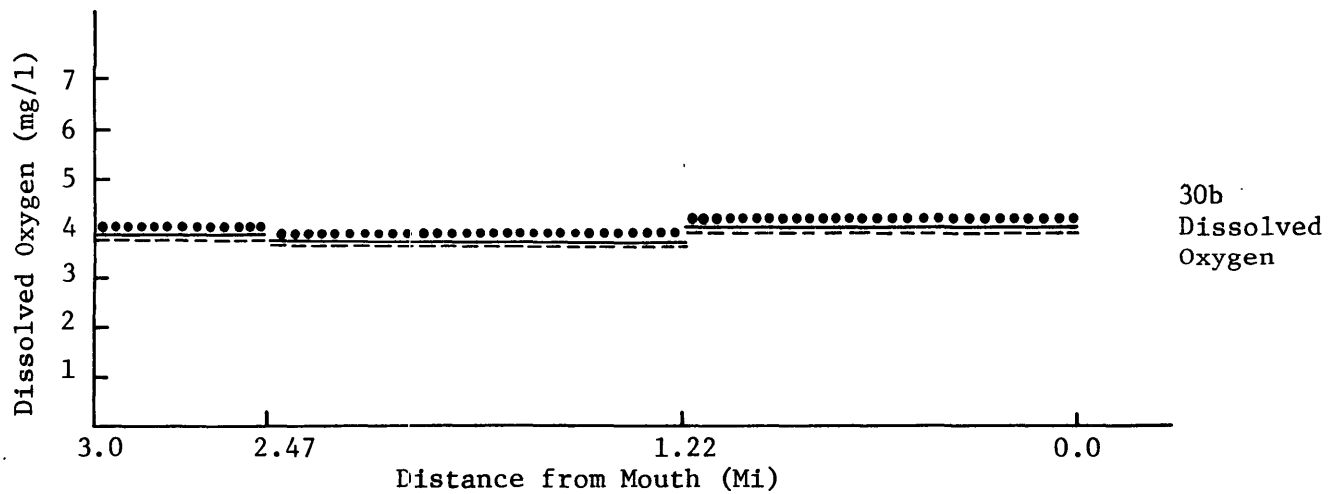
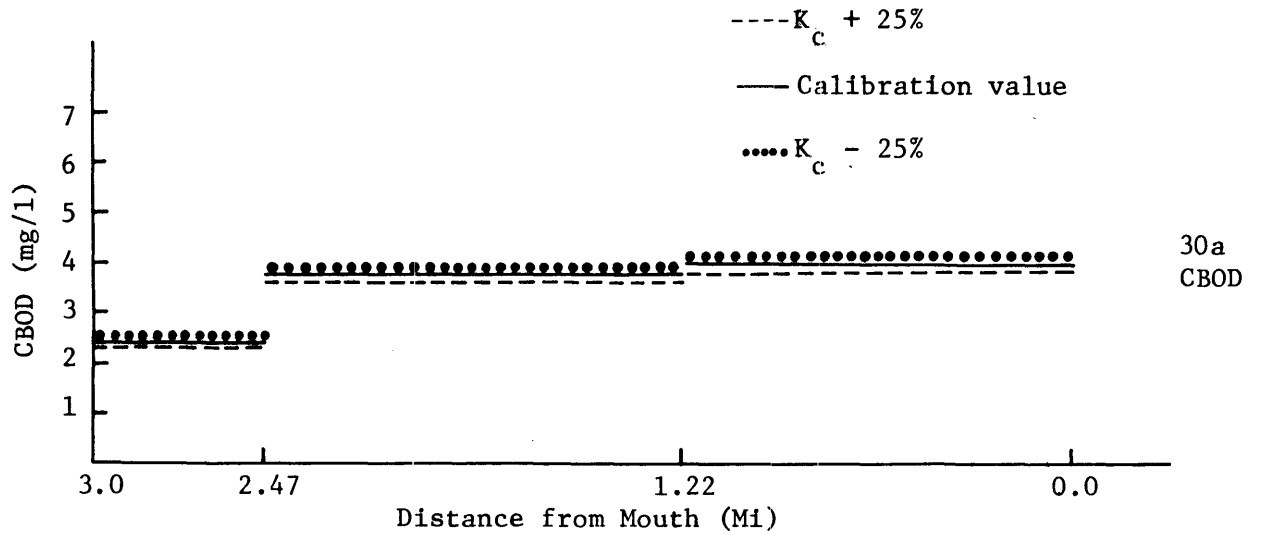


Figure 30. Sensitivity to CBOD decay rate,  $K_c$ .

### C. Hydrolysis and Nitrification Rates

Hydrolysis is the process by which organic nitrogen is converted to dissolved ammonia. A fraction of this ammonia is in turn converted to nitrate through the bacterially mediated process of nitrification. Since roughly 4.33 grams of dissolved oxygen are consumed for every gram of ammonia which is nitrified, this process can be a significant drain on the system D.O. budget. As represented in the model, the maximum rates at which hydrolysis and nitrification can proceed are  $K_{n12}=0.035$  mg/l/day/ $C^0$  and  $K_{n23}=0.035$  mg/l/day/ $C^0$ . To determine the influence of these rates on the creek dissolved oxygen, each was varied individually by  $\pm 25\%$ . The results are shown in Fig. 31a-c for organic nitrogen, ammonia, and D.O. respectively.

It can be seen that varying  $K_{n12}$  by  $\pm 25\%$  results in a change of up to 0.5 mg/l in organic nitrogen concentrations but that this has little influence on the net D.O. concentration since the subsequent change in ammonia concentration due to variations in hydrolysis has little influence on the rate of nitrification.

Varying  $K_{n23}$  by  $\pm 25\%$  results in a change in ammonia concentration of 0.1 mg/l or less. The resulting net change in D.O. is from 0.2 to 0.5 mg/l with the largest impact in the upper reaches of the creek.

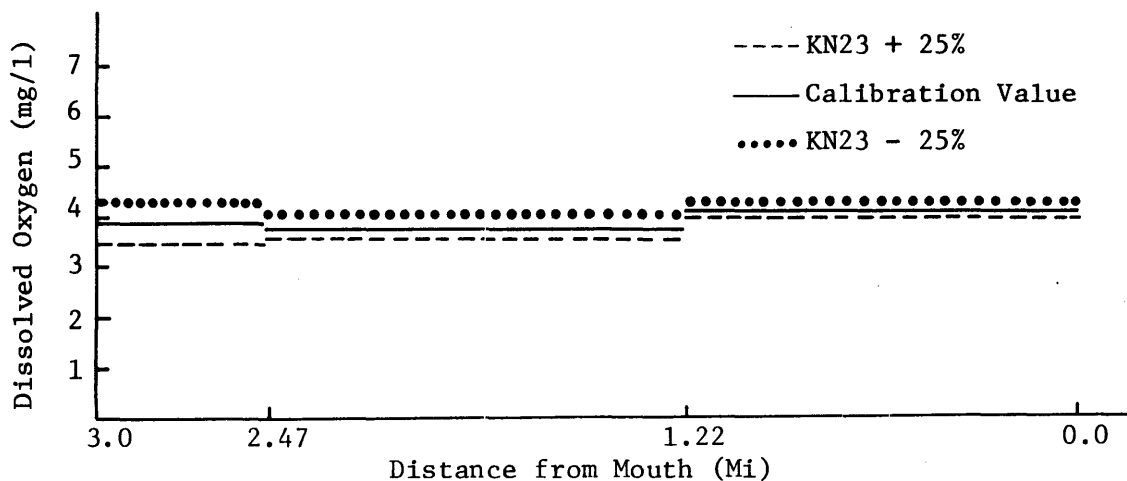
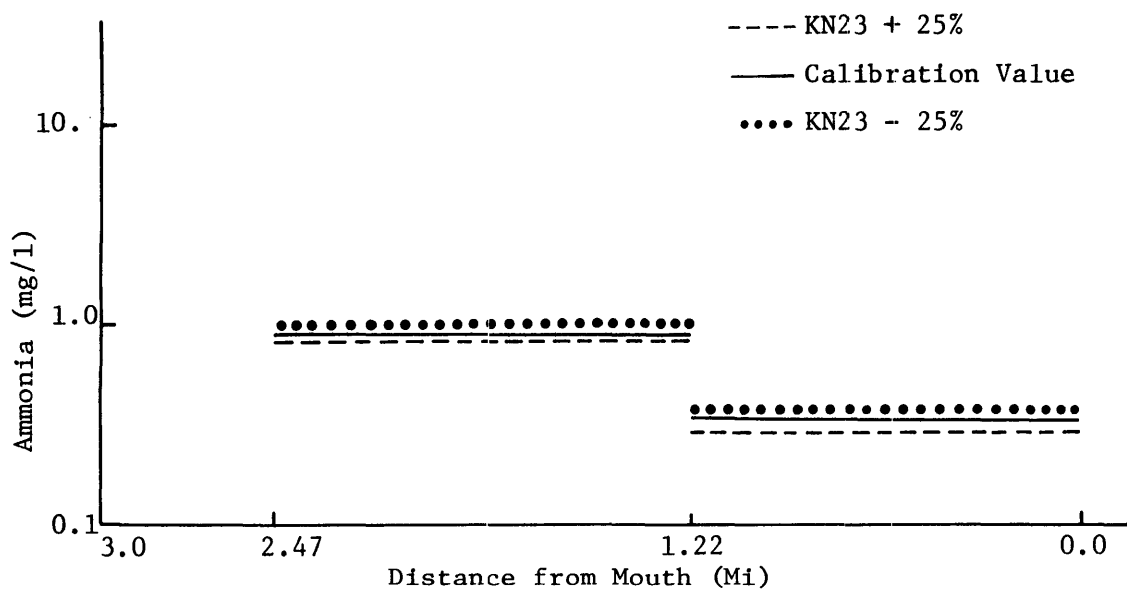
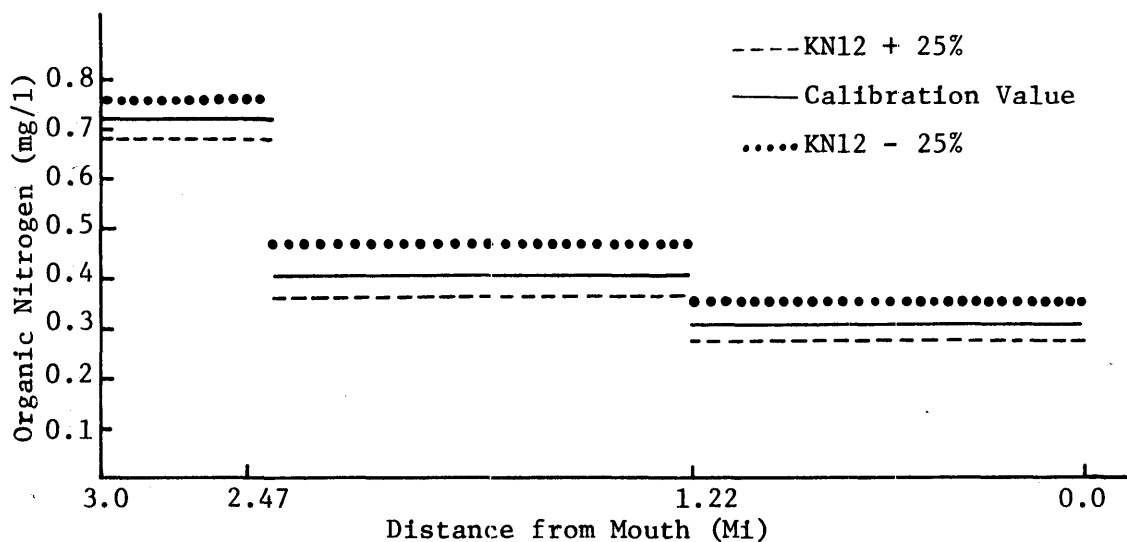


