1982

A water quality study of the Northwest River, Virginia

Albert Y. Kuo
Virginia Institute of Marine Science

Bruce Neilson
Virginia Institute of Marine Science

Paul V. Hyer
Virginia Institute of Marine Science

A WATER QUALITY STUDY OF THE NORTHWEST RIVER, VIRGINIA

by

Albert Y. Kuo
Bruce J. Neilson
Paul V. Hyer

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Acknowledgements

This project has been funded in part by the United States Environmental Protection Agency under assistance agreement number P003085-03 to the Hampton Roads Water Quality Agency.

We would like to thank the personnel of the City of Chesapeake, particularly Messrs. M. Thompson, E. Palmos and J. Rodgers, for their contributions to the field survey and laboratory analysis of the samples. Hampton Roads Sanitation District Commission also contributed laboratory analyses for which we are grateful.

We would also like to express our appreciation to Mr. Paul E. Fisher, Project Director of Hampton Roads Water Quality Agency, Mr. John M. Carlock of Southeastern Virginia Planning District Commission and Mr. Eric Lamberton of the City of Chesapeake for their input during the course of this study, and their review and valuable comments on this report.

Introduction

The Northwest River is a small, coastal plains river lying to the south of the Hampton Roads metropolitan area. It flows in a southeasterly direction from the Dismal Swamp, its headwaters, to North Carolina where it empties into Currituck Sound. Lunar tides in the river are quite small, but flow reversals due to winds are not uncommon.

Previous studies of the river have evaluated its potential as a drinking water source and the environmental changes that would occur as a result of water withdrawal. The latter concern was primarily that downstream locations would experience higher salinity levels once fresh water was withdrawn. More recently the initial Hampton Roads 208 study was conducted and a water quality management plan was developed which addressed both point and nonpoint sources of pollution. However, it was not possible in that study to investigate the effects of pollutant sources on the quality of the Northwest River water. Neither field measurements nor modelling studies of the river were a part of that program.

In recent years the City of Chesapeake has constructed a water treatment plant close to the Northwest River and the City has been withdrawing water for two years. City officials were concerned that significant land use changes in the river drainage basin could alter or degrade the quality of the river water, thereby increasing treatment costs or in the worst case, precluding the use of the water for drinking. To address these concerns, the Hampton Roads Water Quality Agency contracted VIMS to undertake model studies of the river. Field studies to support this work were undertaken primarily by the City of Chesapeake under the general supervision of VIMS. This report details the results of those studies, documents the model which has been applied to this water body, and describes additional studies necessary to make the model a fully usable tool.

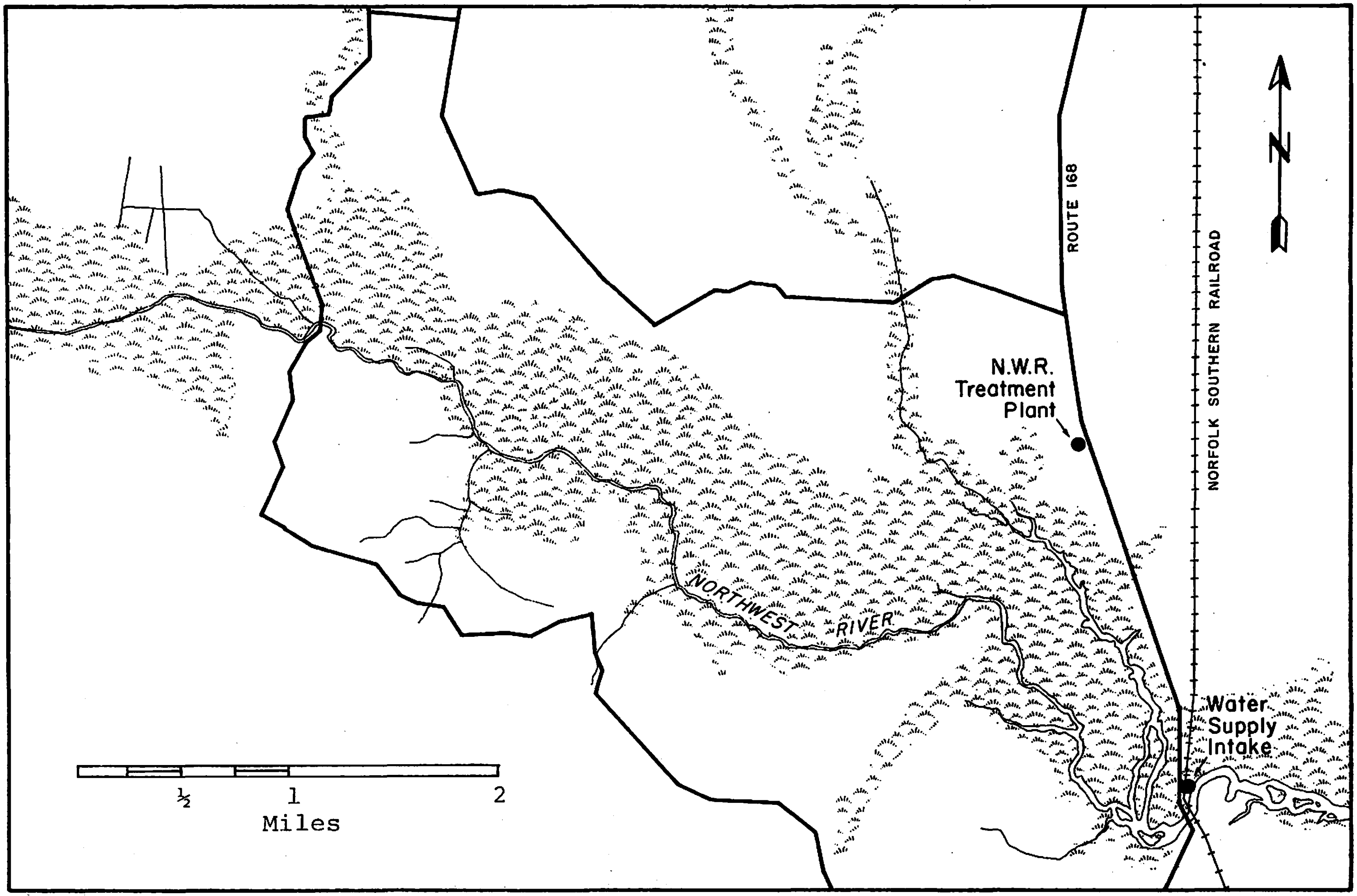


Figure 1. The Northwest River upstream of the water supply intake.

II. FIELD SURVEYS

A series of field surveys were conducted jointly by the personnel of Chesapeake Water Treatment Plant and VIMS. Geometric, hydrographic and water quality data were collected over the period from May 1980 to April 1981. The geometric and hydrographic data were used for the formulation of water quality model. The water quality data were used for the calibration of the model and to assess the water quality condition in the river.

A. River Geometry

The river geometry was measured and characterized by a series of cross-sectional profiles located along the length of the river. Figure 2 shows the location of the transects where the cross-sectional profiles were measured. A fathometer was used for profiling. The accuracy of the depth sounding is 0.5 ft. (15 cm). The water level at water supply intake was measured with a tide staff when the cross-sectional soundings were made. The bathymetric profiles were adjusted to the water level corresponding to 4.05 ft. staff reading, the average over the period of water quality survey (May to November 1980). A sample of profile is shown in Figure 3 for the transect immediately upstream of water supply intake at which the current measurements were made.

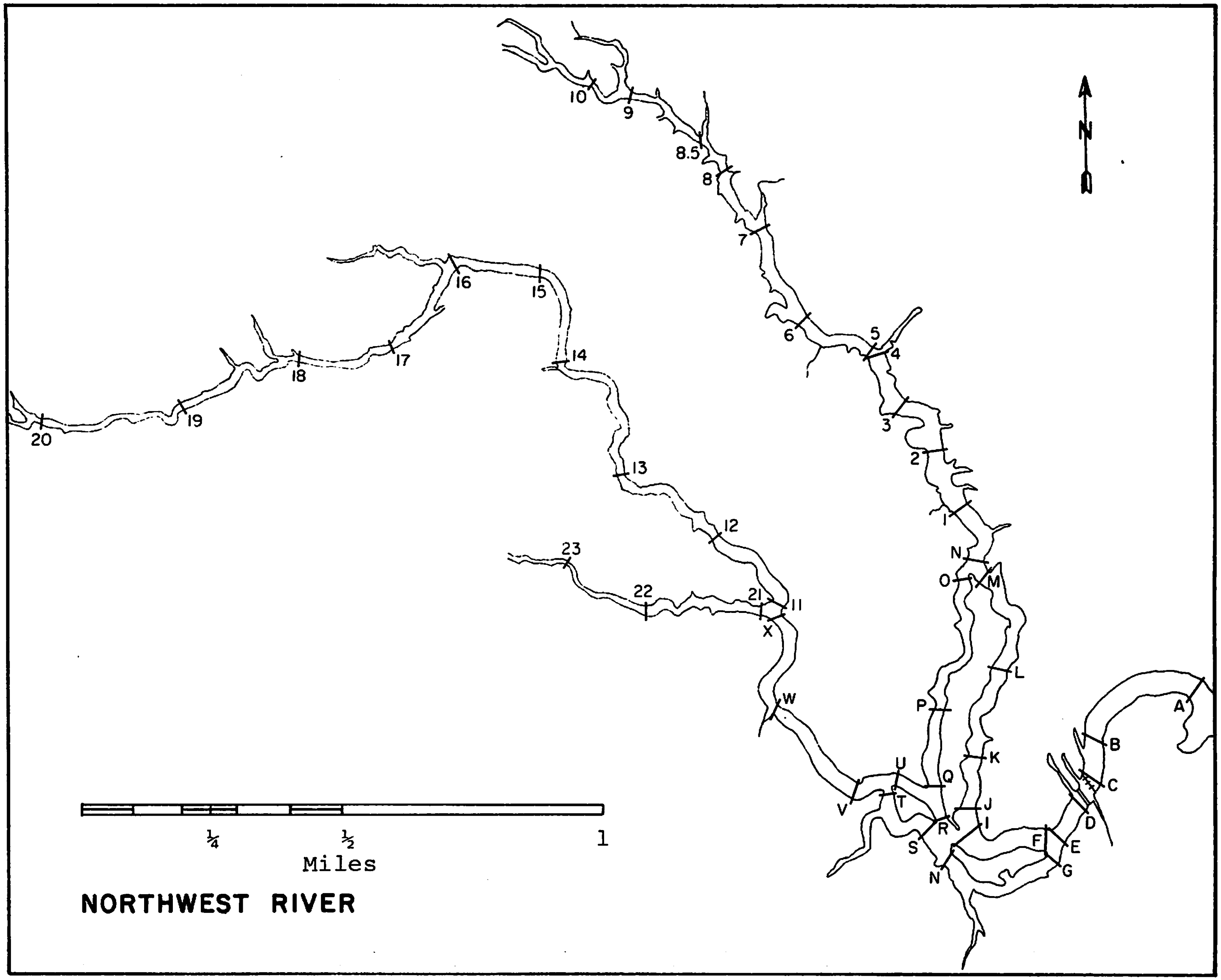


Figure 2. Transect locations of cross-sectional profile measurements.

