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Hydrography and Hydrodynamics of Virginia Estuaries VIII: Mathematical Model Studies of Water Quality of the York River System

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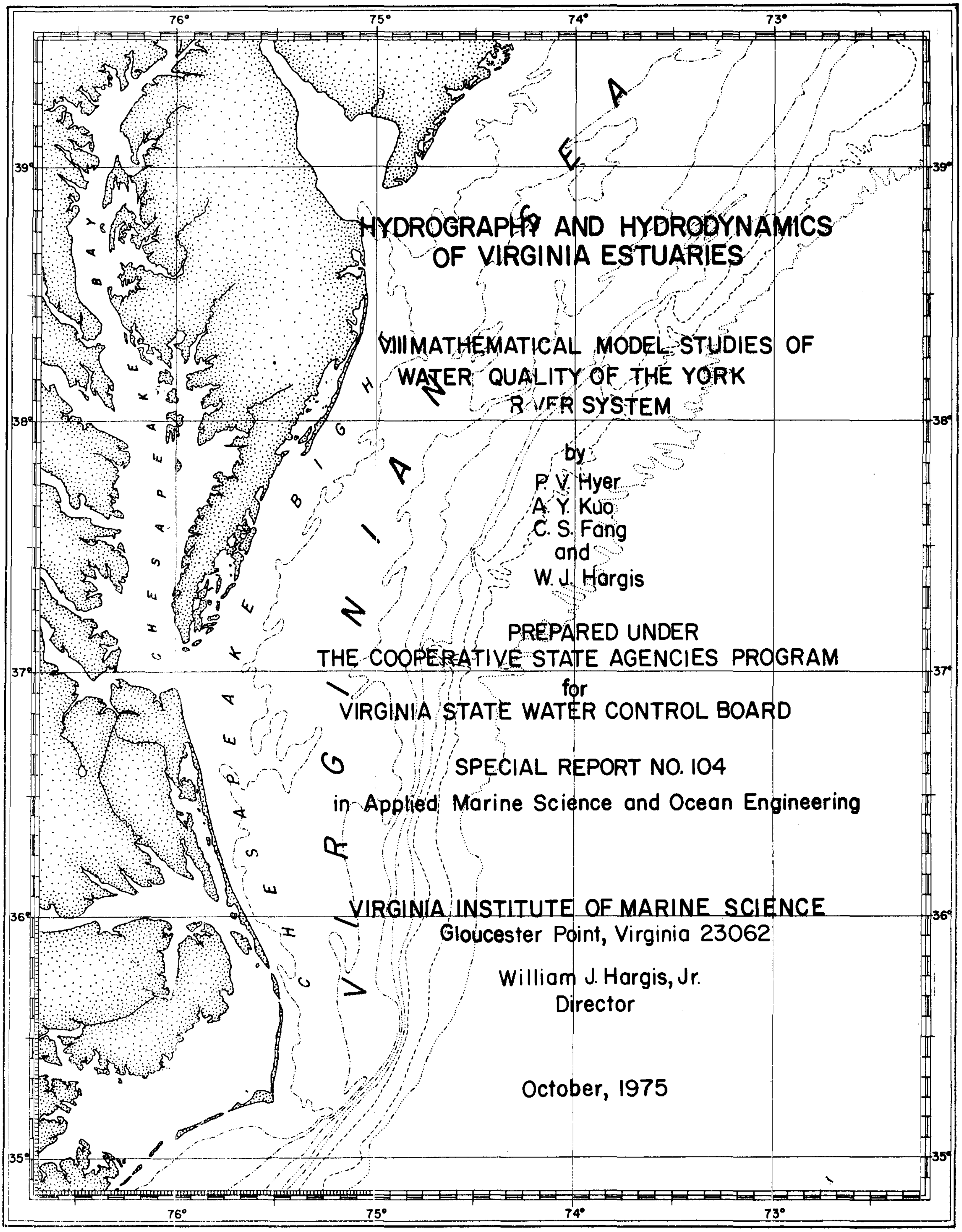

HYDROGRAPHY AND HYDRODYNAMICS OF VIRGINIA ESTUARIES

VIII MATHEMATICAL MODEL STUDIES OF WATER QUALITY OF THE YORK RIVER SYSTEM

by
P. V. Hyer
A. Y. Kuo
C. S. Fang
and
W. J. Hargis

PREPARED UNDER
THE COOPERATIVE STATE AGENCIES PROGRAM
for
VIRGINIA STATE WATER CONTROL BOARD

SPECIAL REPORT NO. 104
in Applied Marine Science and Ocean Engineering

VIRGINIA INSTITUTE OF MARINE SCIENCE
Gloucester Point, Virginia 23062

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TABLE OF CONTENTS

Appendices

LIST OF FIGURES

List of Figures (cont'd)

List of Figures (cont'd)

LIST OF TABLES

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ABSTRACT

Two water quality models were developed, then calibrated and verified using data collected as part of the CSA modeling project.

Intensive hydrographic surveys were conducted along the York estuary in the spring and summer of 1973. Hourly determinations of salinity, temperature, and dissolved oxygen were made for at least thirty-two consecutive hours. Tidal currents were measured at twenty-minute intervals. Monthly slack water runs have been conducted since August, 1970.

From these data, two water quality models were developed, one real-time model and one tidal-average model. The real time model is based on the mass balance equations for salt, BOD and DO, with the convective velocity including both freshwater discharge and tidal current. Taylor's formulation of dispersion coefficient was extended to include the effect of density inhomogeneity in the saline water. The differential equations were solved numerically by an implicit finite-difference scheme using a Gaussian elimination method. In the tidal-average model, the convective velocity consisted of the non-tidal component only. The tidal current was treated as an effective turbulence, making the dispersion term much larger than that of the real time model. The tidal-average model is intended for investigating long-term variations of salinity intrusion.

I. Summary & Conclusions

1. This report concerns the calibration and verification of water quality models for the York River and the data collection and analysis entailed.

2. The York Drainage Basin is relatively unpopulated, and agricultural in nature. Industries include pulp and paper processing, oil refining and fossil-fuel power generation. Recreational water uses are important. The region is characterized by hot summers, relatively dry falls and mild, wet winters.

3. Hydrographic surveys were conducted in April and August 1973, at eight transects in the York plus the mouths of the Mattaponi and Pamunkey. Time series data on salinity, temperature, dissolved oxygen and tidal current were collected at one to three stations on each transect. During the August survey, a batch of dye was released and monitored as it spread.

4. Data on long-term variations were collected by means of monthly or semi-monthly slack water runs. On each slack water run, salinity, temperature, biochemical oxygen demand and dissolved oxygen were sampled at nine transects. Slack water runs were also made at 14 stations on the Mattaponi River and 15 stations on the Pamunkey River.

5. Time-series data from the intensive field surveys reveal tidal periodicity in salinity and dissolved oxygen concentration. Slack water runs data indicate that salinity at

West Point may reach 17.2 ppt in late fall, but decrease to below 1 ppt in spring.

6. In fall, salt water intrudes upstream approximately 26 miles from the mouth of the Pamunkey, near Lester Manor. The upstream limit in the Mattaponi is approximately 19 miles from the mouth, near Mantapike.

7. Critical conditions for oxygen depletion, namely high water temperature and low freshwater discharge were found to occur during the months of August and September. Within one tidal excursion of West Point, dissolved oxygen concentrations as low as 3.5 ppt have been observed. The limited data accumulated since the upgrading of the Chesapeake Corp. treatment facilities in January, 1975 reveal individual measurements of dissolved oxygen concentration below 5.5 parts per million.

8. At the mouth of the York, surface salinity range between 14 parts per thousand and 21 parts per thousand. The range of salinity near the bottom is 16 to 26 parts per thousand. Salinity stratification varies from less than one part per thousand up to eight parts per thousand.

9. Water temperatures in the Mattaponi and Pamunkey, and in the surface layer of the York become quite elevated in the late summer. Near West Point, water temperature in the Pamunkey sometimes approaches 30 degrees centigrade. The winter minimum temperature is about three degrees centigrade, although in some years ice forms on the Mattaponi and Pamunkey.

10. Owing to a combination of thermal and salinity stratification in the reach between the mouth of the York River and the bridge at Gloucester Point, dissolved oxygen concentration below the surface layer tends to be critically low in the summer time. Since the basic assumption of one-dimensional water quality modeling is to ignore such stratification, a two-dimensional model is being developed for the York.

11. A branched-system water quality model was developed for dealing with the Mattaponi, Pamunkey and York as a single system. This model is capable of dealing with four components (salinity, dissolved oxygen, and carbonaceous and nitrogenous biochemical oxygen demand) and includes tidal advection.

12. The intensive survey data of August, 1973 was used to calibrate the model for salinity, dissolved oxygen and biochemical oxygen demand. The model was also calibrated using the results of the dye study which was performed in August, 1973. The water quality model was verified using slack-water run data from September and October, 1970.

13. A branched-system salinity intrusion model was developed for studying the Mattaponi-Pamunkey-York system. This is an inter-tidal model which models tidal mixing by means of a dispersion coefficient.

14. The salinity intrusion model was calibrated and verified using the slack water run data gathered from August 1970 to May 1971.

II. Introduction

The first intensive field survey for the Cooperative State Agencies project was carried out in October, 1969. Time series data for temperature, salinity, dissolved oxygen and tidal current were collected for the Mattaponi and Pamunkey Rivers and a portion of the York. A salinity intrusion model and a water quality model were constructed and verified for this area (Hyer, et al., 1971).

In 1970, the circulation near Yorktown was studied. Alden Laboratories has used these data to construct an hydraulic model of the lower York in order to determine the environmental effects of expanding the Yorktown Generating station. In summer, 1972 slack water runs were made frequently to study the aftermath of Hurricane Agnes (Hyer & Ruzecki, 1974). In 1973, the entire York was surveyed, including stations at the mouths of the Mattaponi and Pamunkey. The field effort satisfied the combined requirements of the CSA modeling project and calibration of the proposed Chesapeake Bay Model.

Water quality and salinity intrusion models were developed employing a more efficient computational method, the implicit scheme. These models were applied to the James (Fang, et al., 1973) and Rappahannock (Kuo, et al., 1975). These models have been modified to deal with branched estuaries and have been applied to the York-Mattaponi-Pamunkey system. The salinity intrusion model is designed to predict high water slack salinity distribution over a time span of several months. The water quality model predicts the distribution of salinity, dissolved oxygen, carbonaceous biochemical oxygen demand and nitrogenous biochemical oxygen demand over a time span of hours to days.

III. Description of Study Area

The tidal portion of the York River watershed has remained relatively rural, with a heavy dependence on farming (chiefly corn and soybeans) and logging. Commercial fishing of oysters, crabs and pelagic fish is also important. Industry is concentrated at both ends of the York. Upstream, at West Point, (see Figure 1) is a pulp and kraft paper mill. Downstream, near the mouth, are an oil refinery and a fossil-fueled electric power plant.

The climate is humid-subtropical. There are approximately 45 inches of rain, of which approximately 12 inches is runoff. Precipitation is lowest between September and January and highest in July and August. Owing to evapotranspiration, however, the heavy thunderstorms of summer have much less effect on fluvial flow than do the rains of spring. Air temperature in January varies from a low of approximately 30°F (-1°C) to a high of 50°F (10°C). In July the mean daily maximum temperature is approximately 88°F (30°C) and the minimum of 68°F (20°C).

The most representative stream gauging stations in the drainage basin are at Hanover, on the Pamunkey and Beulahville on the Mattaponi. The average discharges at these stations are 963 cfs ($27.3 m^3 sec^{-1}$) and 580 cfs ($16.4 m^3 sec^{-1}$) respectively. River discharge tends to be greater than average in the period January - April and much less than average in July - September. The gauging station at Hanover has recorded historical extremes of 40,300 cfs ($1140 m^3 sec^{-1}$) and 12 cfs

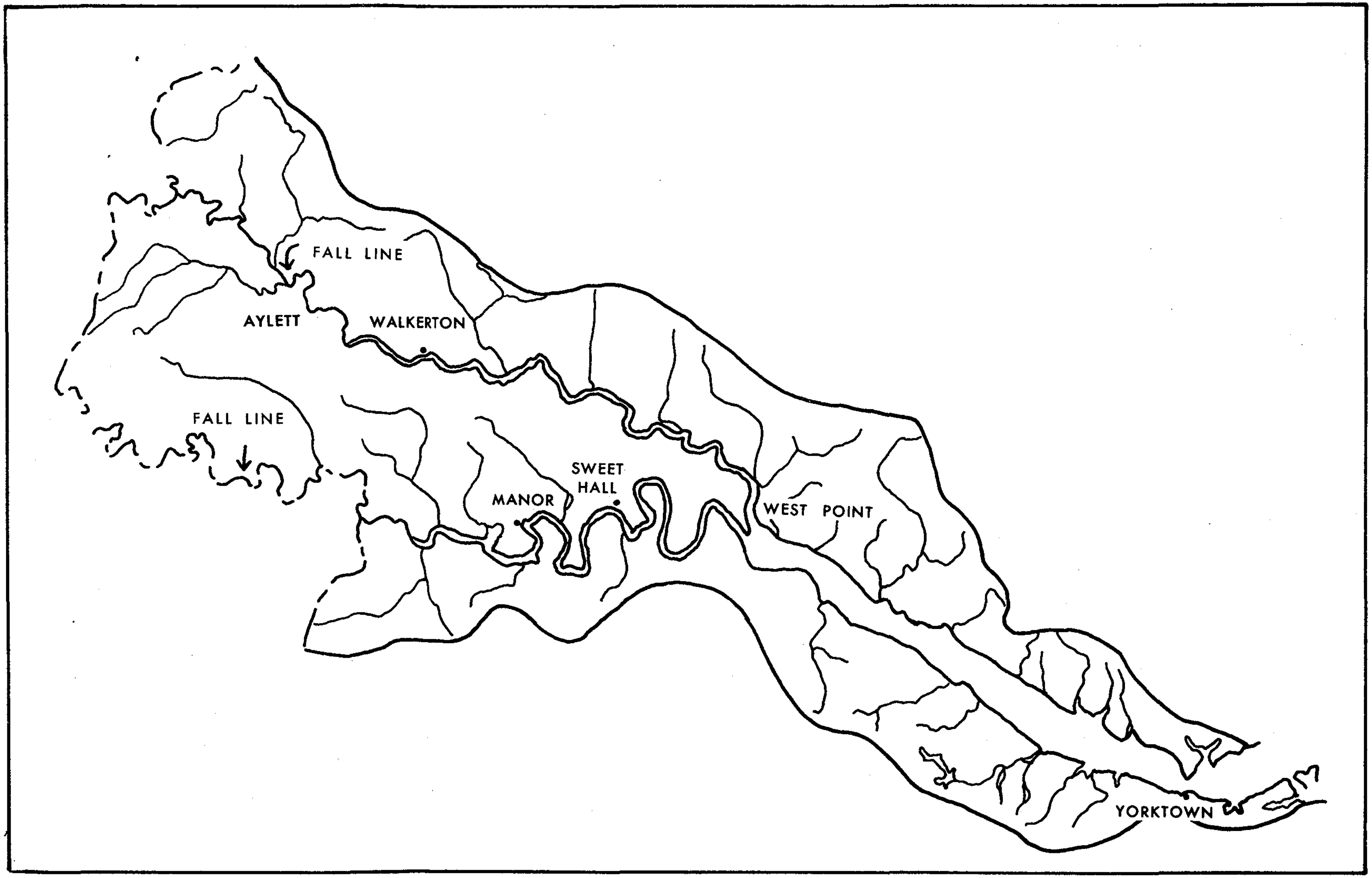


Figure 1. Downstream sub-basin of York drainage basin.

