MODEL AND FIELD STUDIES OF WARE CREEK

Predictions of Salinity Distributions

for Differing Reservoir Release Rates

A Report To

James City County

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Particular thanks go to Byron J. Prugh, Jr. and the staff of the Hydrologic Data Section of the USGS in Richmond, VA. Their rapid and thorough responses to requests for provisional flow data were of extreme value.

Additional thanks go to the staff of the State Water Control Board Surface Water Investigations in Charlottesville, VA for providing provisional flow data.

ABSTRACT

In Summer, 1986 a field program was conducted in Ware Creek from its mouth at the York River to the dam at Richardson's Millpond. The data collected was combined with flow data from USGS and a tide record from NOAA and was used to calibrate and verify a one-dimensional, real-time, hydrodynamic and salinity intrusion model.

The model has been applied to study the effect of the proposed dam and reservoir on the salinity distribution in Ware Creek. The model shows that at a flow of 0.2 MGD, the salinity in most of the creek will be the same as that in the York River at the creek mouth. If the salinity at the river is taken to be 16 ppt, the model shows at the projected average flow of 3.0 MGD, the tidal average salinity will decrease gradually from 16 ppt at the mouth, to 11 ppt at a point 6 km upstream. The salinity will drop sharply from 11 ppt to 0 in the 1.5 km immediately below the dam.

I. INTRODUCTION

James City County has proposed the construction of a water supply reservoir on Ware Creek, which forms a portion of the boundary between James City County and New Kent County. If the proposed project is constructed, one result would be the "export" of water from the Ware Creek drainage basin. Thus, the salinity regime in Ware Creek is likely to change due to both the physical presence of the dam and the altered freshwater inflow.

Both plants and animals are affected by the salinity of the water in which they are located. Thus, an assessment of likely environmental changes in Ware Creek is best achieved if future salinity pattems can be predicted. Mathematical models have been developed to simulate tidal elevations, currents, and salinity intrusion in estuaries. The Virginia Institute of Marine Science was contracted by James City County to apply such a model to Ware Creek and to conduct a field program to acquire the data necessary for the model study. In particular, the intent of the model studies was to predict longitudinal salinity profiles that would be associated with different water release rates.

Fortuitously, the summer of 1986 was a dry one for southeastern Virginia. Consequently, flows observed in the field were of the same magnitude as those suggested for minimum release rates. Thus, the field data alone provide a good estimate of likely salinity patterns. Further, confidence in model predictions always is greatest if the data for model calibration do not differ greatly from the conditions incorporated in the model simulations.

In the following sections of this report, the basic model and the field program are described (Chapter II.), the calibration of the model is documented (Chapter III.), and the predictions for several release rates given (Chapter IV.).

II. DESCRIPTION OF THE MODEL AND FIELD PROGRAM

THE MODEL

The mathematical model of salinity intrusion is based on equations which describe physical processes that occur in the real system. Simplifications and assumptions are made and the equations are written in finite-difference form for solution on a computer. Then the model is calibrated and verified using field observations. After verification the model can be used to predict changes in salinity distribution expected to occur due to changes in the input parameters.

Variations in the lateral and vertical directions are negligible in Ware Creek; therefore, a one-dimensional model was chosen for this study. Because there is great temporal variability in the parameters affecting salinity (especially freshwater inflow), a real-time model is necessary to predict time-varying salinity profiles.

The longitudinal salinity distribution is primarily governed by the geometry of the system, the time history of freshwater inflow, and the tidal dynamics. The model is based on the one-dimensional equations of conservation of volume, momentum, and mass. The governing partial differential equations are generally not solvable by analytical methods. The equations are solved by dividing the creek into a series of finite segments. A system of finite-difference approximations to the original equations is obtained by integrating the equations over the length of each segment. Predictions of surface level, velocity, and salinity are made by solving the finite-difference equations on a digital computer. A semi-implicit solution scheme is used. The surface level at the mouth, the salinity at the mouth, and the freshwater inflow are necessary inputs to the model. A complete description of the model and method of solution can be found in Williams and Kuo (1983) and Wilber (1986).

APPLICATION TO WARE CREEK

Ware Creek is located between New Kent and James City Counties (Virginia) and empties into the western side of the York River between Terrapin Point and Sycamore Landing (Figure II-1). France Swamp, Cow Swamp and Bird Swamp are tributaries to the creek. A dam intercepts the drainage from Bird Swamp to create Richardson's Millpond. The creek meanders through forested wetland, freshwater swamps and saltwater marshes on its way to the river. Counting the many curves and bends along its length, the creek is approximately 9 km long. A large oxbow is found 3.5 km from the mouth. The confluence of the flow from the millpond and that from France and Cow Swamps is located 7.8 km from the mouth. (Figure II-2)

The tide is primarily semi-diurnal. The mean range is 86 cm at the mouth. The dynamic interaction of tide, freshwater inflow, and salinity determine the flow and salinity regimes.

DATA COLLECTION AND ANALYSIS

In order to construct, calibrate, and verify a mathematical model to predict changes in the spatial and temporal distribution of salinity in Ware Creek, field data were needed. Required information included basin geometry, freshwater discharge, salinity distribution, and tidal elevations.

The basic geometric information needed was drainage areas and creek dimensions. The distance from the mouth of Ware Creek to the spillway at Richardson Millpond and the drainage areas associated with each segment of the model were determined by digital planimetry of topographic maps. Detailed bathymetric profiles at a total of 15 transects provided data on the creek's width, mean depth, cross-sectional area, volume, and changes in these parameters over the tidal cycle (Table II-1). The cross-sectional profile was determined by one of two methods. The first, used for the majority of sites, entailed fixing a line perpendicular to the channel and pulling a continuously-recording fathometer mounted on a float across the channel. The creek's width was measured and surface elevation measurements were referenced to the tide gages to determine the mean tide level and changes in area and volume during a tidal cycle. The method utilized for shallow sites used a measured line drawn across the creek and a staff (rather than the fathometer) to determine depths at selected points across the creek.

The major sources of freshwater flow into Ware Creek are Richardson Millpond and France and Cow Swamps. The millpond, which enters the head of Ware Creek and is a controlled flow, has had a flow gage (gage # 01677000) installed on the pond since 1979. This gage records water height above the spillway which can be converted to discharge data by use of a rating table. We obtained millpond flow data from published United States Geological Survey (USGS) records or received provisional data (Water years 1985 and 1986) directly from the USGS.

Combined discharge from France and Cow Swamps enters Ware Creek about 1 kilometer below the millpond and does not have a gage site. In order to estimate the flow contribution from the swamp drainage area, we obtained information for Beaverdam Swamp (gage # 01670000) in Gloucester County, a similar drainage area located about 20 miles to the east of France Swamp. Beaverdam discharge data, provided by the State Water Control Board, was adjusted to account for the differences in drainage areas between the two swamps. The flow information for the period of study is shown in Figures II-3 and II-4.

To measure the longitudinal salinity distribution, slackwater surveys were conducted. They were designed to follow either slack before flood (SBF) or slack before ebb (SBE) as the tidal wave propagated up the creek. Samples were obtained by lowering a submersible pump to draw a 125 ml sample from mid-depth in the creek channel. Salinity samples were analysed in the laboratory using a Beckman RS-7A Salinometer. The salinity profiles for the slackwater surveys are shown in Figure II-5.

To obtain values for temporal salinity distribution at times between slackwater surveys, ISCO (model 1680) automated pump samplers were used. These samplers drew 300 ml samples at selected intervals and were programmed to sample during the 4 daily slacks, which were the times of maximum and minimum salinities. Two sites were selected, one close to the mouth of the creek, and the other about 6.5 km upstream. The samplers were visited weekly to be reloaded with bottles. Salinities were determined with a Beckman RS-7A Salinometer. Observations from both sites are presented in Figures II-6 and II-7.

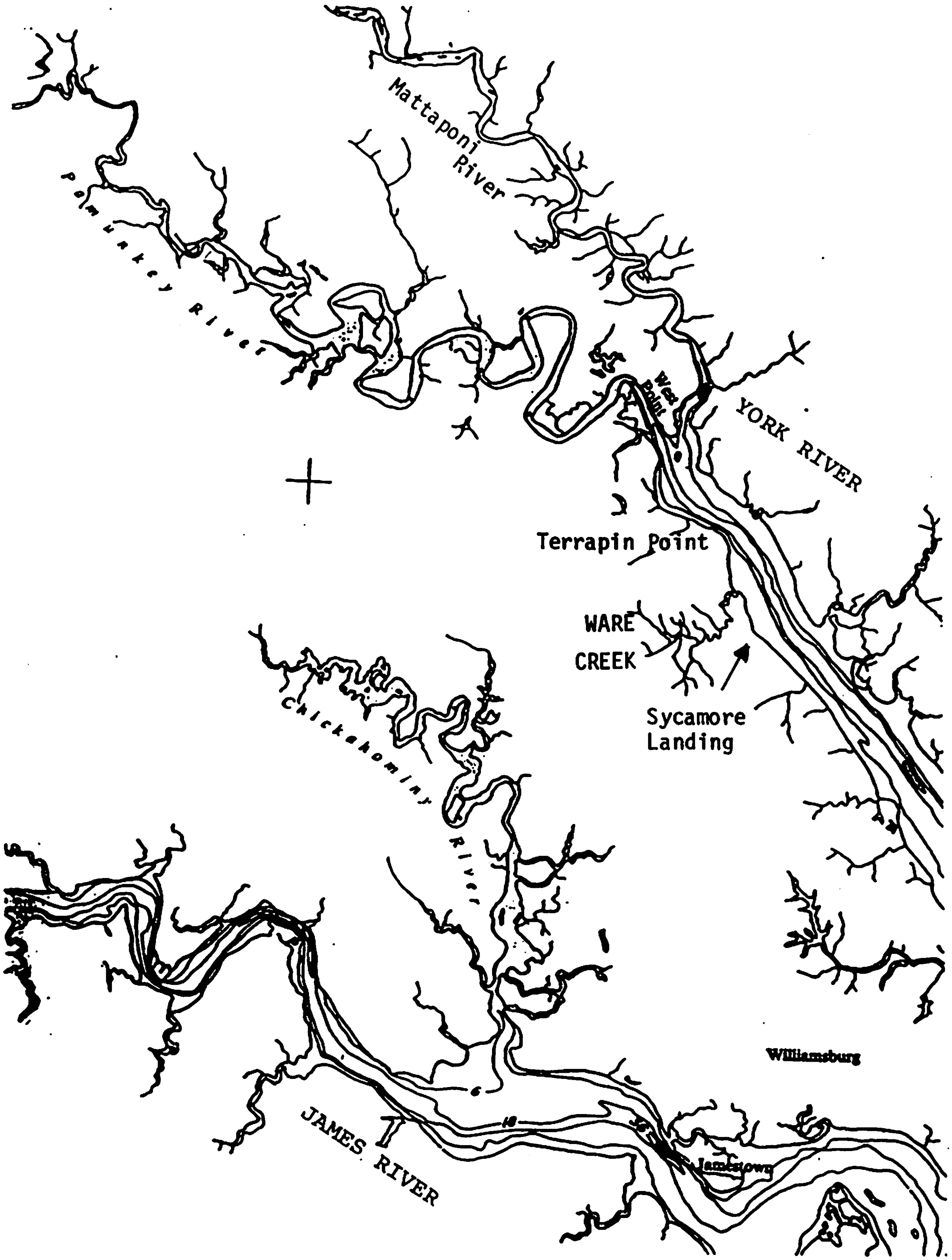
Changes in water surface elevation (due to the tide and meterological events) were recorded using Fischer & Porter (model 35C) water elevation gages. These devices were located at a site close to the mouth of Ware Creek and at another site about 6 km upstream. They record the surface elevation at six-minute intervals for up to 2 months. The data was analysed using a North Star computer and an optical reader and software developed by Mitron Systems. Due to repeated vandalism, much of the tide gage record at the mouth site was lost. The usable sections of that record were compared to the continuous record available from a NOAA tide gage on the York River at VIMS (Gloucester Point, VA). The Gloucester Point record was subsequently modified to approximate surface elevations at Ware Creek.

SEGMENTATION

The estuary was divided into 23 unequal segments by locating 24 transects from the millpond dam to the mouth. Transects were located where bottom profiles were available or where the geometry of the cross-section was relatively simple and representative of that reach of the creek. Figure II-8 shows the locations of the transects. Each transect is numbered starting at the upstream end with #1 reserved as an artificial transect for model calculations. The transect distance is measured from the mouth. Each transect has a surface width, cross-sectional area, and depth of centroid. The depth of the centroid is taken as half the average depth of the transect. Segment i is defined as the reach between transect i and transect i+1. Each segment has a volume and surface area. The drainage area at i is the incremental drainage area entering between transects i-1 and i. It contributes to the segment i-1. The drainage area at the head (segment 2) is the total drainage area upstream of segment 2. Table II-2 shows geometric and drainage area information for each segment at mean tide level.

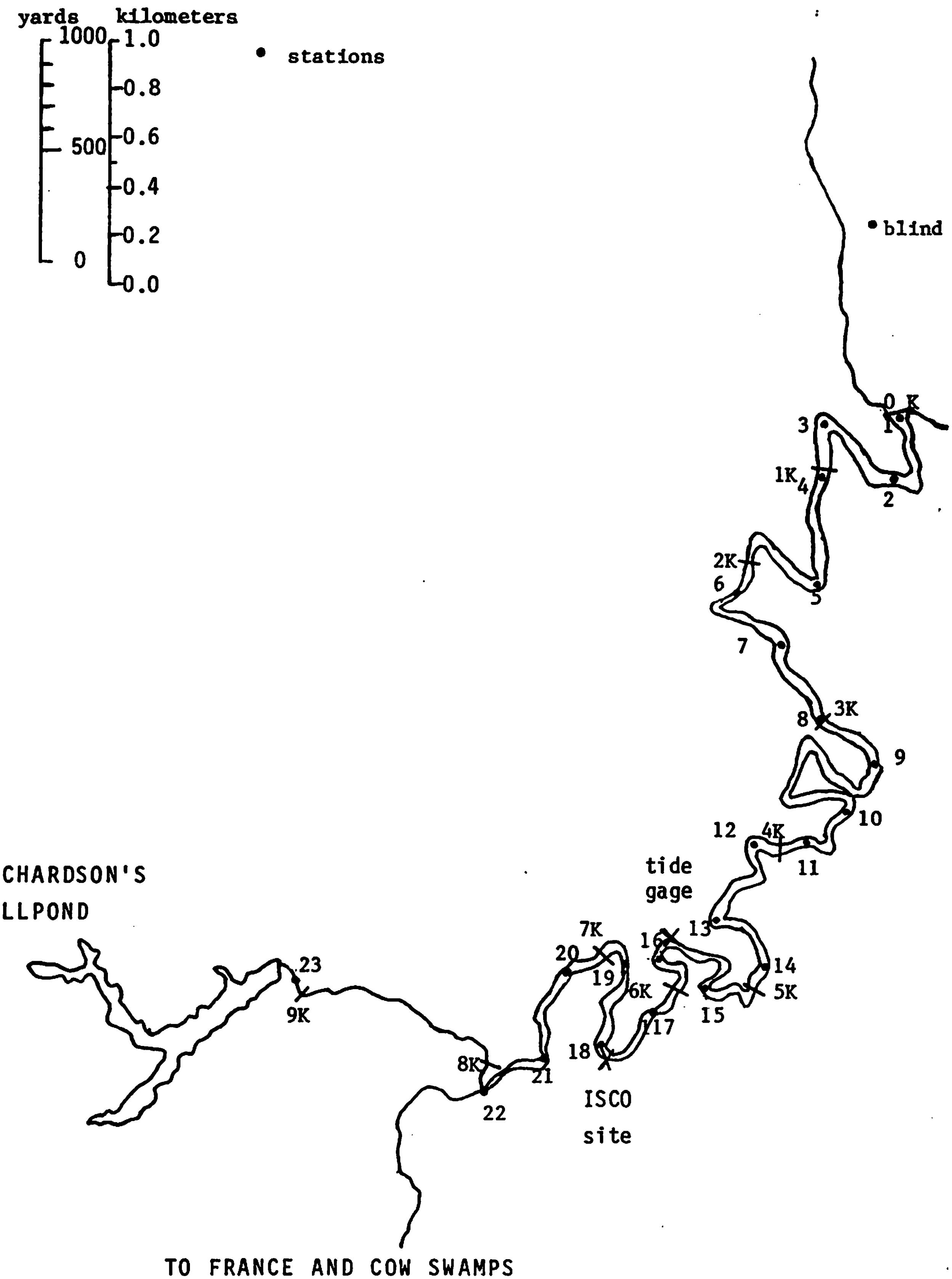
APPLICATION OF THE MODEL

Ware Creek is a relatively small and shallow system. Applying a model to such a system poses problems not encountered in modeling larger estuarine systems. One problem is the high variability of salinity, depth and freshwater inflow in the creek. The variability of salinity can be seen in Figures II-6 and II-7. The salinity measured at the mouth of Ware Creek is that of the York River and the variation is less than 2 ppt during a tidal cycle and less than 7 ppt over the study period. The salinity measured in the creek varied as much as 8 ppt during a tidal cycle and 16 ppt over the study period. The large variability of some parameters will affect the stability of the model. In sections of the creek, the total depth is the same as the tidal range. This can cause the model to become unstable at low tides. It is not unusual for the freshwater flow to increase by two orders of magnitude within a twenty-four period. A sudden shock of flow such as this can also cause the model to become unstable. The model of a sensitive system is usually very sensitive to changes in some inputs.