Figure 31. Sensitivity to KN12, KN23.

#### D. Dissolved Oxygen Boundary Conditions

Dissolved oxygen boundary conditions are specified at both the headwaters and mouth of Parker Creek. Upstream boundary conditions are the D.O. concentrations in the freshwater inflow. The downstream boundary condition is the D.O. concentration in Metomkin Bay. It is important to examine the effect of the D.O. in the inflowing streams and in the tidal prism on the creek dissolved oxygen concentration. To ascertain this effect, the upstream and downstream D.O. boundary conditions were individually varied by  $\pm 1.0$  mg/l. The results are shown in Fig. 32a and 32b.

The upstream, freshwater dissolved oxygen concentration has little influence on the Parker Creek D.O. budget except in the most upstream reaches of the creek where a 1.0 mg/l change in the boundary condition results in a maximum 0.3 mg/l change in the creek D.O. concentration.

The downstream D.O. boundary has a more significant influence on the creek dissolved oxygen concentration since the tidal prism represents a large portion of the high-tide volume of the creek. A 1.0 mg/l change in the D.O. concentration of the tidal prism results in a 0.4 mg/l change in the D.O. in the lower reaches of the creek, a 0.2 mg/l change in the mid-section, and little or no change in the upstream portions.

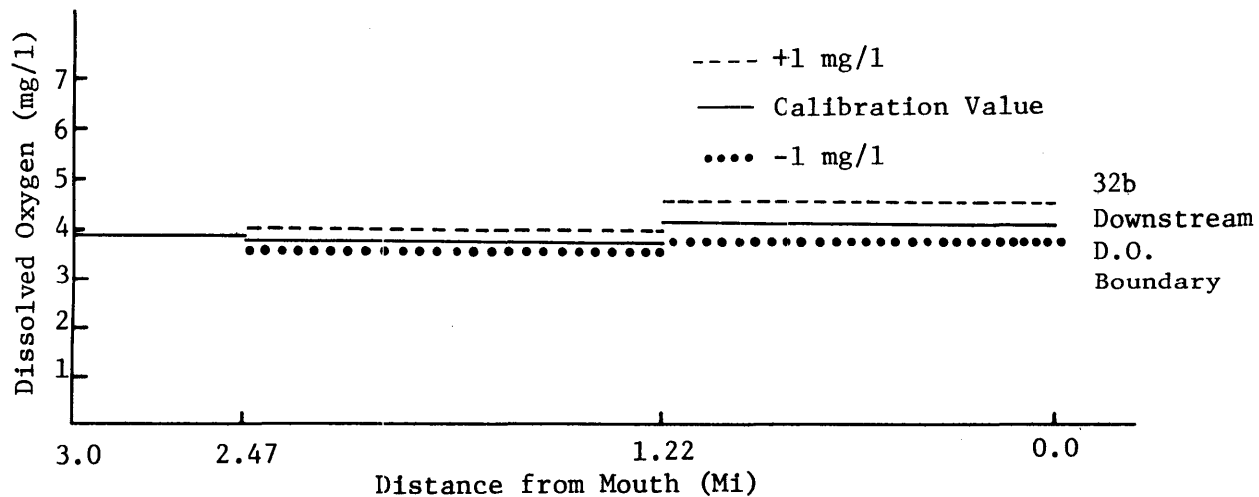
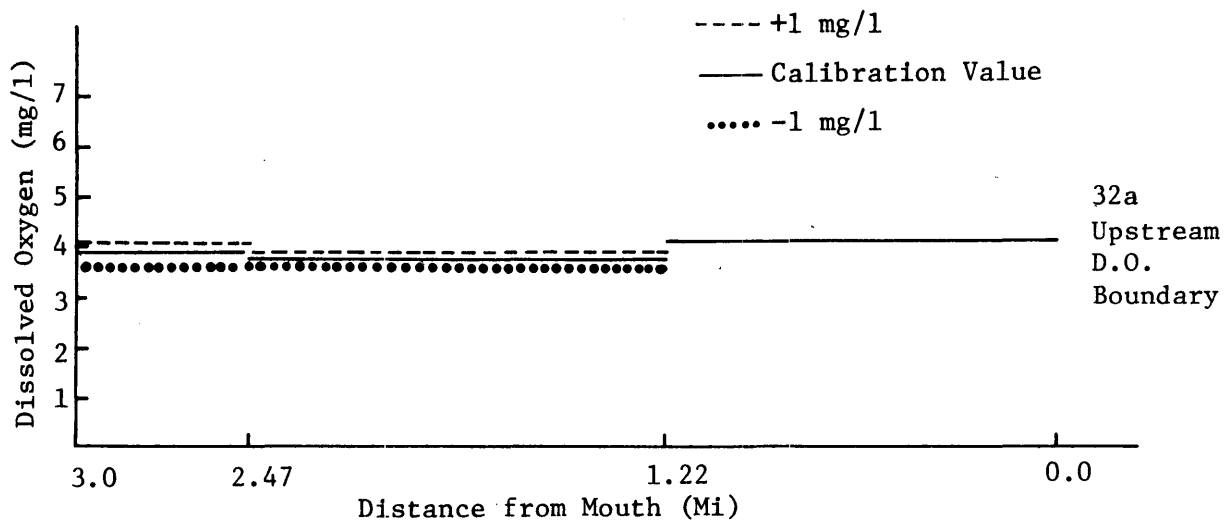


Figure 32. Sensitivity to dissolved oxygen boundary conditions.



#### E. CBOD Boundary Condition

Just as the tidal prism carries a large quantity of dissolved oxygen into the creek, it also brings in quantities of nutrients and organics including CBOD. To ascertain the influence on creek CBOD and D.O. concentrations of CBOD carried in on the tidal prism, the downstream CBOD boundary condition was varied by  $\pm 1.0$  mg/l. The results for CBOD and D.O. are shown in Figs. 33a and b.

It can be seen that a  $\pm 1.0$  mg/l change in downstream CBOD boundary results in a change of roughly 0.8 mg/l CBOD in the lower and mid-sections of the creek and a change of about 0.3 mg/l in the upper reaches. The D.O. variation due to this change in CBOD is small, however, and of the order of 0.2 mg/l or less.

#### F. Non-Point Nutrient and Organic Exchange Rates

Relatively large exchange rates of nutrients and organic materials between the water column and the surrounding marsh have been incorporated in the model. To justify the magnitude of these rates, and to examine the net effect of marsh-water column exchanges upon the creek dissolved oxygen, two sensitivity runs were made. In the first, organic nitrogen, ammonia, and nitrate exchange rates were increased by 25%. In the second, all non-point exchanges were eliminated. The effect on organic nitrogen, ammonia, nitrate, and dissolved oxygen are illustrated in Fig. 34a-d respectively.