($0.3m^3sec^{-1}$) with extremes at Beulahville of 16,900 cfs ($479m^3sec^{-1}$) and 5.9 cfs ($0.17m^3sec^{-1}$).

Tidal waves propagate upstream at approximately fourteen miles per hour although tidal patterns near the mouth are much more complicated. (See Figure 2). As the tidal wave progresses, its amplitude increases. The mean tidal range is 2.2 ft. (0.7m) at Tue Marshes light and 3.0 feet (0.9m) at West Point. The tide range continues to increase in the tributaries, reaching 3.9 feet (1.2m) at Walkerton in the Mattaponi and 3.3 feet (1.0m) at Northbury in the Pamunkey. Tidal action ceases at the fall line, which is approximately three miles upstream of the Rte. 360 bridge in both the Mattaponi and Pamunkey Rivers. The tidal wave also undergoes a change in phase relationship. At Tue Marsh, low water occurs only about an hour after maximum ebb current, indicating an almost pure traveling wave. At West Point, this time difference is about two hours, indicating a shift toward standing wave characteristics. Average tidal current increases from 1.0 feet per second (30cm/sec) near the mouth to 1.8 feet per second (54cm/sec) near West Point but then decreases to 1.5 feet per second (46cm/sec) at Walkerton and 0.8 feet per second (24cm/sec) at Northbury.

Net tidal prism has been calculated from the intertidal volumes of Cronin (1971). Figures 3 & 4 show net tidal prism versus distance upstream for the York, Mattaponi and Pamunkey, respectively. Although monotonic by definition, the tidal prism curves are not linear, but reflect the changes in tidal amplitude and stream geometry as the observer proceeds upstream.

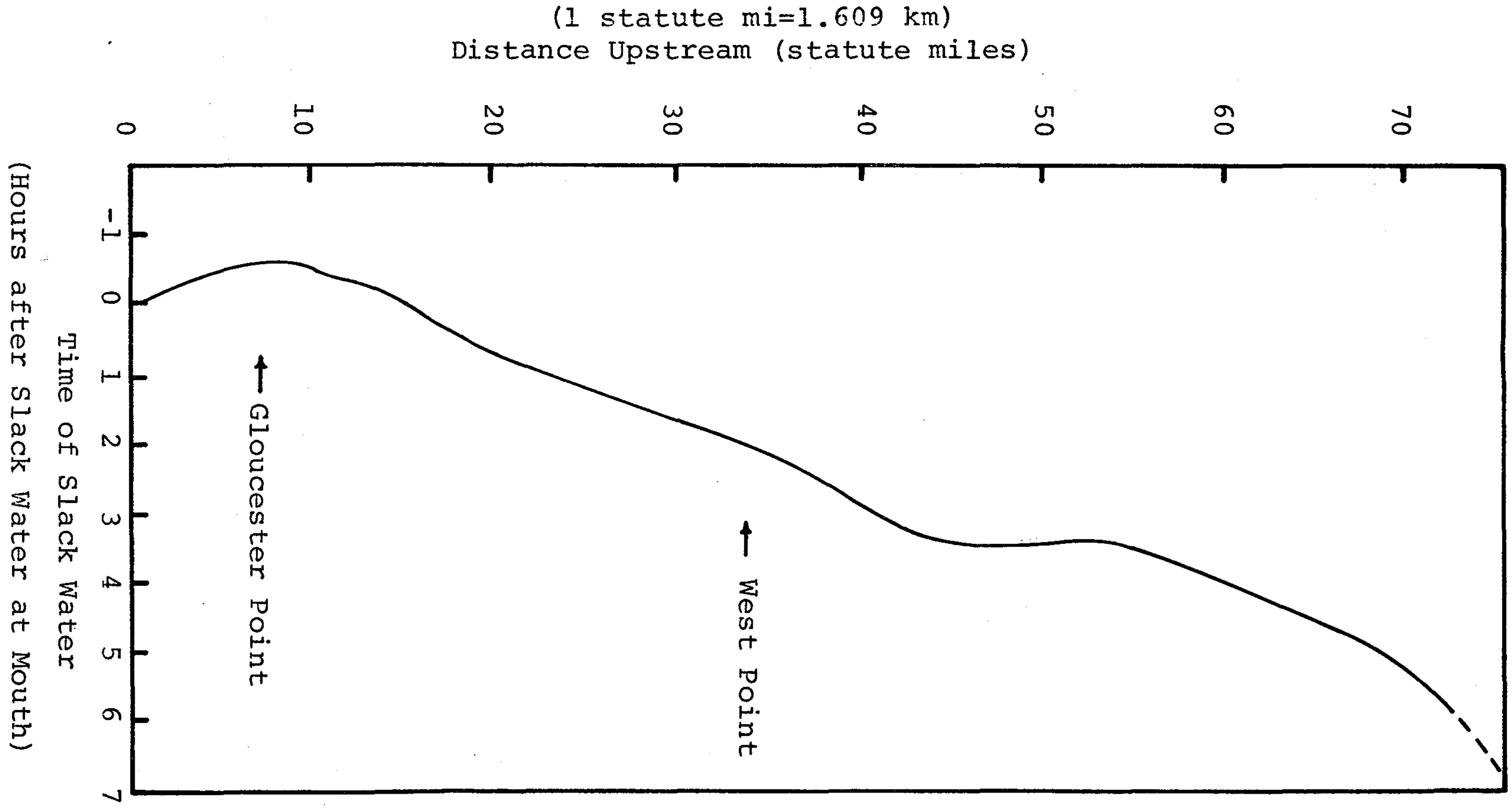


Figure 2. York and Pamunkey time of slack water relative to York River mouth.

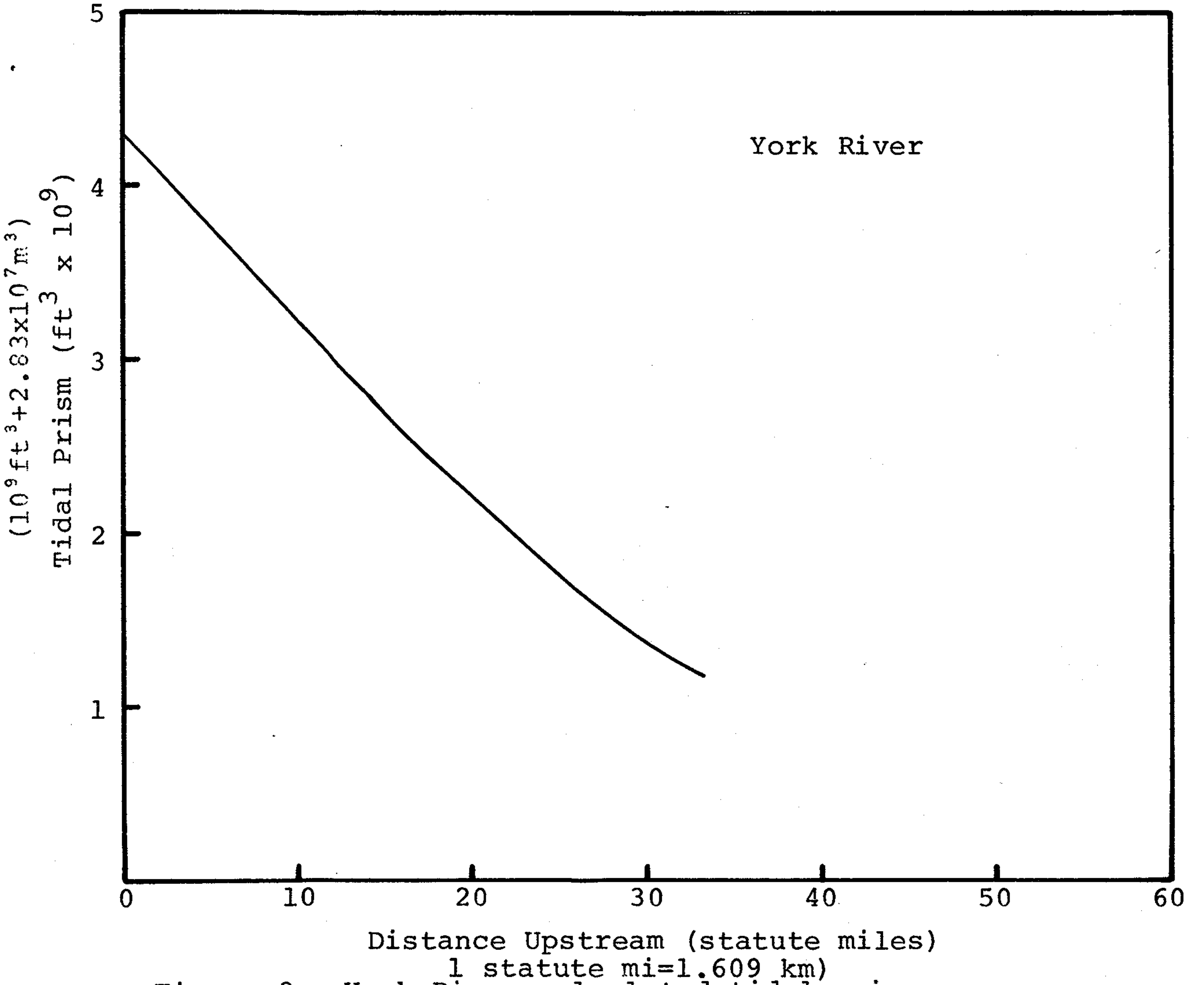


Figure 3. York River calculated tidal prism.

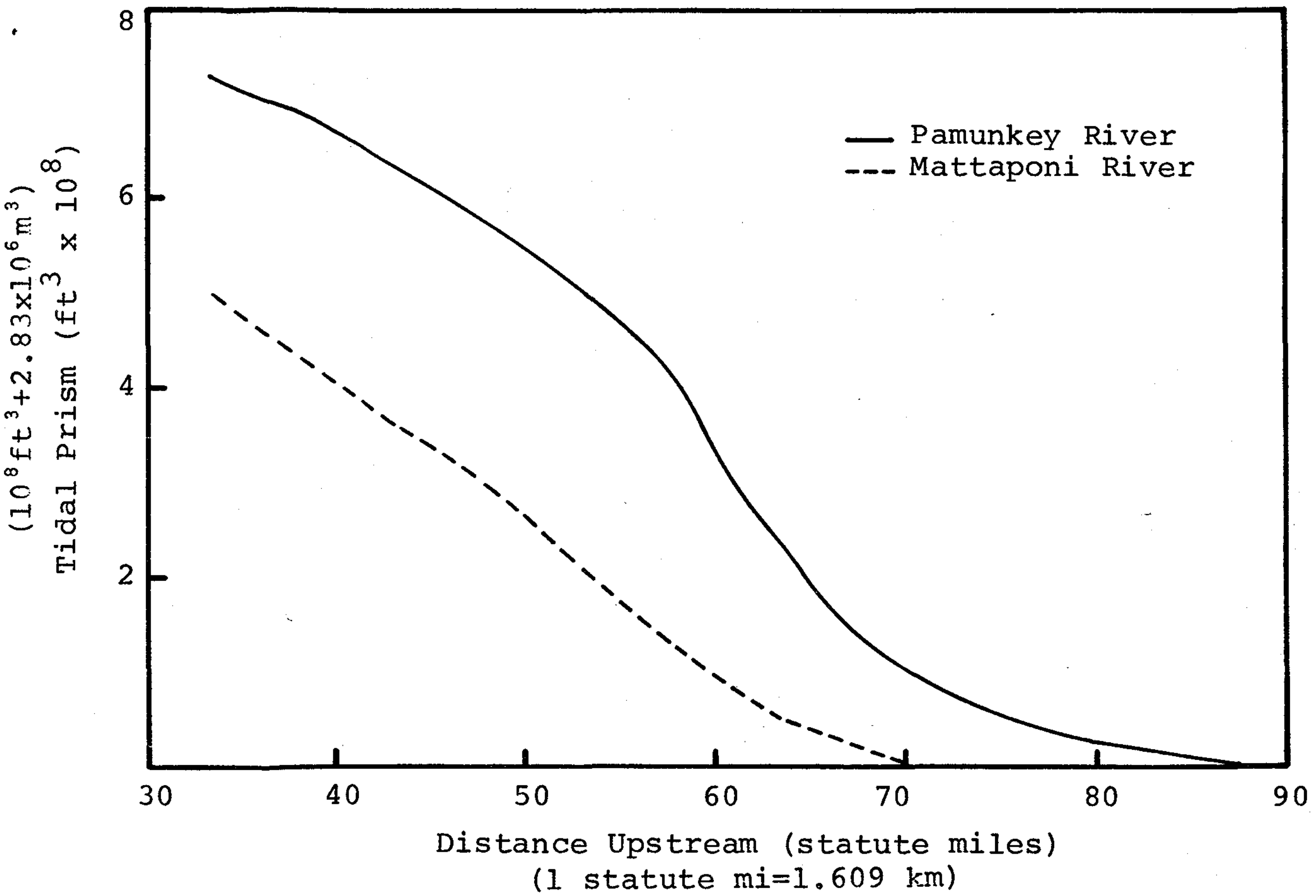


Figure 4. Mattaponi and Pamunkey calculated tidal prism.

IV. HYDROGRAPHIC SURVEY

A. Description of Surveys

In a mathematical model, certain natural phenomena are simulated in order to determine the net result of competition among the phenomena involved. These natural processes in a water body can be divided into two classes - transport and reaction. Transport phenomena are those causing relocation of dissolved or suspended substances without changing them. In estuarine systems, transport phenomena include advection by the mean flow, tidal current and dispersion by turbulent motion. Reaction processes are those that result in the creation or destruction of some substance. In modeling of dissolved oxygen, reaction processes include atmospheric reaeration, photosynthesis, respiration of plants and biochemical decay. Both reaction and transport processes must be determined in order to build accurate mathematical models.