LOCATION OF WARE CREEK

FIGURE II-1



LOCATIONS OF SAMPLING STATIONS ON WARE CREEK

FIGURE II-2

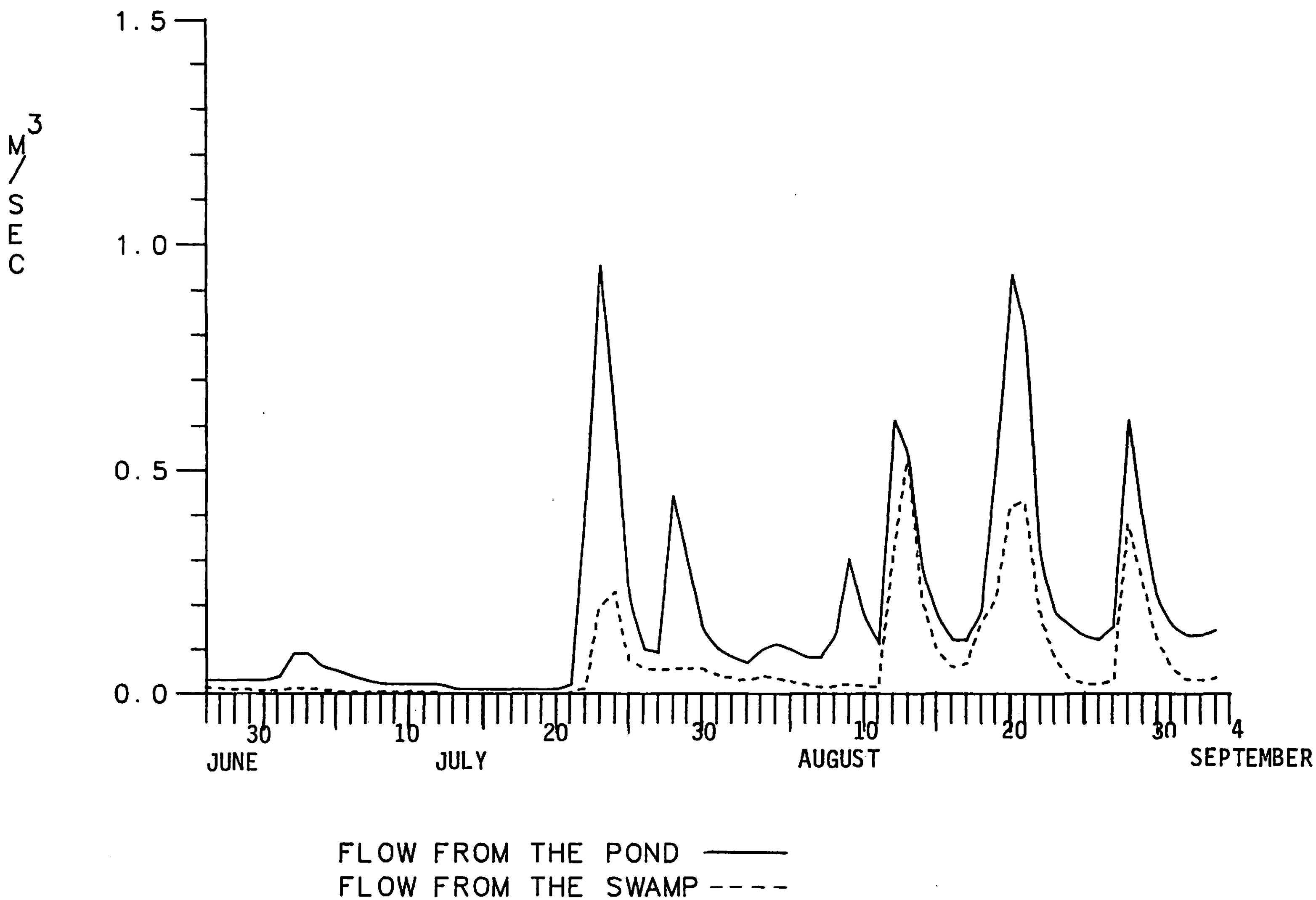
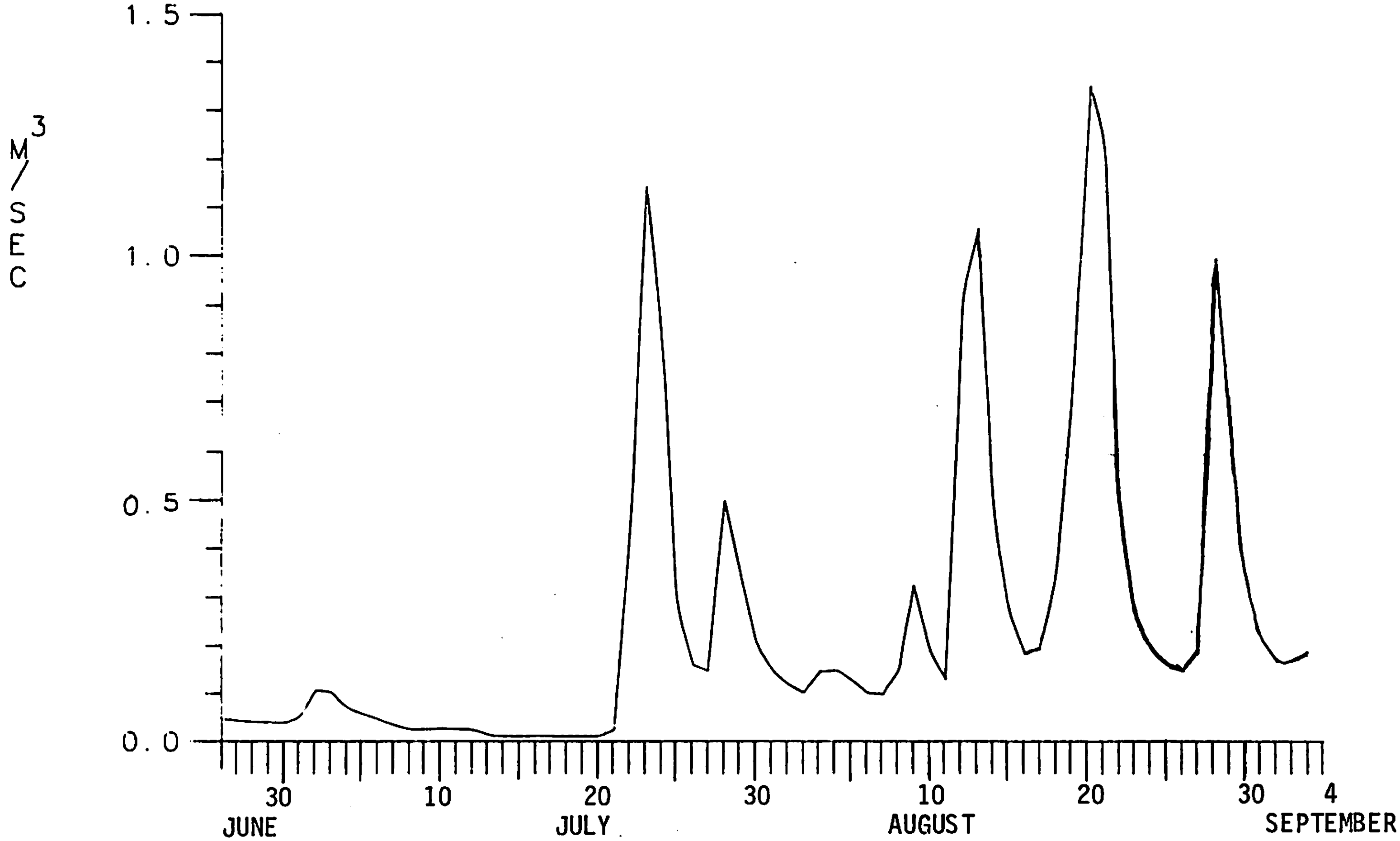

1.5
1.0
0.5
0.0
M^3/SEC
30
10
20
30
10
20
30
4
JUNE
JULY
AUGUST
SEPTEMBER
FLOW FROM THE POND
FLOW FROM THE SWAMP

FIGURE II-3



TOTAL INFLOW FROM THE MILLPOND AND THE SWAMP

FIGURE II-4

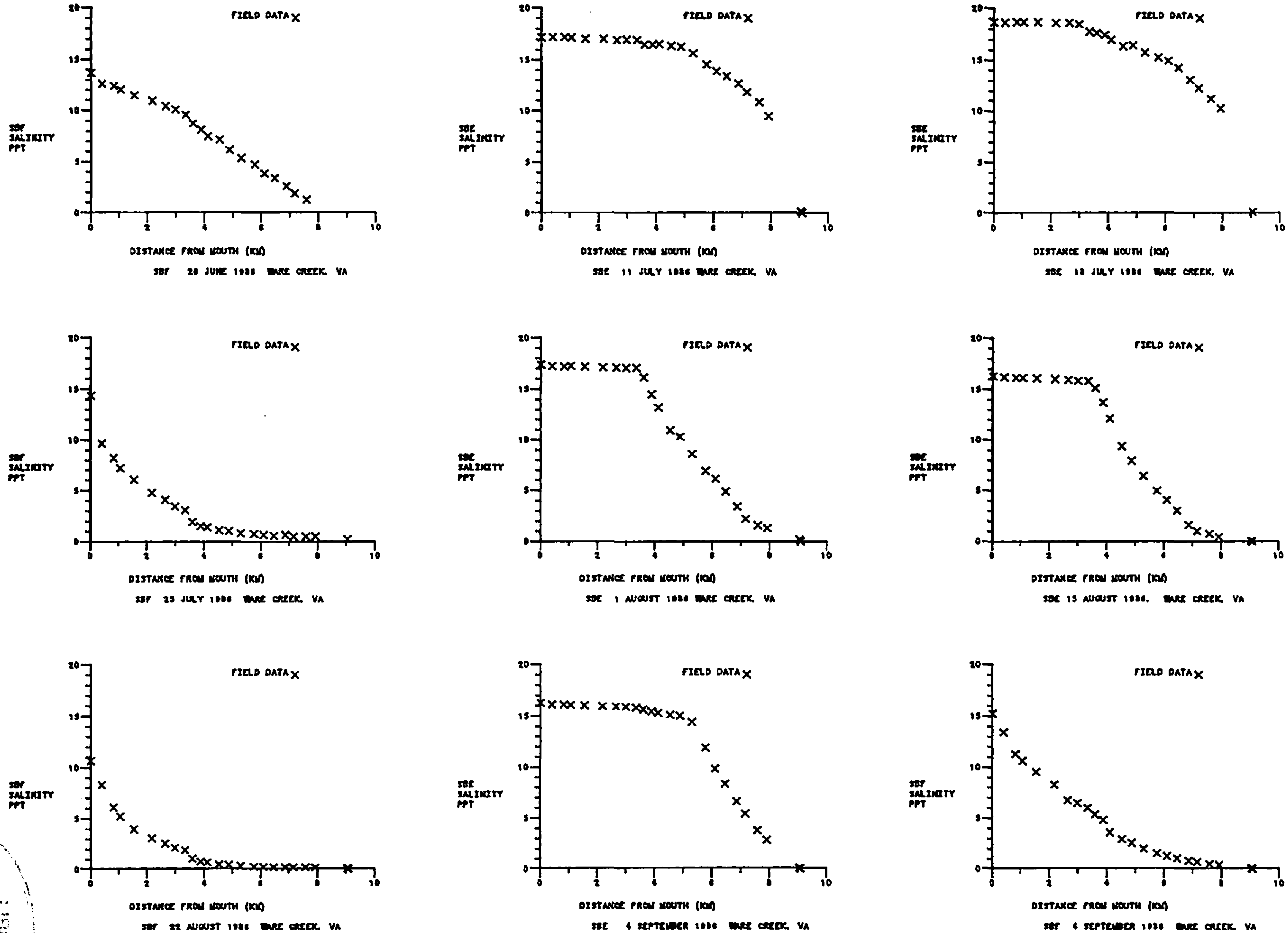
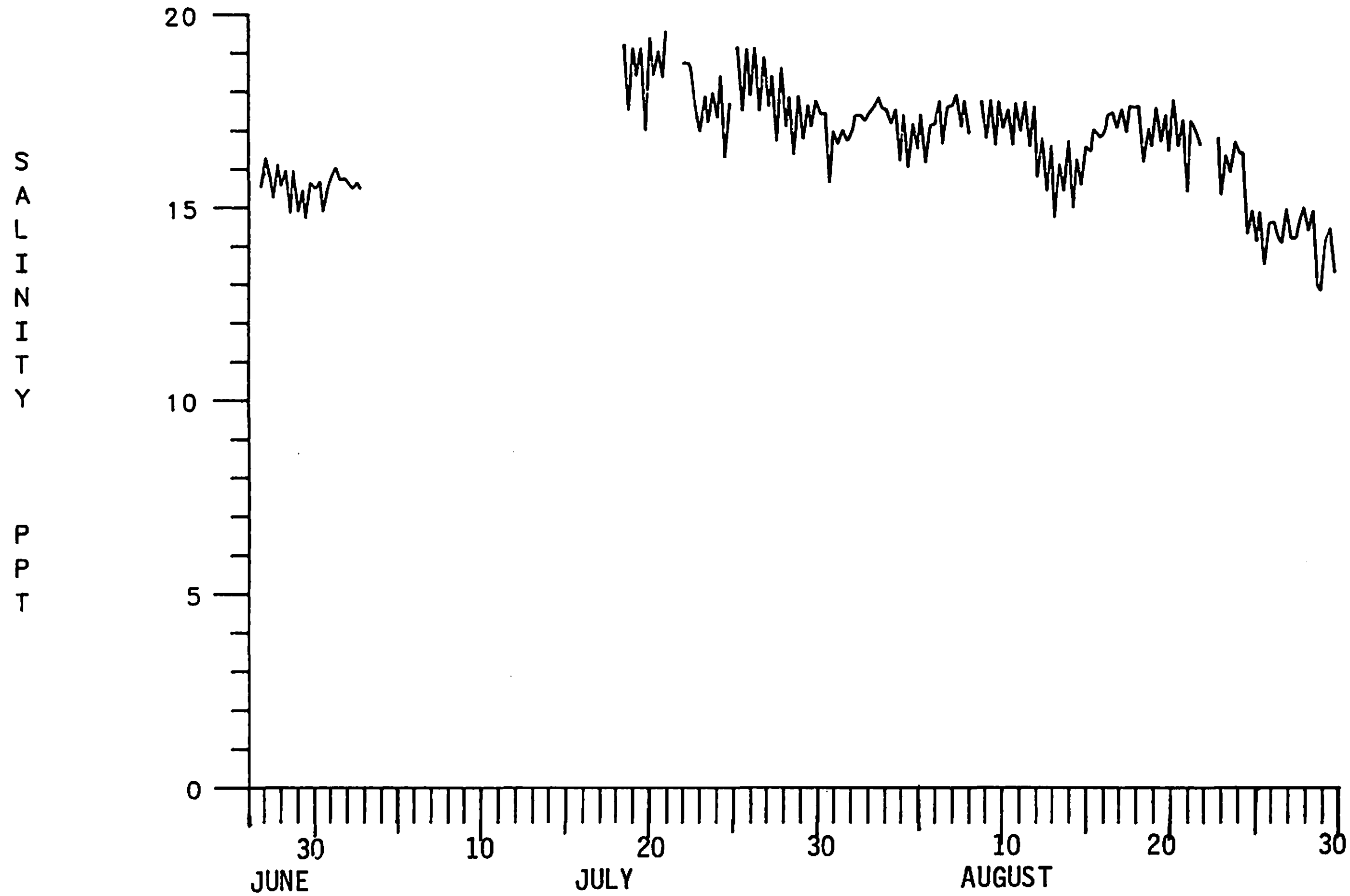
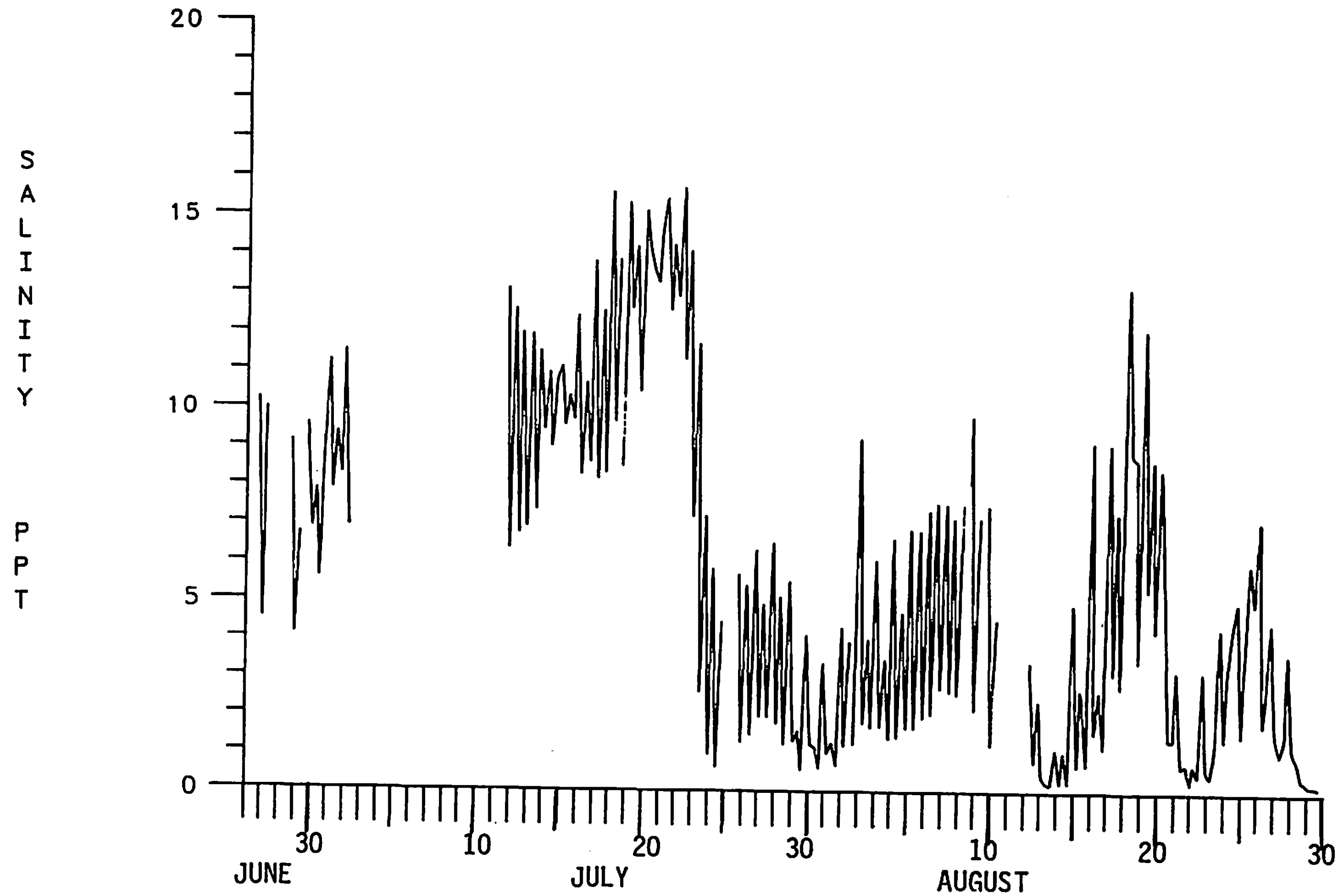