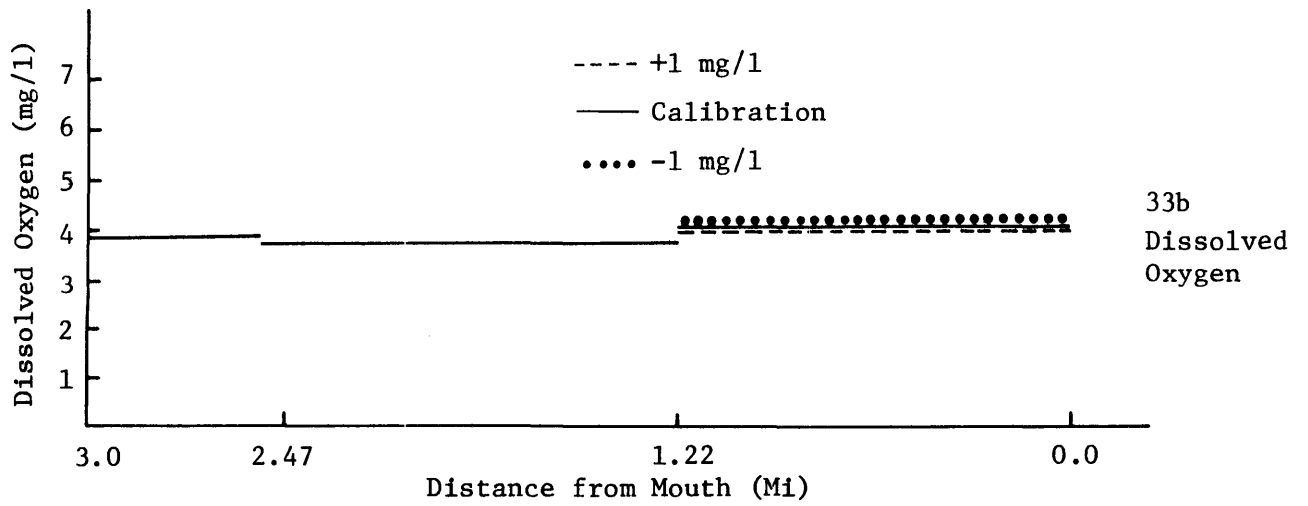
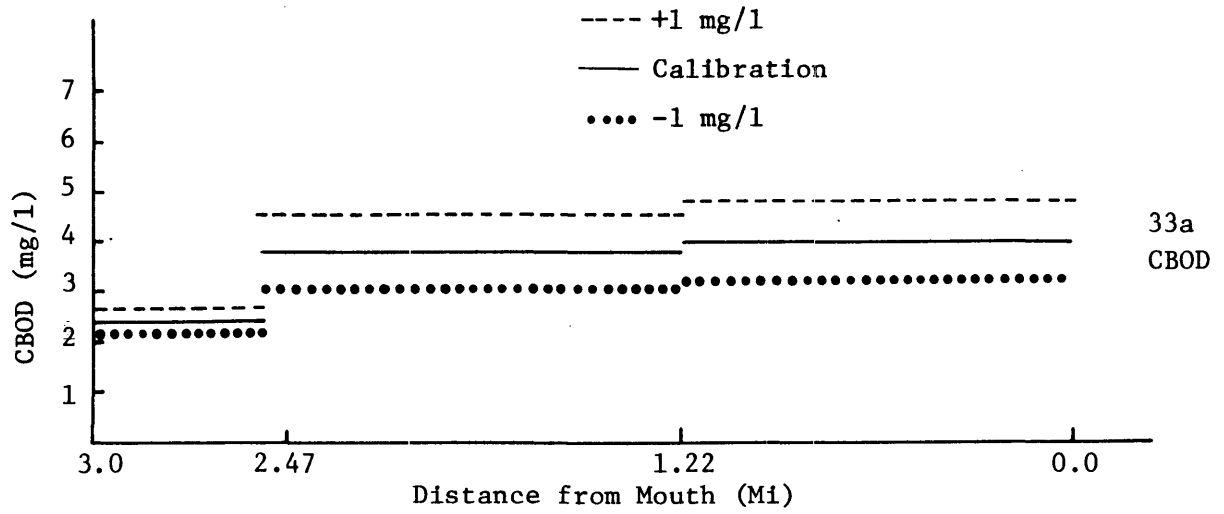


Figure 33. Sensitivity to CBOD boundary conditions.

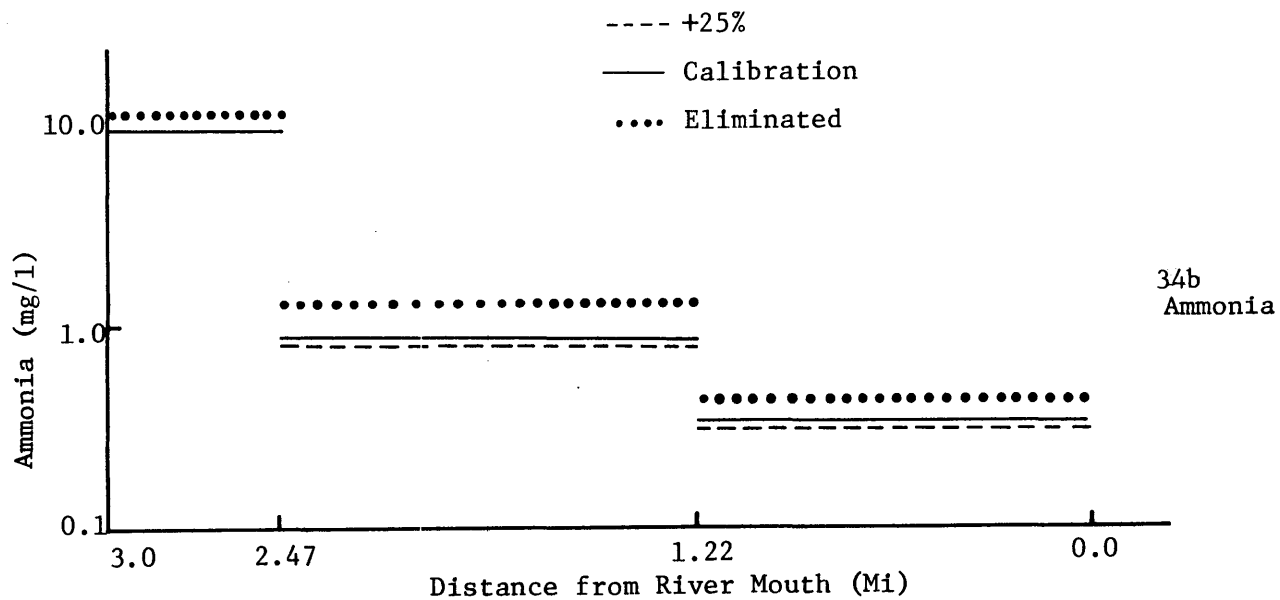
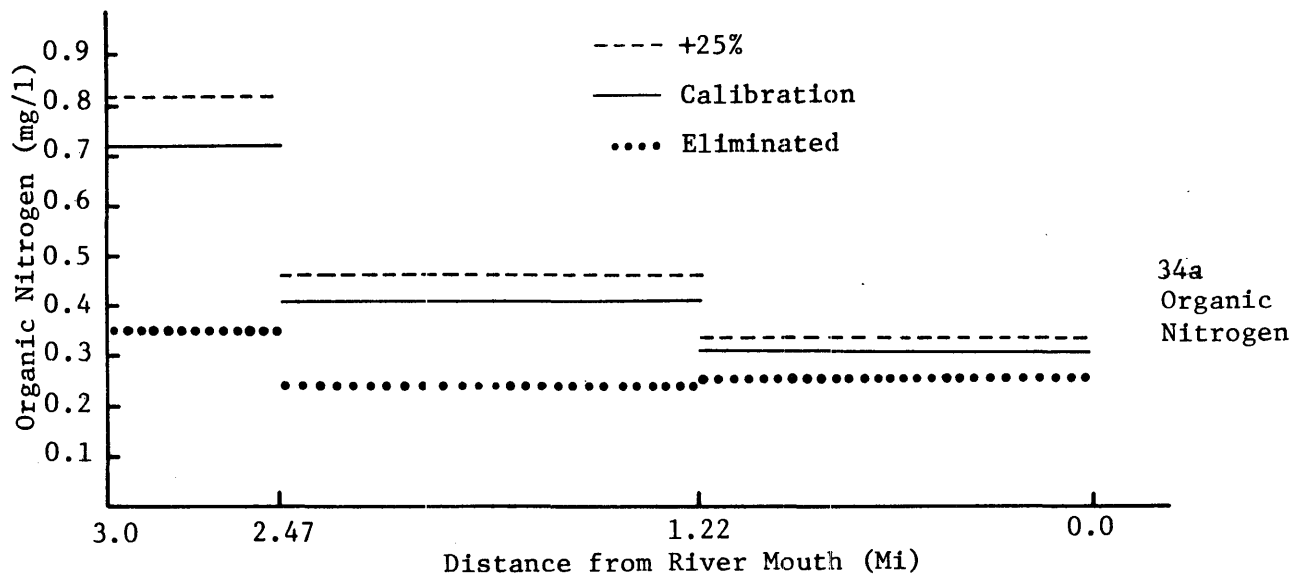


Figure 34. Sensitivity to non-point exchange rates.