A variety of field projects was conducted in order to provide the necessary data. Time-series anchor stations were made in April, 1973 and again in August, 1973 for the length of the York River. Three stations were manned on each of the ten transects (figure 5) for three days and one night. Samples were taken hourly from surface to bottom at two-meter intervals. Dissolved oxygen and dye samples were taken and conductivity and temperature measurements were made at each sample depth. A vertical array of current meters was anchored at each sampling station. These meters recorded average speed and direction over twenty-minute intervals. The meters were put

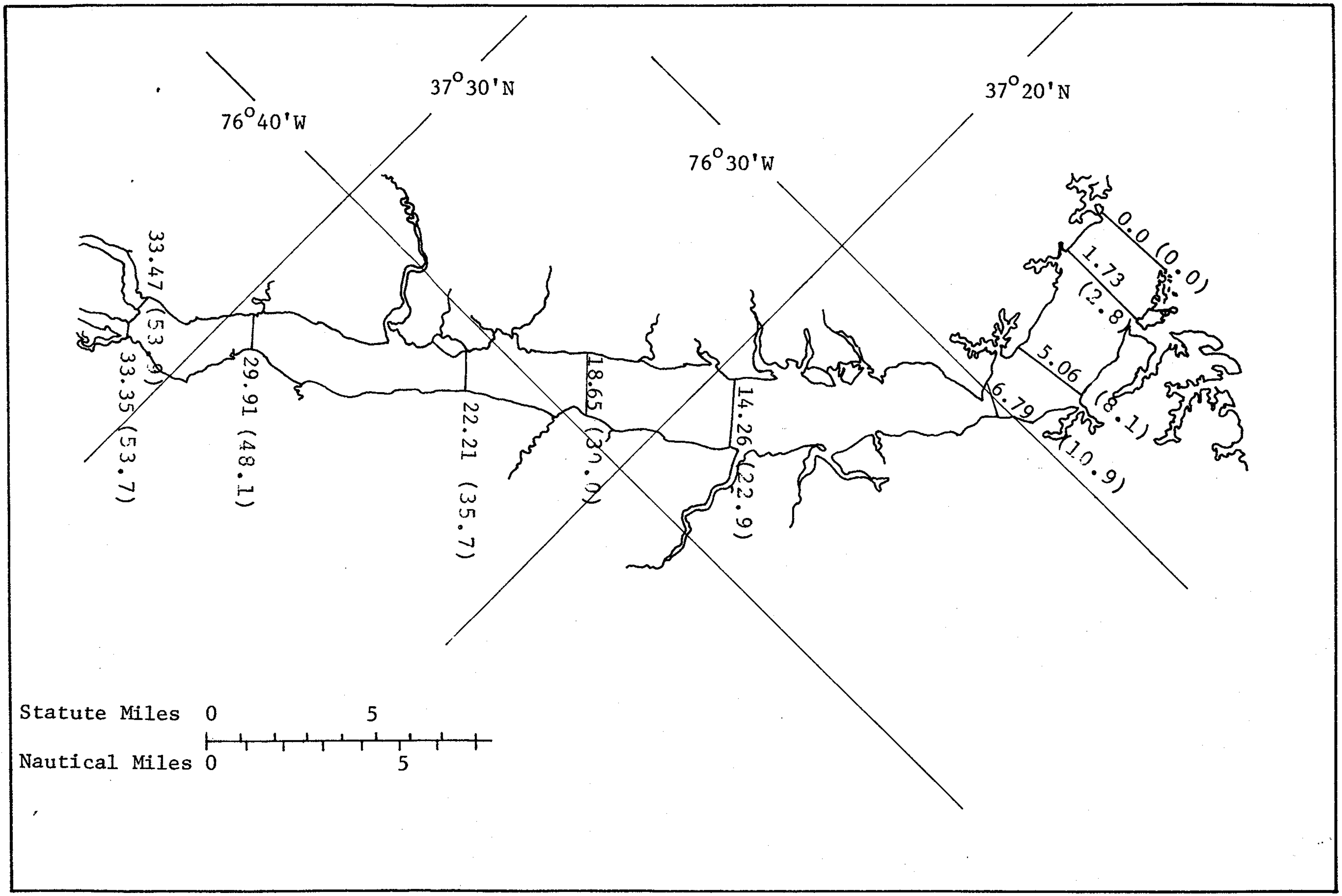


Figure 5.—Location of sampling stations, April and August, 1973.
Distance Upstream in Statute Miles (km).

in place before sampling began and removed after sampling was finished. Vertically, current meters were placed at three to six depths. Survey transects are also shown schematically with landmarks in figure 6.

Concurrently with the August study, a batch of DuPont Rhodamine WT dye was released on August 18. Four barrels, having a total of one thousand pounds of 20% solution by weight, were released at evening slack before ebb at buoy 16. This buoy is located at mile 26.4 (42.5 km) approximately one mile upstream of the mouth of the Poropotank River.

Daily slack water runs were made beginning on August 19. These slack water runs continued for over a week, with samples taken at the surface, mid-depth and bottom. Dissolved oxygen and dye samples were taken and temperature and conductivity were measured.

In addition to the intensive studies mentioned above, there has been a continuing program of slack water runs since 1970. These runs are taken once or twice per month, depending on weather. The slack water stations correspond to the transects of the intensive study. At each slack water station, biochemical oxygen demand (BOD) samples and dissolved oxygen (DO) samples are taken at two meter intervals from surface to bottom. Temperature and conductivity measurements are taken at the same sampling depths.

Both VIMS and the Corps of Engineers made bottom profile surveys. The locations of the transects profiled by VIMS are shown in figure 7 and those of the Corps in Figure 8.

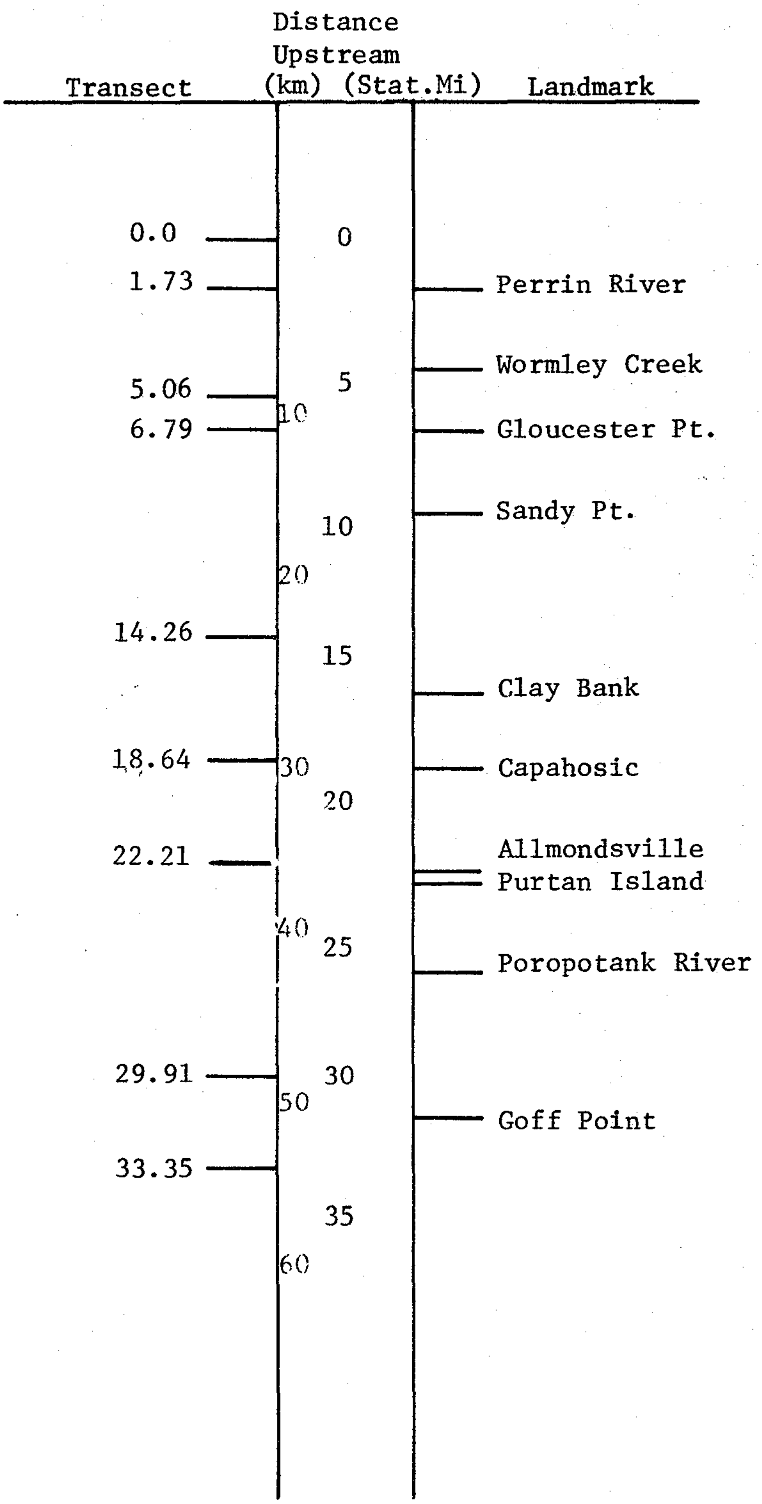


Figure 6. Schematic location of sampling stations, April and August, 1973.

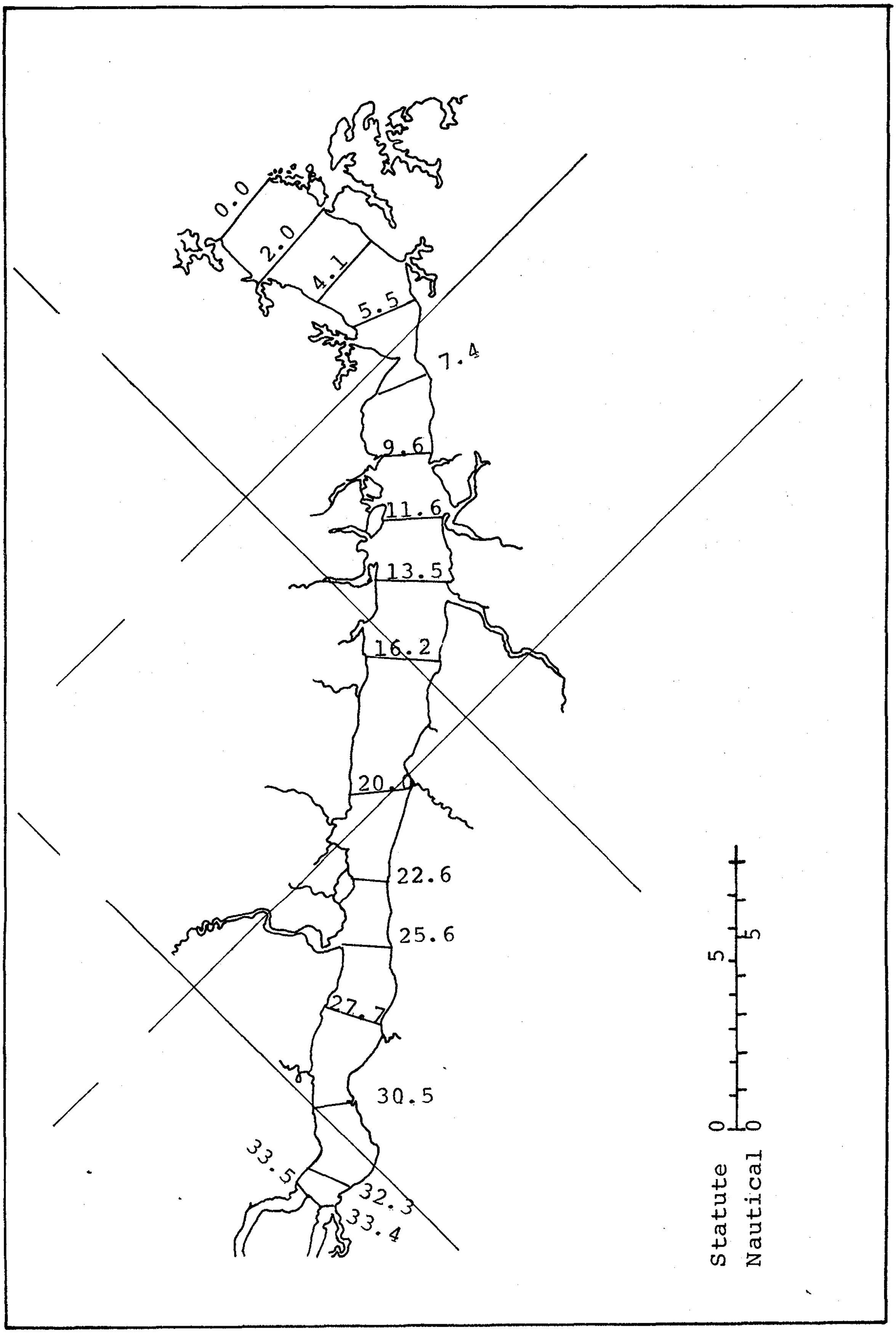


Figure 7. Location of VIMS bathymetric transects, York River.

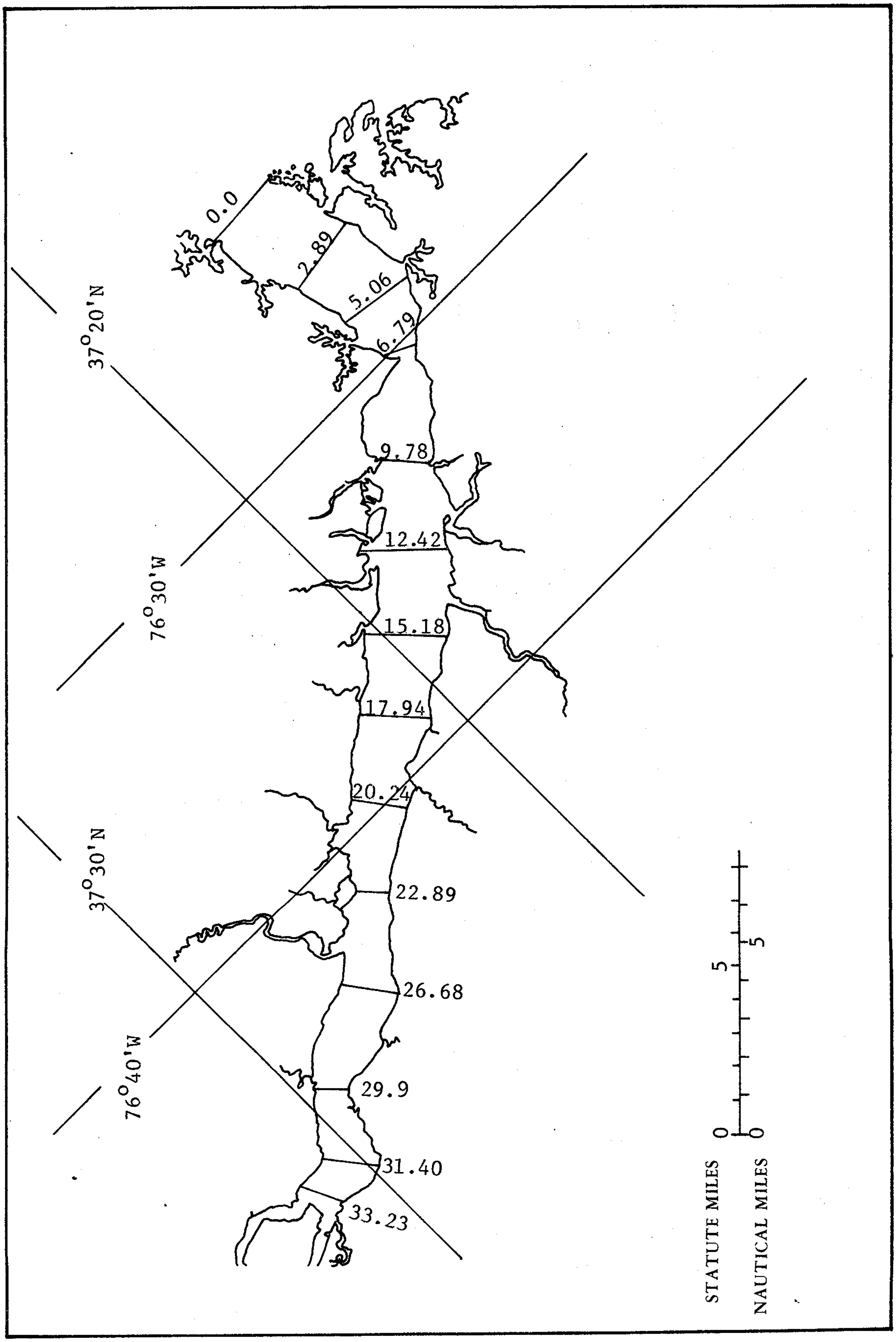


Figure 8. Location of Corp of Engineers bathymetric transects, York River.