FIELD DATA
SBF SALINITY PPT
DISTANCE FROM MOUTH (KM)
SBF 26 JUNE 1986 WARE CREEK, VA
SBE SALINITY PPT
SBE 11 JULY 1986 WARE CREEK, VA
SBE 18 JULY 1986 WARE CREEK, VA
SBF 25 JULY 1986 WARE CREEK, VA
SBE 1 AUGUST 1986 WARE CREEK, VA
SBE 15 AUGUST 1986. WARE CREEK, VA
SBF 22 AUGUST 1986 WARE CREEK, VA
SBE 4 SEPTEMBER 1986 WARE CREEK, VA
SBF 4 SEPTEMBER 1986 WARE CREEK, VA

FIGURE II-5



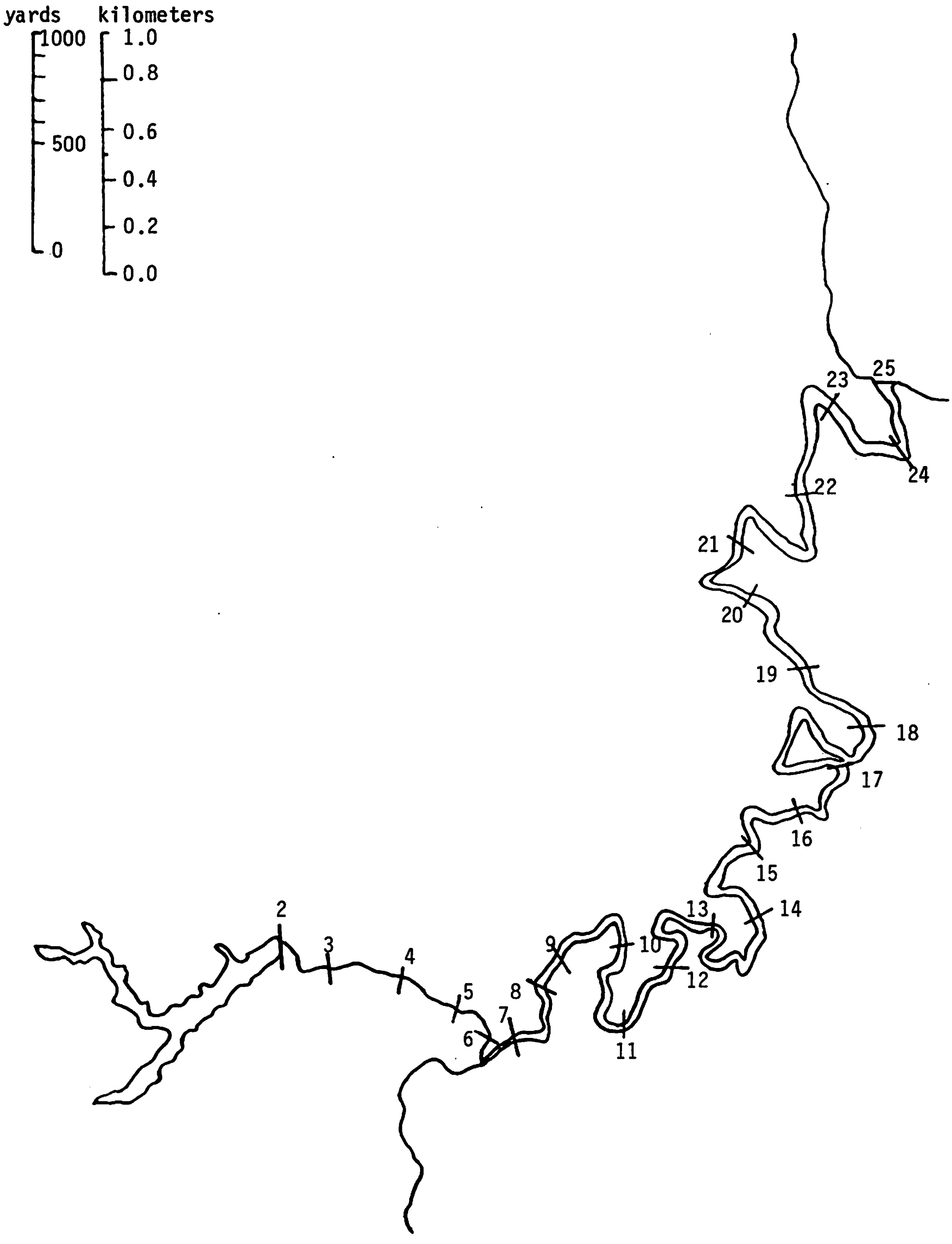
MOUTH ISCO, STARTED 26 JUNE 1986

FIGURE II-6



UPSTREAM ISCO, STARTED 26 JUNE 1986

FIGURE II-7



MODEL SEGMENTS

FIGURE II-8

TABLE II-1

MEASURED WARE CREEK GEOMETRY

PROFILE	DISTANCE (KM)	SURFACE WIDTH (M)	CROSS-SECTIONAL AREA (M^2)	MEAN DEPTH (M)
15	9.08	6.3	2.3	0.36
14	8.82	6.5	3.2	0.50
13	8.24	12.8	5.2	0.40
12	7.96	22.2	13.4	0.60
11	7.75	23.0	17.9	0.78
10	7.24	21.9	24.2	1.10
9	6.83	25.0	25.1	1.00
8	6.00	18.6	28.8	1.56
7	4.75	23.8	24.8	1.02
6	3.89	19.8	32.2	1.62
5	3.25	23.5	45.4	1.92
4	2.48	21.0	42.7	2.04
3	1.24	30.9	57.0	1.84
2	0.71	31.9	57.3	1.80
1	0.0	61.0	128.0	2.08

TABLE II-2

GEOMETRIC DATA FOR WARE CREEK MODEL

SEGMENT NUMBER	DISTANCE FROM MOUTH	WIDTH	CROSS-SECTION AREA	SURFACE AREA	VOLUME	DRAINAGE AREA	DEPTH CENTER OF MOMENT
	(KM)	(M)	(M^2)	(10^3M^2)	(10^3M^3)	(KM^2)	(M)
2	9.08	6.3	2.3	1.66	0.72	16.70	0.18
3	8.82	6.5	3.2	2.54	1.16	0.10	0.25
4	8.51	9.9	4.3	3.06	1.28	1.20	0.22
5	8.24	12.8	5.2	4.90	2.60	0.13	0.20
6	7.96	22.2	13.4	4.75	3.29	0.09	0.30
7	7.75	23.0	17.9	7.70	6.80	26.46	0.39
8	7.41	22.3	22.1	3.76	3.94	0.13	0.50
9	7.24	21.9	24.2	9.61	10.11	0.06	0.55
10	6.83	25.0	25.1	10.90	12.29	0.60	0.50
11	6.36	21.4	27.2	7.20	10.08	0.11	0.66
12	6.00	18.6	28.8	10.86	15.35	0.19	0.78
13	5.45	20.9	27.0	15.65	18.13	0.31	0.67
14	4.75	23.8	24.8	10.90	12.89	0.12	0.52
15	4.27	21.6	28.9	7.87	11.61	2.30	0.68
16	3.89	19.8	32.2	7.51	12.92	0.07	0.81
17	3.53	21.9	39.6	6.36	11.90	5.15	0.89
18	3.25	23.5	45.4	7.57	14.78	0.06	0.96
19	2.92	22.4	44.2	9.55	19.12	0.15	0.99
20	2.48	21.0	42.7	10.26	20.39	0.15	1.02
21	2.03	24.6	47.9	21.92	41.44	0.30	0.98
22	1.24	30.9	57.0	16.64	30.29	0.26	0.92
23	0.71	31.9	57.3	10.98	20.81	2.60	0.90
24	0.42	43.8	86.2	22.01	44.98	0.42	0.96
25	0.0	61.0	128.0			0.05	1.04

III. CALIBRATION OF THE MODEL

HYDRODYNAMIC CALIBRATION

Due to the problems with the tide gage at the mouth of the creek, only the mean tide range has been calibrated from field data. The tidal range was calculated in the model by finding the difference in high and low water at each transect. The predicted range from the model was compared with the mean range from the tide gage installed upstream and range obtained from visual observation of staffs placed along the creek. The value of Manning's friction coefficient was varied until the model predicted range and the observed range agreed. A value for Manning's friction coefficient of 0.030 was found to give good agreement with the observed range. The model reproduces the mean range quite well (Figure III-1).

SALINITY CALIBRATION

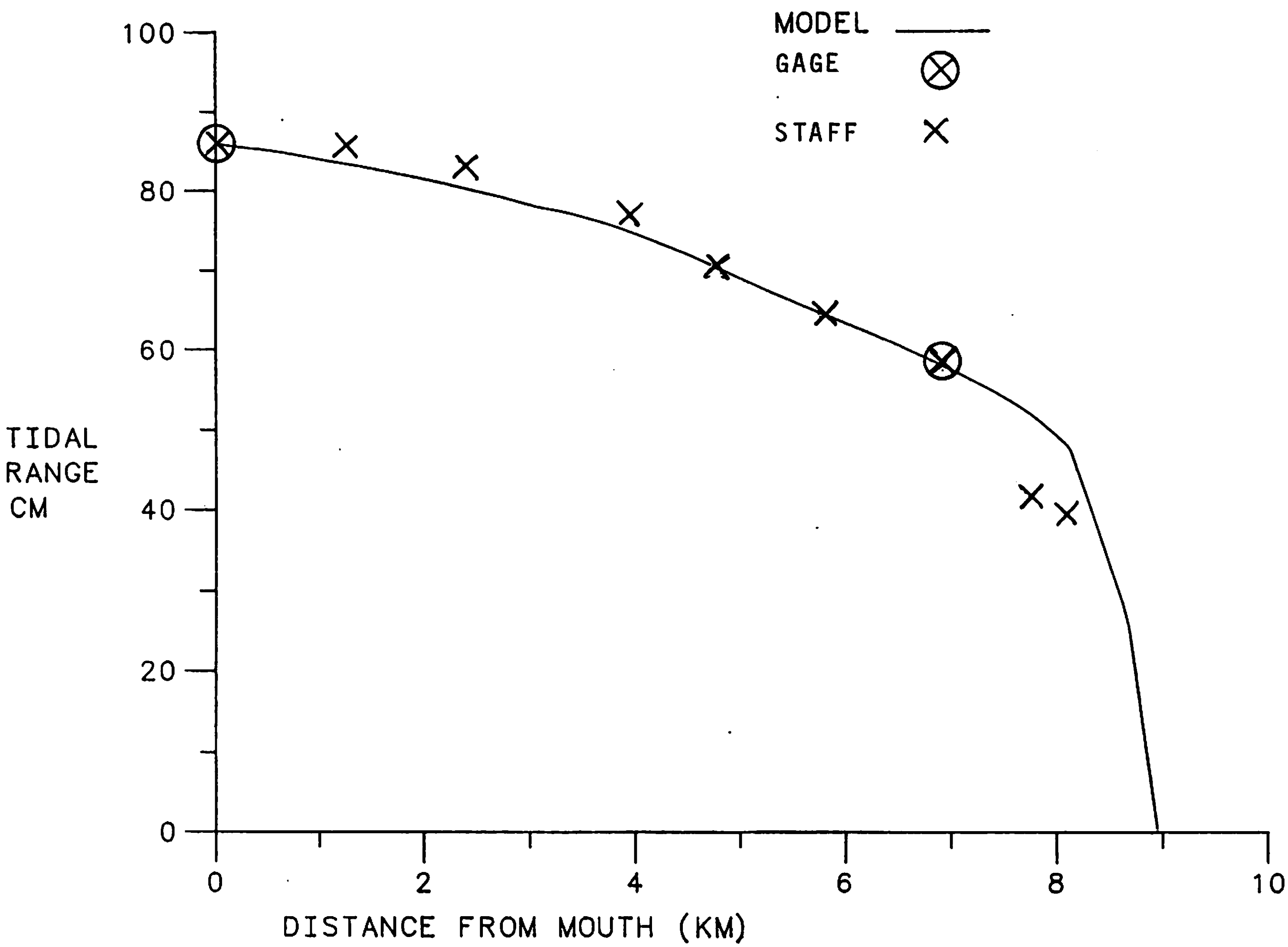
The model was calibrated for longitudinal salinity distribution using the data obtained on slackwater surveys and from the upstream ISCO sampler. Three time-varying boundary conditions were necessary to run the model for longitudinal salinity calibration. These boundary conditions were the freshwater inflow, the surface elevation at the mouth and the salinity at the mouth. The flow from Richardson's Millpond was measured with the USGS gage. The flow record from Beaverdam Swamp was used to calculate the flow from France and Cow Swamps. The tide record from the NOAA gage at

Gloucester Point was modified and hourly tidal heights were input to the model at the downstream boundary. The salinity values obtained using the ISCO sampler at the mouth were used to input the maximum daily salinity at the boundary.

The value of salinity at slackwater in the model was found for each segment by checking the discharge at each time step. When the discharge changed from positive to negative, that time step was considered to be the time of slack before flood. When the discharge changed from negative to positive that time step was considered to be the time of slack before ebb. The model considers the ebb direction as positive. The salinity values calculated by the model were compared with those measured on slackwater surveys.

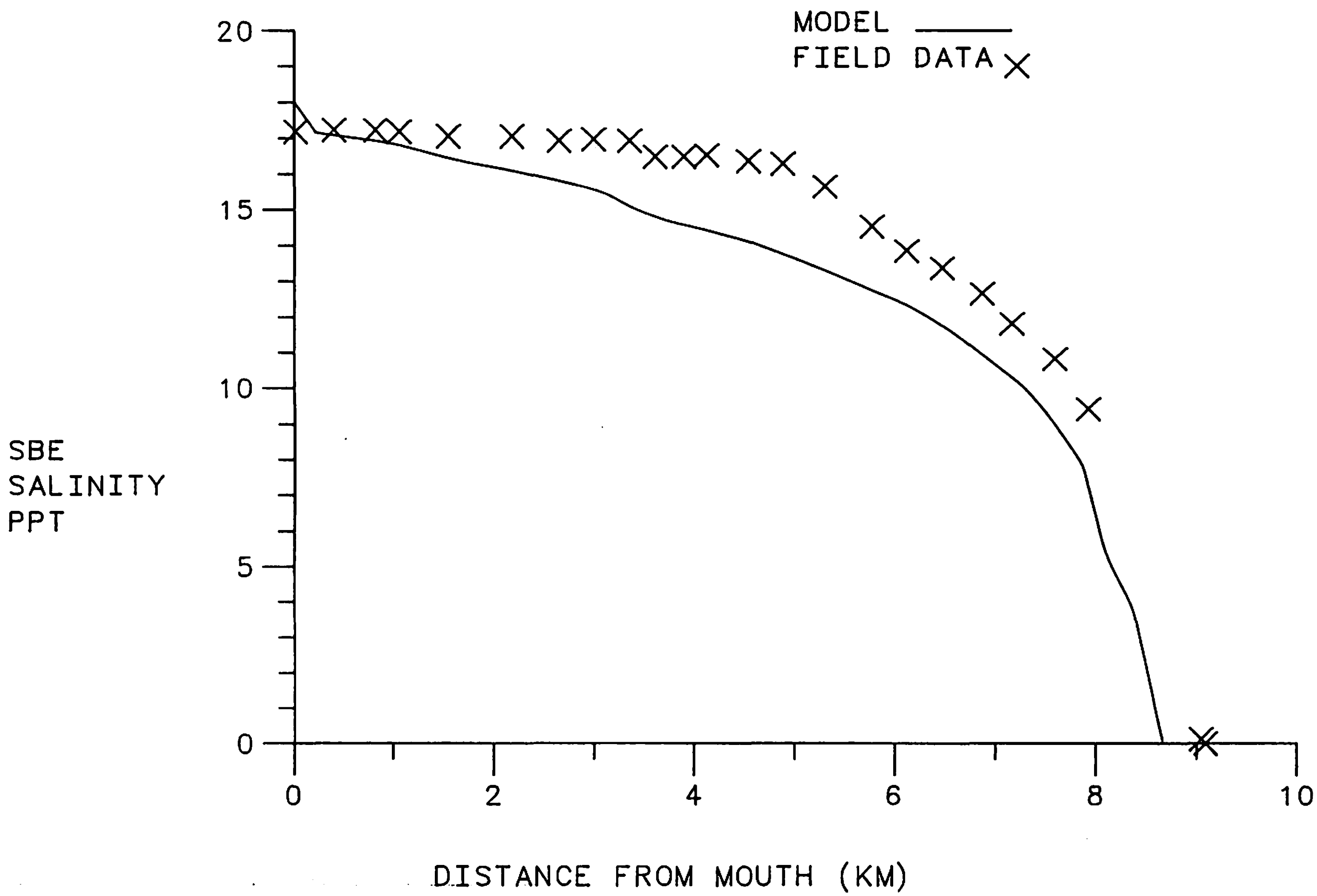
The model was originally calibrated for the period from June 26 to July 21, 1986. The results were in the preliminary report of 15 October 1986. After receiving the data from July 21 through September 4, the model was run for the entire period using the original calibration. The results for the second time period were not as good as those for the first. The freshwater inflow was much greater in the second period than in the first. Adjustments were made in the model and it was again calibrated and verified using data for the entire study period.