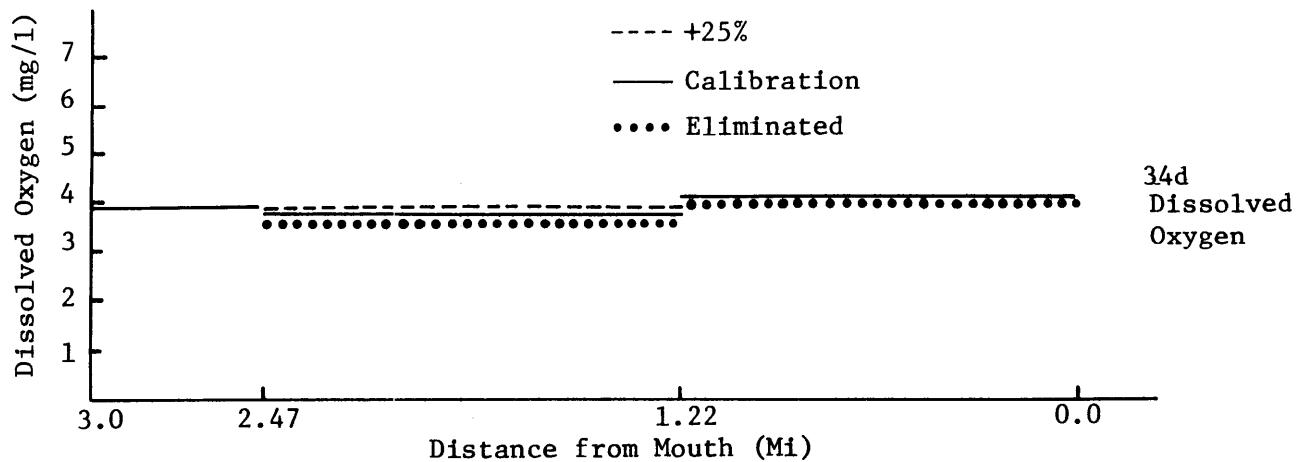
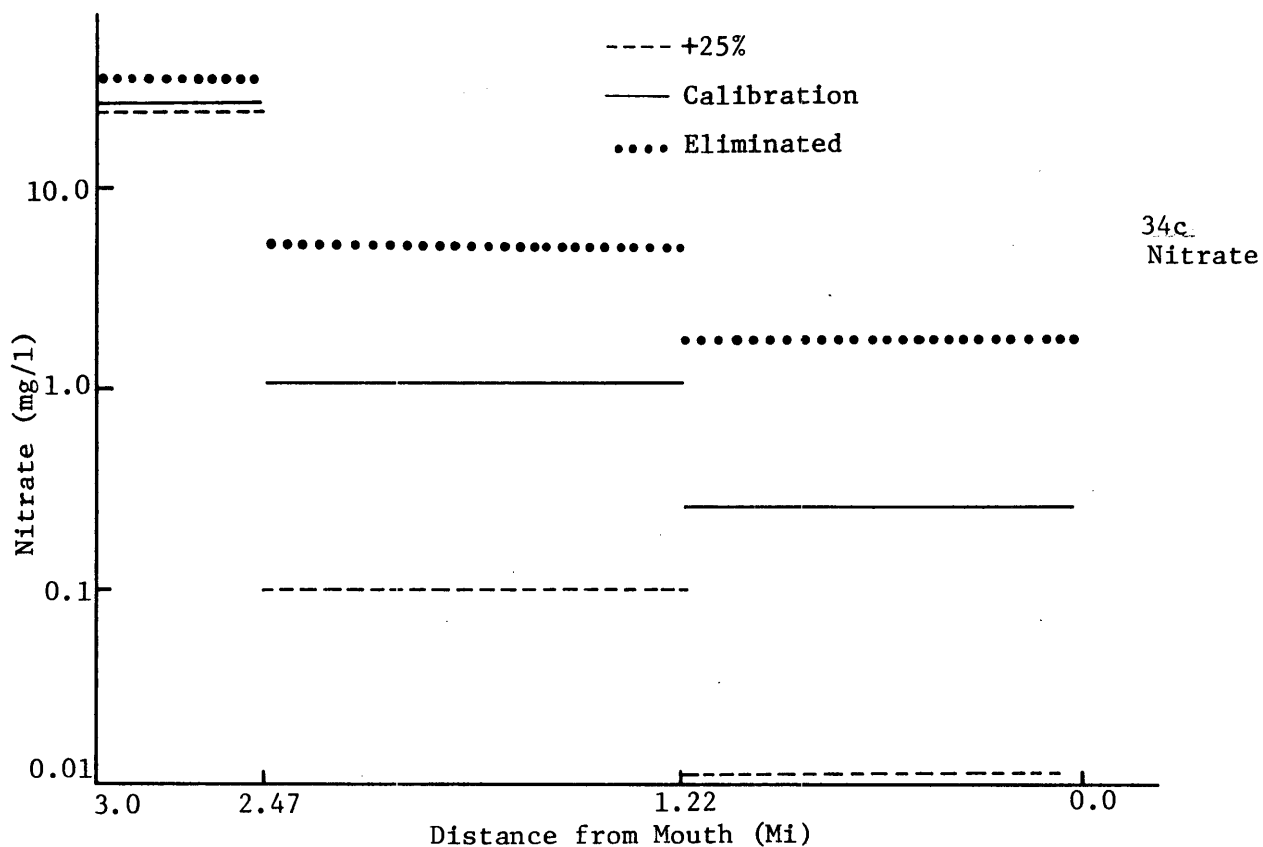


Figure 34 (Cont'd). Sensitivity to non-point exchange rates.

Organic nitrogen and nitrate concentrations show the greatest sensitivity to increasing or eliminating the exchanges. A 25% increase in the marsh contribution of organic nitrogen results in an increase of from 0.3 to 1.0 mg/l in the dissolved concentration. Eliminating the contribution results in a decrease of from 0.8 to 3.7 mg/l organic nitrogen. A 25% increase in the uptake rate of nitrate decreases the dissolved concentration from 0.2 to 2.0 mg/l while eliminating the uptake results in an increase of from 1.5 to 8.0 mg/l nitrate.

Ammonia is less sensitive to changes in the exchange rates. Increasing uptake by 25% results in a decrease of 0.2 mg/l or less in ammonia. Eliminating uptake results in an increase of 0.1 to 0.8 mg/l ammonia.

Varying exchange rates produces only a small change in the creek dissolved oxygen concentration, primarily due to the change in ammonia concentration. The maximum effect is noted in the mid-section of the stream when all exchanges are eliminated and D.O. decreases by 0.3 mg/l.

#### G. Sensitivity to Point-Source Loading

The South Fork of Parker Creek receives both point-source wasteloads and a background input of nutrients and organics. Among the substances introduced to the Parker Creek system through the South Fork are quantities of ammonia and CBOD, both of which influence the dissolved oxygen concentration of the creek. To ascertain the magnitude of

this influence, model runs were made with the CBOD and ammonia eliminated from the South Fork freshwater inputs. When no ammonia was input, the ammonia uptake rates were also set to zero. The results of these runs are presented in Figs. 35a-c.

It can be seen that eliminating the CBOD input results in a decrease in CBOD concentration of from roughly 1.0 to 0.1 mg/l with the greatest effect noted in the most upstream reaches. The improvement in dissolved oxygen obtained by eliminating the CBOD is negligible, however, and of the order of 0.1 mg/l or less.

Eliminating the ammonia inputs produced a more dramatic effect, with decreases of ammonia from 10 mg/l in the upstream reaches to 0.1 mg/l near the mouth of the creek noted. This results in increases in D.O. of from 1.4 mg/l in the upstream reaches to 0.4 mg/l near the mouth of the creek. Thus the ammonia loading has a much greater effect on the creek than the CBOD loading.

#### H. Sensitivity to Benthic Oxygen Demand

A benthic oxygen demand of 2 gm/m<sup>2</sup>/day has been noted in Parker Creek. To examine the effect of this demand on the creek D.O. budget, model runs were made with the demand changed by ±50% - that is, benthic demands of 1 and 3 gm/m<sup>2</sup>/day were utilized. The effect on the creek dissolved oxygen level is shown in Fig. 36.

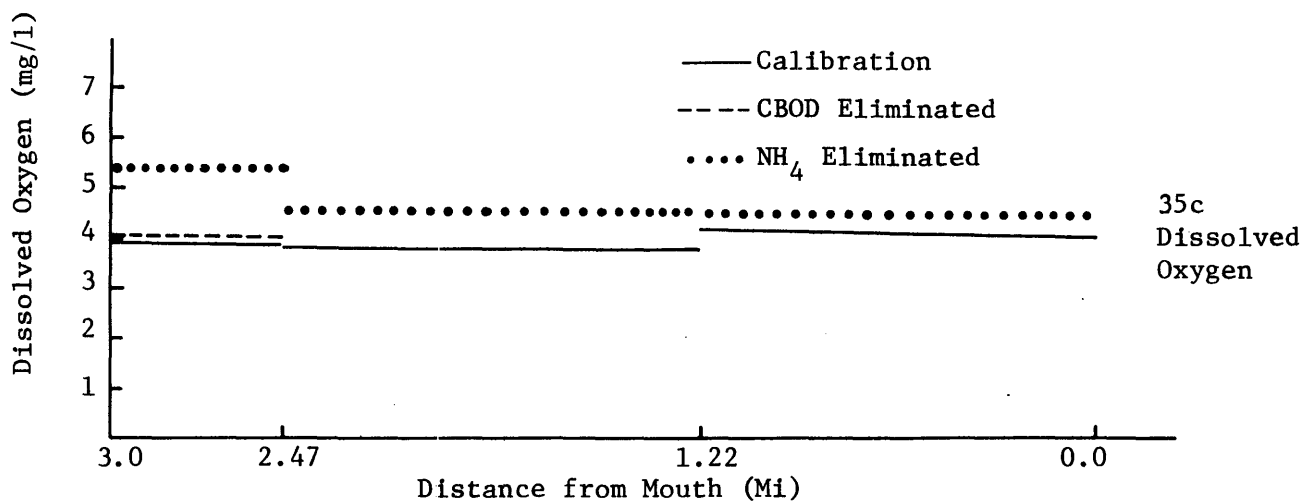
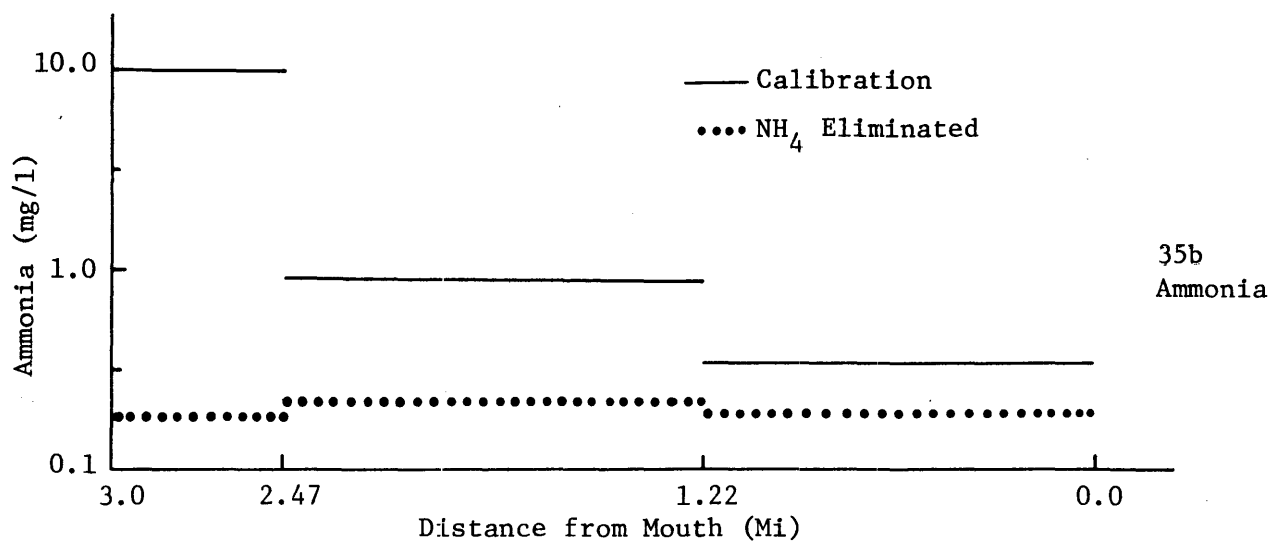
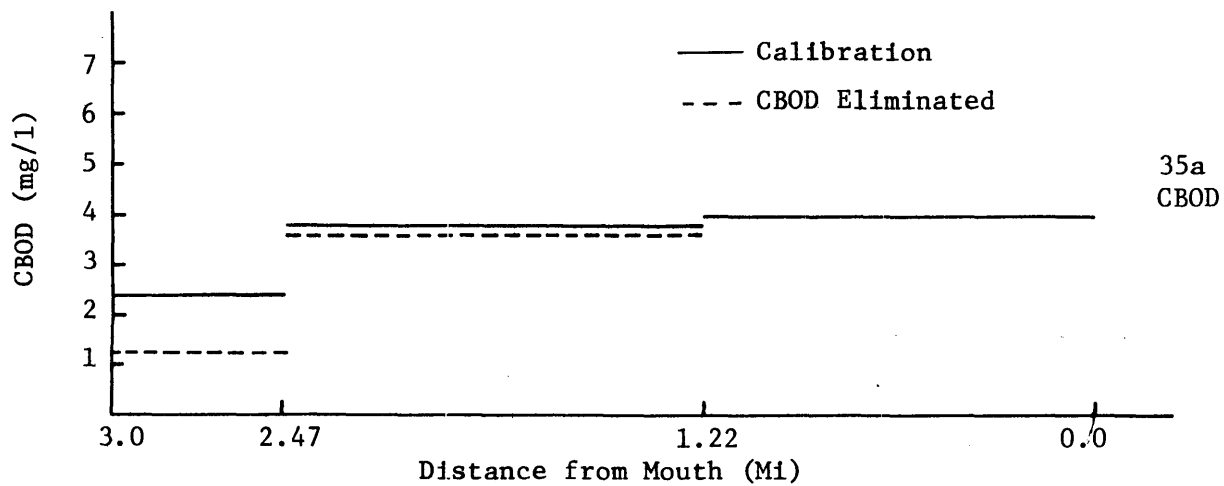