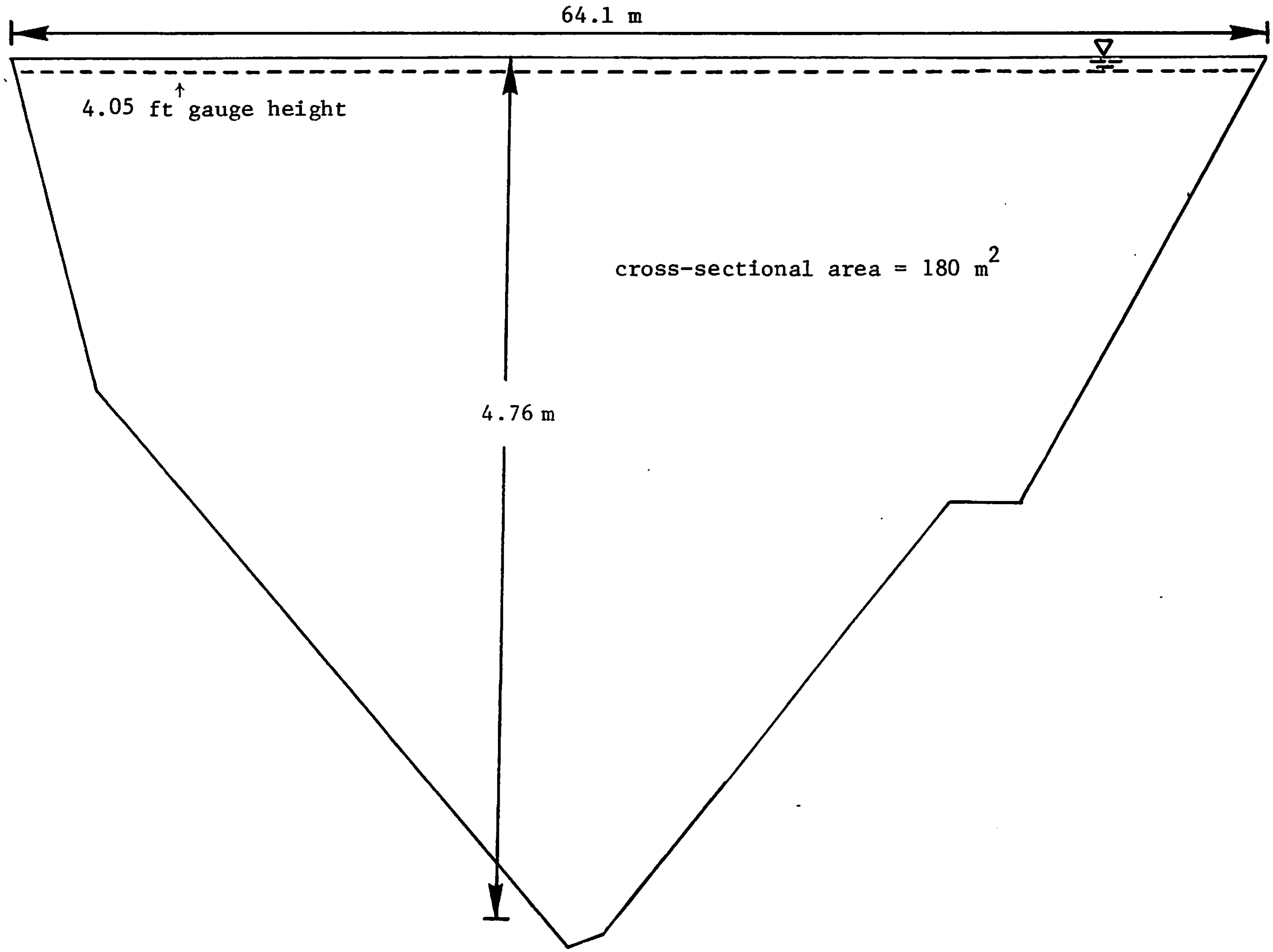


Figure 3. Cross-sectional profile immediately upstream of water supply intake (the vertical and horizontal scales are different).

Table 1. Summary of Geometric Data

(a) Main Stem

Transect	Distance from Intake (m)	X-Sect. Area (m^2)	Surface Width (m)	Mean Depth (m)	Volume (m^3)	Surface Area (m^2)
A	-406	228	69.6	3.3		
					82791	27110
B	0	180	64.1	2.8		
					22106	7530
C	119	191	62.2	3.1		
					14735	5042
D	200	173	62.2	2.8		
					7187	7187
E	320	249	58.3	4.3		
EFG				3.2	11616	3641
F	370	67	37.9	1.8		
					31169	16821
I	630	173	91.4	1.9		
G		229	64.5	3.5		
					53370	20424
H		51	42.5	1.2		
IJRSH				1.6	22191	14225
R	737	82	41.0	2.0		
RQU				1.9	1564	8172
U	928	82	33.5	2.5		
S		79	57.4	1.4		
					15958	9738
T		62	28.6	2.2		
UTV				2.2	13390	6228
V	1055	135	48.0	2.9		
					43066	14129
W	1386	124	37.2			
					43927	11994
X	1725	135	33.6	4.0		
X-11-21				2.8	6928	2484
11	1766	115	37.4	3.1		
					27669	10169
12	2088	57	25.8	2.2		
					24705	9806
13	2458	76	27.3	2.8		
					37958	14446
14	2973	71	28.8	2.5		
					18669	7845
15	3269	55	24.2	2.3		
					20616	7357
16	3531	102	31.8	3.2		
					22725	7663
17	3853	39	15.8	2.5		
					11342	4757

Table 1 (Cont'd)

Transect	Distance from Intake (m)	X-Sect. Area (m^2)	Surface Width (m)	Mean Depth (m)	Volume (m^3)	Surface Area (m^2)
18	4161	34	15.2	2.3		
					17668	7938
19	4586	49	22.2	2.2		
					22653	10468
20	5068	45	21.2	2.1		
(b) Tributaries						
J	0*	68	50.6	1.3		
					11406	7457
K	162	73	41.3	1.8		
					19194	12397
L	456	58	43.2	1.3		
					19692	14623
M	818	51	37.4	1.4		
MNO				1.3	4854	3852
N	867	68	49.4	1.4		
					14640	10048
1	1050	84	54.5	1.5		
					14908	10816
2	1260	58	48.5	1.2		
					13666	9634
3	1455	81	50.0	1.6		
					32356	21952
4	1632	73	54.6	1.3		
					869	618
5	1646	49	31.8	1.5		
					12383	7954
6	1885	55	34.9	1.6		
					15597	10818
7	2202	43	33.3	1.3		
					7500	6051
8	2424	24	21.2	1.2		
					6884	7366
9	2813	11	16.7	0.7		
					2116	2495
10	2978	15	13.6	1.1		
Q	0	37	28.8	1.3		
					8688	6738
P	241	35	27.1	1.3		
					16215	13846
O	716	34	31.2	1.1		

*Distance from tributary mouth

Table 1 (Cont'd)

Transect	Distance from Tributary Mouth (m)	X-Sect. Area (m^2)	Surface Width (m)	Mean Depth (m)	Volume (m^3)	Surface Area (m^2)
21	0	45	34.9	1.3		
					13209	10991
22	382	25	22.7	1.1		
					4953	4339
23	668	10	7.6	1.3		

The longitudinal distances of the transects from the water supply intake were determined from a chart provided by the City of Chesapeake. Table 1 summarizes the geometric data derived from the cross-sectional profiles.

B. Water Surface Elevation

A tide staff was installed near the water supply intake. The reference level was set arbitrarily since only the relative surface fluctuation was of interest to this project. The staff reading was recorded whenever water samples were collected. The data are presented with water quality data in Tables 2 and 3.

The data in Table 2 show that water surface elevation varied erratically from week to week. The expectation that water surface would rise with the event of stormwater runoff was not observed. The water surface was observed to be dropping during intensive survey conducted at time of storm event (see Table 3).

To further investigate the nature of water surface fluctuation, a self-recording tide gauge was installed near the tide staff. The tide gauge recorded water surface elevation once every six minutes for a period from October 1980 to April 1981. The data were compared with precipitation record at Lake Drummond. No direct correlation between water surface elevation and precipitation was found. The water surface fluctuated with a time scale of two to four days, and with occasional periods of four to five days during which it remained relatively constant. It was thus concluded that surface elevation was dominated by wind with a time scale of several days. However, the data also show a long-term trend of dropping surface elevation from May to November, 1980, as a result of low precipitation.

C. Current Velocity

To determine the river discharge, a series of field surveys were conducted to measure the velocity distribution in the transect near the water supply intake. The cross-section was partitioned laterally into five compartments. In each compartment, the velocities were measured with hand-held current meters at every two to three feet in the vertical direction. In general, the current speeds are small, and the directions are variable from surface to bottom as well as from bank to bank. Because of the small topographical relief of the river, the current velocity is dominated by wind. At a calm day, the current velocity is generally less than 2 cm/sec, which is below the accuracy of current meter. At time of gentle breeze, the current speed is about 5 cm/sec and direction is variable. Velocity as high as 10 cm/sec has been measured in the moderate wind condition.

Because of the extremely low current velocity and wind domination, it was determined that quantification of discharge in the sense of river flow is impossible. In fact, the flow of water in this portion of the Northwest River behaves more like a lake or reservoir than a river.

D. Water Quality Surveys

Two types of in-stream water quality surveys were conducted; long-term periodic survey and stormwater impact survey. The long-term survey was conducted weekly from May to November 1980. Water temperature, secchi depth, conductivity and dissolved oxygen were measured in-situ and water samples were collected at the water supply intake location. The water samples were analyzed for color, pH, turbidity, concentrations of chloride, total suspended sediment, BOD, fecal coliform and sulfate by Chesapeake Water Treatment Plant, for TKN, ammonia nitrogen, nitrite nitrogen, nitrate nitrogen and ortho-phosphorus by HRSD (Hampton Roads Sanitary District) laboratory, and for total phosphorus, total organic carbon and chlorophyll 'a' by VIMS. The resulting data are presented in Table 2.

A stormwater impact survey was conducted from 2000 hours September 30 to 0700 hours October 2, 1980, immediately following a storm of 1.50 inch precipitation. The survey was conducted jointly by the personnel of Chesapeake Water Treatment Plant and VIMS. Measurements and water samples were taken hourly at the water supply intake. Water samples were analyzed for the same parameters as those of long-term survey. The data are presented in Table 3.

The data indicate that low dissolved oxygen conditions persisted throughout the study period. More than 80% of observations have DO values less than 5 mg/l.

Table 2 . Long-term Survey Data, 1980

Date	Staff Height, ft	Temp. ^{o}C	D.O. mg/1	BOD mg/1	TOC mg/1	Fecal Colif. /100 ml	Chloride mg/1
5/5	*	19	3.4			27	20
5/12		20	5.6			2	25
5/13	4.95	21	6.5	2.3	31.5	4	25
5/19		21	2.2			2400	25
5/20	4.60	21	2.6	0.8	32.9	612	25
5/27	4.25	23.5	2.0	1.9	30.2	92	20
6/3	4.8	26.5	6.0	2.5	30.0	<1	15
6/9		24	3.0				
6/10	4.7	23.5	1.7	1.3	30.3	280	20
6/11		25	4.8				
6/12		24	2.9				
6/17	3.8	25	4.3	3.9	27.4	<1	20
6/24	4.1	25	6.7	4.1	30.0	6336	25
7/1	4.6	26	1.4	2.5	28.2	4	25
7/8	3.8	27	2.4	0.9	24.1	TNTC **	25
7/15	3.9	28	2.9	1.5	29.3	<1	20
7/22	4.35	29	3.3	3.3	30.5	44	40
7/28	3.95	28	3.5	2.7	26.5	1260	45
8/4	4.45	30	3.8	2.6	28.5	12	80
8/11	3.5	29	3.0	5.3	25.5	170	65
8/18	3.75	24	1.9	3.1	18.2	20	40
8/26	3.75	26	5.2	3.5	23.2	<1	40
9/3	4.7	28	3.8	2.0	11.0	<1	60
9/9	3.5	27	2.1	1.1	21.8	28	55
9/16	3.90	26	4.3	2.8	17.2	<1	65
9/23	3.6	28	5.1	1.0	18.0	10	110
9/30	4.1	22	3.9	1.5	19.2	30	120
10/7	3.25	19	3.9	1.0		65	
10/14	3.80	17	4.2	0.7	17.0	<1	
10/21	3.6	17	3.9	1.2	19.6	115	75
10/28	4.0	15	3.5	2.4	86.1	1200	30
11/4	3.5	13	4.6	0.8	15.8	<1	40

* blank space designates data not taken or missing

** TNTC: too numerous to count

Table 2 (Cont'd)