The comparisons of the predicted longitudinal salinity distributions to data obtained on the slackwater surveys are shown in Figures III-2 through III-10. The longitudinal salinity distribution is predicted better on some dates than on others. Some predictions are high and others are low. The length of the salinity intrusion is predicted well on all occasions. Figure III-11 shows the comparison of the salinity obtained with the ISCO sampler and the salinity predicted at that location in the creek. The model does not predict as large an intra-tidal variation in salinity as measured in the prototype. The tidal average salinity is predicted well throughout the study period.



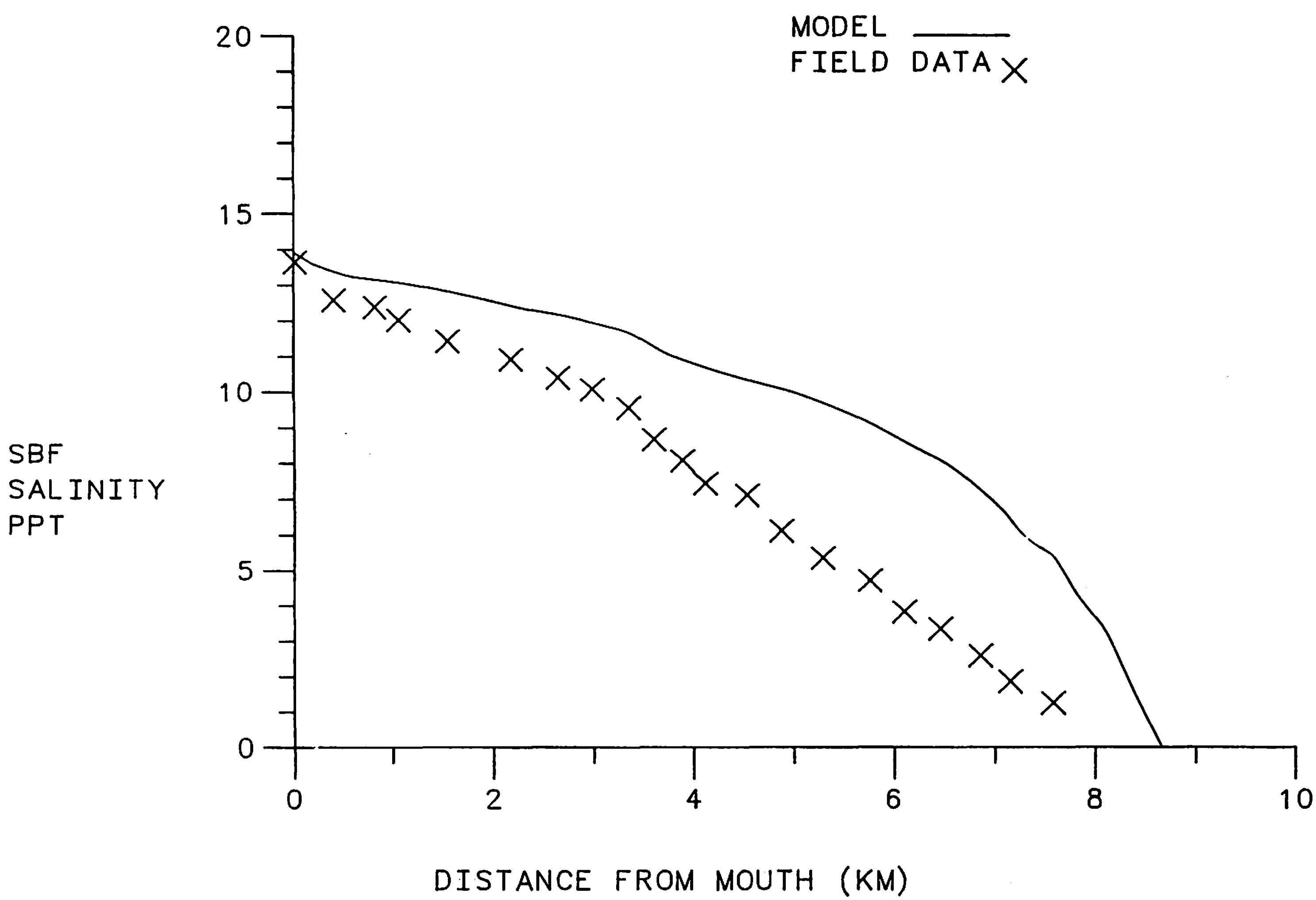