Profiles are shown in Appendix A. VIMS transects are oriented so that the reader is facing upstream, while Corps transects have the opposite orientation.

B. Instrumentation and Analysis

Dissolved oxygen samples were collected in the field in frautschy bottles and transferred to 125 ml sample bottles. These were analyzed in the laboratory using the Azide modification of the Winkler method. BOD samples were collected in frautschy bottles and transferred to 500 ml dark bottles which were incubated at 20°C for five days and then analyzed for DO using the method explained above. Conductivity and temperature were measured using an Inter-Ocean Model 513 CTD. Salinity was calculated according to VIMS laboratory calibration of the CTD unit. Spot check 125 ml salinity samples were analyzed using a Beckman RS-7A salinometer in the laboratory.

Braincon film-recording current meters were used in the survey. Photographic film from these meters was analyzed using a scanner, and the digitized data recorded on tape.

Dye samples were analyzed in the laboratory using a Turner Associates Fluorometer.

All sampling data were keypunched into a standard format and stored in a magnetic disk data file.

Transect widths were determined from Geological Survey 7.5 minute quadrangles. Cross-sectional areas were determined by planimetry of the bottom profile data and adjusted to mean water level. Inter-transect reach lengths were determined from Coast and Geodetic Survey navigation charts.

Tidal fluxes were calculated from the vertical averages of the longitudinal components of velocity. Vertical averages were weighted by station depth to obtain cross-section averages. Tidal flux was computed by multiplying cross-sectional average velocity by mean area as determined by planimetry.

Drainage area statistics have been worked out for Chesapeake Bay and all its tributaries (Seitz 1971).

C. Results

Summaries of the data collection are contained in the Appendices. The observed cross-sectional profiles are shown in Appendix A. Appendix B summarizes the intensive field studies of 1973. Appendix C shows the results of the dye study of August, 1973 and Appendix D contains a tabulation of the computed tidal current and tidal flux from current meter records of July and August, 1973. Ebb tides are positive and flood tides negative. Appendix E shows the observed tidal heights at Elsing Green for July and August, 1973. This meter is maintained by the Surveillence and Field Studies Branch of the Water Control Board.

Geometrical data required for the model are summarized in Table 1. Data for the Mattaponi and Pamunkey are taken from an earlier report (Hyer, 1971). Accumulated drainage areas for the York, Mattaponi and Pamunkey are shown in Figures 9 & 10.

Table 1

Geometrical Data for York River System

Stream	Distance Upstream (statute mi.)	Cross-Section Area (ft^2)	Transect Mean Depth (ft)	Accumulated Drainage Area (mi^2)
Pamunkey	86.80	837.00	4.20	1203
	85.20	900.00	10.40	1211
	84.10	1000.00	9.70	1217
	82.80	1300.00	9.60	1224
	81.80	1500.00	7.20	1231
	80.60	1800.00	9.40	1242
	79.50	1950.00	5.90	1247
	78.30	2100.00	5.00	1257
	77.20	2600.00	4.20	1265
	76.10	2900.00	10.00	1274
	74.90	3500.00	6.50	1284
	73.80	4200.00	7.90	1294
	72.80	4600.00	6.80	1303
	71.80	5100.00	9.10	1310
	70.50	5900.00	7.90	1333
	69.20	6700.00	8.10	1338
	68.00	7500.00	8.60	1347
	66.80	8500.00	5.10	1356
	65.80	9200.00	5.40	1365
	64.70	10200.00	11.40	1373
	63.40	11200.00	7.90	1380
	62.20	12200.00	3.40	1386
	61.10	13100.00	16.70	1390
	59.90	14000.00	16.40	1398
	58.80	14800.00	19.20	1403
	57.70	15300.00	13.20	1409
	56.50	16100.00	14.80	1414
	55.40	16800.00	10.90	1417
	54.20	17400.00	16.80	1419
	53.00	18100.00	17.70	1421
	51.80	18800.00	32.40	1424
	50.70	19600.00	21.80	1426
	49.50	20300.00	40.20	1429
	48.30	21000.00	13.80	1432
	47.30	21800.00	19.60	1433
	46.30	22500.00	14.40	1434
	44.90	23600.00	18.90	1437
	43.70	24500.00	26.70	1440
	42.60	25600.00	24.00	1441
	41.50	26500.00	24.40	1444
	40.30	27600.00	18.40	1446
	39.00	28900.00	14.40	1448
	38.00	30000.00	24.90	1450
	36.50	31800.00	18.30	1453

Table 1 (cont'd)

Stream	Distance Upstream (statute mi.)	Cross-Section Area (ft^2)	Transect Mean Depth (ft)	Accumulated Drainage Area (mi^2)
Pamunkey (cont'd)	35.70	33200.00	25.20	1455
	34.60	36000.00	20.50	1457
	34.00	37500.00	20.80	1458
	33.40	46900.00	18.00	1459
Mattaponi	70.60	750.00	9.60	723
	69.70	1700.00	4.50	726
	68.80	1900.00	4.00	728
	67.80	2200.00	6.40	734
	66.90	2800.00	7.20	736
	66.00	3000.00	2.30	745
	65.10	3500.00	3.40	749
	64.20	4000.00	7.20	752
	63.20	4600.00	3.30	752
	62.30	5200.00	5.30	760
	61.40	5800.00	5.90	764
	60.50	6400.00	6.90	768
	59.50	7000.00	9.70	769
	58.60	7600.00	4.80	772
	57.70	8300.00	19.90	777
	56.50	9000.00	15.80	781
	55.70	9540.00	5.50	791
	54.80	10100.00	14.30	801
	54.00	10600.00	16.10	808
	53.20	11100.00	10.40	810
	52.30	11700.00	15.10	821
	51.50	12200.00	14.10	832
	50.70	12800.00	17.40	834
	49.80	13300.00	20.50	838
	49.00	13800.00	22.40	843
	48.20	14400.00	11.30	845
	47.30	14900.00	12.70	847
	46.20	15400.00	13.80	853
	45.00	16000.00	17.00	858
	44.20	16300.00	23.60	861
	43.30	16500.00	21.00	865
	42.40	17200.00	19.40	870
	41.60	18000.00	18.80	875
	40.80	19500.00	17.40	881
	40.00	20400.00	15.00	881
	39.20	21400.00	10.20	884
	38.50	22500.00	11.40	890
	37.70	23600.00	30.30	891
	36.90	24700.00	12.30	897
	36.20	25900.00	14.60	903
	35.40	27200.00	11.60	906

Table 1 (cont'd)

Stream	Distance Upstream (statute mi.)	Cross Section Area (ft^2)	Transect Mean Depth (ft)	Accumulated Drainage Area (mi^2)
Mattaponi (cont'd)	34.60	28500.00	14.60	912
	34.10	29900.00	17.00	915
	33.50	31500.00	15.60	918
York	32.3	55000.00	10.50	2386
	29.9	69200.00	10.10	2409
	27.7	77500.00	11.10	2427
	25.6	86500.00	12.30	2466
	22.6	98800.00	15.20	2488
	20.0	111400.00	15.20	2502
	17.9	136000.00	19.30	2517
	16.2	152400.00	17.50	2546
	14.3	162500.00	14.40	2569
	12.4	167000.00	26.20	2581
	9.8	173500.00	29.60	2590
	6.8	178500.00	51.00	2598
	5.1	250000.00	33.80	2602
	2.9	283200.00	42.90	2605
	0.0	289500.00	40.20	2608

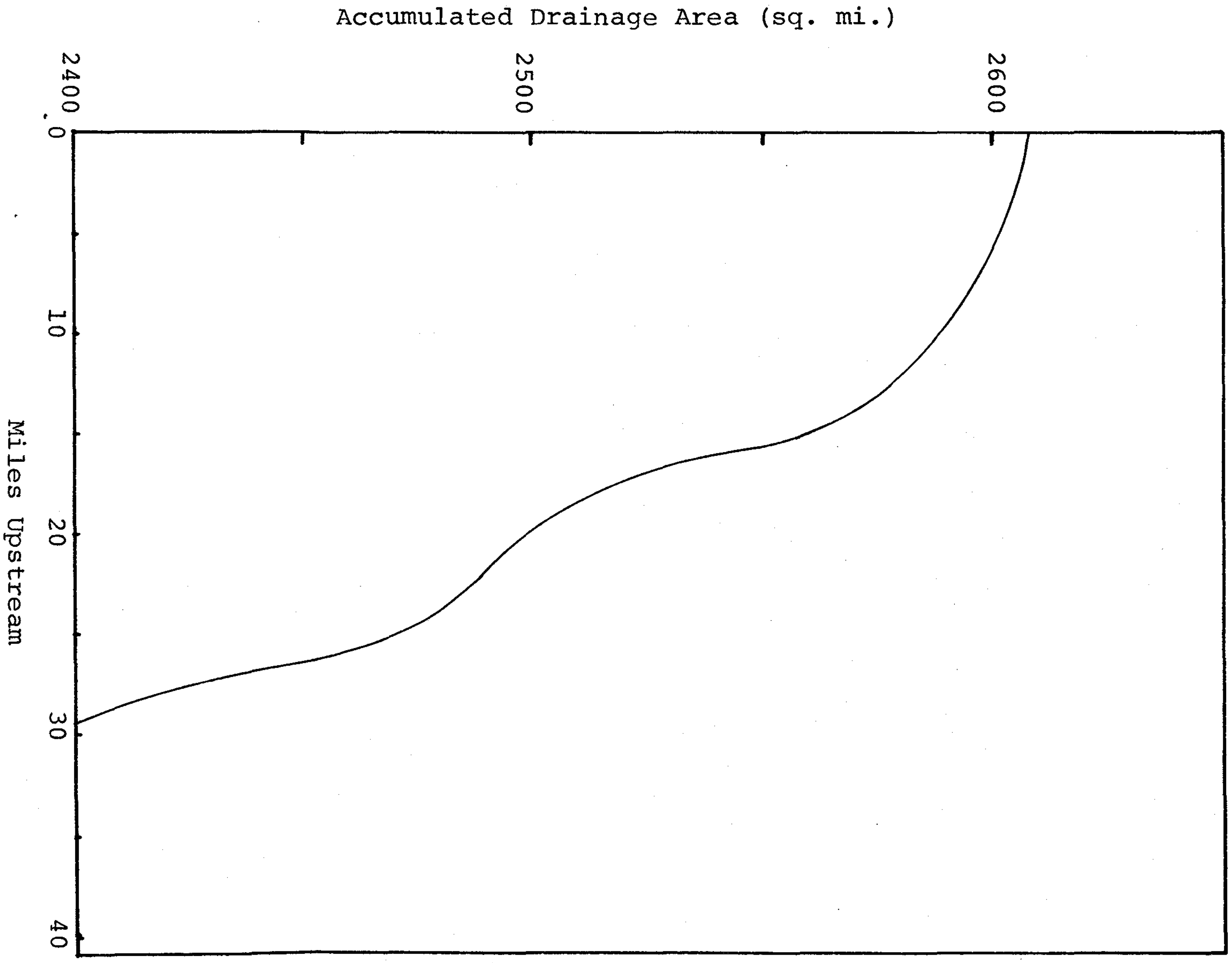


Figure 9. Accumulated drainage area for York River.