Date	TKN mg/l	Ammonia N,mg/l	Nitrite N,mg/l	Nitrate N,mg/l	Total P,mg/l	Ortho P,mg/l	Chlorophyll µg/l
5/5						0.8	
5/12						0.09	
5/13					0.254		
5/19						0.14	
5/20	2.20	1.19	0.01	0.28	0.092		14.4
5/27	1.60	0.6	0.11	0.58	0.108	0.08	
6/3	1.41		0.02		0.113		
6/9						0.07	
6/10		0.55	0.02	0.68	0.166	0.05	24
6/17	1.21	0.17	0.02	0.19	0.084	0.09	24.5
6/24	1.23	0.69	0.01	0.14	0.742	0.11	26.2
7/1	1.27	0.36	0.006	0.10	0.34	0.04	
7/8	0.98	1.44	<0.001	0.04	0.284	0.06	7.4
7/15	1.07	0.44	0.012	0.13	0.096	0.04	0.7
7/22	0.91	0.33	0.006	0.014	1.224	0.062	19.4
7/28	1.07	0.34	0.006	0.014	0.104	0.055	0.3
8/4	0.08	0.10	0.006	0.014	0.418	0.043	9.9
8/11	0.75	0.09	0.006	0.004	0.067	0.031	5.8
8/26	0.55	0.11	0.005	0.004		0.166	15.3
9/3	0.17	1.21	0.008	0.057		0.064	7.2
9/9	0.31	0.14	0.005	0.32		0.028	8.2
9/16	0.19	0.046	0.005	0.015		0.037	15.3
9/23	1.21	0.31	0.014	0.031		0.041	8.7
9/30	1.21	0.19	0.013	0.044		0.037	8.7
10/7							4.0
10/14	0.81	0.14	0.008	0.036		0.024	7.2
10/21	0.25	0.10	0.008	0.035		0.031	2.8
10/28	0.17	0.11	0.019	0.146		0.11	1.1
11/4							0.9

Table 2 (Cont'd)

Date	Secchi depth,ft	Turbidity NTU	TSS mg/1	pH	Sulfate mg/1	Conductivity μmho	Color Co.Pt.
5/5	1.0	3.2	3	7.1	17.5		225
5/12	1.7	3.7	12	7.0	12		250
5/13	1.5	3.3	12	6.6	6.7	130	180
5/19		2.4	54	6.3	13		275
5/20	1.5	4.6	13	6.4	7.2	128	250
5/27	1.4	5.1	10	6.5	14.3	135	200
6/3	2.0	3.6	5	6.9	6.9	132	200
6/10	1.7	3.5	2	6.7	9.56	130	200
6/17	1.5	2.7	10	7.1	10.7		200
6/24	1.5	2.3	5	6.6	13.7	145	200
7/1	2.0	2.5	2	6.2	12.1	152	275
7/8	1.3	1.8	19	6.5	10.4	170	250
7/15	1.5	2.4	30	6.5	12.8	180	175
7/22	2.0	2.2	8	7.1	10.4	265	175
7/28	1.3	2.3	11	6.3	15.7	240	175
8/4	2.3	2.7	10	6.6	12.1	365	175
8/11	2.3	2.4	30	6.6	14.6	300	150
8/18	1.5	4.8	14	6.7	7.95	175	175
8/26	2.0	3.3	6	6.8	7.68	190	125
9/3	2.0	2.1	2.1	6.8	20.3	300	150
9/9	2.5	2.1	5	6.5	12.3	255	125
9/16	2.0	2.1	5	6.7	29.6	230	120
9/23	2.5	2.8	2	6.9	16.5	440	120
9/30	1.5	3.1	12	7.2	8.2	350	140
10/7	2.0	5.5	5	6.4	14.8	255	140
10/14	1.5	3.7	13	6.6	17.6	280	120
10/21	2.0	4.9	10	6.5	20.8	250	120
10/28	0.5	49	46	6.3	12.6	125	100
11/4	1.0	15	9	6.1	18.1	125	175

Table 3 . Intensive Survey Data, 1980

Date	Time	Staff Height, ft.	Temp. °C	D.O. mg/1	BOD mg/1	Fecal Colif. /100 ml	Chloride mg/1
9/30	1000	4.10	22	3.9	1.5	30	120
9/30	2000	3.97	23	4.2	1.3	530	90
	2100	3.91	22	3.9	0.7	540	85
	2200	3.85	22	3.7	1.0	480	90
	2300	3.85	21.5	3.7	0.7	140	90
	2400	3.81	22	3.75	0.6	2330	85
10/1	0110	3.72	22	3.8	0.2	7620	90
	0200	3.68	22	3.7	0.6	1680	85
	0300	3.62	22	3.8	1.3	1960	85
	0407	3.62	22	3.7	0.3	3620	85
	0505	3.60	21.5	3.7	0.7	950	85
	0600	3.53	22	3.7	0.4	<1	85
	0700	3.49	21.5	3.7	0.6	1450	85
	0800	3.45	21.5	3.6	0.4	390	80
	0900	3.44	21.5	3.6	0.7	770	85
	1010	3.39	20.3	3.9	0.8	770	85
	1100	3.36	20.3	3.9	0.6	3980	80
	1204	3.39	20.3	4.3	0.9	240	85
	1306	3.45	20.4	4.4	1.1	70	85
	1403	3.46	20.6	4.8	1.3	60	80
	1505	3.44	20.9	4.9	1.3	60	80
	1607	3.39	21.0		1.2	20	80
	1703	3.35	22	4.6	1.7	40	80
	1806	3.31	22	4.3	1.5	70	80
	1903	3.35	21.5	4.4	1.3	60	75
	2000	3.38	22	4.5	1.5	60	80
	2100	3.41	21	4.3	1.3	80	80
	2200	3.44	21.5	4.4	1.7	30	80
	2300	3.40	21	4.4	1.3	50	75
10/2	0007	3.43	21.5	4.4	1.6	70	*
	0100	3.43	21.5	4.3	2.0	150	
	0200	3.42	21.5	4.0	1.3	80	
	0305	3.43	21.5	3.6	1.7	20	
	0405	3.47	21.5	3.6	1.2	70	
	0500	3.49	21.5	3.6	1.5	40	
	0605	3.52	21.5	3.6	1.6	60	
	0700	3.54	21.5	3.6	1.5	60	
	Average	3.52	21.5	4.01	1.09	817	83

*blank space designates data not taken or missing

Table 3. (Cont'd)

Time	TKN mg/l	Ammonia N, mg/l	Nitrite N,mg/l	Nitrate N,mg/l	Total P,mg/l	Ortho P,mg/l	Chlorophyll µg/l
1000	1.21	0.19	0.013	0.044		0.037	8.7
2000	1.14		0.010	0.040		0.080	7.4
2100	1.21		0.009	0.037		0.032	5.8
2200	1.09	0.14	0.010	0.036		0.048	4.6
2300	1.21	0.13	0.010	0.032		0.025	4.9
2400	1.09	0.15	0.008	0.036		0.027	4.7
0110	1.09	0.16	0.009	0.037		0.032	4.8
0200	0.98	0.24	0.008	0.055		0.034	5.5
0300	0.93	0.19	0.009	0.047		0.030	5.5
0407	0.93	0.13	0.009	0.028		0.029	4.4
0505	1.12	0.18	0.009	0.031		0.031	5.0
0600	1.09	0.19	0.011	0.065		0.082	4.6
0700	0.98	0.17	0.009	0.038		0.034	5.0
0800	0.93	0.17	0.009	0.034		0.030	6.6
0900	1.52	0.14	0.009	0.035		0.032	
1010	0.93	0.20	0.005	0.033		0.005	6.8
1100	0.81	0.14	0.008	0.031		0.008	7.9
1204	1.92	0.26	0.010	0.033		0.010	9.6
1306	0.72	0.18	0.010	0.035		0.010	11.6
1403	0.86	0.20	0.009	0.035		0.009	15.9
1505	0.67	0.29	0.010	0.043		0.010	12.2
1607	0.62	0.15	0.010	0.034		0.029	10.9
1703	0.62	0.17	0.010	0.032		0.029	10.7
1806	0.62	0.15	0.010	0.033		0.032	9.8
1903	0.62	0.19	0.010	0.032		0.031	6.6
2000	0.50	0.22	0.009	0.035		0.037	5.9
2100	0.50	0.14	0.008	0.031		0.027	5.7
2200	2.06	0.17	0.009	0.032		0.030	5.7
2300	0.60	0.01	0.008	0.035		0.007	5.0
0007	0.46	0.18	0.011	0.040		0.029	5.6
0100	0.39	0.16	0.009	0.035		0.029	4.6
0200	0.39	0.16	0.010	0.036		0.044	5.8
0305	0.39	0.15	0.009	0.027		0.029	5.0
0405	0.67	0.29	0.005	0.033		0.043	5.8
0500	2.11	0.26	0.002	0.035		0.024	5.0
0605	0.32	0.20	0.005	0.047		0.071	4.1
0700	0.46	0.14	0.005	0.037		0.054	5.5
Avg.	0.90	0.18	0.009	0.037		0.032	6.7

Table 3. (Cont'd)

Time	Secchi Depth,ft.	Turbidity NTU	TSS mg/1	pH	Conductivity µmho	Color Co.Pt.
1000	1.5	3.1	12	7.2	350	140
2000	2.0	3.0	13	6.6	332	150
2100	2.0	3.2	12	6.7	332	160
2200	2.0	3.3	12	6.7	332	120
2300	2.0	3.6	14	6.7	330	120
2400	2.0	3.6	11	6.7	328	120
0110		3.4	10	6.7	330	120
0200		3.6	13	6.8	331	120
0300		3.2	5	6.8	330	120
0407		3.4	15	6.7	330	100
0505		3.2	12	6.7	328	120
0600		3.1	8	6.7	320	120
0700	2.0	3.1	9	6.7	325	120
0800	2.0	3.0	14	6.7	320	120
0900	2.5	3.6	13	6.7	310	100
1010	2.0	3.7	4	6.7	309	160
1100	2.5	3.6	4	6.8	310	120
1204	2.5	3.4	2	6.8	310	120
1306	2.5	3.7	7	6.8	315	120
1403	2.0	3.0	6	6.9	315	100
1505	2.0	3.2	6	6.8	319	120
1607	2.2	3.2	6	6.8	320	100
1703	2.5	3.1	2	6.7	310	120
1806	2.5	3.4	5	6.7	315	120
1903		3.1	7	6.7	315	120
2000		3.3	2	6.7	315	120
2100		3.0	3	6.7	315	100
2200		3.1	6	6.7	305	140
2300		3.0	7	6.7	310	120
0007		3.3	3	6.6	305	120
0100		3.4	5	6.6	305	100
0200		3.6	3	6.7	300	120
0305		3.7	9	6.7	301	140
0405		3.6	5	6.6	300	140
0500		3.2	10	6.6	305	120
0605		3.2	2	6.6	300	100
0700		3.3	5	6.6	305	100
Avg.	2.2	3.3	8	6.7	316	120

Fecal coliform concentration is highly variable, reaching several thousand per 100 ml immediately after stormwater runoff and dropping to none in a matter of weeks. No excessive chlorophyll concentration was observed throughout the growing season. The low level of inorganic nutrients and the restricted light penetration of the dark-colored water both limit the excessive algal growth. The pH values of the water are generally less than 7.0, with an average value of 6.64.

III. WATER QUALITY MODEL

A. Theoretical Background

Based on the data from a series of current measurements in the river transect near water supply intake (see Section II-C), it was concluded that this portion of the river behaves more like a lake than a river. The average flow velocity is extremely low, and the instantaneous velocity is highly variable in response to wind. Therefore, a lake ecosystem model was developed for this study.