PREDICTED VS MEASURED TIDE RANGE

FIGURE III-1



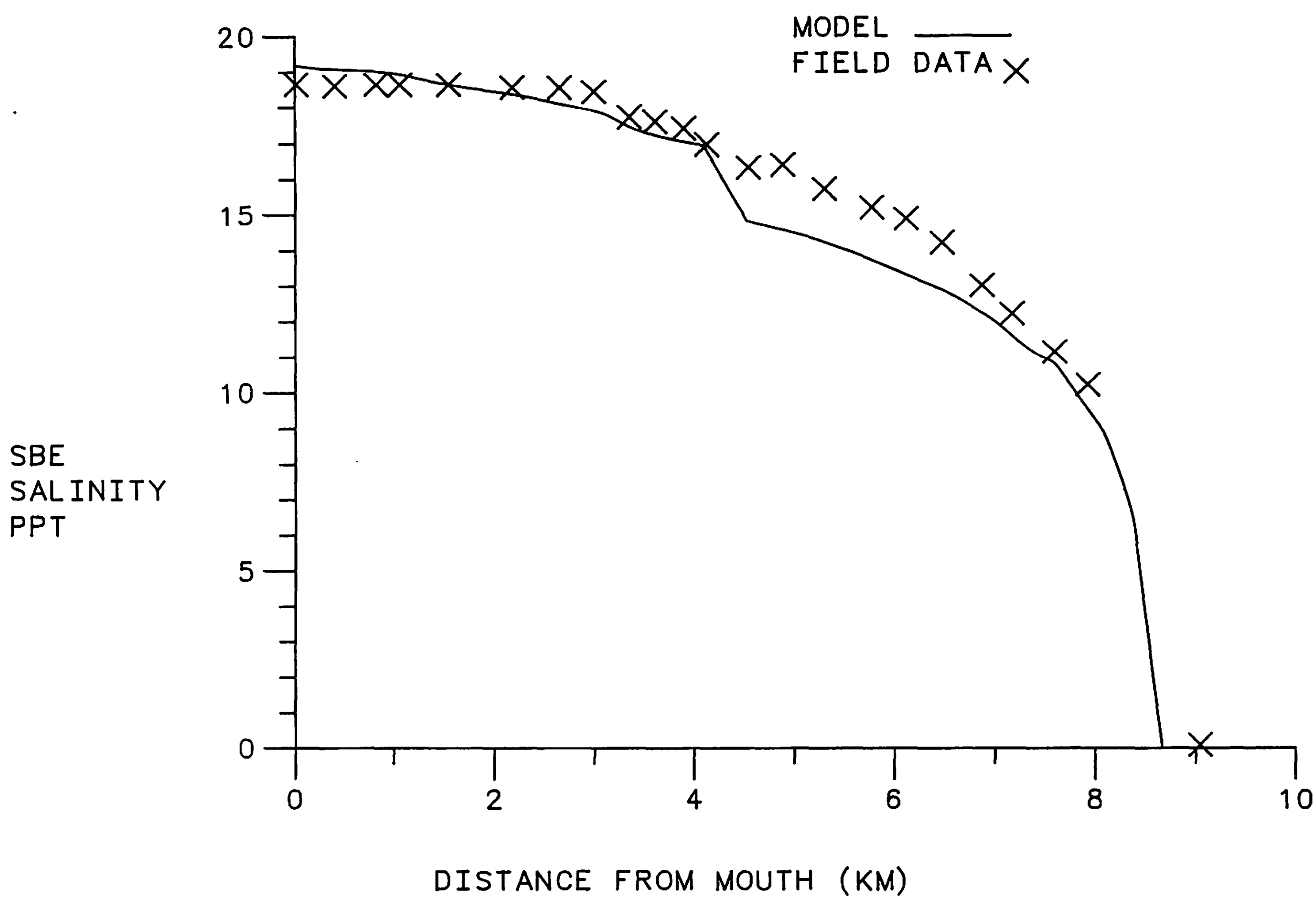
SBE 11 JULY 1986 WARE CREEK, VA

FIGURE III-2



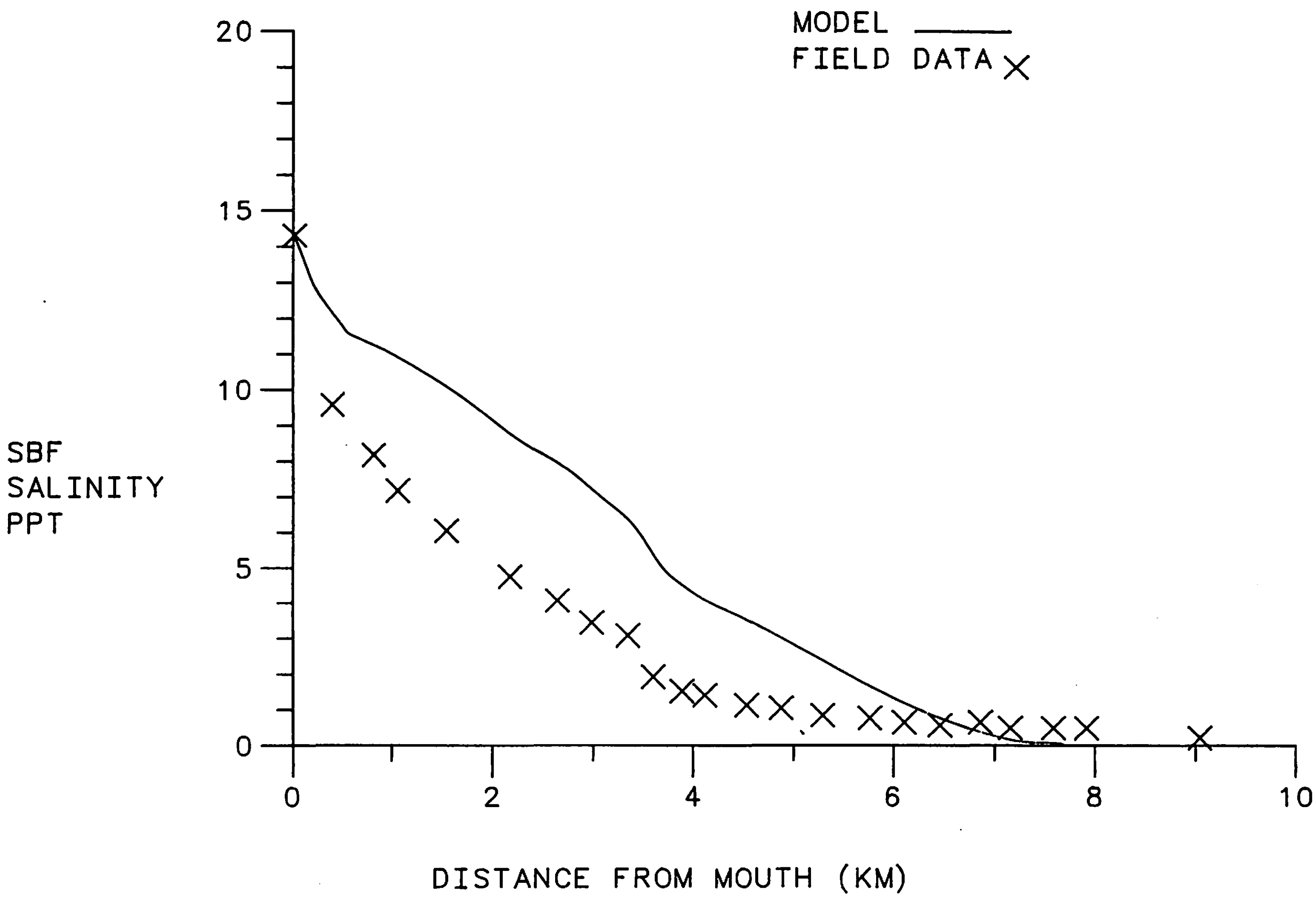
SBF 26 JUNE 1986 WARE CREEK, VA

FIGURE III-3



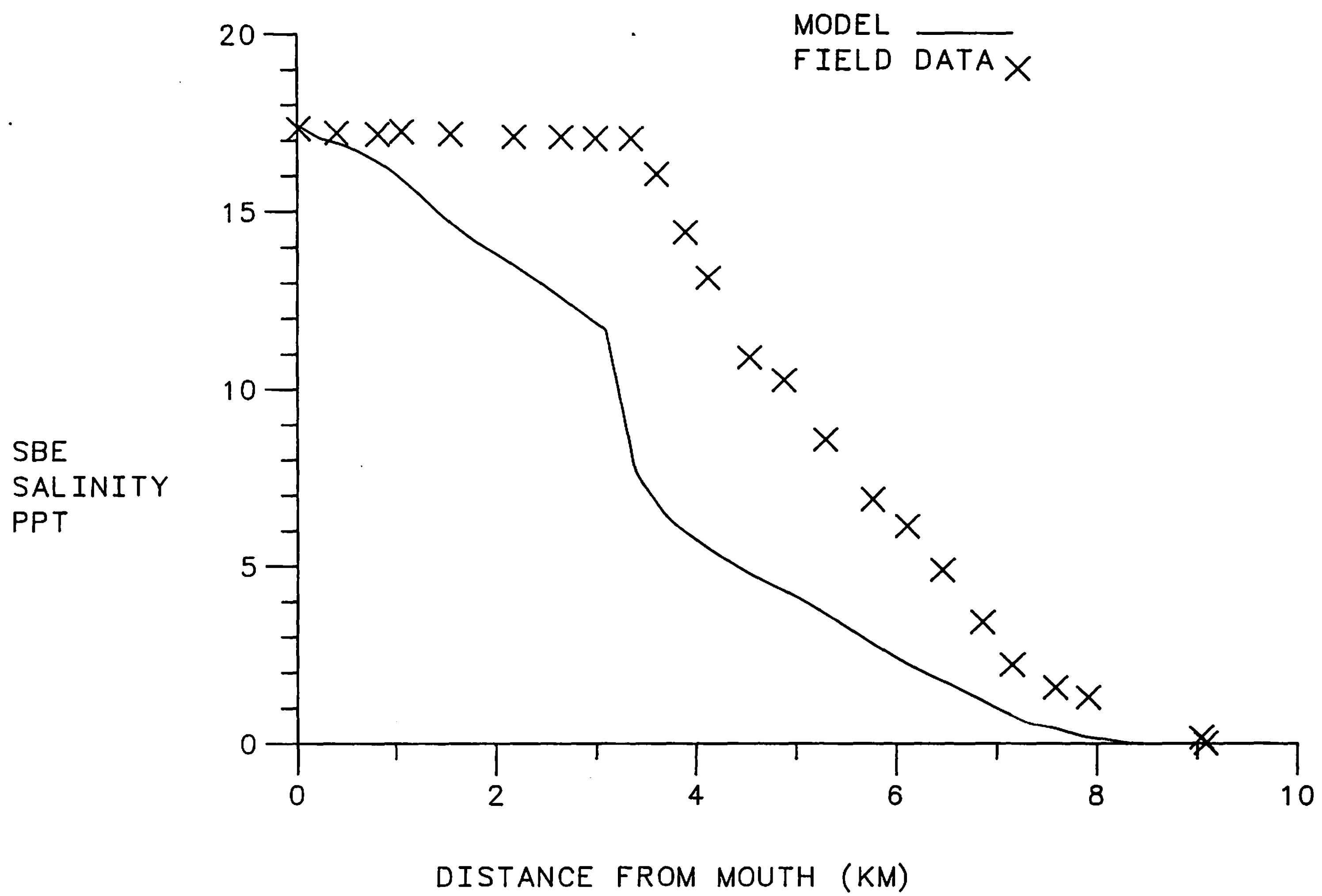
SBE 18 JULY 1986 WARE CREEK, VA

FIGURE III-4



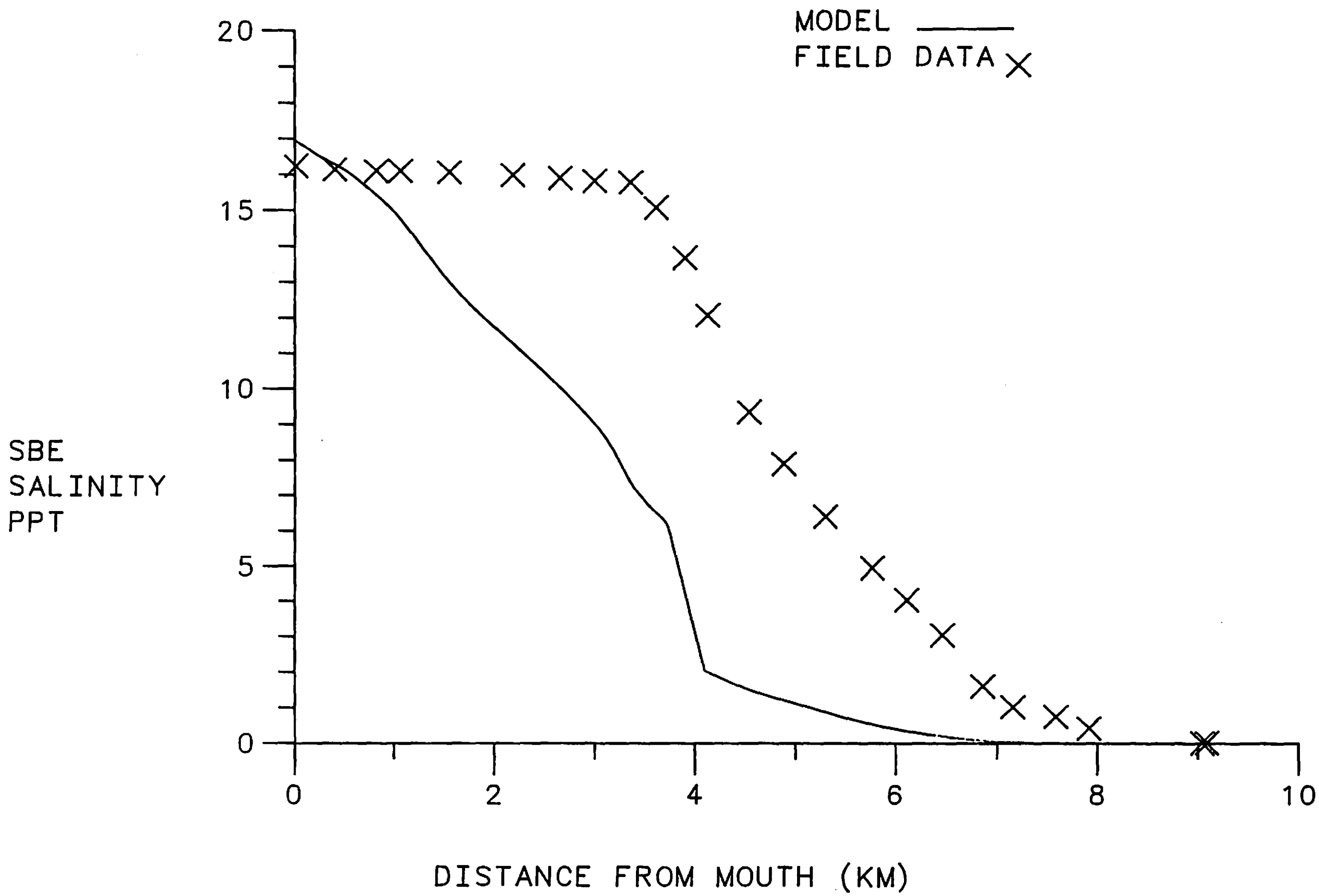
SBF 25 JULY 1986 WARE CREEK, VA

FIGURE III-5



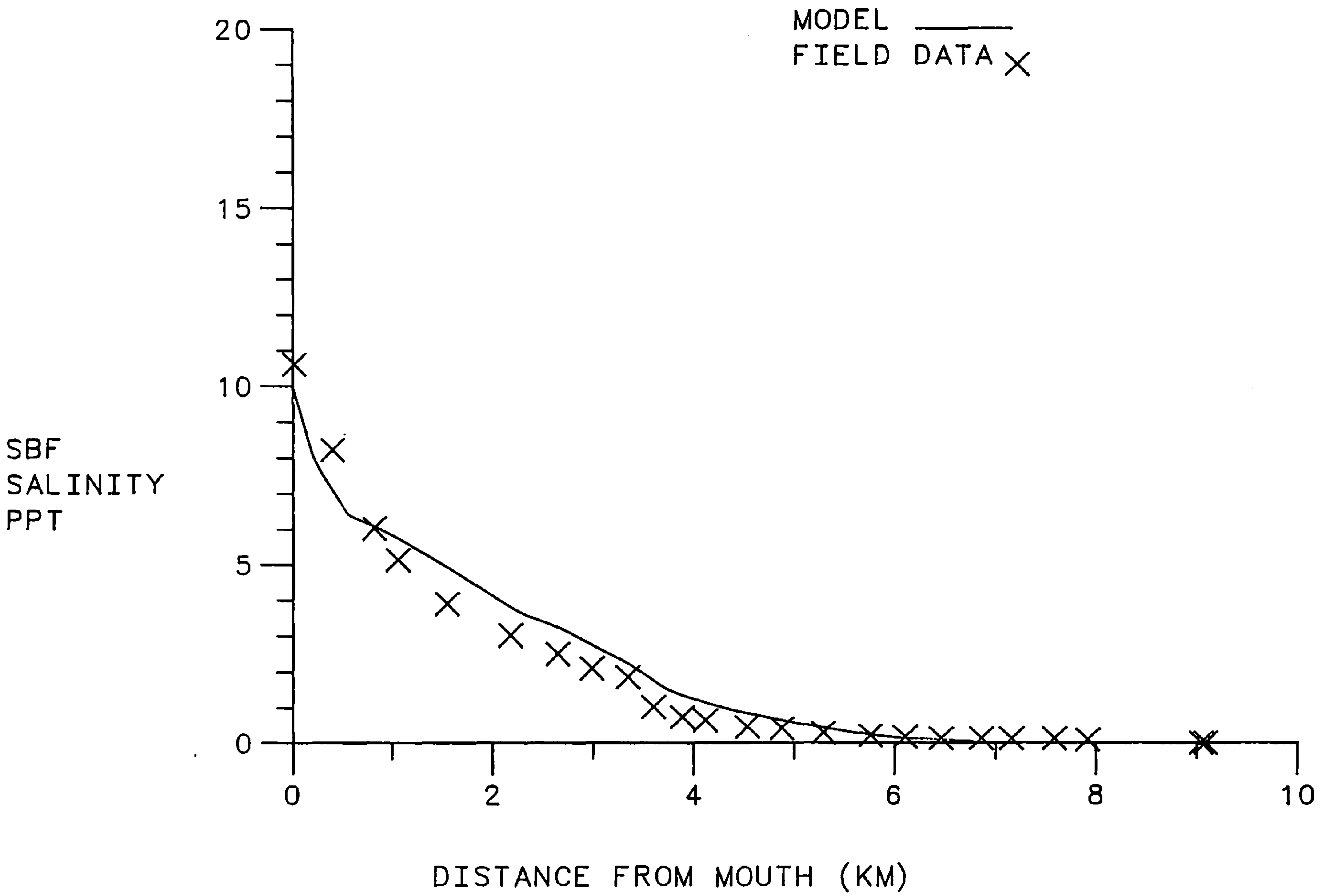
SBE 1 AUGUST 1986 WARE CREEK, VA

FIGURE III-6



SBE 15 AUGUST 1986, WARE CREEK, VA

FIGURE III-7



SBF 22 AUGUST 1986 WARE CREEK, VA

FIGURE III-8

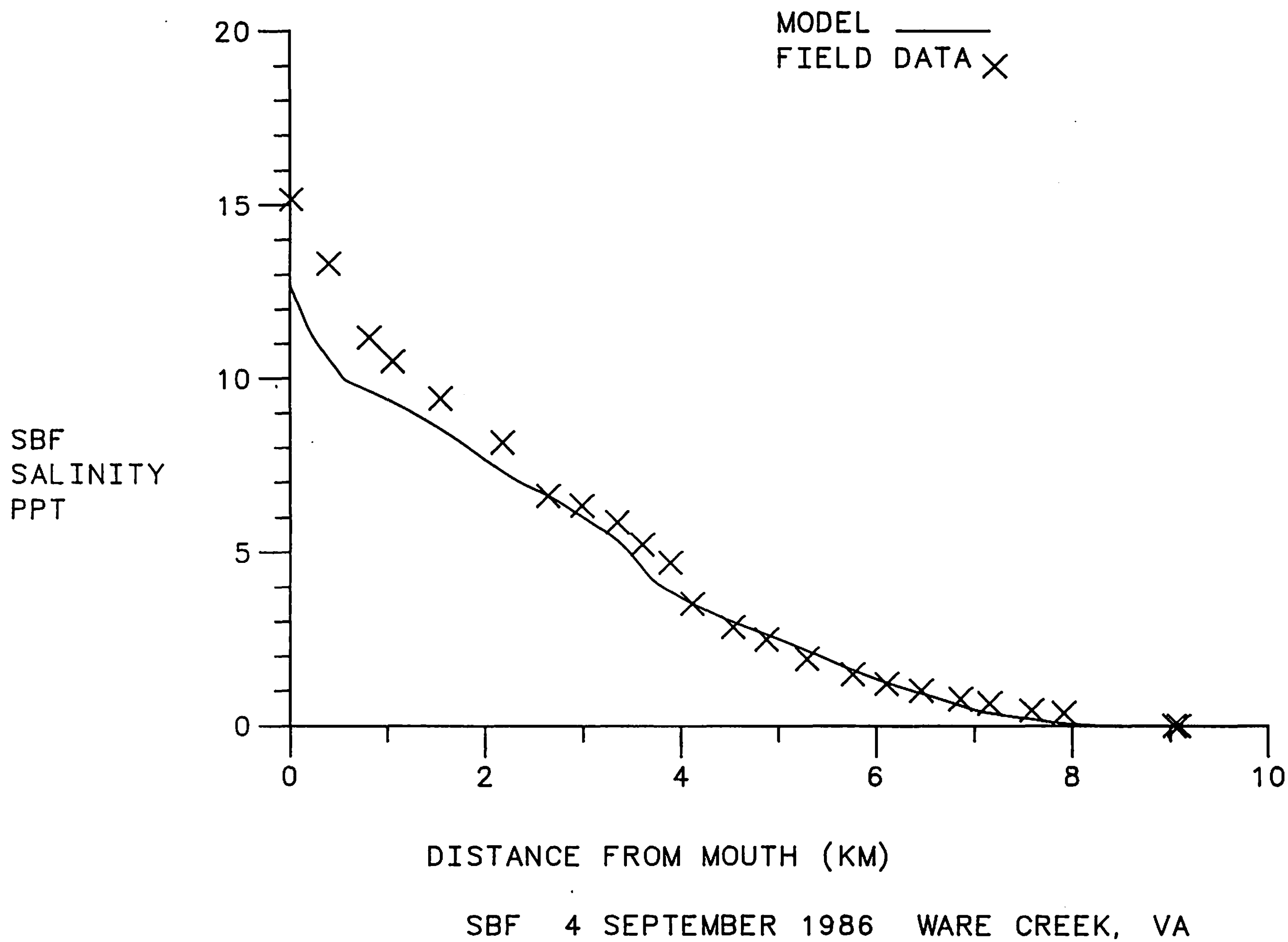
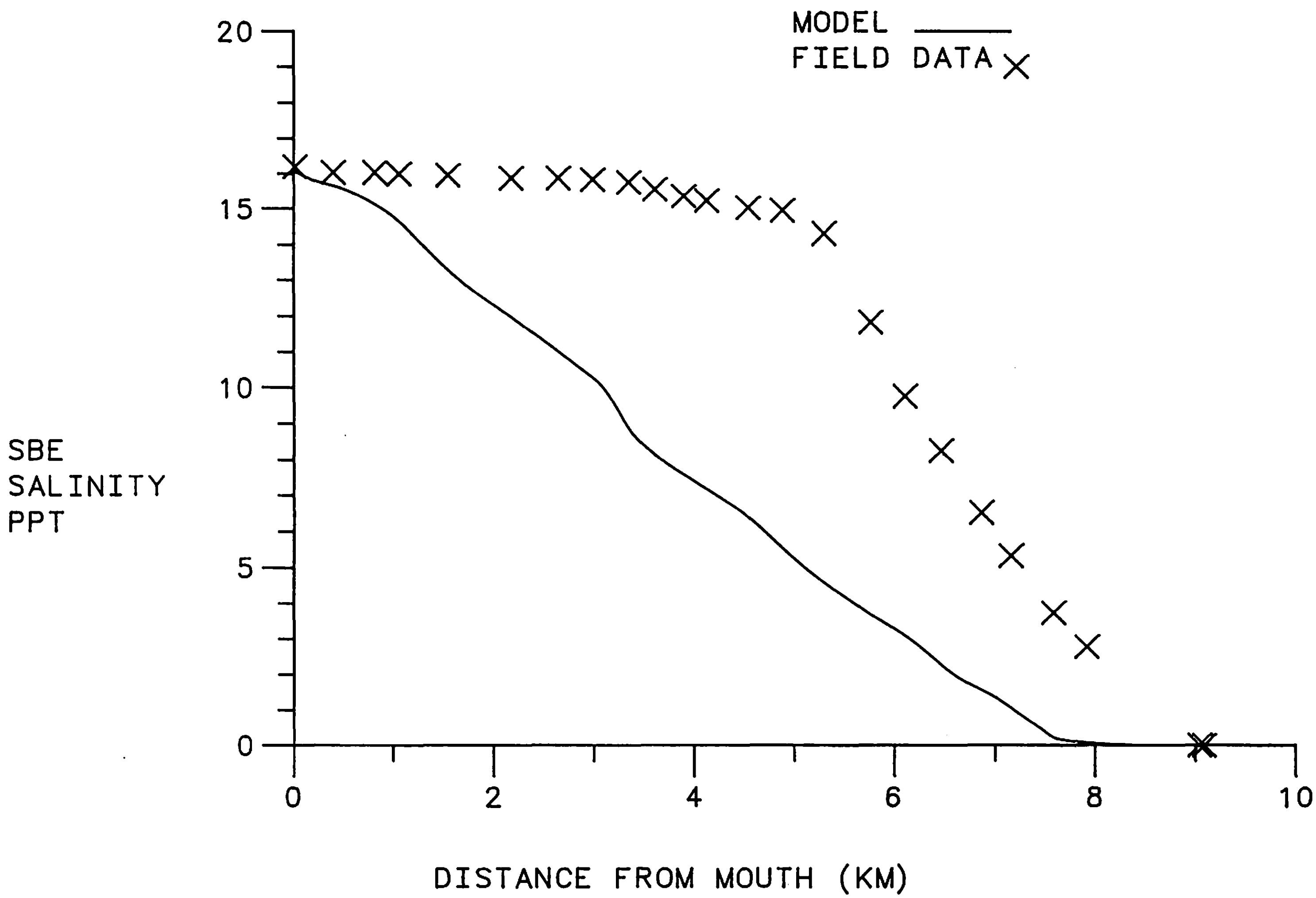
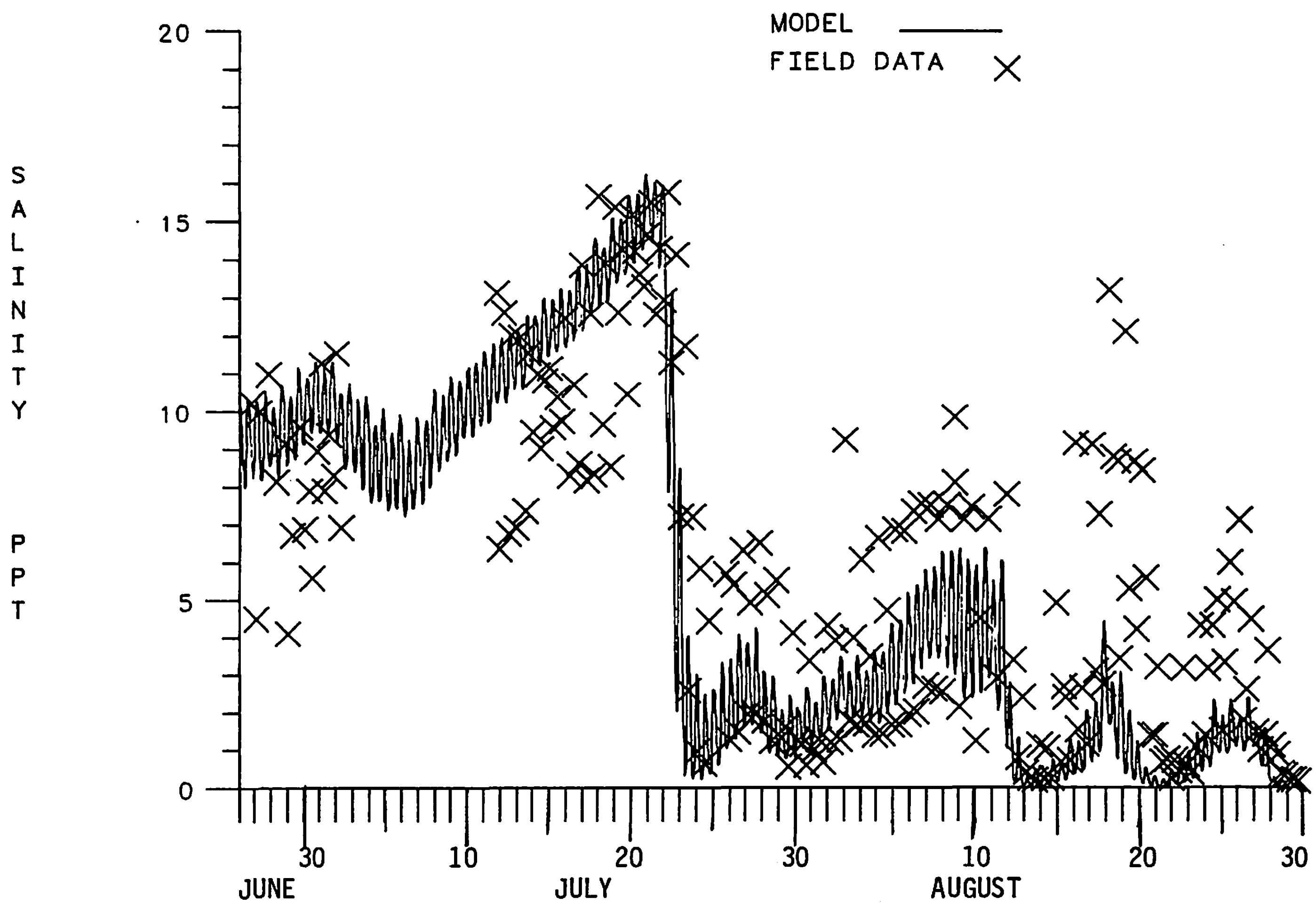