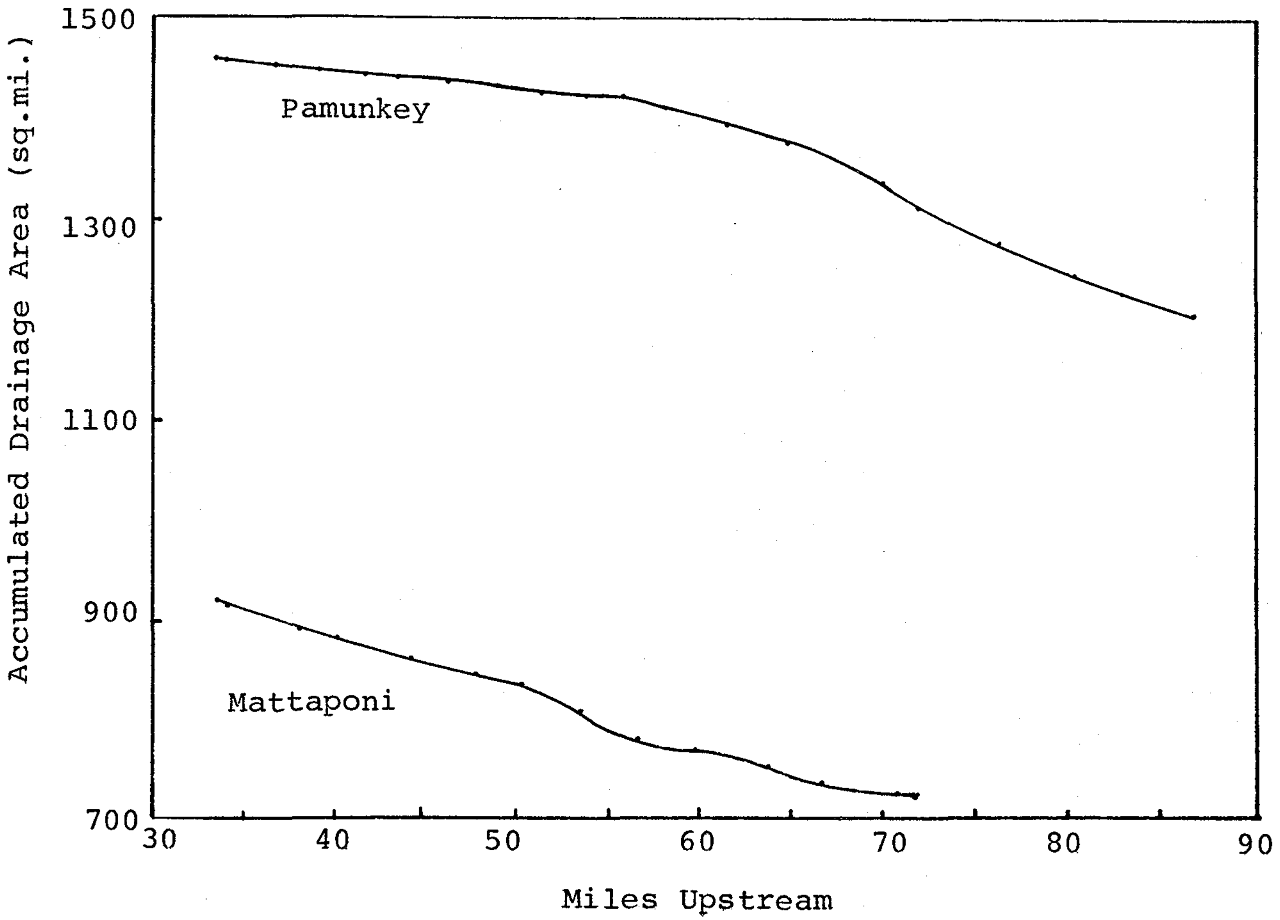


Figure 10. Accumulated drainage areas for Mattaponi and Pamunkey Rivers.

All observed transects (both Corps & VIMS) were used for the inter-reach volumes. Transects to use in the model were chosen so that there would not be a great variance in reach length. In consequence, the transects in Table 1 are taken partly from the VIMS set and partly from the Corps of Engineers set.

Tables 2 & 3 show the daily discharge at Hanover and Beulahville for the months of June, July and August, 1973.

Since the stations occupied during the intensive field survey were occupied for over a day continuously and were spread across transects, the measurements taken provide data on the spatial variability of parameters and on the temporal variability, including diurnal and tidal oscillations. The tidal variations of dissolved oxygen and salinity are particularly important. Slack water data are useful in signaling trends in salinity distribution, and to show the response of dissolved oxygen to a variety of conditions, of fresh water inflow, water temperature and waste loading.

Table 2

DISCHARGE RECORDS, 1973

Pamunkey River at Hanover

DAY	June FLOW, CFS	July FLOW, CFS	August FLOW, CFS
01	1380	455	172
02	190	473	249
03	868	435	308
04	785	380	330
05	795	348	322
06	630	335	346
07	548	308	313
08	485	297	269
09	443	302	216
10	428	236	187
11	405	220	153
12	380	185	142
13	359	169	203
14	344	162	302
15	328	158	282
16	311	242	225
17	363	269	172
18	465	216	162
19	665	180	326
20	685	162	650
21	570	165	1130
22	530	181	1260
23	500	190	1050
24	430	178	758
25	370	183	515
26	335	251	420
27	313	264	361
28	357	234	322
29	355	181	238
30	405	153	187
31		150	31
Total	15022	7662	11601
Max.	1380	473	1260
Min.	190	150	31
Avg.	485	247	374

Table 3

DISCHARGE RECORDS, 1973

Mattaponi River at Beulahville

DAY	June FLOW, CFS	July FLOW, CFS	August FLOW, CFS
01	1030	211	144
02	710	216	324
03	513	214	616
04	599	196	683
05	570	170	605
06	435	157	412
07	358	142	284
08	324	151	219
09	305	141	198
10	286	136	169
11	263	448	139
12	245	552	120
13	223	443	107
14	211	307	106
15	196	227	132
16	179	193	253
17	198	182	396
18	246	172	382
19	274	153	281
20	287	138	233
21	277	125	453
22	262	178	1160
23	274	194	1620
24	310	207	1590
25	287	248	1100
26	246	209	906
27	212	168	769
28	200	142	411
29	223	127	295
30	237	114	240
31		105	203
Total	9980	6261	14550
Max.	1030	552	1620
Min.	179	105	106
Avg.	333	202	469

V. WATER QUALITY MODEL STUDY

A one-dimensional real-time, intra-tidal model was developed for the York River System. The model is based on the mass balance equation to simulate the distributions of CBOD (carbonaceous oxygen demand), NBOD (nitrogenous oxygen demand), DO (dissolved oxygen) and salinity. The basic structure of the model is the same as the estuarine water quality model used in previous studies (Kuo, et al., 1974). That report contains a detailed description of the inner workings of the model. However, the York River System is branched, so that the algorithm was modified to allow for interaction occurring at the junction. The modification to match the condition at the confluence of the three branches is essentially the same as that of salt intrusion model. Details are given in Section VI-5 of this report.

A. Segmentation of the River

Channel geometry used in the model is shown in Table 1. Cross-section area for the York was derived from cross-section measurements made by VIMS and the Corps of Engineers; for the Mattaponi and Pamunkey, VIMS transects were supplemented by CBI data (Cronin, 1971); inter-transect distances were determined from navigation charts; reach volumes were computed from cross-sectional area and reach length. Drainage area was computed by CBI (Seitz, 1971).

Tidal currents were calculated from accumulated tidal prism volume (Cronin, 1971) and cross-sectional area. Freshwater inflow was determined from flow gauge records (USGS, 1971, etc.) at Hanover and Beulahville as shown in tables 2 & 3. Fresh water inflow was augmented for downstream lateral inflow assuming hydrologic homogeneity. Tidal phase progression rate was computed by VIMS (Ruzecki, 1974), relying on tidal current tables and current meter data.

B. Calibration and Verification

The model was calibrated for salinity and dissolved oxygen using the results of the intensive field study of August, 1973. Fresh water inflow data were provided by the U. S. Geological Survey (1973). Effluent loading data were provided by the Virginia Water Control Board (see table 4). Outfall locations are shown in figure 11. During this period of time, waste outflow from the Chesapeake Corporation was high; however, waste treatment has since been upgraded considerably. Bottom oxygen demand measurements were made by VIMS in the vicinity of West Point.

The intensive survey included time series from anchor stations and also slack water runs. Both sets of data have been used in calibration. Figures 12 & 13 show the comparison of the cross-section average of the anchor station data with the model results for salinity and dissolved oxygen, respectively. The error brackets indicate the extremes of the observed values. Figures 14 & 15 compare a composite result of five slack before flood runs with the corresponding model result. Figures 16 & 17 compare the composite result of four slack before ebb runs with the

Table 4

Point Source Loadings in York River

Name	Type	Receiving Stream	River Mile	Model Reach	5-Day Carbonaceous BOD Loading lb/day	Water Flow MGD
Town of West Point	Municipal	West Point Creek (Mattaponi)	34.1	43	90	0.30
Chesapeake Corp.	Industrial	Pumunkey River	34.3	46	36700	11.1
Town of Toano	Municipal	Ware Creek	25	49	20	.015
Camp Peary	Municipal	Carters Creek	15	57	10	0.06
Cheatham Annex	Municipal	York River	11	58	24	0.054
Sanitary District No. 1			10	58	142	0.47
Naval Weapons Station	Municipal	Felgates Creek	9	58	57	0.20
Colonial Nat'l Historical Park	Municipal	Yorktown Creek	5	60	25.5	0.049
Coast Guard Reserve Center	Municipal	York River	3	61	30	0.019
VEPCO	Industrial	York River	3	61	62	586
American Oil Co.	Industrial	York River	1	62	1060	64.8

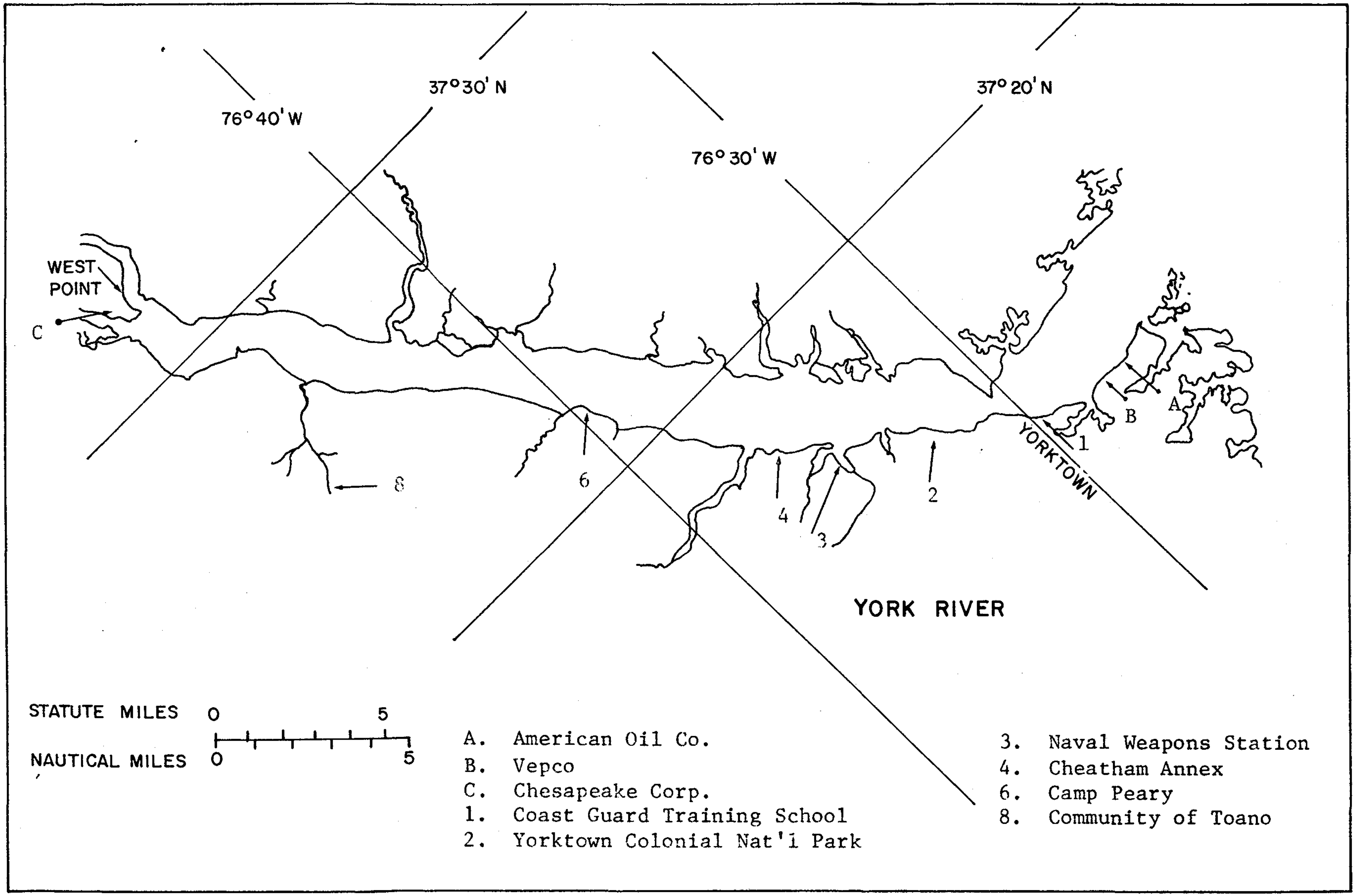


Figure 11. Location of waste water outfalls reaching the York River.

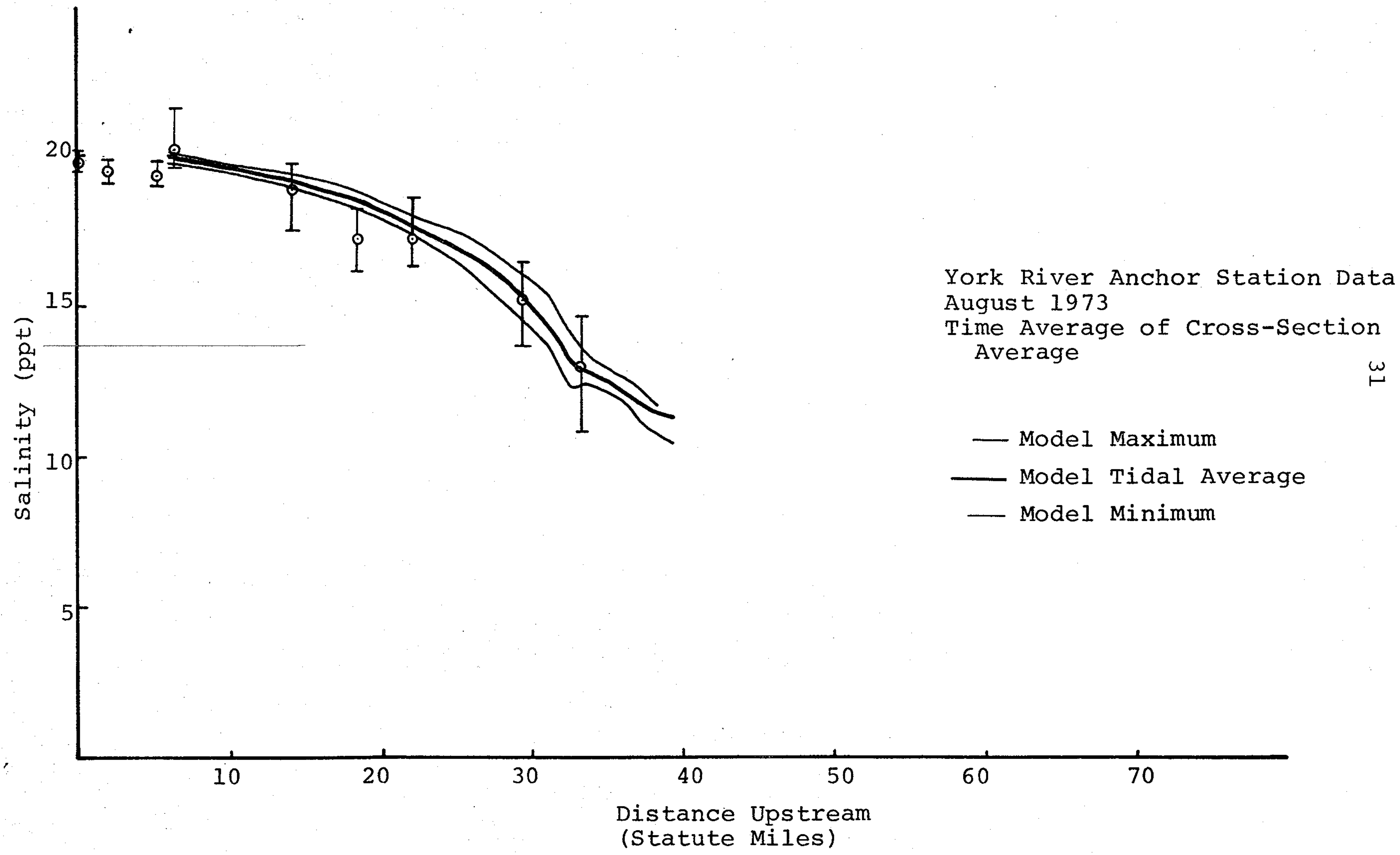


Figure 12. Comparison of model results with observed salinity at anchor stations, August, 1973.