The portion of the river upstream of the water supply intake is treated as a single-segment water body. The water surface elevation and concentrations of dissolved substances are characterized by the values at the intake. The conservation of water volume may be written as

$$\frac{dV}{dt} = \sum_{i=1}^{N} QI_i(t) - QO(t), \text{ or} \tag{1a}$$

$$S\,\frac{dh}{dt} = \sum_{i=1}^{N} QI_i(t) - QO(t) \tag{1b}$$

where

- V is volume of the water body,
- S is surface area of the water body,
- h is water surface elevation,
- QI_i is the flow rate of the ith inflow,
- QO is the discharge out of the water body,
- t is time,
- N is total amount of inflow.

since a lake or reservoir has a buffering capacity to any inflow of water, the discharge, or outflow may be expressed as

$$QO(t) = \sum_{i=1}^{N} \int_{o}^{\tau} a_i(\tau) QI_i(t-\tau) d\tau \tag{2}$$

where $a_i(\tau)$ is the linear response function for the ith inflow which satisfies the constraint

$$\int_{o}^{\infty} a_i(\tau) d\tau = 1.0$$

The mass conservation of a dissolved substance may be written as

$$\frac{d}{dt} (VC) = \sum_{i=1}^{N} QI_i(t)\ CI_i(t) - QO(t)C(t) + Se + Si \tag{3}$$

where

- C is the concentration of a dissolved substance in the water body,
- CI_i is the concentration in the ith inflow,
- Se is external source or sink across air-water or sediment-water interface,
- Si is internal source or sink due to biochemical reactions.

The first two terms on the right-hand-side of the equation represent the physical transport of dissolved or suspended substances and therefore, they have the same formulations for all substances. The last two terms of the equation represent the external additions and internal biochemical reactions which will differ for different substances. The kinematics of the ecosystem model developed for the Lynnhaven River (Ho, Kuo and Neilson, 1977) under previous 208 study was adopted to this study. The model treats nitrogen, phosphorus, oxygen demanding organic material, dissolved oxygen and chlorophyll as an interacting system of eight components. Figure 4 is a schematic diagram showing the biochemical interaction among the components. Each rectangular box represents one component simulated by the model, with its name in the computer program shown in parenthesis. The arrows between components represent biochemical transformation of one component into the other. The arrows with one end not attached to any component represent the external sources (or sinks), or internal sources (or sinks). The mathematical formulation of the terms Se and Si for each of the eight components are identical to those used in the previous 208 study (Ho, Kuo and Neilson, 1977).

The model also simulates conservative substances and coliform bacteria as two independent systems. The formulation of these systems are also the same as the salinity and coliform bacteria respectively of the model used in previous 208 study.

B. Finite Difference Approximations

To solve the differential equations with a digital computer, they have to be first approximated with finite difference forms and then, integrated numerically over

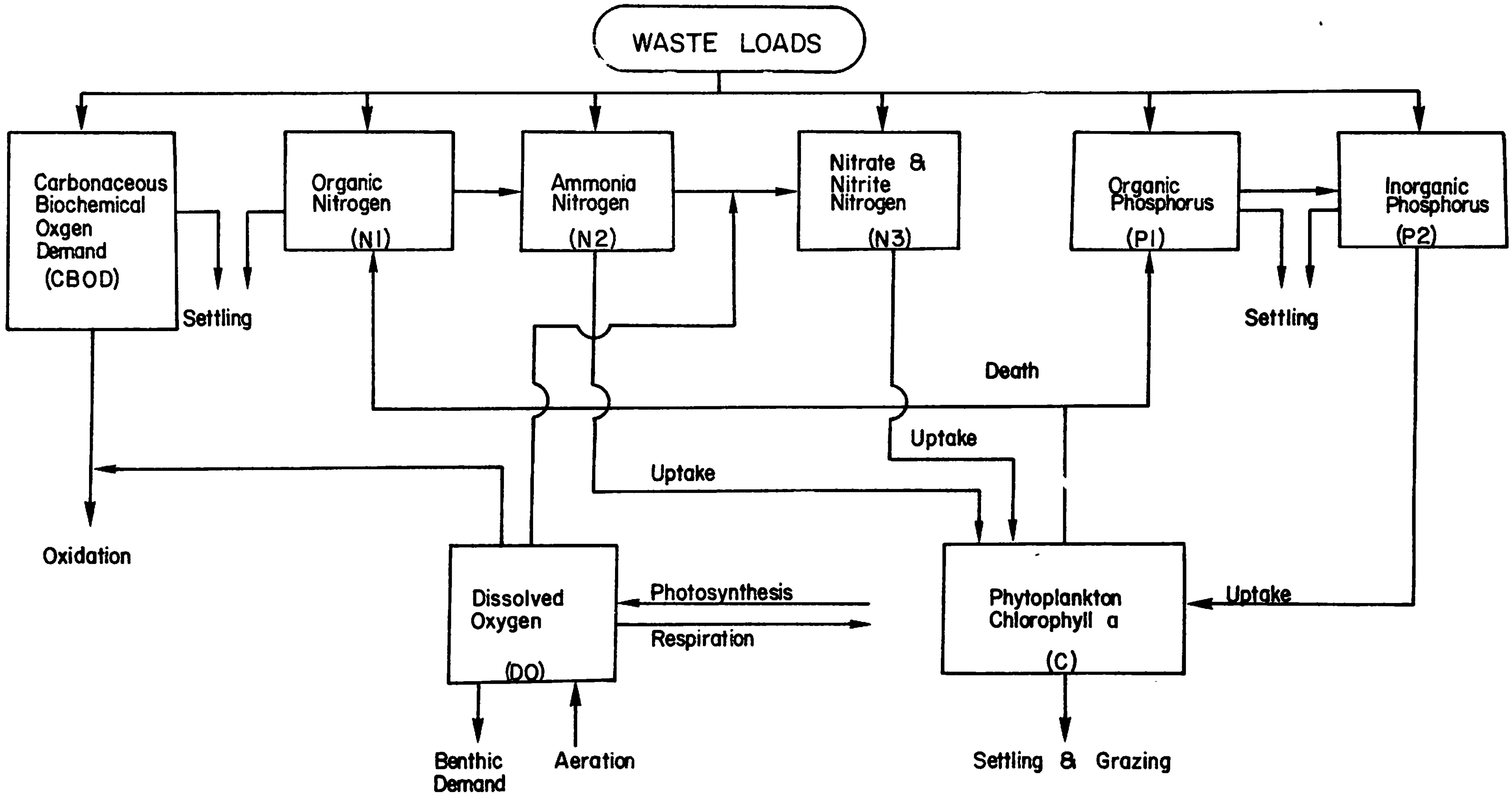


Figure 4. Schematic of Ecosystem Model.

successive finite time intervals. The following are the finite difference forms of equations (1), (2) and (3).

$$V_n = V_{n-1} + \left(\sum_{i=1}^{N} QI_{i,n} - QO_n \right) \Delta t \tag{4a}$$

$$h_n = h_{n-1} + (V_n - V_{n-1})/S \tag{4b}$$

$$QO_n = \sum_{i=1}^{N} \sum_{j=0}^{\infty} a_{ij} QI_{i,n-j} \tag{5}$$

$$C_n V_n = C_{n-1} V_{n-1} + \left(\sum_{i=1}^{N} QI_{i,n} CI_{i,n} - QO_n \cdot C_{n-1} \right) \Delta t$$

$$+ (S_e + S_i) \Delta t, \quad \text{if } QO_n \leq V_{n-1} \tag{6a}$$

or

$$C_n = \sum_{i=1}^{N} QI_{i,n} CI_{i,n} \Big/ \sum_{i=1}^{N} QI_{i,n} + (S_e + S_i) \Delta t \tag{6b}$$

$$\text{if } QO_n > V_{n-1}$$

where

Δt is time increment,

V_n, h_n and C_n are volume, surface elevation and concentration respectively at time $n\Delta t$,

$QI_{i,n}$ and QO_n are the average ith inflow and outflow respectively over the time increment from $(n-1)\Delta t$ to $n\Delta t$.

With initial conditions V_o, h_o and C_o given at some instance, equations (4), (5) and (6) may be used to calculate V_n, h_n and C_n as function of time step n, i.e., the time varying water volume, surface elevation and concentration.

C. Model Application

The model was applied to the portion of the Northwest River upstream of Chesapeake water supply intake. The bathymetric survey provides the necessary geometric data of the water body (Section II-A). The water surface elevation averaged over the period from May to November, 1980 corresponds to the staff reading of 4.05 ft. At this level, the surface area is $4.28 \times 10^6 ft^2$, volume is $28.5 \times 10^6 ft^3$ and mean depth is 6.66 ft.

There is no gauging station on the Northwest River. The model input data of inflow, QI_i, were generated by a nonpoint source model STORM. The whole drainage area upstream of water supply intake was considered a single watershed and only one inflow was generated, together with the pollutant loadings from nonpoint source. A brief description of the application of STORM model is given in the next section.

The model was run to simulate the river water quality conditions over the period from April 1 to October 31, 1980. In addition to the nonpoint source input of runoff and pollutants, the following data are also required for model simulation:

(1) Temperature: The water temperature was input into the model as a sinusoidal function of time with annual cycle. The amplitude and phase of the function were derived by fitting the weekly survey data.

(2) Solar radiation: The data measured by VIMS at Gloucester Point, VA were used. These data were also approximated with a sinusoidal function of annual cycle.

(3) Extinction coefficient: A constant light extinction coefficient of 3.3/meter was used throughout the simulation period. This value was derived from the average secchi depth measured in the weekly surveys. The extinction coefficient is related to secchi depth by

$$\text{extinction coefficient} = 1.7/\text{secchi depth}$$

D. Nonpoint Source Discharges

The in-stream water quality model requires time dependent nonpoint source loadings among their inputs. These inputs are obtained from the output of the STORM model. This model uses rainfall data and land-use patterns to calculate quantity and quality of runoff. Input constants for the STORM model from a previous validation by Malcolm-Pirnie were used for a '208' study of the Lynnhaven system (Kuo and Neilson, 1981). These input constants include the storage and runoff characteristics of various land-use types, unit hydrograph characteristics and evaporation rates.

It has been established that, given the same inputs, VIMS' version of STORM will yield the same outputs as Malcolm-Pirnie, within a small margin of difference due to differing machine configurations (Kuo and Neilson, 1982).

For application to this study, the STORM model required 1980 rainfall data and land-use patterns for 1980. Rainfall data from the Lake Drummond record were used.

Daily totals are summarized in Table 4. Land-use patterns were provided by the Southeastern Virginia Planning District Commission. The land uses for 1980 are summarized in Table 5. The land-use categories were those used by Malcolm-Pirnie in running the STORM model. The daily accumulation method was used, with nonurban parameters, as is appropriate for a rural watershed. Agricultural area constitutes a large percentage of the Northwest River drainage basin. The calibration model predictions for the HRWQA Management Plan (1978) were consistently higher than the field results (see pp. 45-46, app. 5). For total nitrogen, one runoff event was overestimated by a factor of five and the other by a factor of ten. For total phosphorus, one event was overestimated by three percent, but the other event was overestimated by a factor of four. Therefore the accumulation rates for nitrogen and phosphorus were reduced by factors of five and two, respectively.

The output from the STORM model had to be recast into a form suitable for input to the water quality model. This was done by means of a computer program which performed the following operations:

- read the STORM output as contained in disk file;
- partitioned the total nitrogen and total phosphorus into the species required by the instream water quality model;
- generated an output disk file containing, for each rainfall event, the nonpoint source loadings plus a sequence date referring to the beginning of the rainfall record used (April 1)

Table 4

1980 Daily Precipitation Record (Lake Drummond)

Date	April	May	June	July	Aug	Sept	Oct
1							1.09
2							0.23
3							
4					0.40		0.15
5	0.32						
6				0.75		0.35	0.06
7						0.18	
8	0.05						
9		0.03		0.03			
10	0.08			0.17	1.33		
11					0.69	0.05	
12							0.06
13				0.93			
14	0.22						
15	0.33						
16					0.58		
17							
18		0.10		0.59			
19		1.40			0.16	0.05	0.88
20		0.42			0.76		1.10
21							
22							
23							
24				0.48			
25						0.15	2.10
26		0.02	0.20			0.51	0.03
27							
28	1.00						
29	0.37			0.07			0.03
30	0.06		0.42			0.03	0.30
31							0.15

Table 5

Land Use Patterns for Northwest River Basin
(Basin 3103, Upstream of Rte. 168)

Category	Area (Acres)	Percent of Total
Residential-Nonurban (RES-NU)	1255.7	2.19
Commercial-Nonurban (COM-NU)	444.8	0.78
Light Industry (INDUS)	158.8	0.28
Forest	43631.6	76.20
Agricultural (AGRIC)	11735.0	20.50
Total	57225.9	100.00

NOTE: The table was compiled from the data supplied by the Southeastern Virginia Planning District Commission.