MODEL
FIELD DATA
SBF
SALINITY
PPT
20
15
10
5
0
0
2
4
6
8
10
DISTANCE FROM MOUTH (KM)
SBF 4 SEPTEMBER 1986 WARE CREEK, VA

FIGURE III-9



SBE 4 SEPTEMBER 1986 WARE CREEK, VA

FIGURE III-10



UPSTREAM ISCO, STARTED 26 JUNE 1986

FIGURE III-11

IV. MODEL PREDICTIONS

After the model was calibrated for the hydrodynamics and salinity regimes for the creek as it exists today, the model configuration was changed to include the proposed dam and reservoir. The proposed dam would be located 7.6 km from the creek mouth. The geometry data for this configuration is shown in Table IV-1.

The model was run with a constant inflow for fifty tidal cycles for the model to reach steady-state. The tidal input was the same as that used in the hydrodynamic calibration. The downstream boundary salinity was kept constant at 16 ppt. This is typical of river salinities measured during the summer of 1986.

The proposed minimum release rate for the reservoir is approximately 0.4 MGD. The model was run with inflow at this rate and at half and twice this rate. Figures IV-1 through IV-3 show the tidal average longitudinal salinity distributions with flows of 0.2 MGD (0.00875 m^3/sec), 0.4 MGD (0.0175m^3/sec), and 0.8 MGD (0.0350 m^3/sec).

The model was then run to simulate the average flow condition once the reservoir is filled and the proposed maximum safe yield is withdrawn. The thirty-five year average flow for Beaverdam Swamp is 7.27 ft^3/sec (USGS Water Resources Data, Virginia 1984). The drainage area for Beaverdam Swamp is 6.63 mi^2. The drainage area for the proposed reservoir will be 17.5 mi^2. Therefore, the thirty-five year average flow into the proposed reservoir is estimated to be 19.19 ft^3/sec (12.4 MGD). The proposed maximum safe yield from the reservoir is 9.4 MGD. The average flow over the dam is estimated to be 3.0 MGD (0.134 m^3/sec). The predicted salinity distribution under this flow regime is shown in Figure IV-4.

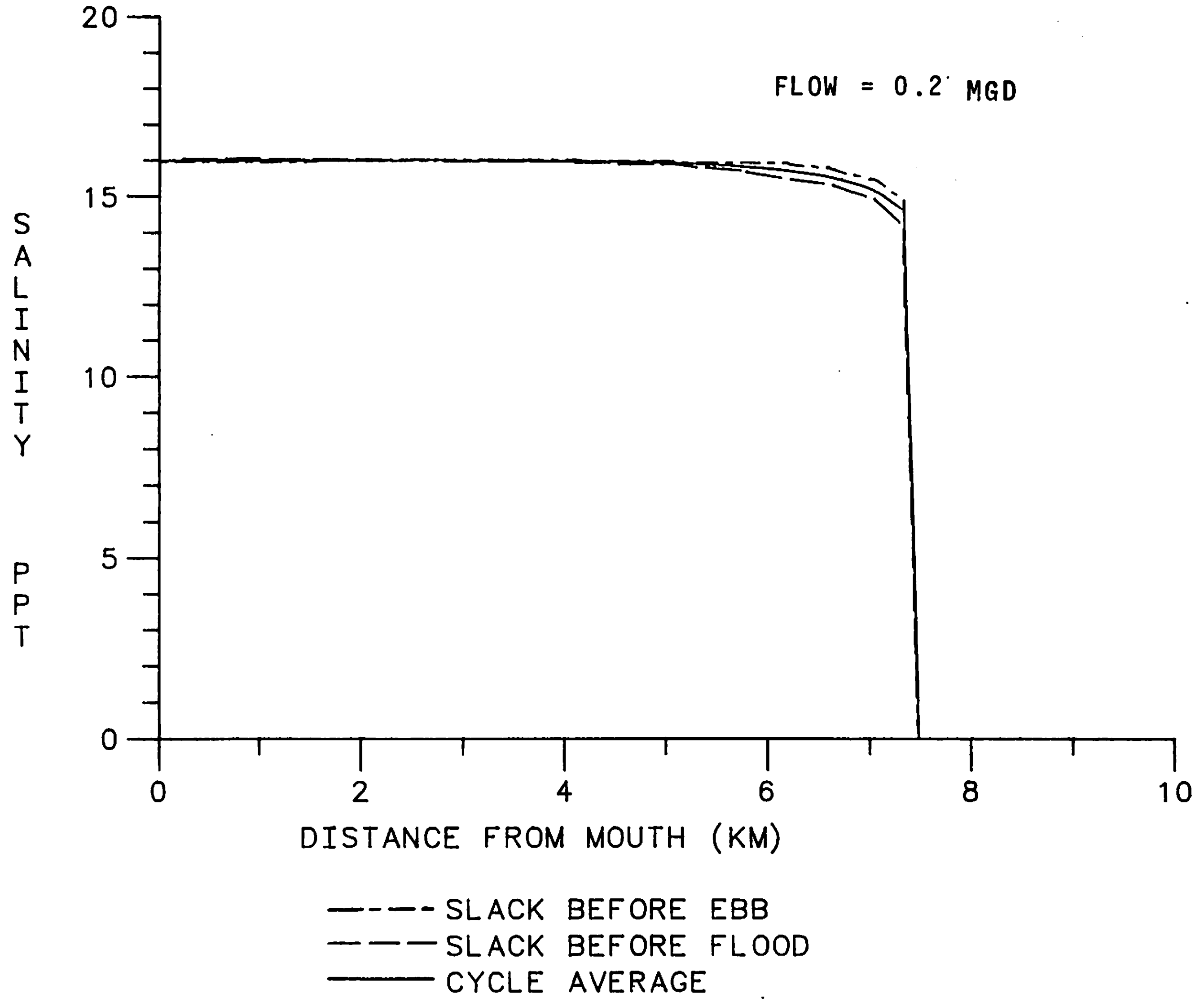
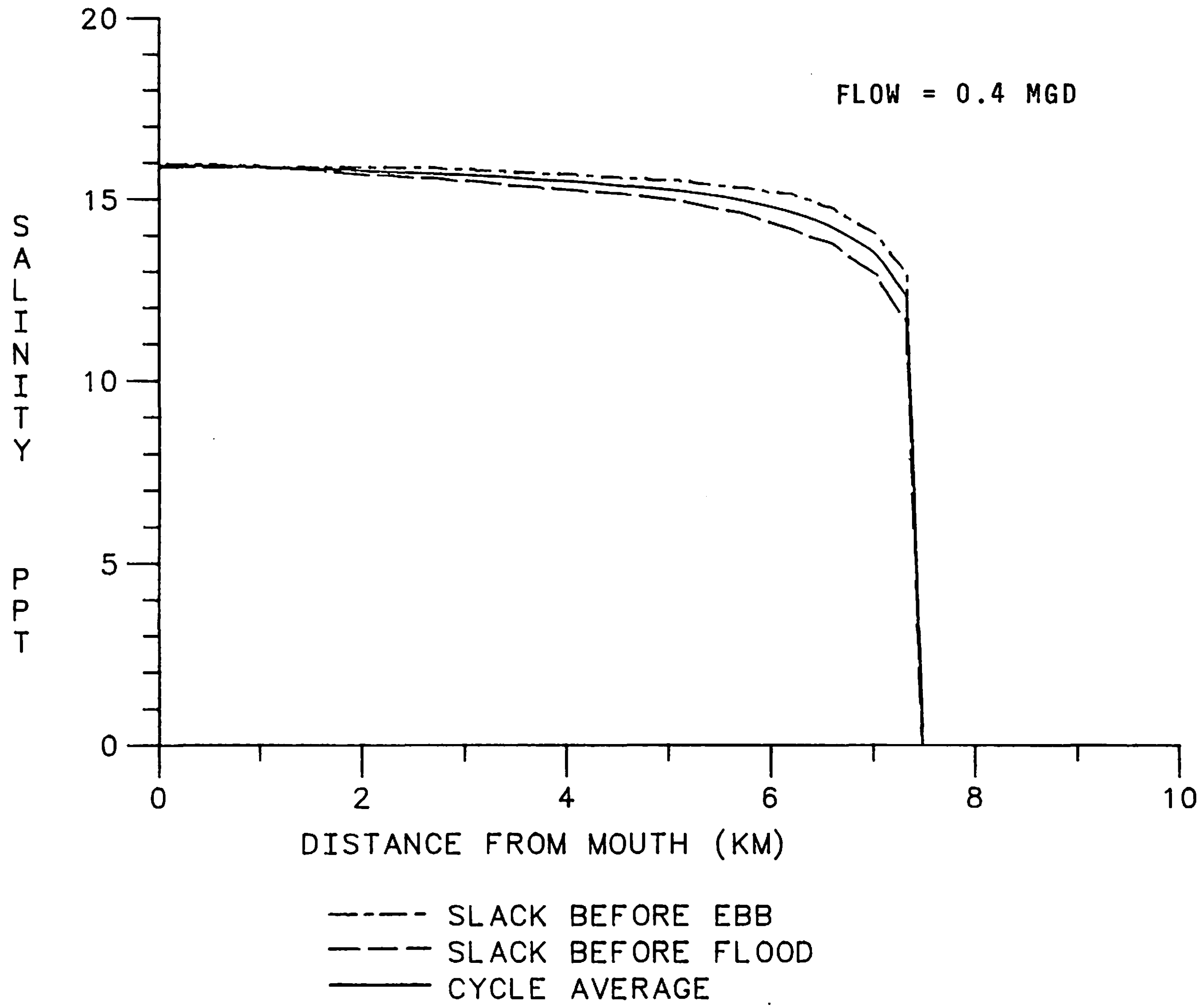

FLOW = 0.2 MGD
SALINITY PPT
20
15
10
5
0
0
2
4
6
8
10
DISTANCE FROM MOUTH (KM)
SLACK BEFORE EBB
SLACK BEFORE FLOOD
CYCLE AVERAGE

FIGURE IV-1



FLOW = 0.4 MGD
SALINITY PPT
20
15
10
5
0
0
2
4
6
8
10
DISTANCE FROM MOUTH (KM)
SLACK BEFORE EBB
SLACK BEFORE FLOOD
CYCLE AVERAGE

FIGURE IV-2

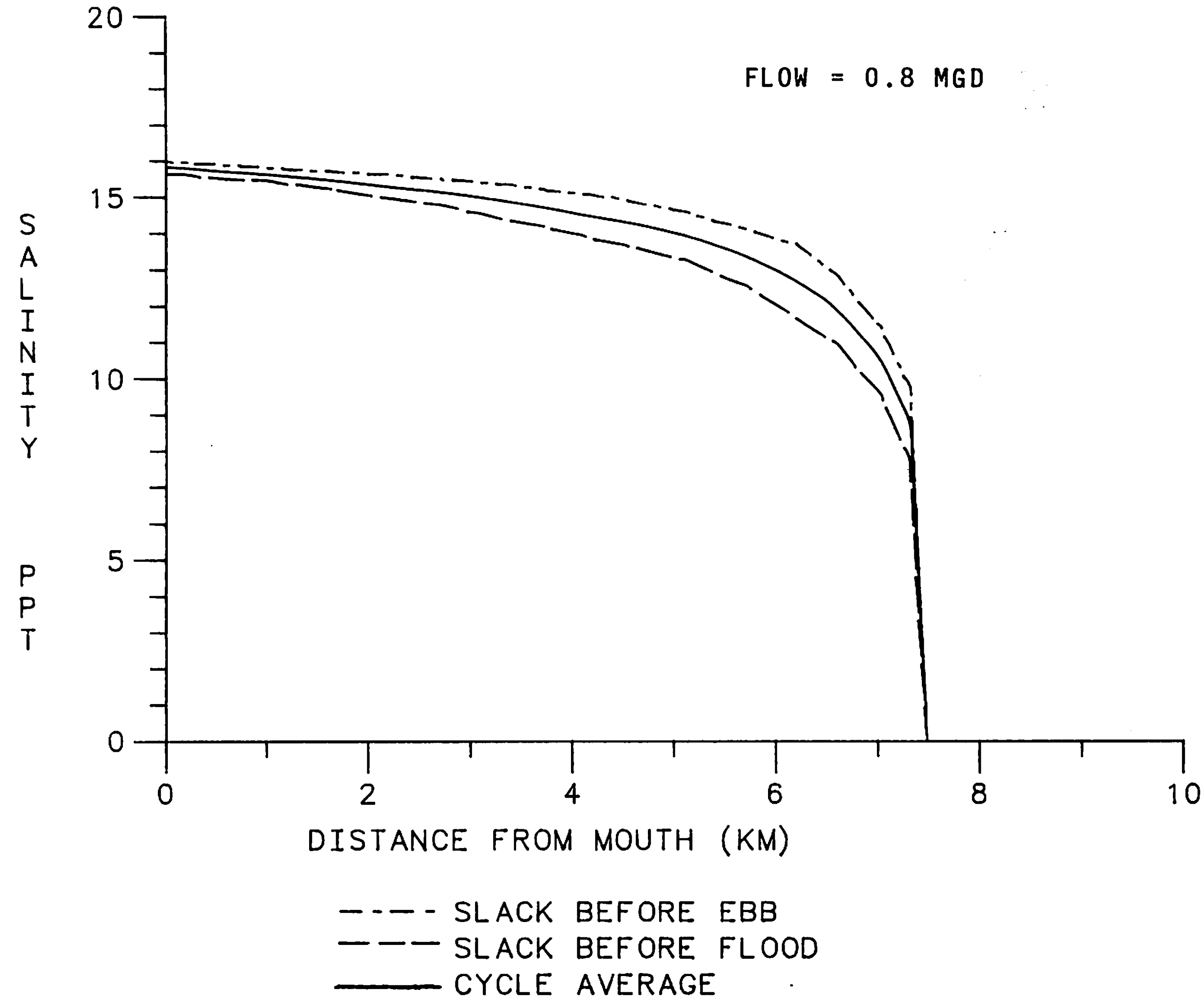

FLOW = 0.8 MGD
SALINITY PPT
20
15
10
5
0
0
2
4
6
8
10
DISTANCE FROM MOUTH (KM)
SLACK BEFORE EBB
SLACK BEFORE FLOOD
CYCLE AVERAGE