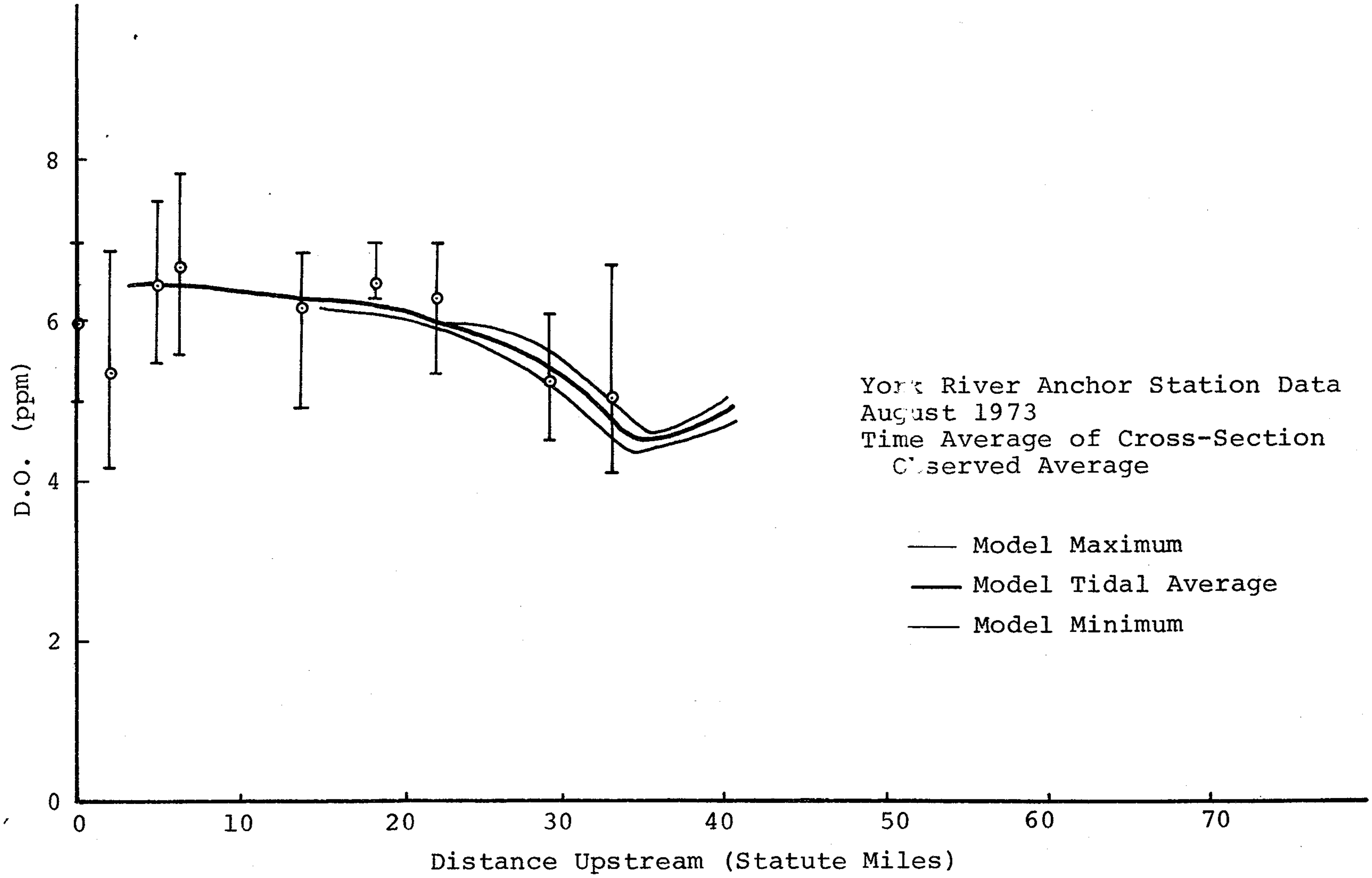


Figure 13. Comparison of model results with observed dissolved oxygen at anchor stations, August, 1973.

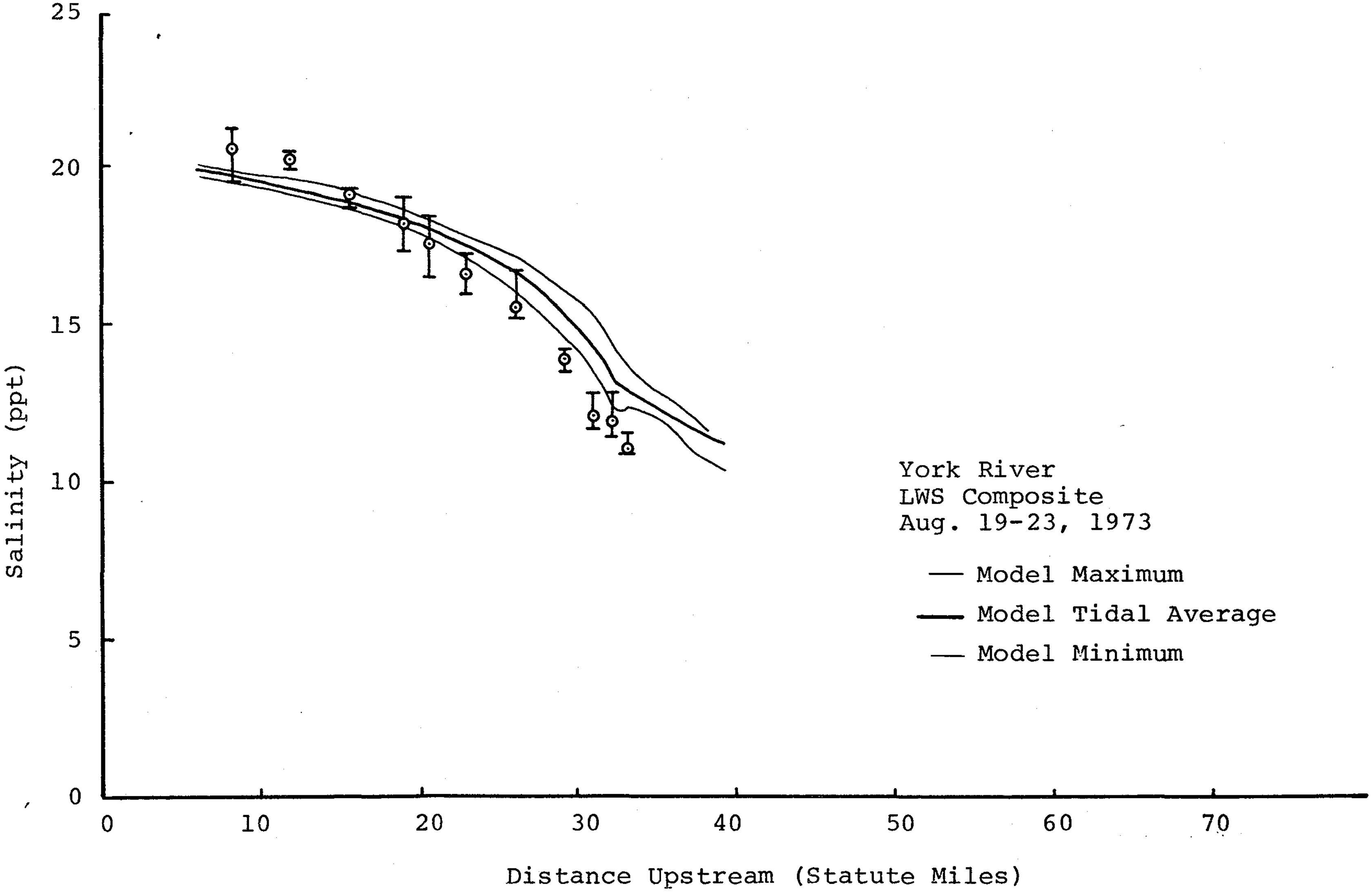


Figure 14. Comparison of model results with slack before flood salinity, August 19-23, 1973.

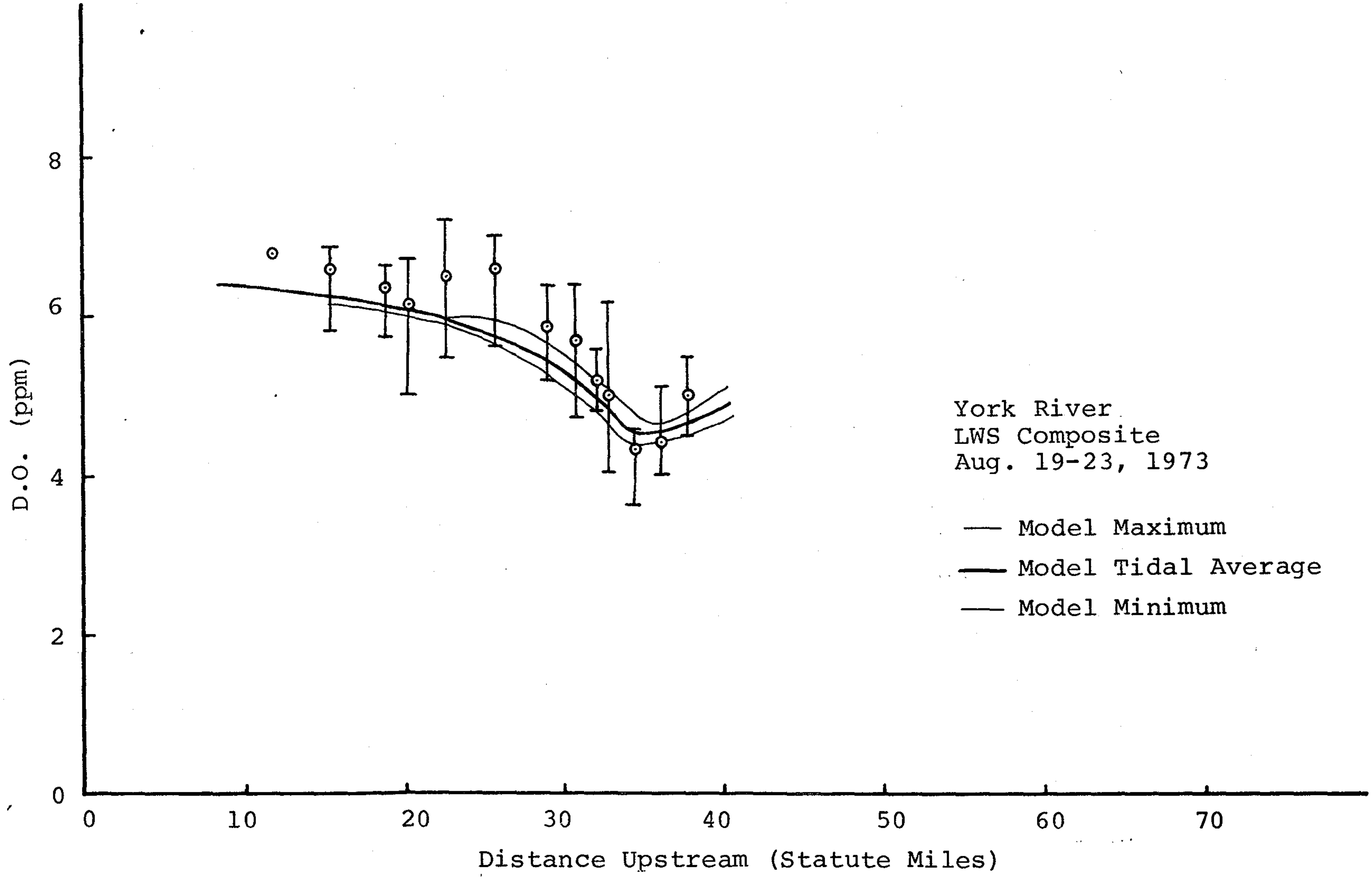


Figure 15. Comparison of model results with slack before flood dissolved oxygen, August 19-23, 1973.

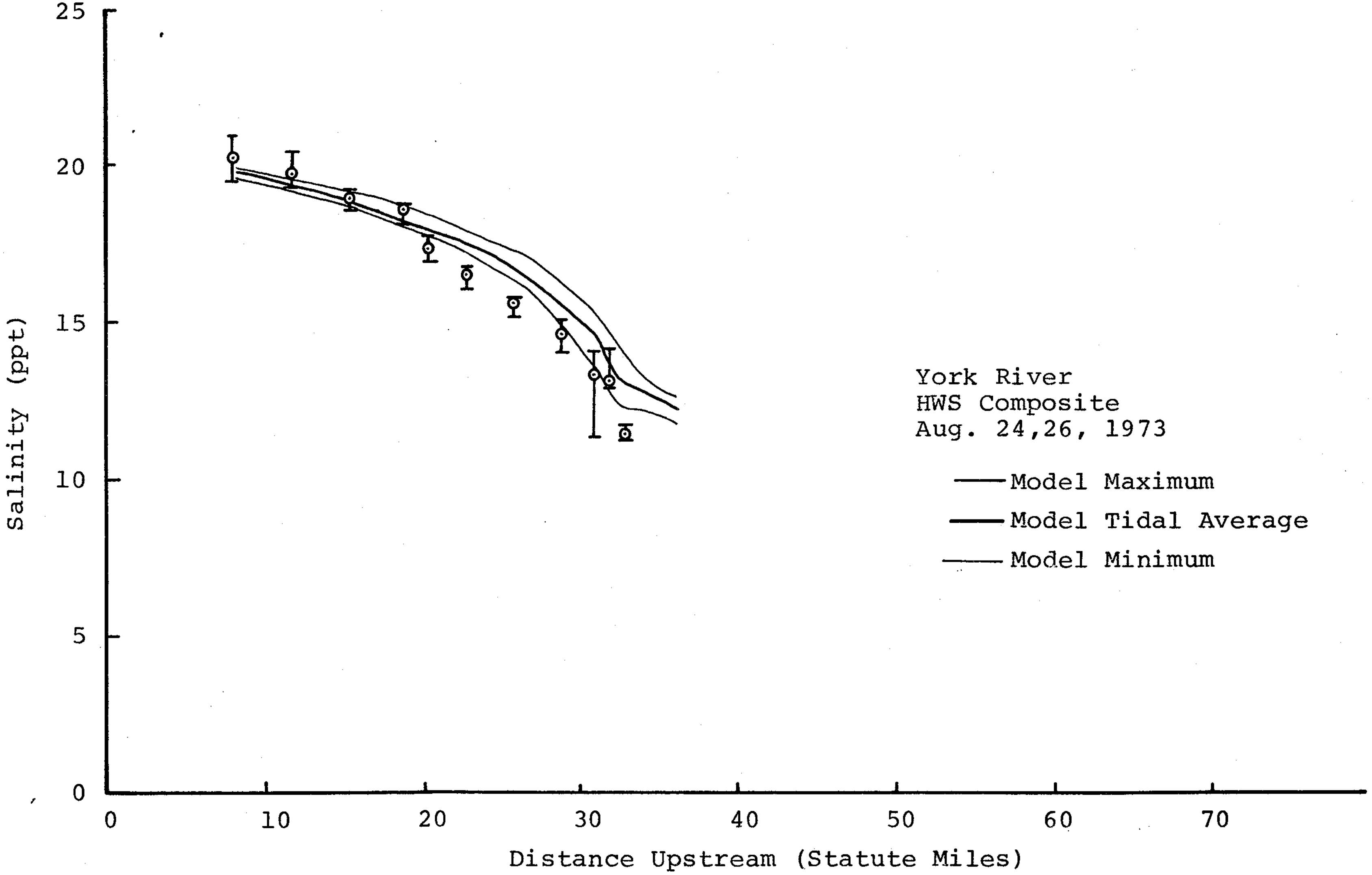


Figure 16. Comparison of model results with slack before ebb salinity, August 24-26, 1973.