This file was accessed by the water quality model to generate a time history of in-stream water quality.

E. Calibration and Validation

In the formulation of the ecosystem model adopted for this study, there are a number of rate constants and coefficients, especially biochemical rate constants, which cannot be assigned a priori values. The values of these constants were obtained through the calibration procedure. In this procedure, model prediction of water quality, based on values derived from literature or from experience, are compared with actual field data. The calibration constants are then adjusted (within reasonable limit) in an iterative fashion until a satisfactory agreement between predicted water quality and field data is obtained.

Comparison of the calibrated model predictions with field measurements of water quality is the first step in proving the applicability of a model. A more rigorous proof is through the validation procedure in which the calibrated model is used to provide a second set of water quality predictions for comparison with a second set of field data.

If the agreement between the second set of predictions and field data is good, the model is considered validated and confidence in its predictive capability is implied. If the agreement is poor, the model must be reexamined and recalibrated until a "best fit" to the field data is obtained.

Since the lake ecosystem model predicts only the average water quality condition of the water body, it is inexpensive to run for a long-term simulation. The model predictions for both calibration and validation were obtained through a single, continuous simulation. The initial conditions on the concentrations of water quality parameters were assumed to be those typical in the river long after a storm event. The time-varying surface runoff, nonpoint source of pollutants, water temperature and solar radiation were input to the model on a daily basis. The model was run to simulate the river water quality condition for a period from April to November, 1980.

Since the intensive survey data consist of hourly measurements or samplings of more than 30 hours, they may be averaged to reduce experimental scatterings. Their average values were used to calibrate the model. Each of the weekly survey data was a single measurement or grabbed sample. They tend to have higher experimental error. These data were used as indications of how well the model may be validated.

The model was calibrated by adjusting the values of model rate constants and coefficients until the simulated results on October 1 agreed with the average values of intensive survey data. When close agreements were achieved, the model predictions for other time periods were also compared with weekly survey data. In some instances, the calibrated rate constants were further adjusted to improve the agreement between model results and weekly survey data.

The coliform bacteria is a model parameter independent of all others in the model. It may be calibrated independently by adjusting the die-off rate. A die-off rate of 0.4/day produces the best agreement between model results and field data. Figure 5 shows the comparison.

All other model parameters constitute an interdependent system. The model rate constants were adjusted to reproduce the measured chlorophyll 'a' concentration first. Then the simulation of prototype dissolved oxygen concentration was attempted. Finally, nutrient transfer coefficients and settling rates were adjusted to achieve the simulation of nitrogen, phosphorus and CBOD concentrations. The values of the calibrated coefficients and constants are listed in Table 6.

The model results are compared with field data in figures 6 to 13. The flow rates of the stormwater runoff are shown in figure 14. These figures indicate that the model results have sharp and instant response to the stormwater runoff events, while the field data lack such clear-cut response. The model simulates the prototype water quality only in the sense of grossly average conditions. The large swamp area boarding the river may be responsible for this discrepancy.

Table 6. Calibrated Model Rate Constants

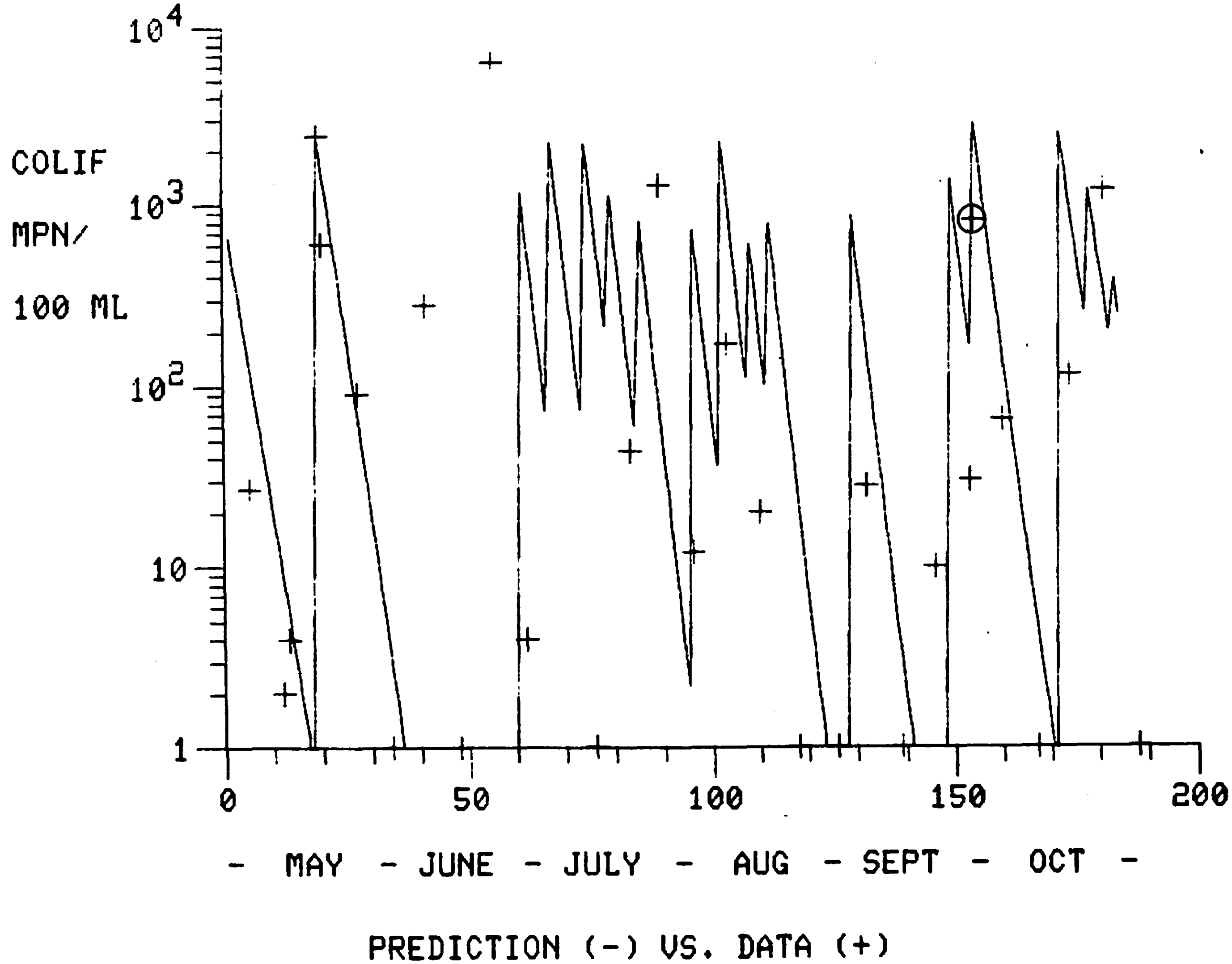
	Units	
Organic-N to ammonia hydrolysis rate constant	1/day/^{o}C	0.004
Ammonia nitrification rate constant	1/day/^{o}C	0.004
Organic-N Settling rate	1/day	0.20
Nitrite + Nitrate escaping rate	1/day	0.80
Organic-P to inorganic-P transfer rate constant	1/day/^{o}C	0.004
Organic-P settling rate	1/day	0.30
Inorganic-P settling rate	1/day	0.05
CBOD decay rate at 20^{o}C	1/day	0.04
CBOD settling rate	1/day	0.1
Saturation light intensity	langleys/day	300
Saturation phytoplankton growth rate constant	1/day/^{o}C	0.07
Nitrogen Michaelis constant	mg/l	0.025
Phosphorus Michaelis constant	mg/l	0.005
Carbon-chlorophyll ratio	mg/μg	0.05
Nitrogen-chlorophyll ratio	mg/μg	0.01
Phosphorus-chlorophyll ratio	mg/μg	0.001
Plankton settling rate	1/day	0.0
Endogenous respiration rate constant	1/day/^{o}C	0.008
Zooplankton grazing rate	1/day	0.0
Photosynthetic quotient		1.0
Respiration quotient		1.0

The nonpoint source model STORM does not simulate the routing of stormwater runoff. It produces stormwater runoff and pollutant loadings to the receiving water body the day precipitation occurs. However, the swamp on both banks of the river may serve as a buffer zone, which not only delays the stormwater runoff but also broadens the hydrograph and pollutograph. The swamp vegetations may even uptake some forms of nutrients in one season and release them in another. The quantitative knowledge on the role played by the swamp is beyond the scope of this study.

F. Suggested Studies of the Effects of Swamp

The model study indicates that there is a significant gap between the STORM model and the lake ecosystem model. Ultimately, a swamp model simulating the effects of the swamp on river water quality has to be developed to bridge the gap. Only then, the models may be fully usable for assessing water quality impacts of alternative land-use schemes. At present, there are three aspects of swamp effects of which the fundamental knowledge is still lacking. They are: 1) the characteristics of hydrograph as the stormwater moves through the swamp, 2) trapping and sedimentation of particulate pollutants by the broad, shallow swamp, 3) nutrient uptake (and/or release) by swamp vegetation. None of these are trivial matters and all require extensive field investigation to support theoretical reasoning. However, no model can be confidently formulated without any of them.

Figures 5 - 13. Comparisions of model results with field data. (⊕ indicates average value of intensive survey data)



COLIF
MPN/
100 ML
10^4
10^3
10^2
10
1
0
50
100
150
200
- MAY - JUNE - JULY - AUG - SEPT - OCT -
PREDICTION (-) VS. DATA (+)

Figure 5

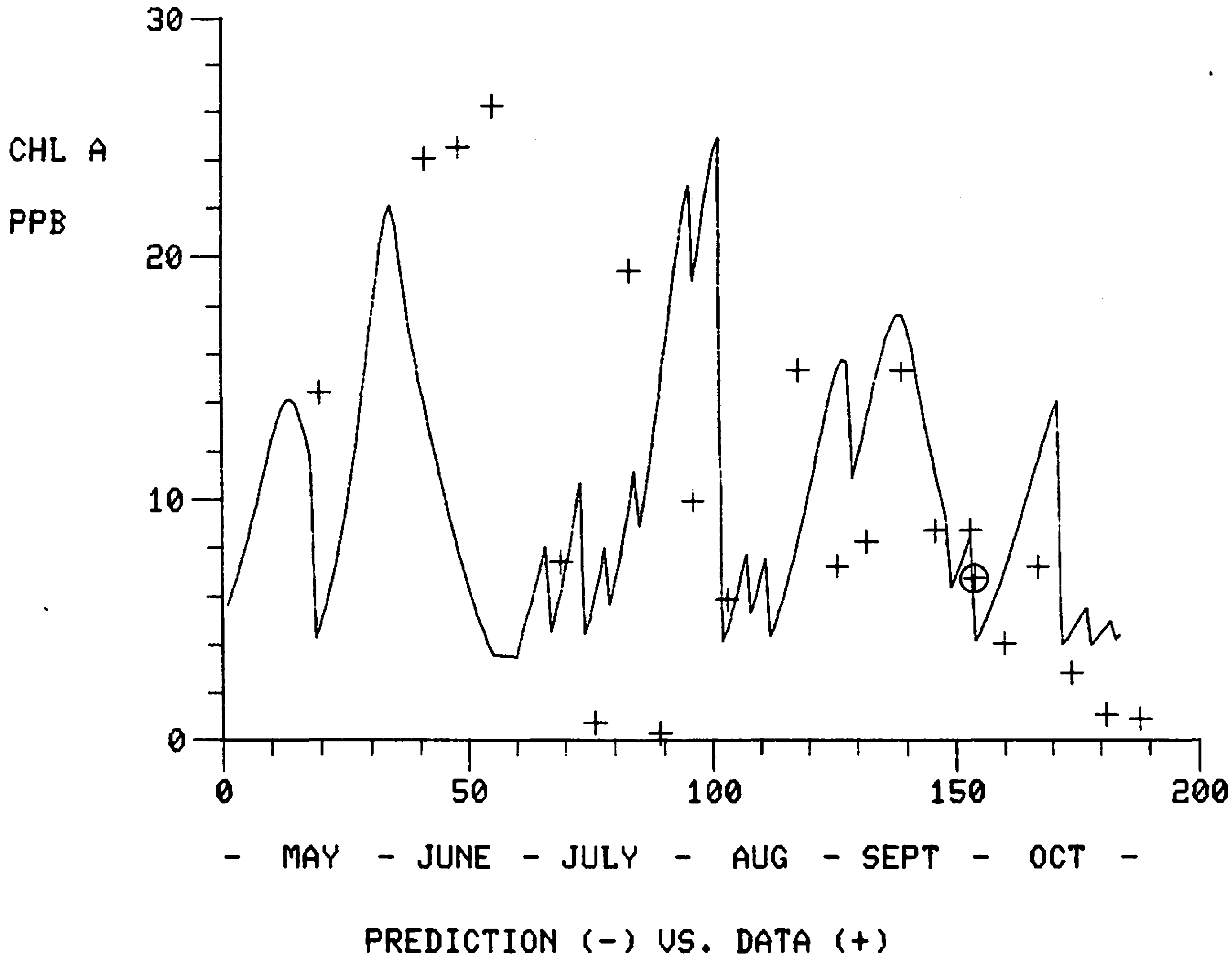

CHL A
PPB
30
20
10
0
0
50
100
150
200
- MAY - JUNE - JULY - AUG - SEPT - OCT -
PREDICTION (-) VS. DATA (+)