FIGURE IV -3

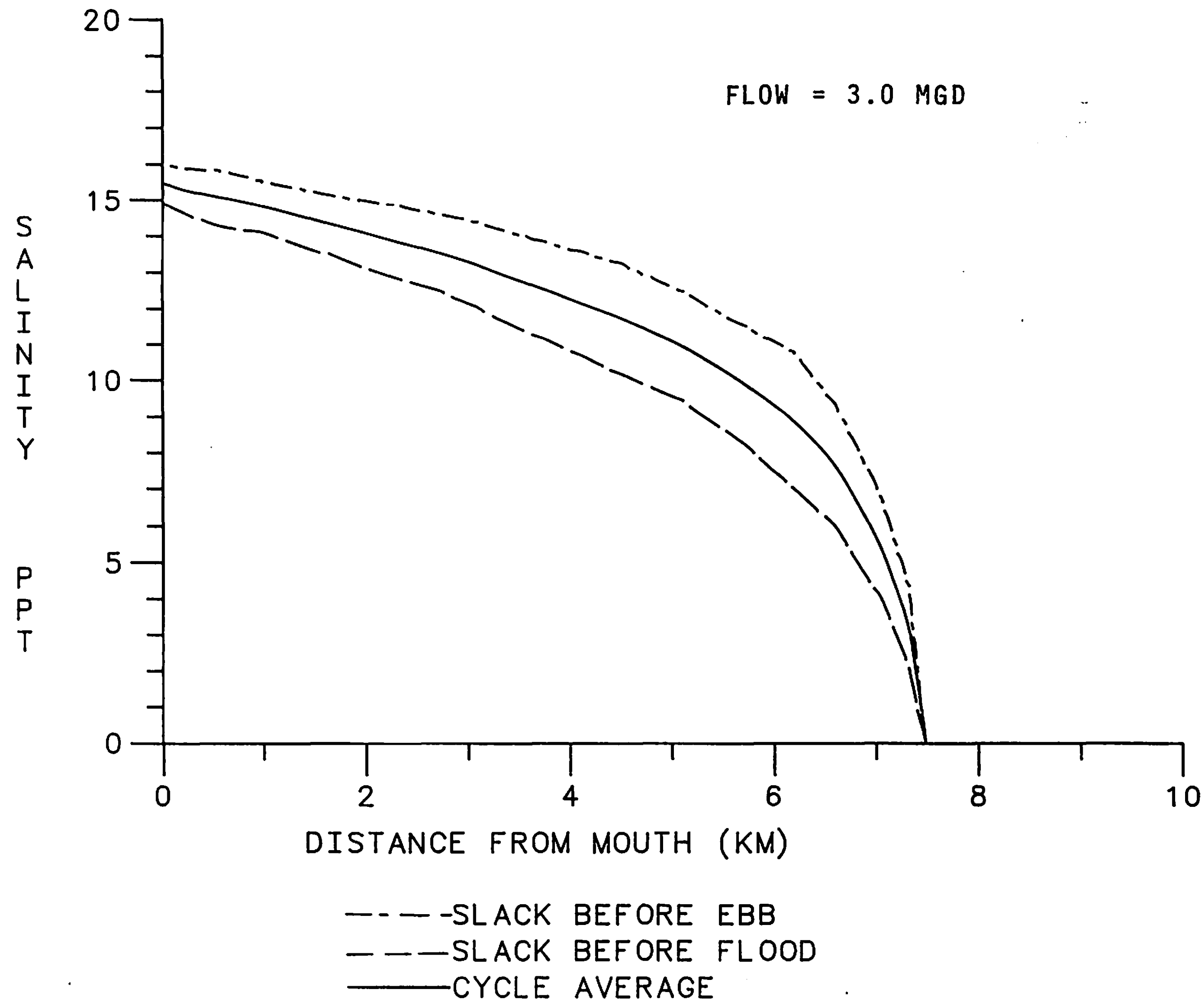

FLOW = 3.0 MGD
SALINITY PPT
20
15
10
5
0
0
2
4
6
8
10
DISTANCE FROM MOUTH (KM)
SLACK BEFORE EBB
SLACK BEFORE FLOOD
CYCLE AVERAGE

FIGURE IV-4

TABLE IV-1

GEOMETRIC DATA FOR MODEL WITH PROPOSED DAM

SEGMENT NUMBER	DISTANCE FROM MOUTH (KM)	WIDTH (M)	CROSS-SECTION AREA (M^2)	SURFACE AREA (10^3M^2)	VOLUME (10^3M^3)	DRAINAGE AREA (KM^2)	DEPTH CENTER OF MOMENT (M)
2	7.58	23.0	17.9	3.85	3.40	1.00	0.52
3	7.41	22.3	22.1	3.76	3.94	0.00	0.85
4	7.24	21.9	24.2	9.61	10.11	0.00	0.92
5	6.83	25.0	25.1	10.90	12.29	0.00	0.68
6	6.36	21.4	27.2	7.20	10.08	0.00	0.82
7	6.00	18.6	28.8	10.86	15.35	0.00	1.14
8	5.45	20.9	27.0	15.65	18.13	0.00	0.95
9	4.75	23.8	24.8	10.90	12.89	0.00	0.76
10	4.27	21.6	28.9	7.87	11.61	0.00	0.85
11	3.89	19.8	32.2	7.51	12.92	0.00	0.92
12	3.53	21.9	39.6	6.36	11.90	0.00	1.12
13	3.25	23.5	45.4	7.57	14.78	0.00	1.34
14	2.92	22.4	44.2	9.55	19.12	0.00	1.45
15	2.48	21.0	42.7	10.26	20.39	0.00	1.52
16	2.03	24.6	47.9	21.92	41.44	0.00	1.38
17	1.24	30.9	57.0	16.64	30.29	0.00	1.19
18	0.71	31.9	57.3	10.98	20.81	0.00	1.13
19	0.42	43.8	86.2	22.01	44.98	0.00	1.45
20	0.0	61.0	128.0			0.00	1.68

REFERENCES

Wilber, A. C. (1986) **Formulation of a Longitudinal Dispersion Coefficient in Partially Mixed Estuaries and Application in a One-Dimensional Real-Time Model.** Thesis. Virginia Institute of Marine Science, College of William and Mary in Virginia.

Williams, S. A. and Kuo A. Y. (1984) **Water Quality Studies of Little Hunting Creek.** Special Report No. 268. Virginia Institute of Marine Science, College of William and Mary in Virginia.

WARE CREEK TIDAL WETLANDS

Potential Responses of the Vegetation Community to Altered Salinity Distributions

A Report To

James City County

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Final Report

21 January 1987

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ABSTRACT

The tidal wetland vegetation of Ware Creek was inventoried during the summer of 1986. Comparisons of the 1986 vegetation patterns with those documented by inventories conducted in 1979 and 1980 indicated the composition of the vegetative community may be changing through time. The observed changes are deemed consistent with hypothesis that the vegetation community will respond to changes in salinity distribution within the Ware Creek system. Using information available on salinity tolerances of dominant plant species within the Ware Creek system, the impacts of reservoir construction and consequent modification of salinity distributions are predicted. The principal impacts are anticipated to include loss of the tidal freshwater vegetation and reduction or elimination of the oligohaline assemblage.

I. CURRENT STATUS

The tidal portion of the Ware Creek drainage basin supports approximately 490 acres of vegetated wetlands. As a whole the plant community is relatively diverse containing at least 26 relatively common species (see Table 1). At present these areas can be divided into four general types on the basis of species composition and dominance. For purposes of this report, we have classified them as mesohaline 1, mesohaline 2, oligohaline and tidal freshwater (Figure 1). This classification reflects the fact that the types are arrayed along the salinity gradient from the mouth to headwaters of Ware Creek.

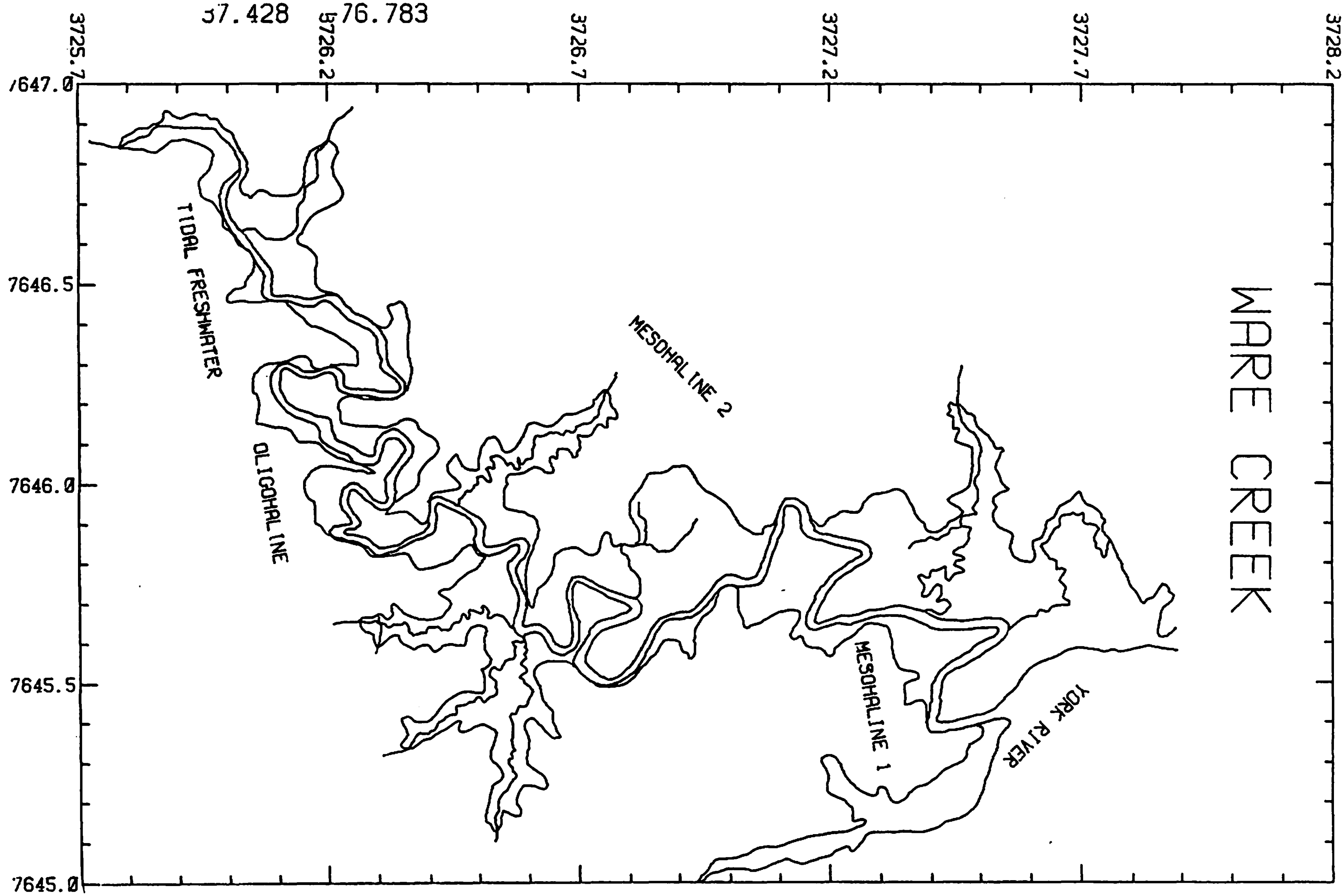
Delineation of the areal extent of each type of marsh is dependent upon determination of dominant vegetation patterns (e.g. Wass and Wright, 1965), and the presence or absence of indicator species (e.g. Anderson et al, 1968). The composition and dominance patterns for each type of wetlands are detailed in Table 2. Mesohaline 1 wetlands are located at the mouth of Ware Creek and extend upstream approximately 2.5 kilometers. These wetlands contain several species but are dominated by *Spartina alterniflora* Mesohaline 2 wetlands also contain many of the same species, but *Spartina cynosuroides* becomes dominant in this type. These wetlands currently extend from the 2.5 kilometer point to approximately the 5.5 kilometer point along Ware Creek. The oligohaline wetlands are typified by the occurrence of species with low salinity tolerance (typically 6ppt and less). In this system *Peltandra virginica* and *Rumex verticillatus*

TABLE 1. Annotated plant list with respective salinity ranges (modified from Kadlec and Wentz, 1974; Odum et al., 1984) of the Ware Creek wetlands. M1=mesohaline *Spartina alterniflora* dominated marsh, M2=mesohaline *Spartina cynosuroides* dominated marsh, OM=oligohaline marsh, TF=tidal freshwater marsh.

SPECIES	SALINITY RANGE(ppt)	WETLAND TYPES			
		M1	M2	OM	TF
Acer rubrum	0.5	-	-	-	T
Amaranthus cannabinus	0-25	-	T	T	T
Amelanchier sp.	* <1	-	-	-	T
Atriplex patula	6->25	T	-	-	-
Cephalanthus occidentalis	0-6	-	-	-	T
Echinocloa spp.	0-6	-	-	-	T
Hibiscus moscheutos	0-25	-	T	T	T
Iva frutescens	0->25	5	T	T	-
Juncus roemerianus	0->25	T	-	-	-
Panicum virgatum	0-10	T	-	-	-
Peltandra virginica	0-10	-	-	T	10
Phragmites communis	0-25	T	T	T	T
Pontederia cordata	0-6	-	-	-	10
Rumex verticillatus	3-7	-	T	10	T
Sagittaria latifolia	0-6	-	-	-	T
Scirpus americanus	0-25	T	25	30	5
Scirpus cyperinus	0-25	-	-	-	T
Scirpus robustus	6-17	T	T	T	-
Scirpus validus	0-6	-	-	-	10
Spartina alterniflora	6->25	65	20	20	T
Spartina cynosuroides	6-25	15	40	30	T
Spartina patens/ *Distichlis spicata*	6->25	10	10	-	-
Typha angustifolia	0-25	-	T	T	T
Typha latifolia	0-25	T	-	T	T
Zizania aquatica	0.5	-	-	T	60
TOTAL NUMBER OF SPECIES		11	11	13	19

*=Personnal observations.

1 .18000 4.051 37.43333
37.428 76.783



3

TABLE 2. Dominant vegetation of the four wetland types of Ware Creek with respective salinity ranges (modified from Kadlec and Wentz, 1974; Odum et al.,1984).

MESOHALINE 1	%COVER	SALINITY RANGE(ppt)
Dominant species:		
Spartina alterniflora	65.0	6->25
Spartina cynosuroides	15.0	6-25
Spartina patens/ Distichlis spicata	10.0	6->25
Iva frutescens	5.0	6->25
Subdominant species:		
Atriplex patula	<1.0	6->25
Juncus roemerianus	<1.0	0->25
Panicum virgatum	<1.0	0-10
Phragmites communis	<1.0	0-25
Scirpus robustus	<1.0	6-17
Scirpus americanus	<1.0	0-25
Typha latifolia	<1.0	0-25

MESOHALINE 2		
Dominant species:		
Spartina cynosuroides	40.0	6-25
Scirpus americanus	25.0	0-25
Spartina alterniflora	20.0	6->25
Spartina patens/ Distichlis spicata	10.0	6->25
Subdominant species:		
Amaranthus cannabinus	<1.0	0-25
Hibiscus moscheutos	<1.0	6-25
Iva frutescens	<1.0	6->25
Phragmites communis	<1.0	0-25
Rumex verticillatus	<1.0	0-6
Scirpus robustus	<1.0	6-17
Typha angustifolia	<1.0	0-25

TABLE 2(cont.).

OLIGOHALINE	%COVER	SALINITY RANGE(ppt.)
Dominant species:		
Spartina cynosuroides	30.0	6-25
Scirpus americanus	30.0	0-25
Spartina alterniflora	20.0	6->25
Rumex verticillatus	10.0	0-6
Subdominant species:		
Amaranthus cannabinus	<1.0	0-25
Hibiscus moscheutos	<1.0	6-25
Iva frutescens	<1.0	6->25
Peltandra virginica	<1.0	0-6
Phragmites communis	<1.0	0-25
Scirpus robustus	<1.0	6-17
Typha angustifolia	<1.0	0-25
Typha latifolia	<1.0	0-25
Zizania aquatica	<1.0	0-6
TIDAL FRESHWATER		
Dominant species:		
Zizania aquatica	60.0	0-6
Pontederia cordata	10.0	0-6
Scirpus validus	10.0	0-6
Peltandra virginica	10.0	0-6
Scirpus americanus	5.0	0-25
Subdominants:		
Amaranthus cannabinus	<1.0	0-25
Acer rubrum	<1.0	0.5
Amelanchier sp.	<1.0	*<1
Cephalanthus occidentalis	<1.0	0-6
Echinocloa spp.	<1.0	0-6
Hibiscus moscheutos	<1.0	6-25
Phragmites communis	<1.0	0-25
Rumex verticillatus	<1.0	0-6
Sagittaria latifolia	<1.0	0-6
Scirpus cyperinus	<1.0	0-25
Spartina alterniflora	<1.0	0->25
Spartina cynosuroides	<1.0	0-25
Typha angustifolia	<1.0	0-25
Typha latifolia	<1.0	0-25

*= personnal observations.

served as indicators. At present this type of wetland occupies the area between creek kilometer 5.5 and kilometer 6.5. Above kilometer 6.5 the wetlands support a significantly different assemblage of species, most of which cannot tolerate salinities in excess of 6ppt. In Ware Creek, the headwaters or tidal freshwater area is identified by the appearance of *Zizania aquatica*, *Acer rubrum* and *Amelanchier* sp., all of which have salinity tolerances below 0.5ppt (Anderson et al, 1968; Kadlec and Wentz, 1974; Odum et al, 1884).

Of the 26 wetland species identified in the Ware Creek marshes, only four were found in all four wetland types. Each of the ubiquitous species (*Spartina alterniflora*, *S. cynosuroides*, *Scirpus americanus* and *Phragmites communis*) tolerate salinities of 25ppt or greater. Three species were unique to the mesohaline 1 wetlands, eight to the tidal freshwater wetland and none to the mesohaline 2 nor oligohaline wetlands. Two of the unique species of the mesohaline 1 wetland, *Atriplex patula* and *Juncus roemerianus*, have high salinity tolerances, while the third, *Panicum virgatum*, is the only component of the assemblage with a low salinity tolerance (0 to 10ppt). In comparison, all the unique species of the tidal freshwater system, except *Scirpus cyperinus*, can only tolerate low salinities (<7ppt, Kadlec and Wentz,1974; Odum et al, 1984).

On the basis of the composition and specific salinity tolerances of the various wetland types it is evident that the mesohaline wetland types would be relatively stable in the presence of long term salinity level increases. On the other hand, the tidal freshwater wetlands would be particularly susceptible to any persistent increase in salinity.