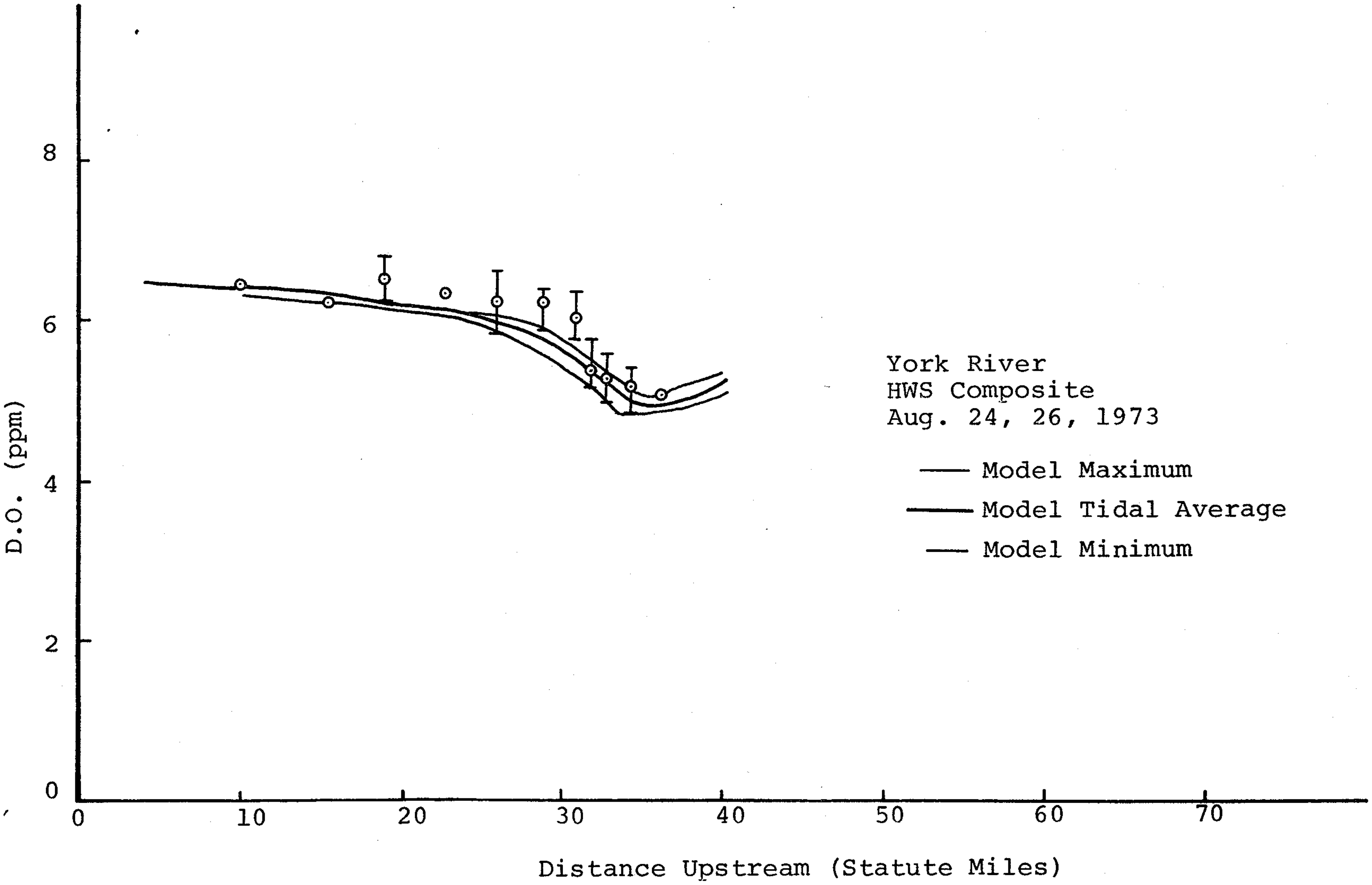


Figure 17. Comparison of model results with slack before ebb dissolved oxygen, August 24-26, 1973.

corresponding model result. In these cases, the error brackets indicate the extremes of the individual slack water run vertical averages.

As a further calibration, the batch dye release of August 18, 1973 was simulated in the model. This simulation was achieved by treating nitrogenous BOD as a conservative substance with no continuous sources and zero boundary conditions. The initial concentration was zero except for a value of 1.3 (parts per billion) in reaches 51 and 52. This concentration represents the initial total mass of dye, namely 1000 lbs. of 20% solution, distributed evenly over the volumes of these two reaches.

Comparison of observed dye distribution and model results are shown in figures 18 through 25. Since the initial dye release was at slack before ebb, slack before flood observations correspond to tidal half-cycles after release and slack before ebb observations correspond to integral tidal cycles after release.

The model was verified with data from two slack water before ebb runs made in 1970. A run was made on the Pamunkey on September 29. The observations and model results are shown in figures 26 & 27. The Mattaponi was surveyed on October 1. The comparisons between observation and model results are shown in figures 28 & 29.

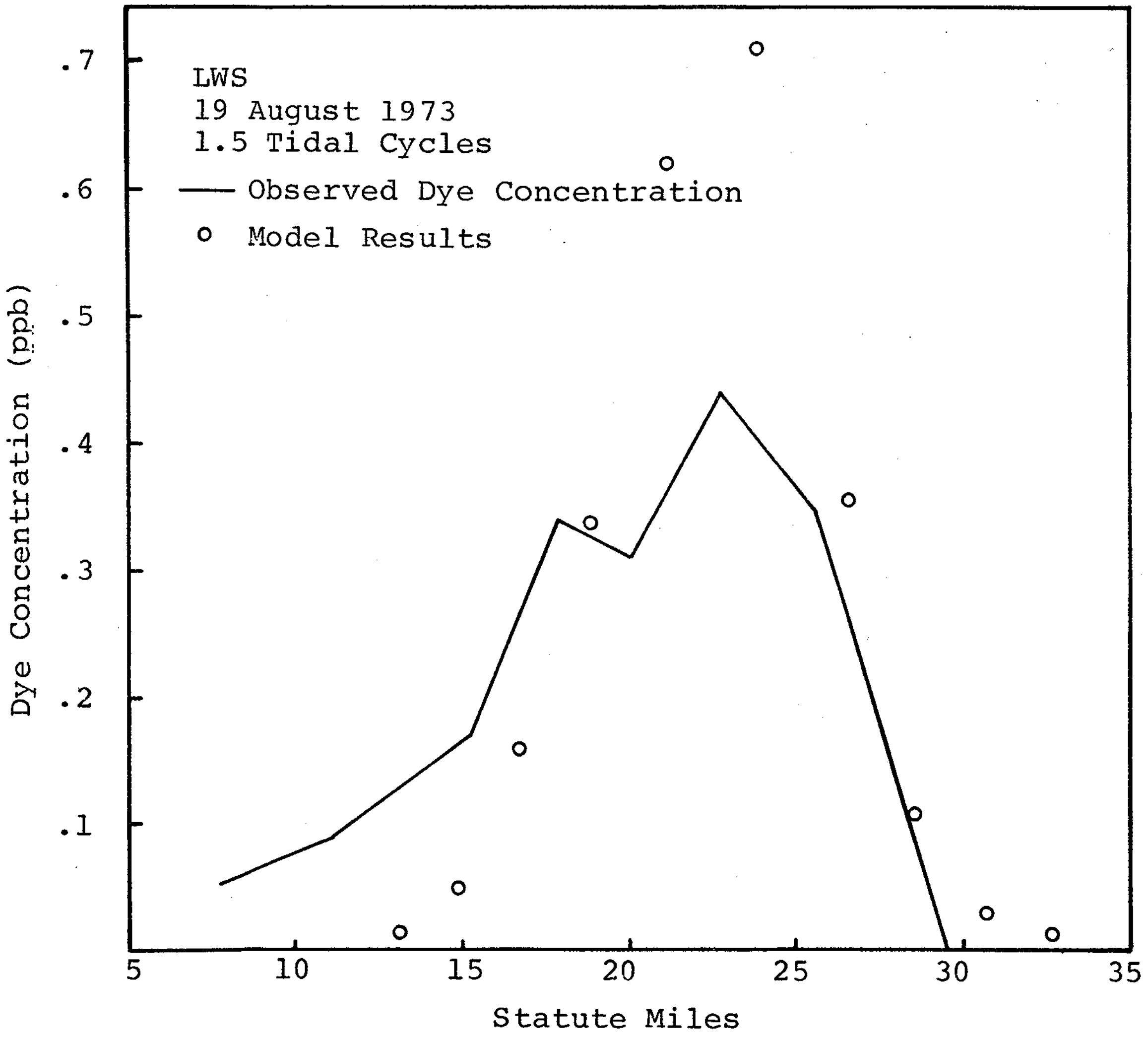


Figure 18. Observed slack before flood dye distribution, August 19, 1973 with corresponding model result.

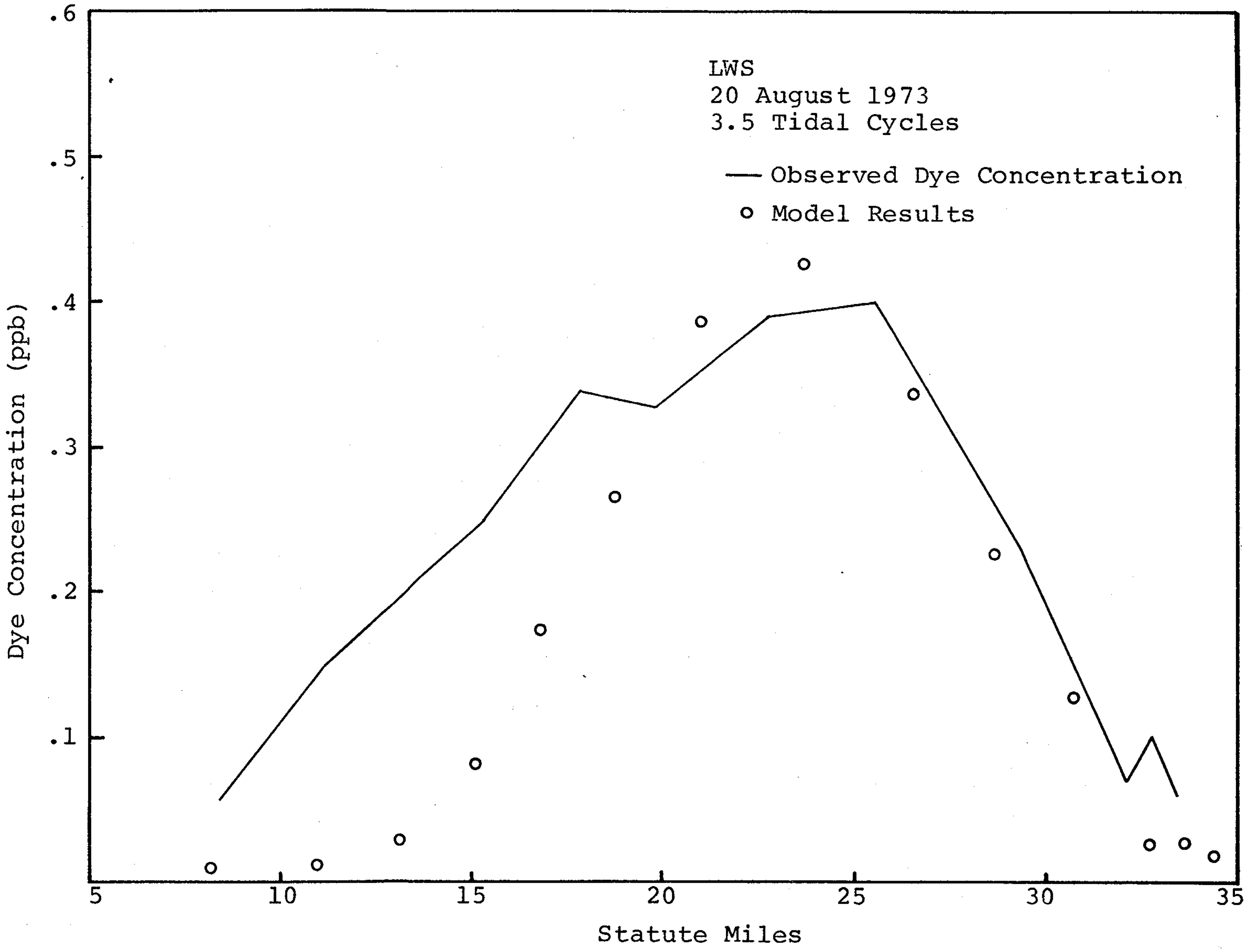


Figure 19. Observed slack before flood dye distribution, August 20, 1973 with corresponding model result.