Figure 6

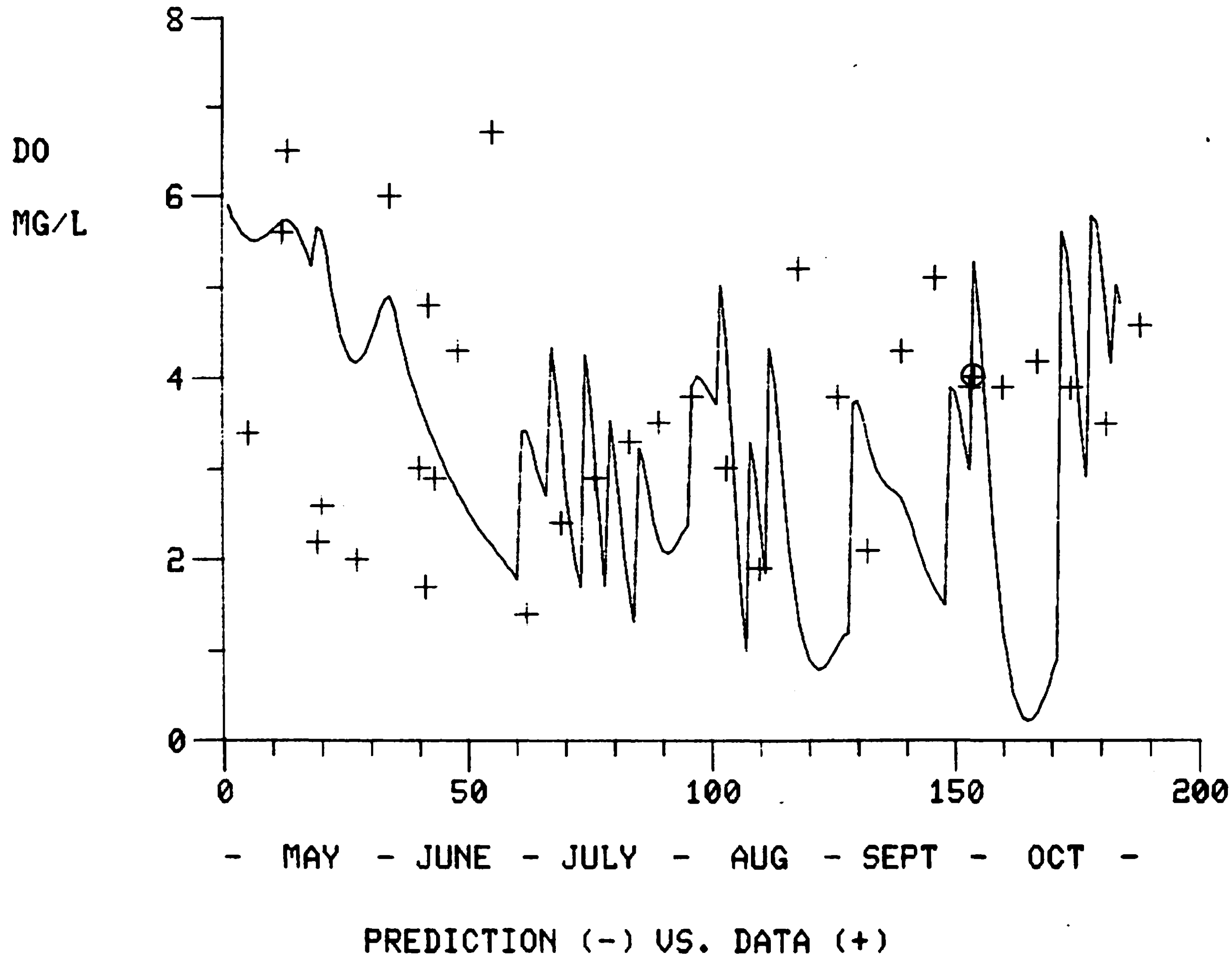
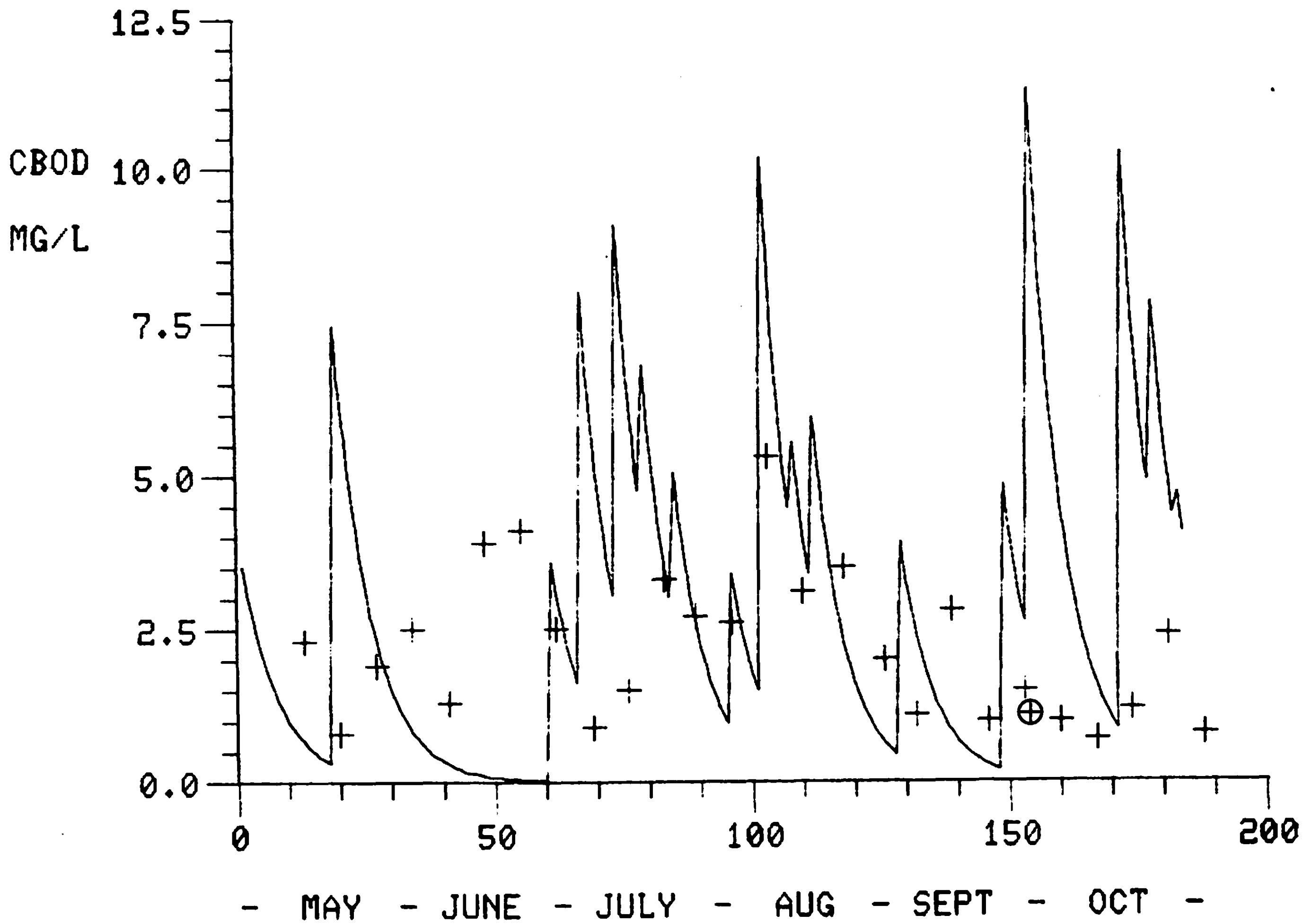

DO
MG/L
8
6
4
2
0
0
50
100
150
200
- MAY - JUNE - JULY - AUG - SEPT - OCT -
PREDICTION (-) VS. DATA (+)

Figure 7



PREDICTION (-) VS. DATA (+)

Figure 8

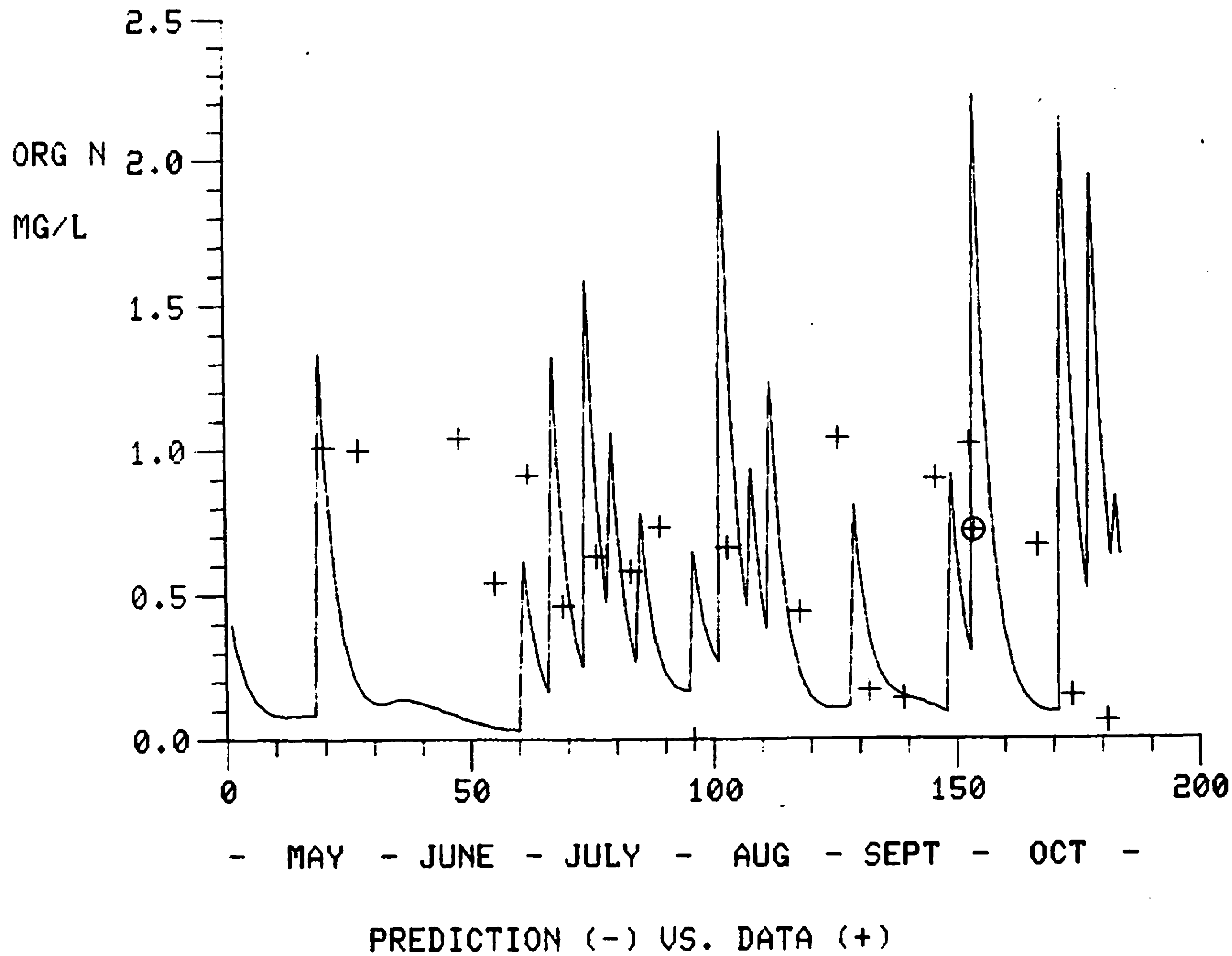

ORG N
MG/L
2.5
2.0
1.5
1.0
0.5
0.0
0
50
100
150
200
- MAY - JUNE - JULY - AUG - SEPT - OCT -
PREDICTION (-) VS. DATA (+)