Figure 35. Sensitivity to point source loadings.

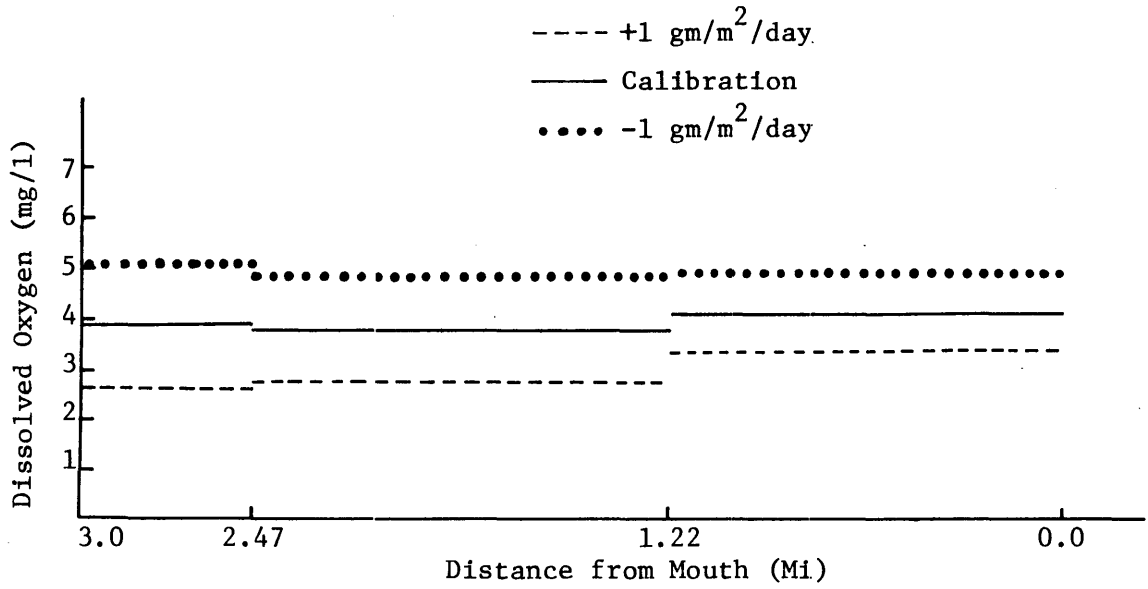


Figure 36. Sensitivity to benthic oxygen demand.



It is noted that a  $1.0 \text{ gm/m}^2/\text{day}$  change in the benthic oxygen demand results in a change of from 1.2 to 0.8 mg/l D.O., with the largest effect noted in the shallow, upstream portion of the creek.

## Chapter 5

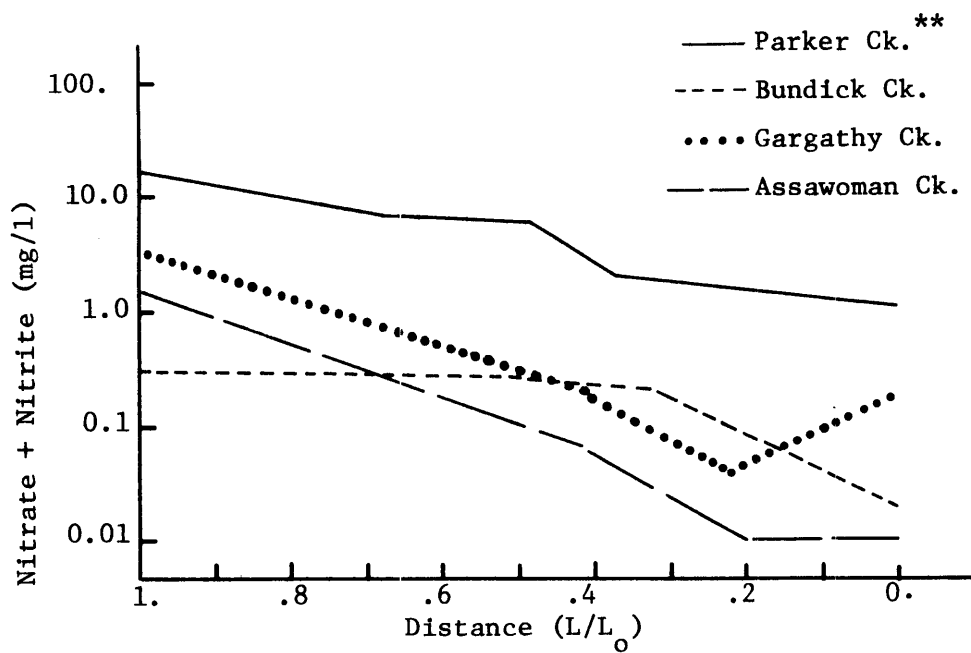
### Results of Comparative Surveys

Development of a water quality plan for Parker Creek is hampered by lack of knowledge of the ambient conditions to be expected in a marsh system in the absence of any artificial inputs. This same lack of knowledge makes it difficult to discern the effects on the system of the present wasteloading. To partially remedy this deficiency, a comparative water quality survey was conducted on Sept. 21, 1978 in Parker Creek and three similar non-impacted creeks - Bundick Creek, Gargathy Creek, and Assa-woman Creek. The sampling program and data collected during the survey were detailed in Chapter 1. An analysis of the data is presented in the remainder of this chapter.

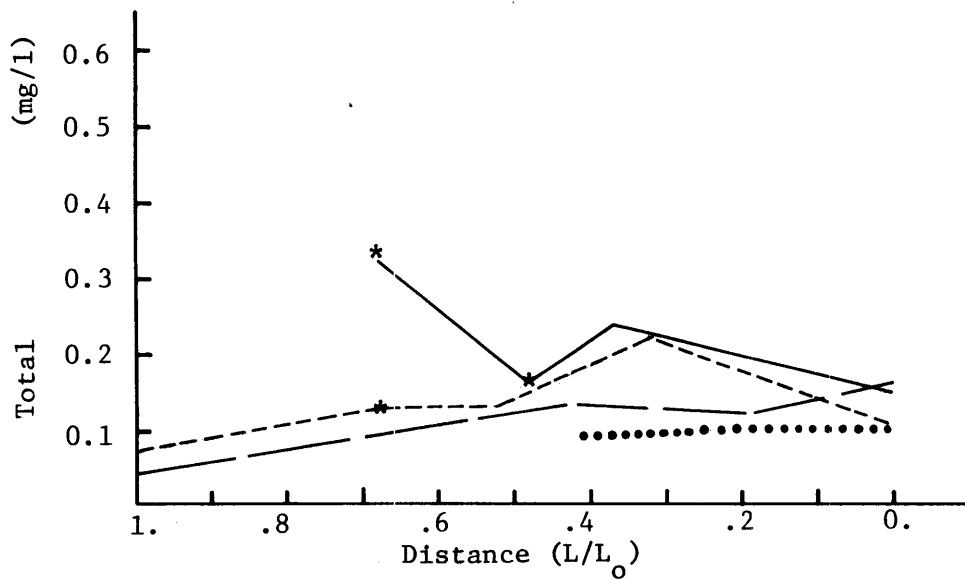
#### A. Water Quality Parameters

Nitrate, phosphorus,  $\text{CBOD}_5$ , dissolved oxygen and total suspended solids data collected during the comparative stream survey are presented graphically in Figs. 37a-e. Values shown represent the averages of the samples collected during slack-before-flood and slack-before-ebb runs. To facilitate comparisons, the distance from the mouth of each creek,  $L$ , is normalized by the total length of the tidal portion of the creek,  $L_0$ .