II. HISTORICAL TRENDS

The intertidal wetlands of Ware Creek were surveyed and described as part of the wetland inventories of James City County (Moore, 1980) and New Kent County (Doumlele, 1979). The field work in both cases was performed during 1977, approximately nine years ago. At that time the wetlands vegetative community types ranged from a typical brackish water mixed community at the mouth of Ware Creek to a typical freshwater mixed community at the headwaters of the creek.

The wetlands were reinventoried in August 1986. While the general pattern of distribution remains the same, there are some notable compositional changes indicative of a trend toward increasing salinities in the creek. The principal observed changes occur in two reaches. At the mouth, the marshes along the first 2.5 kilometers of the creek now contain a larger proportion of *Spartina alterniflora* than was present nine years ago. Between creek kilometer 3.5 and kilometer 6.5 the population of *Peltandra virginica* has decreased (apparently retreating upstream) and the population of *Spartina cynosuroides* has increased (apparently spreading upstream). This change is indicative of a contraction of the oligohaline reach in the creek (that reach with average salinities between 0.5ppt and 5.0ppt).

It is noteworthy that the tidal freshwater portion of the creek, as indicated by vegetative composition, has not changed. This reach begins at about the 6.5 kilometer point and extends to the headwaters.

We do not know whether the pattern of change in plant distribution represents a trend which may extend beyond the end points of our observation period. The distribution of plant species may be expected to correspond to salinity distribution in an otherwise homogeneous system, assuming a uniform supply of propagules. Consequently, in Ware Creek, the plant communities can reasonably be expected to reflect long term salinity patterns and the changes we have observed over a nine year period should therefore indicate contemporaneous trends in salinity distributions.

Some corroboration of the assumption that alteration of vegetation patterns in the Ware Creek system are driven primarily by long term changes in the salinity distribution can be found in review of local rainfall records. To the extent that rainfall may indicate trends in runoff and therefore be correlated positively with salinity levels, the rainfall in the Ware Creek area over the last nine years should have been generally below average. This would indicate potential increases in salinity levels in the creek over the same time period, and correspond to the observed changes in vegetation patterns. In fact, local rainfall during spring and summer months (April through September) from 1977 to 1986 has generally been below, and frequently well below, the average of 24.08 inches (based on the thirty year period from 1951 through 1980).

POTENTIAL WETLAND IMPACTS OF RESERVOIR CONSTRUCTION

Construction of the proposed reservoir will directly impact the flow of freshwater into Ware Creek, altering salinity distributions as presented in other sections of this report. Basically the long term average salinities are predicted to increase, most markedly in the headwaters of the creek. In order to evaluate the impact of this change on the distribution of wetland vegetation types, we have applied a simple model developed by van der Valk (1981). The model is a conceptual approach to the depiction of allogenic succession in a vegetated system. Utilization of the model requires identification of an environmental parameter which allows or inhibits growth of plant species in the system. In the model the parameter serves as a "sieve" which controls the establishment of species following alteration of the system. The successional model also requires consideration of the life histories of plants (e.g. under what conditions can the propagules survive and germinate, and what modes of reproduction are important) and evaluation of the source of propagules (e.g. assessment of the seed bank).

Application of the successional model to Ware Creek required several steps. First, the salinity tolerance ranges for the dominant species in each general vegetation type were identified. Second, the predicted change in average salinities for the reach inhabited by each vegetation type was determined. This information is presented in Figure 2. The conceptual successional model uses this information to predict which species will survive the alteration of the system (in

FIG. 2. Dominant species and their salinity range (modified from Kadlec and Wentz, 1974 and Odum et al., 1984). "I" denotes the maximum salinity tolerance of the least tolerant species. "P" denotes the predicted (new) salinity regime expected due to a decrease in fresh water runoff. The arrow indicates a salinity shift. Only species that have a maximum range at or above "P" would be expected to survive in the latter conditions.

```
MESOHALINE 1                                SALINITY RANGE (ppt.)
(no shift: 16ppt/16ppt)                           I/P
Spartina alterniflora        |      6---------|---------<25
Spartina cynosuroides        |      6---------|-------25
Spartina patens/             |
      Distichlis spicata     |      6---------|---------<25
Iva frutescens               |      6---------|---------<25

MESOHALINE 2                                SALINITY RANGE (ppt.)
(shift from 14ppt to 16ppt)                      I>P
Spartina cynosuroides        |      6-------|-|-------25
Scirpus americanus           |--------------|-|-------25
Spartina alterniflora        |      6-------|-|---------<25
Spartina patens/
      Distichlis spicata     |      6-------|-|---------<25

OLIGOHALINE                                 SALINITY RANGE (ppt.)
(shift from 7ppt to 14ppt)           I ---> P
Spartina cynosuroides        |      6|------|---------25
Scirpus americanus           |-------|------|---------25
Spartina alterniflora        |      6|------|------------<25
Rumex verticillatus          |   3---7      |

TIDAL FRESHWATER                            SALINITY RANGE (ppt.)
(shift from 0.5ppt to 10ppt)  I -----> P
Zizania aquatica             |-0.5     |
Pontederia cordata           |-|----6  |
Scirpus validus              |-|----6  |
Peltandra virginica          |-|--------10
Scirpus americanus           |-|--------|-------------25
```

this case changes in salinity distribution). Figure 3 and Figure 4 present model output for the dominant and subdominant species (respectively) of each general vegetation type in Ware Creek. It is apparent from this analysis that the tidal freshwater and the oligohaline plant assemblages will be most impacted by the predicted changes in salinity distribution.

Propagules for species currently present in the Ware Creek system are assumed to be generally available throughout the system. Therefore establishment of species in any given reach after alteration of the salinity regime will be controlled primarily by the potential survival of the propagules. Figure 5 and Figure 6 present the lists of propagules available in the oligohaline and tidal freshwater reaches of Ware Creek as it currently exists. The figures depict the potential survival of the propagules with respect to the predicted salinity for each reach.

Using this information, we would expect the species composition of each of the four present reaches of Ware Creek to change following construction of the reservoir as detailed in Table 3. Based on the life histories and reproductive modes of the species present in the system, it is anticipated that development of a stable community structure following completion of the reservior would require several years (Odum, 1985). Those species intolerant of the elevated salinities in each reach would probably be lost within a year or two. In the same time period species which reproduce primarily through seed dispersal would be expected to become short term dominants in the headwaters of the creek. These would include species such as <u>Amaranthus cannabinus</u> and <u>Atriplex patula</u>. With time, possibly three

FIG. 3. Conceptual succession model (dominant species).

MESOHALINE 1

Existing Vegetation (order of dominance)	Salinity Before	Salinity After	Predicted Vegetation (order of dominance)
	16ppt	16ppt	
Spartina alterniflora	----------------	--------->	Spartina alterniflora
Spartina cynosuroides	----------------	--------->	Spartina cynosuroides
Spartina patens/ Distichlis spicata	----------------	--------->	Spartina patens/ Distichlis spicata
Iva frutescens	----------------	--------->	Iva frutescens

MESOHALINE 2

Existing Vegetation (order of dominance)	Salinity Before	Salinity After	Predicted Vegetation (order of dominance)
	14ppt	16ppt	
Spartina cynosuroides	----------------	--------->	Spartina cynosuroides
Scirpus americanus	----------------	--------->	Scirpus americanus
Spartina alterniflora	----------------	--------->	Spartina alterniflora
Spartina patens/ Distichlis spicata	----------------	--------->	Spartina patens/ Distichlis spicata

OLIGOHALINE

Existing Vegetation (order of dominance)	Salinity Before	Salinity After	Predicted Vegetation (order of dominance)
	7ppt	14ppt	
Spartina cynosuroides	----------------	--------->	Spartina cynosuroides
Scirpus americanus	----------------	--------->	Scirpus americanus
Spartina alterniflora	----------------	--------->	Spartina alterniflora
Rumex verticillatus	---------------->|		

TIDAL FRESHWATER

Existing Vegetation (order of dominance)	Salinity Before	Salinity After	Predicted Vegetation (order of dominance)
	0.5ppt	10ppt	
Zizania aquatica	---------------->|		
Pontederia cordata	---------------->|		
Scirpus validus	---------------->|		
Peltandra virginica	----------------	--------->	Peltandra virginica(?)
Scirpus americanus	----------------	--------->	Scirpus americanus

FIG. 4. Conceptual succession model (subdominant species).

MESOHALINE 1

Existing Vegetation (alphabetical order)	Salinity Before 16ppt	Salinity After 16ppt	Predicted Vegetation (alphabetical order)
Atriplex patula	----------|	---------->	*Atriplex patula*
Juncus roemerianus	----------|	---------->	*Juncus roemerianus*
Panicum virgatum	----------|	---------->	*Panicum virgatum*
Phragmites communis	----------|	---------->	*Phragmites communis*
Scirpus americanus	----------|	---------->	*Scirpus americanus*
Scirpus robustus	----------|	---------->	*Scirpus robustus*
Typha latifolia	----------|	---------->	*Typha latifolia*

MESOHALINE 2

Existing Vegetation (alphabetical order)	Salinity Before 14ppt	Salinity After 16ppt	Predicted Vegetation (alphabetical order)
Amaranthus cannabinus	----------|	---------->	*Amaranthus cannabinus*
Hibiscus moscheutos	----------|	---------->	*Hibiscus moscheutos*
Iva frutescens	----------|	---------->	*Iva frutescens*
Phragmites communis	----------|	---------->	*Phragmites communis*
Rumex verticillatus	---------->|		
Scirpus robustus	----------|	---------->	*Scirpus robustus*
Typha angustifolia	----------|	---------->	*Typha angustifolia*

OLIGOHALINE

Existing Vegetation (alphabetical order)	Salinity Before 7ppt	Salinity After 14ppt	Predicted Vegetation (alphabetical order)
Amaranthus cannabinus	----------|	---------->	*Amaranthus cannabinus*
Hibiscus moscheutose	----------|	---------->	*Hibiscus moscheutos*
Iva frutescens	----------|	---------->	*Iva frutescens*
Peltandra virginica	---------->|		
Phragmites communis	----------|	---------->	*Phragmites communis*
Scirpus robustus	----------|	---------->	*Scirpus robustus*
Typha angustifolia	----------|	---------->	*Typha angustifolia*
Typha latifolia	----------|	---------->	*Typha latifolia*
Zizania aquatica	---------->|		

FIG. 4(cont.). Conceptual succession model (subdominant species).

TIDAL FRESHWATER

Existing Vegetation (alphabetical order)	Salinity Before 0.5ppt	Salinity After 10ppt	Predicted Vegetation (alphabetical order)
Amaranthus cannabinus	---------------|	--------->	*Amaranthus cannabinus*
Acer rubrum	----------------------->|		
Amelanchier sp.	------------------->|		
Cephalanthus occidentalis	---------->|		
Echinocloa spp.	------------------->|		
Hibiscus moscheutos	-----------------|	--------->	*Hibiscus moscheutos*
Phragmites communis	-----------------|	--------->	*Phragmites communis*
Rumex verticillatus	---------------->|		
Sagittaria latifolia	--------------->|		
Scirpus cyperinus	------------------|	--------->	*Scirpus cyperinus*
Spartina alterniflora	---------------|	--------->	*Spartina alterniflora*
Spartina cynosuroides	---------------|	--------->	*Spartina cynosuroides*
Typha angustifolia	------------------|	--------->	*Typha angustifolia*
Typha latifolia	---------------------|	--------->	*Typha latifolia*

FIG. 5. Available plant propagules and their potential survival in the oligohaline marsh (x=predicted salinity). Only species with a salinity range greater than the predicted salinity of the area would be possible components of a successional system.

```
SPECIES                           SALINITY RANGE
                           .5  5    10   15   20   25
                           _|___|____|____|____|____|_______

Acer rubrum                |.            x
Amaranthus cannabinus      |-------------x-----------
Amelanchier sp.            |.            x
Atriplex patula            |      -------x-----------
Cephalanthus occidentalis  |------       x
Echinocloa spp.            |------       x
Hibiscus moscheutos        |-------------x-----------
Iva frutescens             |-------------x------------------
Juncus roemerianus         |-------------x------------------
Panicum virgatum           |----------   x
Peltandra virginica        |----------   x
Phragmites communis        |-------------x-----------
Pontederia cordata         |------       x
Rumex verticillatus        |  -----      x
Sagittaria latifolia       |------       x
Scirpus americanus         |-------------x-----------
Scirpus cyperinus          |-------------x-----------
Scirpus robustus           |     --------x---
Scirpus validus            |------       x
Spartina alterniflora      |     --------x------------------
Spartina cynosuroides      |     --------x-----------
Spartina patens/           |
      Distichlis spicata   |     --------x------------------
Typha angustifolia         |-------------x-----------
Typha latifolia            |-------------x-----------
Zizania aquatica           |.            x
                           |____________________________________________
                                |    |    |    |    |
                            .5  5    10   15   20   25
                                  SALINITY RANGE
```

FIG. 6. Available plant propagules and their potential survival in the tidal freshwater marsh (x=predicted salinity). Only species with a salinity range greater than the predicted salinity of the area would be possible components of a successional system.

```
SPECIES                           SALINITY RANGE
                          .5   5    10   15   20     25
                          ____|____|____|____|_____|______
Acer rubrum               |.        x
Amaranthus cannabinus     |---------x---------------

Amelanchier sp.           |.        x
Atriplex patula           |      ---x---------------
Cephalanthus occidentalis |------   x
Echinocloa spp.           |------   x
Hibiscus moscheutos       |---------x---------------
Iva frutescens            |---------x----------------------
Juncus roemerianus        |---------x----------------------
Panicum virgatum          |---------x
Peltandra virginica       |---------x
Phragmites communis       |---------x---------------
Pontederia cordata        |------   x
Rumex verticillatus       |  -----  x
Sagittaria latifolia      |------   x
Scirpus americanus        |---------x----------------
Scirpus cyperinus         |---------x----------------
Scirpus robustus          |     ----x-------
Scirpus validus           |------   x
Spartina alterniflora     |     ----x----------------------
Spartina cynosuroides     |     ----x----------------
Spartina patens/          |
      Distichlis spicata  |     ----x----------------------
Typha angustifolia        |---------x----------------
Typha latifolia           |---------x----------------
Zizania aquatica          |.        x
                          |_________________________________________
                              |    |     |     |     |
                           .5 5    10    15    20    25
                                  SALINITY RANGE
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TABLE 3. Changes in species richness.

TYPE	SPECIES LOST	SPECIES GAINED
Mesohaline 1	none	*H. moschoetos* *S. cyperinus* *T. latifolia*
Mesohaline 2	*R. verticillatus*	*A. patula* *J. roemerianus* *S. cyperinus* *T. latifolia*
Oligohaline	*P. virginica* *R. verticillatus* *Z. aquatica*	*A. patula* *J. roemerianus* *S. cyperinus* *S. patens*/*D.spicata*
Tidal Freshwater	*A. rubrum* *Amelanchier* sp. *C. occidentalis* *Echinocloa* spp. *P. virginica* *P. cordata* *R. verticillatus* *S.latifolia* *S. validus* *Z. aquatica*	*A. patula* *I. frutescens* *J. roemerianus* *S. robustus* *S. patens*/*D. spicata*

to five years, species which reproduce most successfully by vegetative means (e.g. *Spartina alterniflora*, *S. cynosuroides* and *Scirpus americanus*) would be expected to replace the former group as the dominants in the system.

The net result of these changes, predicted on the basis of an altered salinity distribution, would be the loss of the tidal freshwater vegetation from Ware Creek and a great reduction or elimination of the oligohaline assemblage. This impact would be expected for any modification of the inflow of freshwater to Ware Creek which produces average salinities in excess of 5ppt at the headwaters of the tidal creek.

The conclusion that the tidal freshwater wetlands of Ware Creek would be lost and the oligohaline wetlands reduced or eliminated is based on predicted salinity distributions under a regime of 0.4 MGD discharge from the reservoir. Under significantly higher discharge regimes somewhat different impacts may be realized on the downstream vegetation. By way of example, the estimated average flow conditions once the reservoir is filled and the maximum safe yield is withdrawn (i.e. 3.0 MGD) result in predicted headwater salinities much lower than the proposed minimum discharge regime levels. Using these salinity levels to predict vegetation patterns, we would still expect the tidal freshwater assemblage to be lost. The oligohaline assemblage, however, would probably survive, occupying the reach currently containing the tidal freshwater assemblage.

It is important that any interpretation of the foregoing information be cognizant of the following considerations.

1. The vegetation/salinity correlations are based on long-term averages. The effects of short-term variations in salinity on vegetational patterns is not known. Therefore, the vegetation patterns observed in Ware Creek wetlands may be the residual consequences of plant responses to undocumented deviations from average conditions. In the case of the Ware Creek reservoir this raises at least two possibilities. First, short-term fluctuations in salinity levels during the interval between construction of the reservoir and attainment of some steady state operating conditions, may alter or determine the development of down stream vegetational patterns. Second, the reservoir, once operational, may have the effect of dampening the variations in salinity distributions currently found in the Ware Creek system. The proposed minimum discharge level will effectively create a maximum potential salinity level for the headwaters. The result, over long time periods, may be a new physical stability in the system. Theoretically, this consequence would increase the importance of biological interactions and decrease the importance of physical factors in determination os community structure. Our understanding of the system is insufficient at present to forecast the specific results of these changes.

2. Long-term information about community structure in Ware Creek or similar systems is not available. Therefore, we are unable to adequately address the role of natural variability in the system. The nine-year period we are able to document indicates the system may not be in a fixed steady state. The possibility of a dynamic

equilibrium realized over a longer time scale cannot be evaluated, however.

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