Figure 9

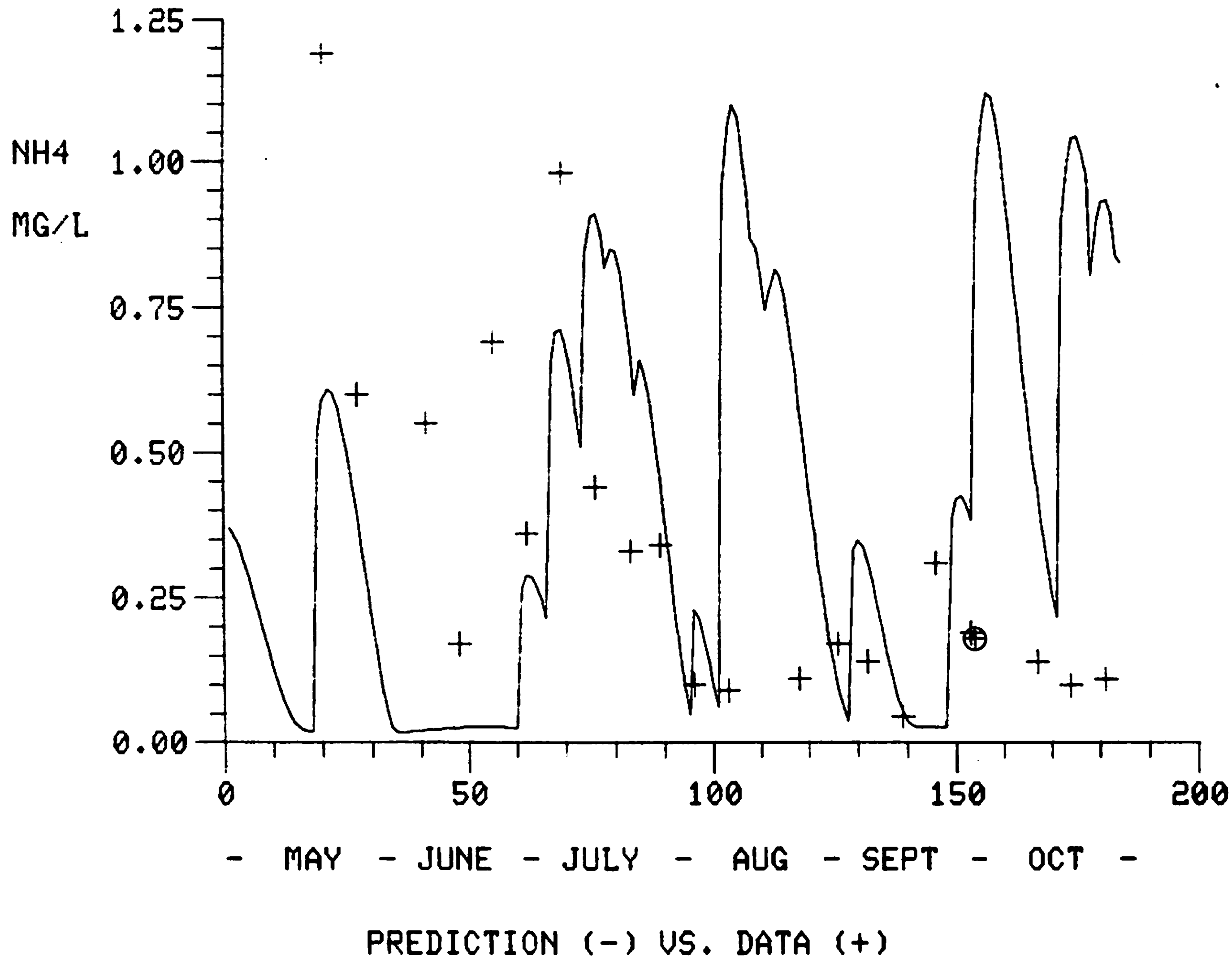

NH4
MG/L
1.25
1.00
0.75
0.50
0.25
0.00
0
50
100
150
200
- MAY - JUNE - JULY - AUG - SEPT - OCT -
PREDICTION (-) VS. DATA (+)

Figure 10

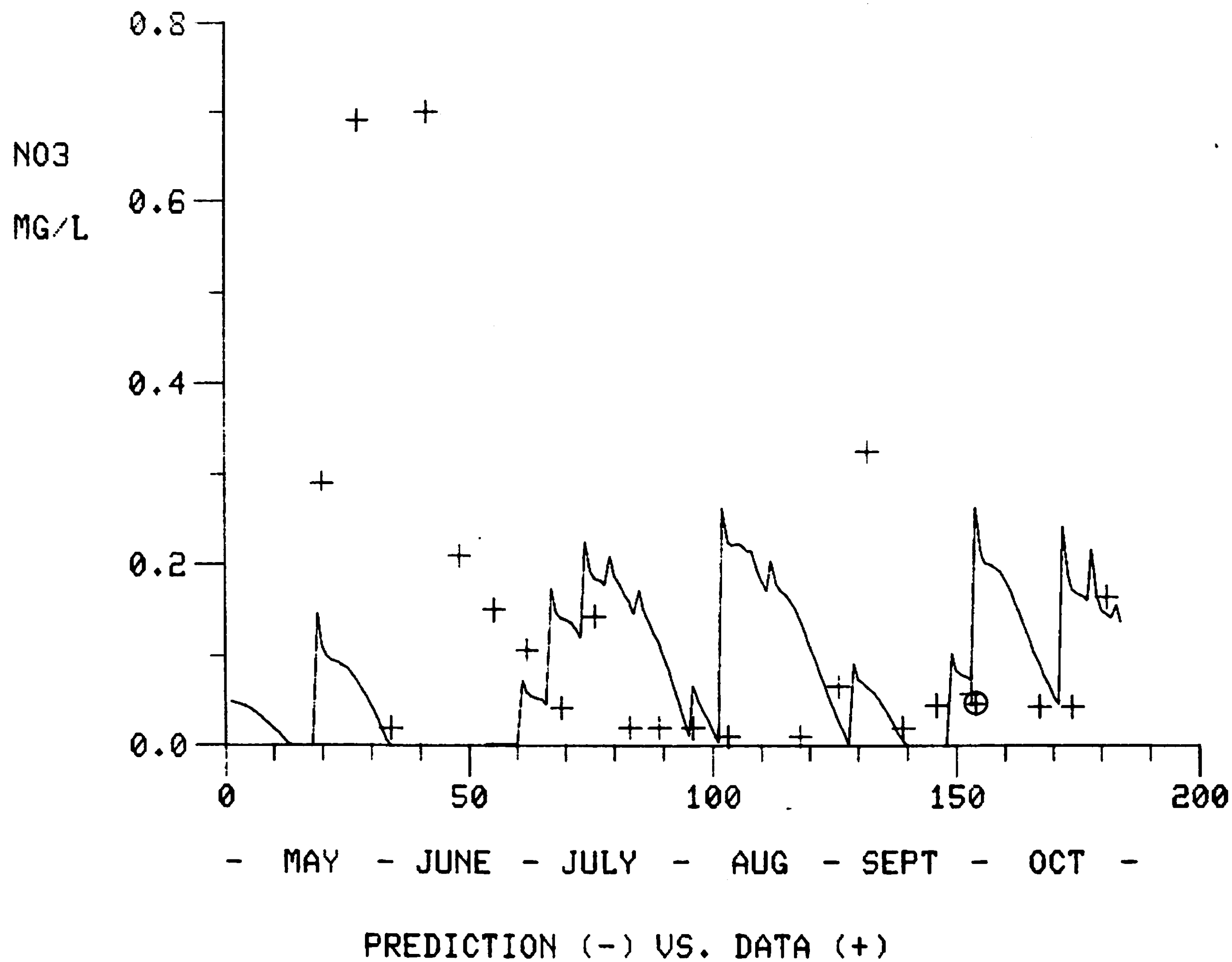

NO3
MG/L
0.8
0.6
0.4
0.2
0.0
0
50
100
150
200
- MAY - JUNE - JULY - AUG - SEPT - OCT -
PREDICTION (-) VS. DATA (+)

Figure 11

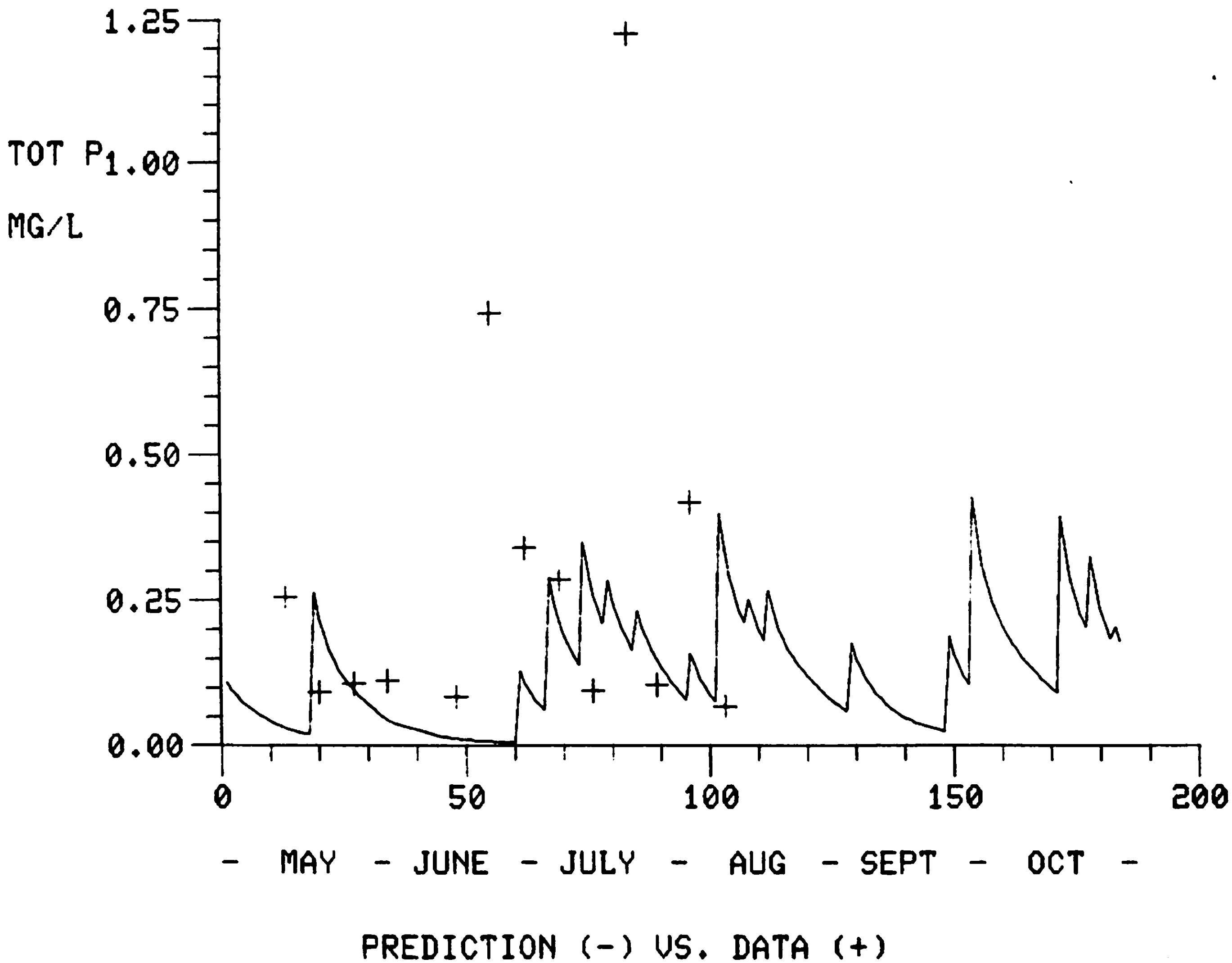

1.25
TOT P 1.00
MG/L
0.75
0.50
0.25
0.00
0
50
100
150
200
- MAY - JUNE - JULY - AUG - SEPT - OCT -
PREDICTION (-) VS. DATA (+)