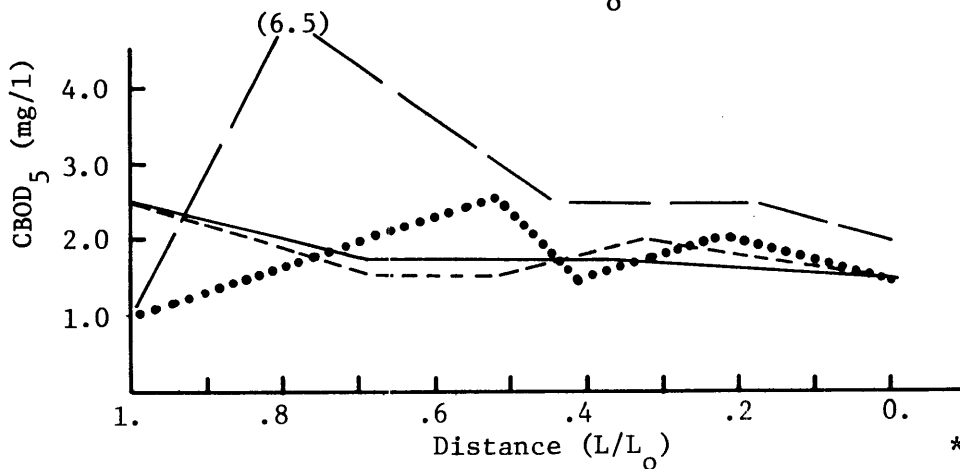
The average and variance of the station-averaged nitrate,  $\text{CBOD}_5$ , dissolved oxygen and total suspended solids parameters for the tidal portion of each creek are given in Table 14.



37a  
Nitrate +  
Nitrite



37b  
Total  
Phosphorus

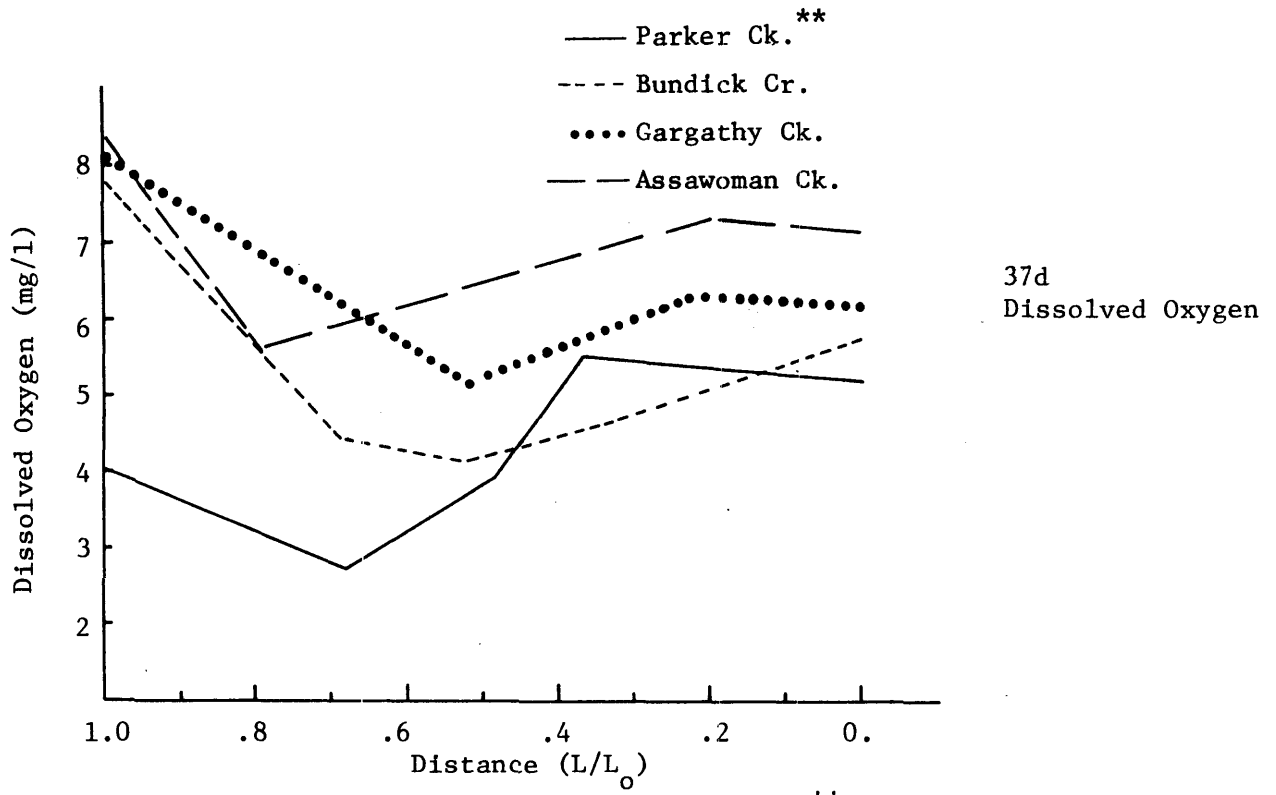


37c  
CBOD<sub>5</sub>

\* SBE or SBF only

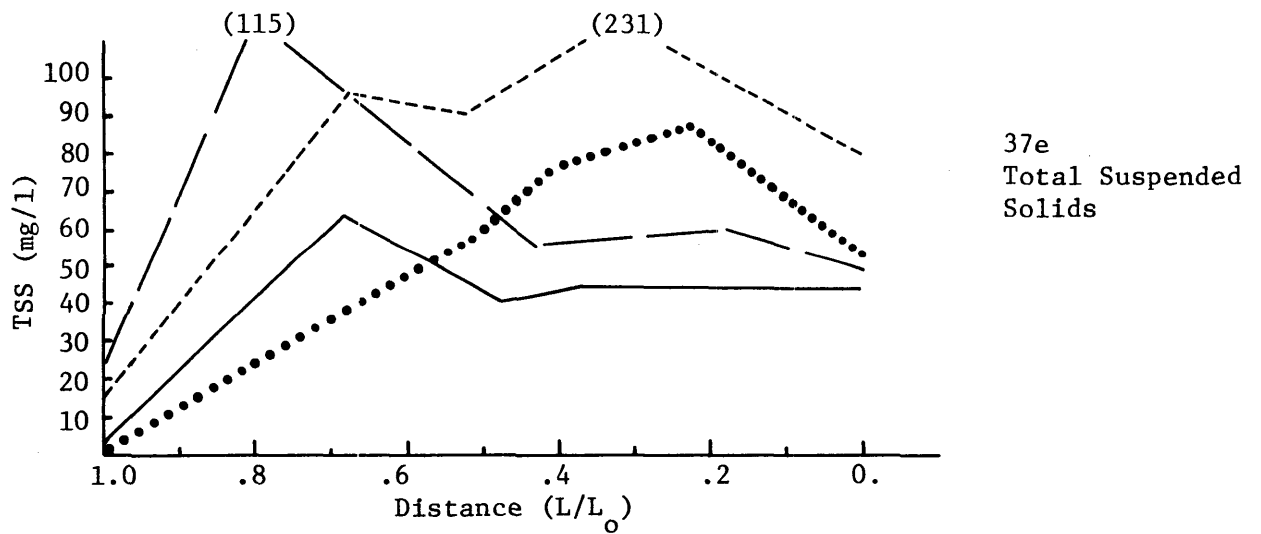
\*\* South Fork and Main Stem only

Figure 37. Results of Comparative Creek surveys.



37d  
Dissolved Oxygen

\*\* South Fork and Main Stem Only



37e  
Total Suspended Solids

Figure 37 (Cont'd). Results of comparative creek surveys.

It can be seen that the nitrate concentrations in Parker Creek are one to two orders of magnitude greater than the levels observed in the remaining creeks. Elevated phosphorus values are also observed, suggestive of concurrent higher concentrations of this nutrient but the data is too sparse to be conclusive.

CBOD<sub>5</sub> in Parker Creek averages in the same range or lower than in the nonimpacted creeks. Total suspended solids are also in the same range or lower.

Parker Creek dissolved oxygen values are depressed below the values of the other creeks in the upper half of the stream, roughly the portion consisting of the waste-receiving South Fork. In the lower half of the creek, dissolved oxygen values are in the same range as the other creeks. These findings are consistent with the results of the sensitivity analysis which indicated that the upper portion of Parker Creek is most sensitive to wasteflows while the lower portion is dominated by conditions in Metomkin Bay. Taken as an average, the Parker Creek D.O. level also is less than the other creeks.

Table 14. Average Parameter Values - Comparative Survey

	NO <sub>3</sub> (mg/l)		CBOD <sub>5</sub> (mg/l)		D.O. (mg/l)		TSS (mg/l)	
	$\bar{X}$	S <sup>2</sup>	$\bar{X}$	S <sup>2</sup>	$\bar{X}$	S <sup>2</sup>	$\bar{X}$	S <sup>2</sup>
Parker Ck.	5.99	33.3	1.5	0.3	4.38	1.03	45	567
Bundick Ck.	0.23	0.02	1.8	0.2	5.37	2.21	103	6357
Gargathy Ck.	0.15	9x10 <sup>-3</sup>	1.9	0.2	5.79	0.23	59	225
Assawoman Ck.	0.03	1x10 <sup>-3</sup>	3.4	4.4	6.69	0.59	72	894

## B. Benthic Oxygen Demand

Benthic oxygen demand measures were taken at a total of nine stations in the Parker Creek-Metomkin Bay system. Five stations were located on Parker Creek itself, two on non-impacted control creeks, and two on Metomkin Bay (Fig. 7). The results of the sampling are summarized in Fig. 33. It can be seen that measured benthic demands throughout the system are highly variable, and that no trend of higher or lower values in Parker Creek is evident compared to the other creek and bay stations.

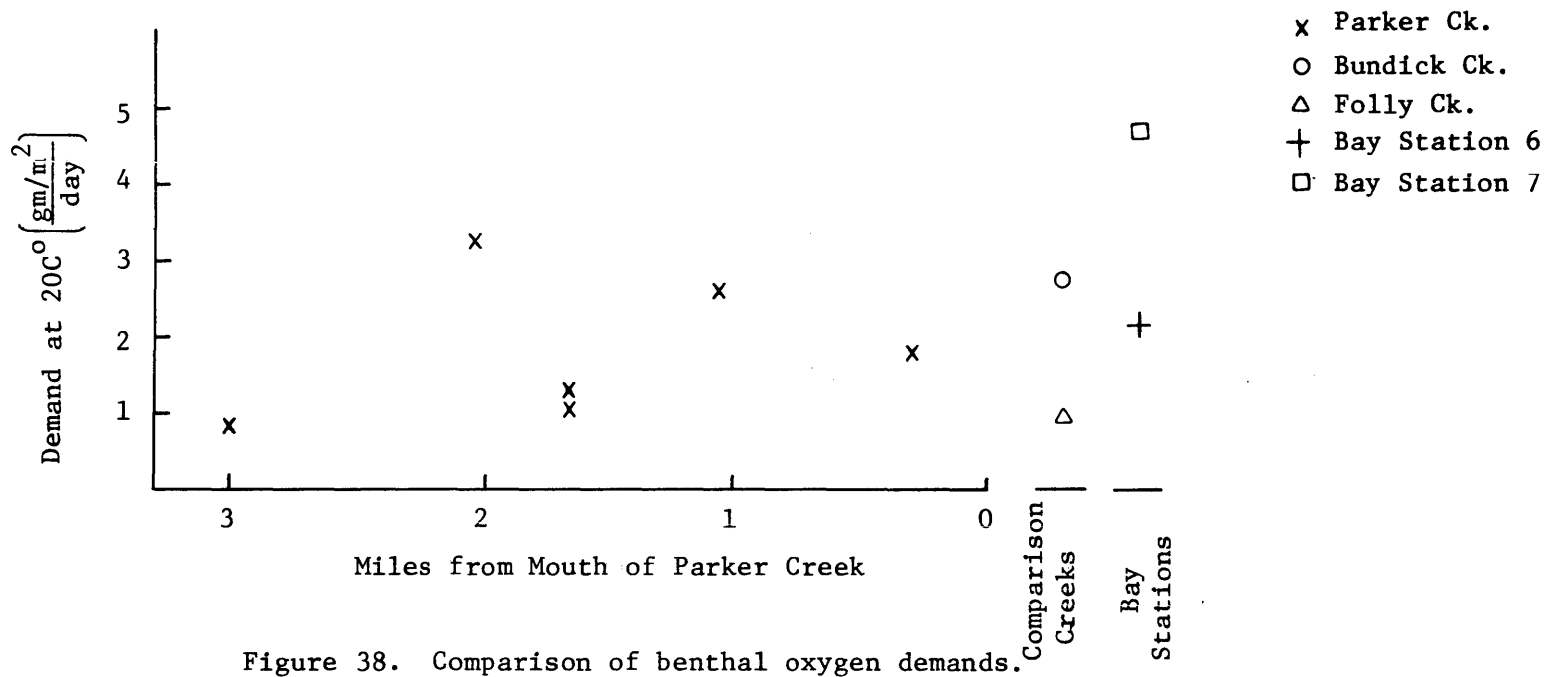


Figure 38. Comparison of benthic oxygen demands.

## Chapter 6

### Analysis and Conclusions

The topics addressed in this report may be classified into three broad headings: the present status of Parker Creek, the sensitivity of the creek system to selected parameters and inputs, and a comparison of conditions in Parker Creek with several similar but non-impacted creeks. A summary of the findings in each of these areas is presented below.

#### A. Present Status of Parker Creek

At present, Parker Creek is characterized by high nutrient concentrations, especially nitrogen, and low to moderate concentrations of dissolved oxygen. During an intensive survey conducted over a twenty-six hour period on Aug. 21-Aug. 23, 1978, ammonia and nitrate concentrations as high as 19 and 55 mg/l, respectively, were observed. Daily average concentrations ranged from 0.2-15 mg/l for ammonia and 0.4-45 mg/l for nitrate. Total phosphorus concentrations averaged from 0.13 to 0.23 mg/l with extremes as high as 0.51 mg/l occurring.

During this same period, dissolved oxygen concentrations ranged from low values of 1.0 mg/l or less to a high value of over 7.0 mg/l. Daily average values were uniformly below 5.0 mg/l with a minimum average of 3.0 mg/l occurring.

During two slackwater surveys conducted on Sept. 13, 1978, lower nitrogen concentrations and higher phosphorus and dissolved oxygen levels were observed. Nitrate



concentrations varied from less than 0.1 mg/l to 11.0 mg/l while total phosphorus ranged from less than 0.1 mg/l to 0.88 mg/l. The dissolved oxygen data, available from only three of the six stations, shows minimum values of 4.8 mg/l and maximum values over 7.5 mg/l.

A second set of slackwater runs was conducted on Sept. 21, 1978. During this survey, extreme nitrate concentrations were again noted with several observations exceeding 10 mg/l and a maximum of 28 mg/l occurring. Total phosphorus concentrations ranged from less than 0.1 mg/l to more than 0.6 mg/l. Concurrent with the elevated nitrate levels, depressed D.O. concentrations occurred. Low concentrations in the range of 2.2-3.3 mg/l were noted with maximum concentrations in excess of 7 mg/l also observed.

Concentrations of organics - organic nitrogen, chlorophyll 'a', and CBOD (a measure of organic carbon) - in Parker Creek were similar during the Aug. 21 and Sept. 13 surveys but lower during the Sept. 21 survey.

During the intensive survey, organic nitrogen concentrations of approximately zero to greater than 1 mg/l were noted. Average concentrations varied from 0.4 to 0.86 mg/l. Chlorophyll 'a' concentrations ranged from 1-65  $\mu$ g/l and averaged 7-45  $\mu$ g/l. Values of CBOD<sub>u</sub> from less than 2 mg/l to almost 17 mg/l were observed with averages ranging from 2.7 to 4.6 mg/l. Corresponding values of chlorophyll 'a' and CBOD<sub>u</sub> during the Sept. 13 survey were 5-77  $\mu$ g/l and 2.5 to 13 mg/l respectively.

During the Sept. 21 survey, chlorophyll 'a' values of only 1-7  $\mu\text{g}/\text{l}$  occurred.  $\text{CBOD}_5$  measurements of 1 to 4  $\text{mg}/\text{l}$ , corresponding to ultimate values of approximately 2.5 to 10.0, were noted with the average  $\text{CBOD}_5$  concentration about 1.5  $\text{mg}/\text{l}$ .

The Parker Creek system possesses the ability to remove large quantities of nutrients from the water column. During the intensive survey, an order of magnitude difference was noted between the quantities of ammonia and nitrate entering and leaving the system. Of the 2000  $\text{lb}/\text{day}$  of these nutrients entering the creek during the survey, only about 200  $\text{lbs.}$  were flushed out at the mouth. Of the remainder removed from the water column, about 200  $\text{lbs.}$  were recycled as organic nitrogen and the balance stored, at least temporarily, in the sediments and as biomass.

These findings agree with the results of a number of workers who have investigated the nutrient uptake of *Spartina alterniflora* (the dominant plant in the low marsh portion of Parker Creek) and the potential of employing marshes to remove nutrients from wastewaters. Broome, et al. (1973) and Patrick and Delaune (1976) have both reported increased uptake and yield when *Spartina alterniflora* was fertilized with nitrogen and phosphorus or nitrogen alone. Chalmers, et al (1976) reported increased soil retention as well, noting that marsh plots fertilized with sewerage sludge retained approximately 50% of the applied nitrogen in the marsh soils.

While there is strong evidence to suggest at least temporary buffering of the nutrient inputs to the water column by the marsh, the results must still be considered as tentative. The nutrient filtering effect was noted during the *Spartina* growing season and would be expected to proceed at reduced levels, if at all, during the remainder of the year. In addition, no data is available to examine the eventual recycling of the nutrients as organics or to determine the saturation level of mineral uptake by the marsh.

#### B. Sensitivity of the Creek System

The sensitivity analysis of Parker Creek was directed primarily at determining those factors which have the greatest influence on dissolved oxygen concentrations in the water column. Analyses of the influence of CBOD, NBOD (ammonia), dissolved oxygen boundary conditions, marsh-water column mass exchanges, and benthic oxygen demand were conducted.

It was determined that neither the amount of CBOD present nor the decay rate had much effect on the creek D.O. concentrations. Ammonia (or NBOD) has a more significant impact. Point-source inputs of ammonia produce a deficit of from 1.4 to 0.4 mg/l D.O. within the creek with the greatest impact near the headwaters of the South Fork.

Dissolved oxygen concentrations in the freshwater flows have little influence on the D.O. in the creek except at the extreme upstream portions where a 1 mg/l change in

freshwater D.O. produces a maximum 0.3 mg/l change in the creek concentration. This relative insensitivity is due to the small fraction of the creek volume represented by the freshwater flows. The downstream boundary condition, considered to be the D.O. concentration in the tidal prism, has a greater effect on the creek D.O. balance due to the greater fraction of the creek volume represented by the tidal prism. A 1 mg/l change in the downstream D.O. concentration results in a change of 0.4-0.2 mg/l throughout roughly 80% of the creek, with the largest effect noted in the downstream segment near the mouth of the creek.