Figure 12

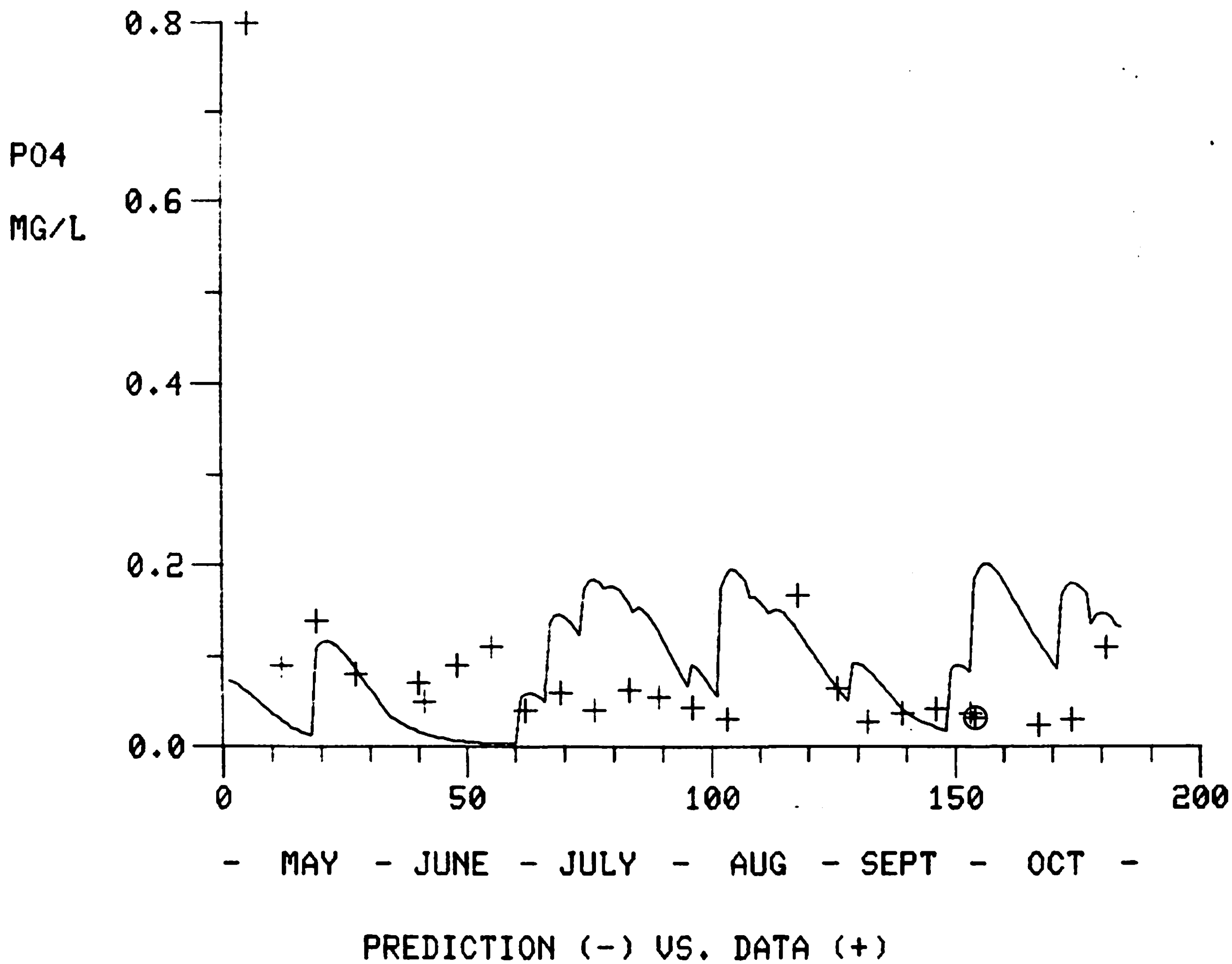

PO4
MG/L
0.8
0.6
0.4
0.2
0.0
0
50
100
150
200
- MAY - JUNE - JULY - AUG - SEPT - OCT -
PREDICTION (-) VS. DATA (+)

Figure 13

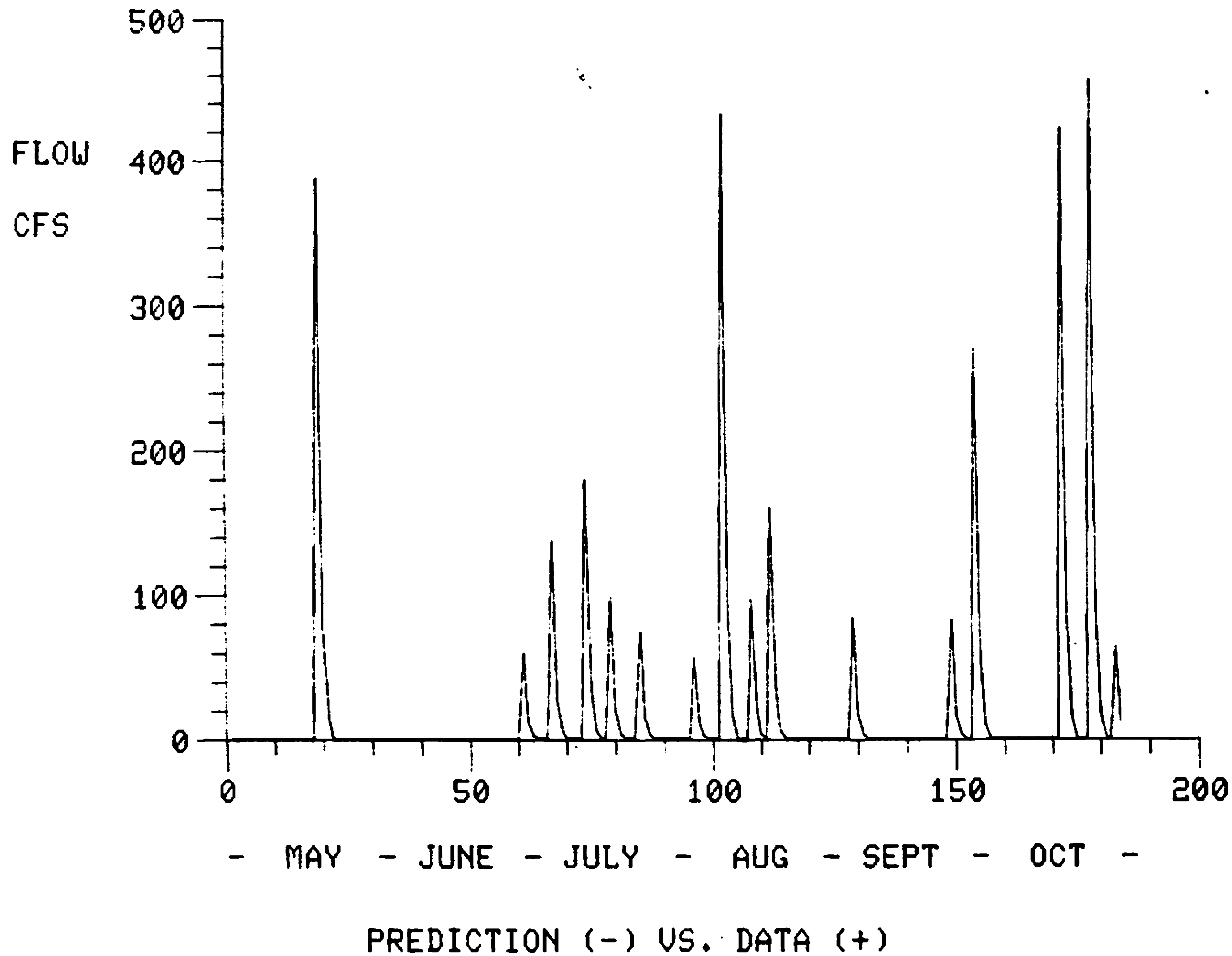


Figure 14. Flow rates of nonpoint source runoff.

IV. DISCUSSION AND CONCLUSIONS

The hydrodynamic characteristics of the portion of the Northwest River upstream of the Chesapeake water intake resemble that of a lake or reservoir more than a fluvial stream. The mean water velocity is small (less than 2 cm/sec), and the instantaneous velocity is highly variable, depending on wind conditions. The water surface fluctuation is even more complicated than that of a typical lake or reservoir, because it lacks an outlet control. The water may move freely in and out of this segment of river in response to wind direction. This situation makes the simulation of wind effect much more difficult. The model developed in this study makes no attempt to simulate the water quality response to the changing wind condition, it only simulates the condition average over all wind conditions.

A model was developed to simulate the water quality in the river in response to stormwater runoff. The model takes the output of the nonpoint source model STORM as input, and calculates the concentrations of water quality parameters in the river. The water quality parameters simulated by the model include dissolved oxygen, organic nitrogen, ammonia nitrogen, nitrite and nitrate nitrogen, organic phosphorus, inorganic phosphorus, carbonaceous biochemical oxygen demand, chlorophyll 'a' and fecal coliform bacteria. The model predicts the fecal coliform concentration in the river quite well. The model is accurate in the sense of gross average for other parameters.

Both the model results and field data indicate that the coliform concentration in the river is highly variable. It may reach a concentration of several thousands per 100 ml immediately after storm, and drops to near zero in a matter of a week. No excessive phytoplankton growth was predicted by the model nor indicated by the field data. The low inorganic nutrient concentrations and restricted light penetration both contribute to the limited growth. Dissolved oxygen concentrations are generally low, below 5 mg/l for most of the time. Low reaeration rate and high oxygen demanding organic materials appear to be responsible.

The river water quality conditions respond to stormwater runoff in a slower pace than model prediction. The direct coupling of the nonpoint source model STORM and the in-stream water quality model apparently 'short-circuit' a gap between them. The role of the swamp area bordering the river banks is not accounted for by either model. The comparison between the model results and prototype data suggests that the swamp acts like a buffer zone lessening the magnitude and extending the duration of stormwater impact. However, the quantification of the role played by the swamp is a subject requiring much more study.

At present state, the model is useful for the qualitative assessment of water quality impacts from alternative land-use schemes. Even though the model can not confidently predict how much improvement or degradation of river water quality a land-use scheme would cause, it could indicate the directions and relative magnitudes of water quality changes.

REFERENCES

Ho, G. C., A. Y. Kuo and B. J. Neilson, 1977. "Mathematical Models of Little Creek Harbor and the Lynnhaven Bay System". VIMS Spec. Rep. in Appl. Mar. Sci. and Ocean Eng., No. 145.

Kuo, A. Y, P. V. Hyer and B. J. Neilson, 1982. "A Mathematical Model for the Study of Storm Water Impact on the Water Quality of Lynnhaven Bay, Va.". VIMS Spec. Rep. in Appl. Mar. Sci. and Ocean Eng., No. 262.