Marsh/water-column mass exchanges have only a small effect on the creek dissolved oxygen. Restoring to the water column the ammonia removed by the marsh would decrease D.O. by a maximum of 0.3 mg/l. This minor effect is due to the 2nd order kinetics of the nitrification reaction and to the ammonia concentration distribution within the creek. In the upstream portions of the creek, where the ammonia concentration is high, nitrification is proceeding at nearly the saturation rate and additional quantities of ammonia can have little or no effect on the stream D.O. budget. Near the mouth of the creek, where the nitrification reaction is not saturated, the ammonia added by eliminating uptake produces only a minimal increase in dissolved ammonia (due to the volume of the downstream segments) and hence, a minimal decrease in dissolved oxygen.

The benthic oxygen demand, influential from the headwaters to the mouth of the creek, is perhaps the most important factor in the creek dissolved oxygen budget. A  $1 \text{ gm/m}^2/\text{day}$  change in benthic demand results in a 0.8 to 1.2 mg/l change in D.O. concentration, with the larger effect noted near the headwaters of the stream.

For purposes of analysis, Parker Creek may be divided into two portions, an upstream regime and a downstream regime. The upstream regime, consisting of the portions of the branches near the headwaters, is characterized by large freshwater flows relative to the local tidal prism. In this regime, conditions are therefore dominated by the freshwater flows and the principal components of the D.O. deficit are ammonia in the point source inputs (in the South Fork) and benthic oxygen demand.

The downstream regime consists of the main stem and the immediately adjacent portions of the branches. In this regime, conditions are dominated by the tidal prism and the principal components of the D.O. deficit are the deficit in the flood waters from Metomkin Bay and, again, the benthic oxygen demand.

### C. Comparative Creek Surveys

Simultaneous slack-before-flood and slack-before-ebb sampling runs were conducted on Parker Creek and three other Eastern Shore creeks, Bundick, Gargathy, and Assawoman, for purposes of comparison. The results confirm

that nitrate levels in Parker Creek are extremely high with observed concentrations one to two orders of magnitude greater than in the other creeks. The average nitrate concentration noted in Parker Creek was approximately 6 mg/l compared to averages of the order 0.1 mg/l in the other creeks. The survey results are suggestive of elevated phosphorous levels as well.

Parker Creek CBOD<sub>5</sub> and total suspended solids (TSS) levels were of the same order or lower than in the other creeks. The average CBOD<sub>5</sub> in Parker Creek was 1.5 mg/l compared to 1.8-3.4 mg/l for the non-impacted creeks and Parker Creek TSS averaged 45 mg/l compared to 59-103 mg/l in the other creeks. Thus there is no evidence to suggest that Parker Creek is impacted beyond natural levels by CBOD<sub>5</sub> or TSS wasteflows.

As an average, the Parker Creek D.O. concentration was lower than the other creeks, 4.38 mg/l compared with 5.37 to 6.69 mg/l. This difference is especially noticeable in the upper portion of the South Fork, the upstream regime, where Parker Creek D.O. levels were on the order of 2 mg/l lower than in the upstream portions of the other creeks. Near the mouth of Parker Creek, the downstream regime, dissolved oxygen concentrations compared favorably with the levels observed in the non-impacted creeks.

Dissolved oxygen levels of 4 mg/l or less were observed to occur, in some instances, in the creeks receiving no wasteflows, suggesting that concentrations of this order occur as a natural process. Nonetheless, the dissolved oxygen concentration in the upstream portion of the South Fork of Parker Creek is still depressed below the minimum values observed in the other creeks.

Benthic oxygen demand readings in Parker Creek were highly variable, ranging from 0.9 to 3.3 gm/m<sup>2</sup>/day (at 20°C) and averaging 2.0 gm/m<sup>2</sup>/day. Comparative readings in other creeks and in Metomkin Bay ranged from 1.0 to 4.8 gm/m<sup>2</sup>/day suggesting that the benthic oxygen demand in Parker Creek is within natural limits.

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## Appendix A - Metomkin Bay Survey

In conjunction with the Parker Creek intensive survey, a second intensive survey was conducted on Metomkin Bay. Six stations (Fig. A1) were sampled, a single station (B6) occupied from 2300 hrs. on Aug. 21 to 0000 hrs. on Aug. 23, and five stations occupied from 1200 hrs. Aug. 23 to 1400 hrs. Aug. 24. At each station, samples were taken of the following parameters at the intervals designated:

Total Kjeldahl Nitrogen	(two hours)
Ammonia Nitrogen	(two hours)
Nitrite + Nitrate Nitrogen	(two hours)
Total Phosphorus	(two hours)
Chlorophyll 'a'	(one hour)
CBOD <sub>5</sub>	(one hour)
Dissolved Oxygen	(one hour)
Salinity	(one hour)
Temperature	(one hour)

The results of the survey are summarized in Table A1.

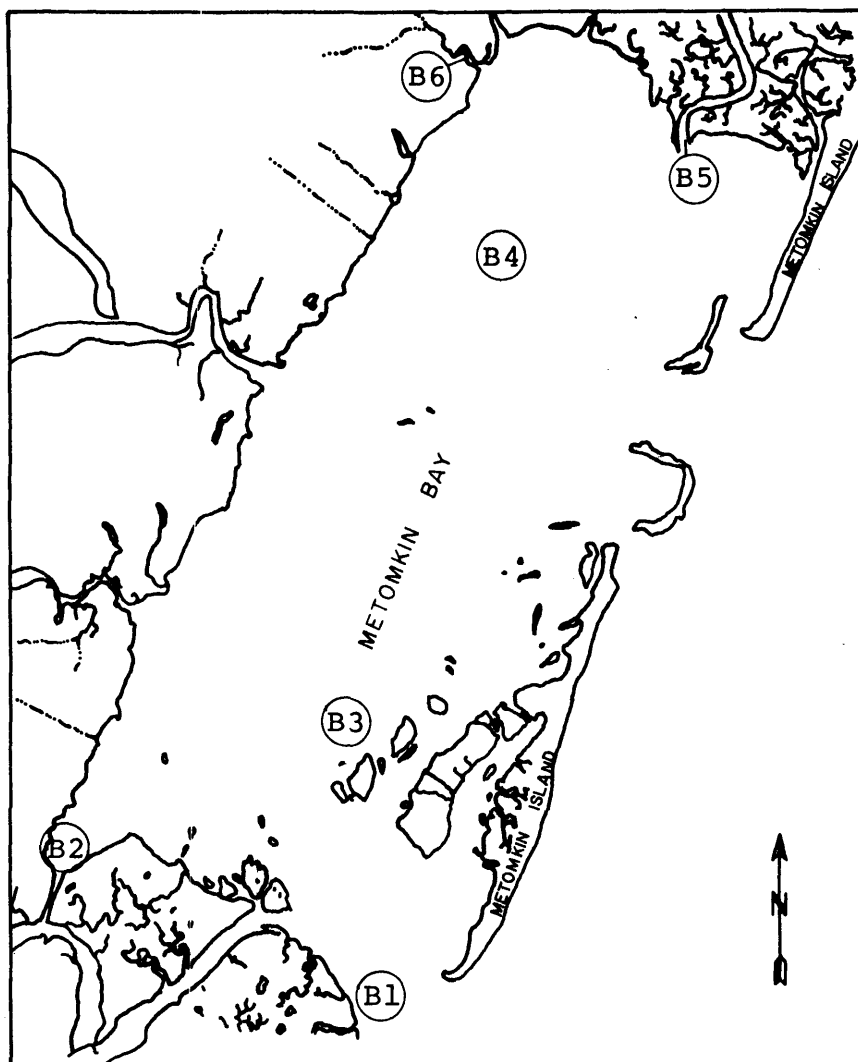


Figure A1. Metomkin Bay sample stations.

Table A1. Metomkin Bay Intensive Water Quality Survey

Station	TKN mg/l	NH <sub>4</sub> mg/l	NO <sub>3</sub> + NO <sub>2</sub> mg/l	Tot. P mg/l	Chl. 'a' µgm/l	CBOD <sub>5</sub> mg/l	D.O. mg/l	Salinity ppt	Temp. C <sup>o</sup>
B1									
mean	0.74	0.21	0.02	0.06	2.1	1.5	6.1	31.1	25.3
range	0.40-1.70	0.0-0.65	<0.01-0.02*	0.02-0.15	<1.0-4.7	1.0-4.0	4.4-7.6	30.8-32.7	23.8-29.0
B2									
mean	0.58	0.19	0.04	0.11	3.0	1.7	6.0	31.0	25.6
range	0.25-1.20	0.03-0.54	<0.01-0.12	0.03-0.28	1.0-7.3	1.0-2.5	4.9-7.3	30.8-31.2	23.8-29.0
B3									
mean	0.45	0.10	0.01	0.07	2.7	2.2	6.3	31.0	26.0
range	0.30-0.70	0.0-0.28	<0.01-0.1	0.03-0.17	1.1-6.5	1.0-3.0	4.5-7.8	30.9-31.2	23.5-27.8
B4									
mean	0.44	0.16	0.01	0.08	4.3	2.3	6.2	31.4	25.6
range	0.08-0.75	0.0-1.03	<0.01-0.01	0.02-0.18	1.9-8.3	1.0-4.0	4.9-7.5	31.2-31.6	22.9-27.1
B5									
mean	0.61	0.15	0.01	0.09	4.0	2.1	5.7	31.4	25.8
range	0.49-1.00	0.03-0.25	<0.01-0.01	0.03-0.21	<1.0-8.3	1.0-3.0	4.7-7.1	31.0-31.7	23.3-28.3
B6									
mean	0.70	0.25	0.09	0.27	4.5	2.0	3.7	31.2	26.1
range	0.08-1.10	0.03-0.54	0.03-0.15	0.08-0.83	1.2-9.2	1.0-3.0	2.1-5.5	28.6-32.1	23.2-30.0

\* < less than