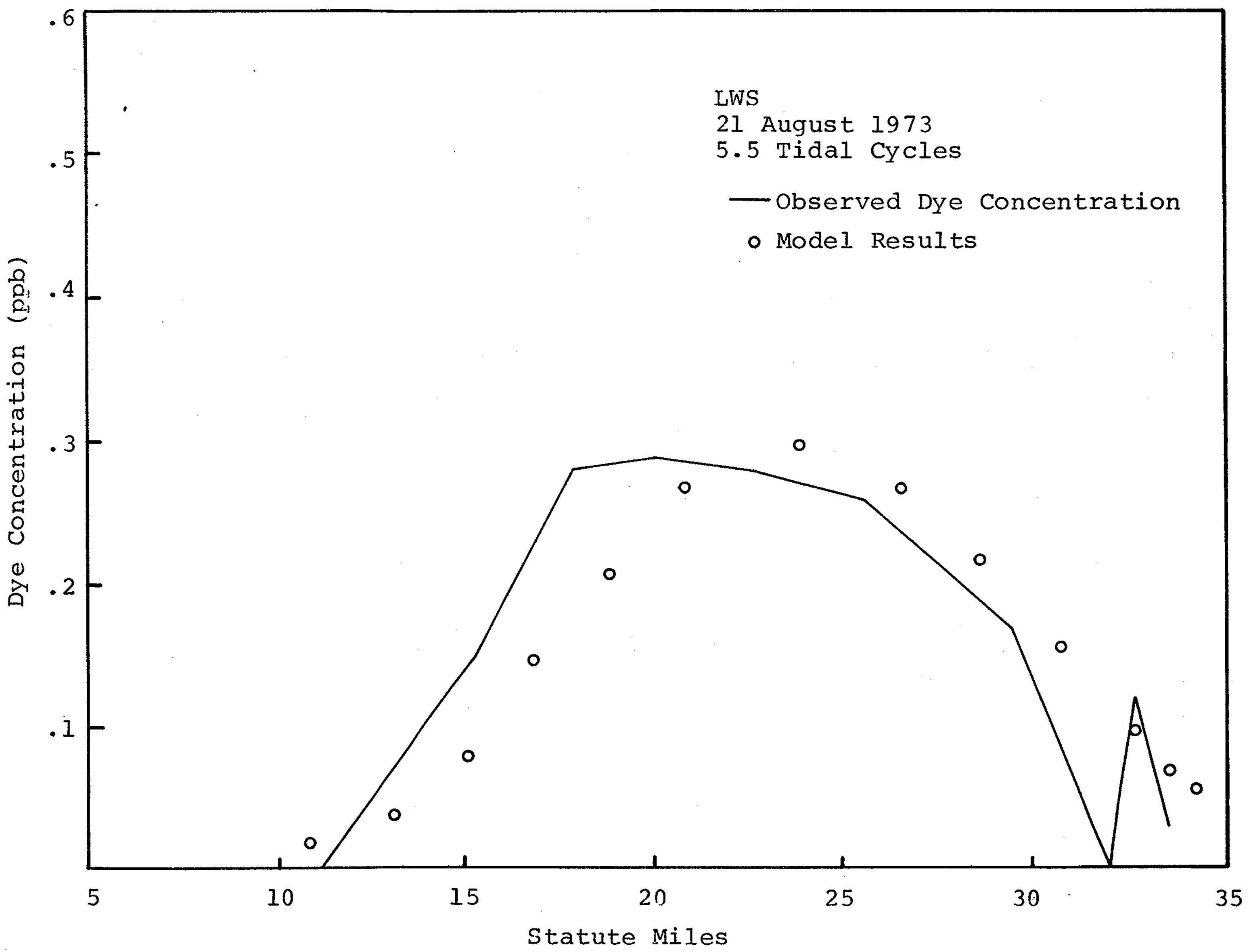


Figure 20. Observed slack before flood dye distribution, August 21, 1973 with corresponding model result.

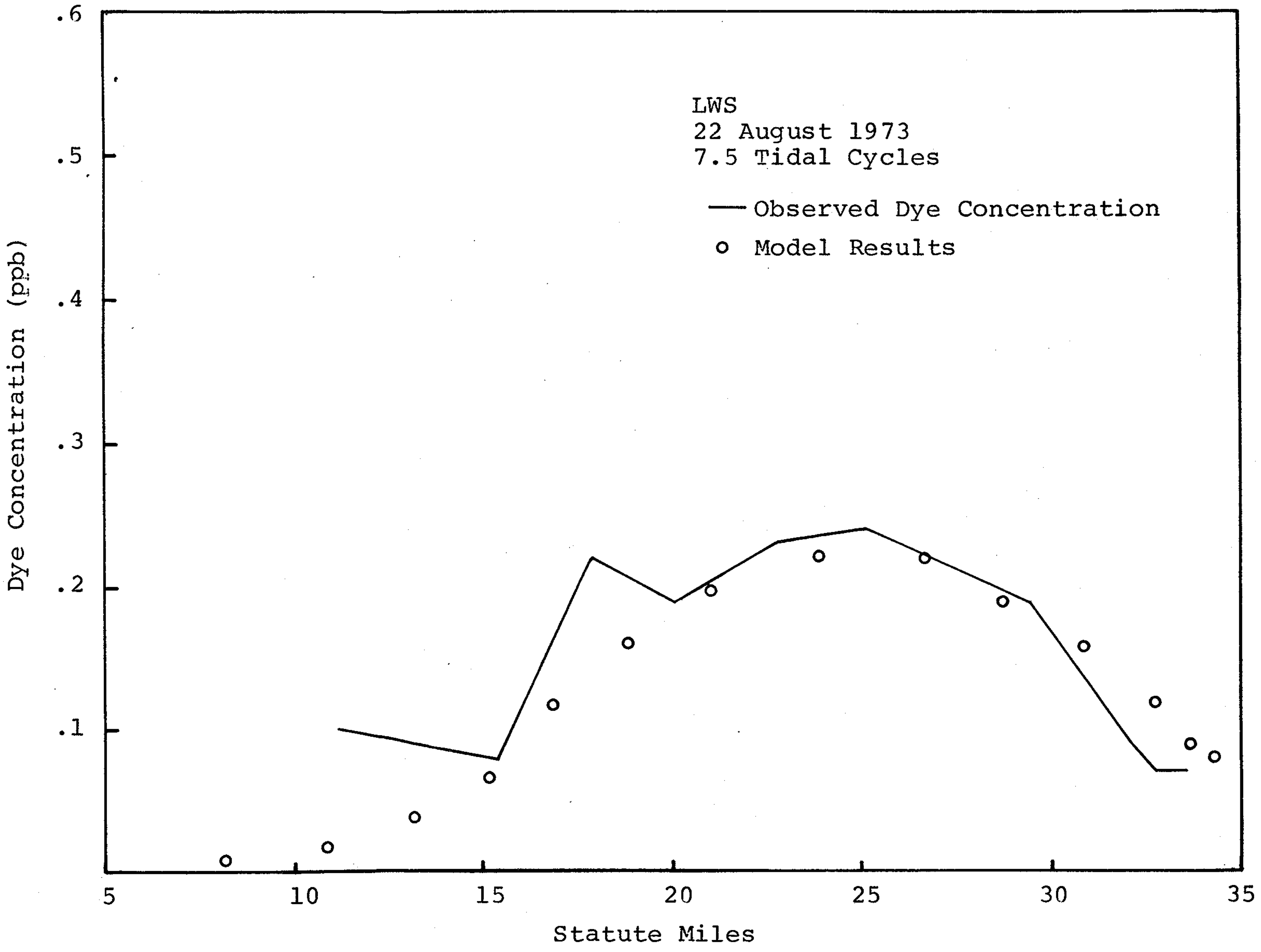


Figure 21. Observed slack before flood dye distribution, August 22, 1973 with corresponding model result.

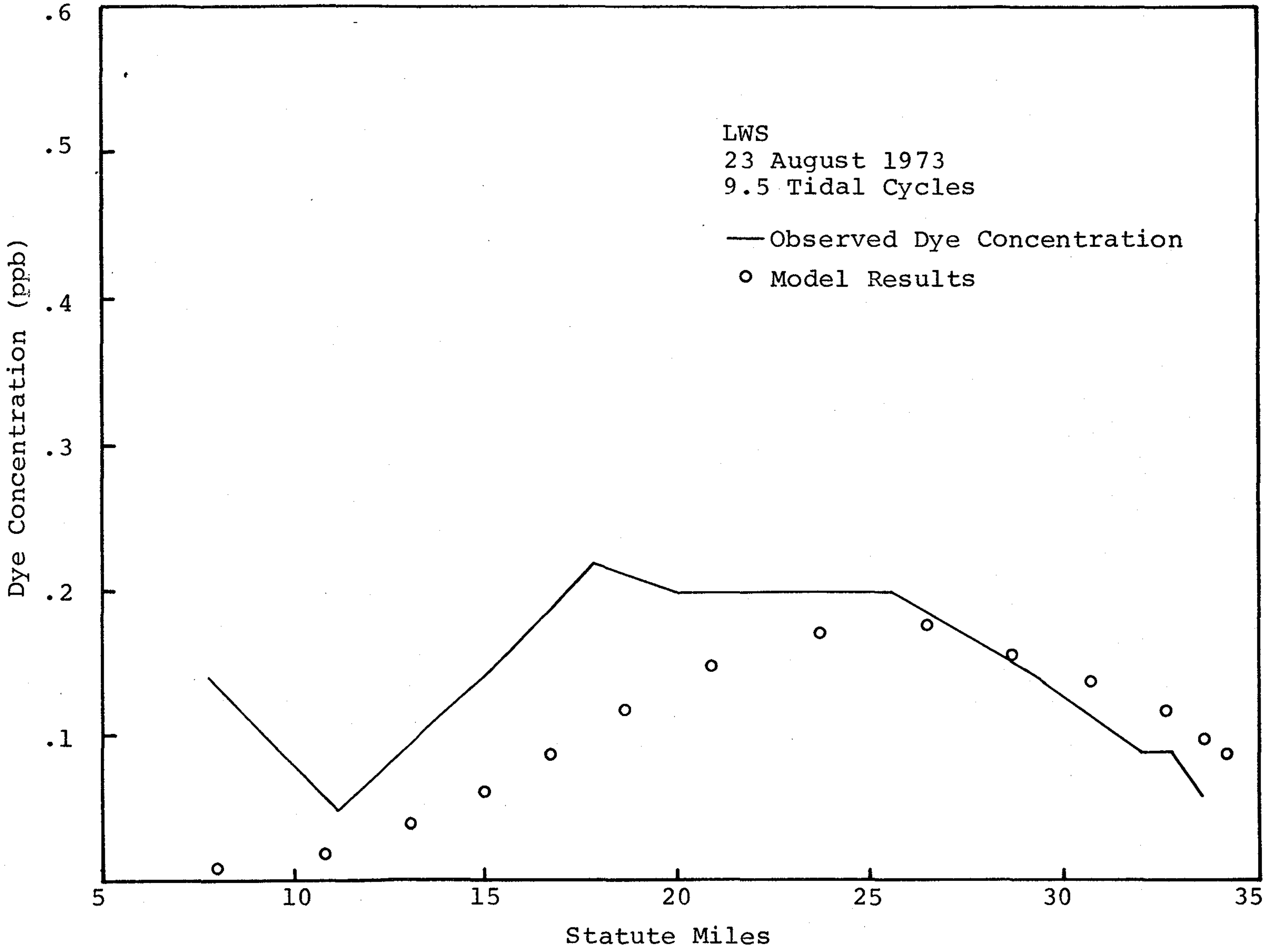


Figure 22. Observed slack before flood dye distribution, August 23, 1973 with corresponding model result.

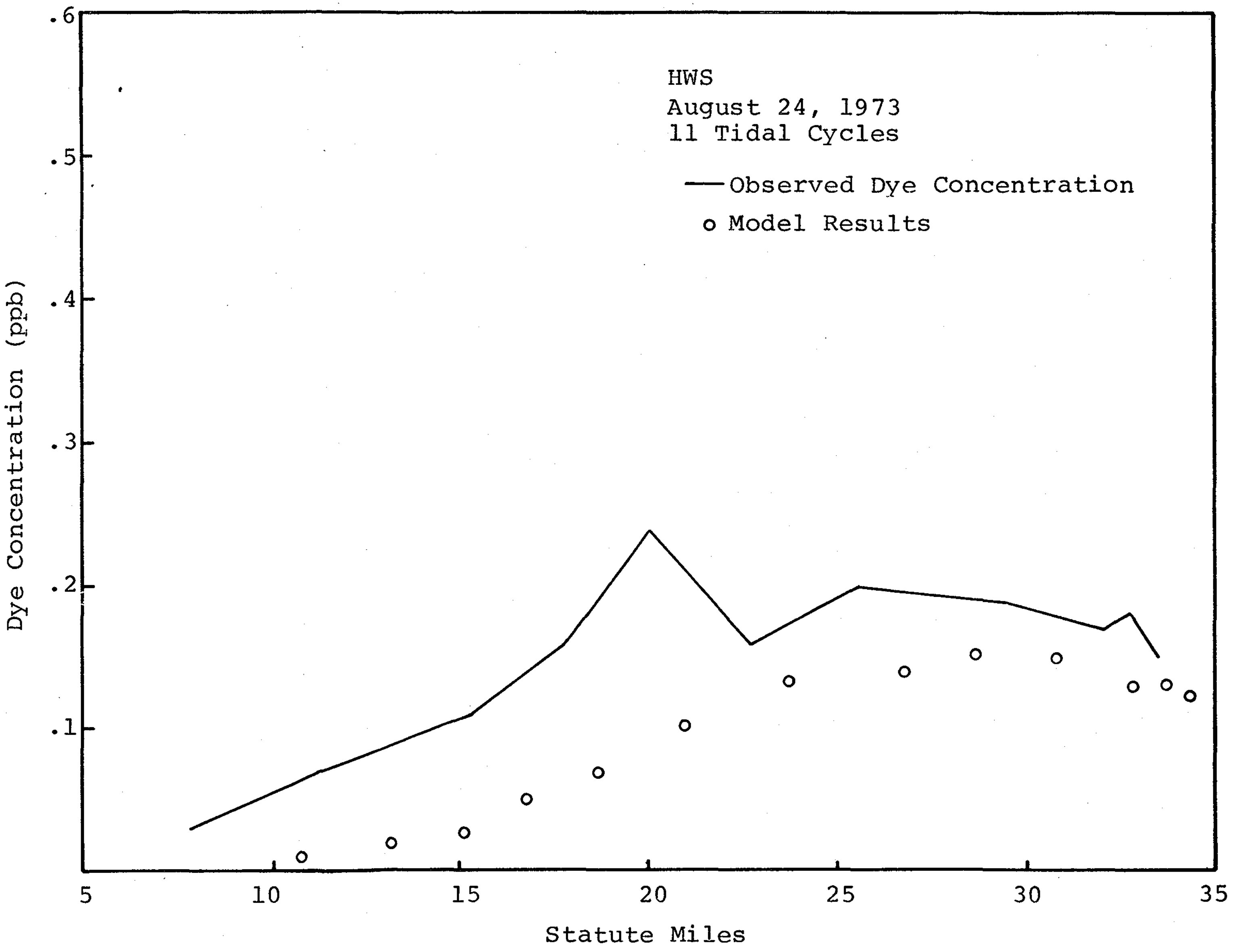


Figure 23. Observed dye distribution, August 24, 1973 with corresponding model result.

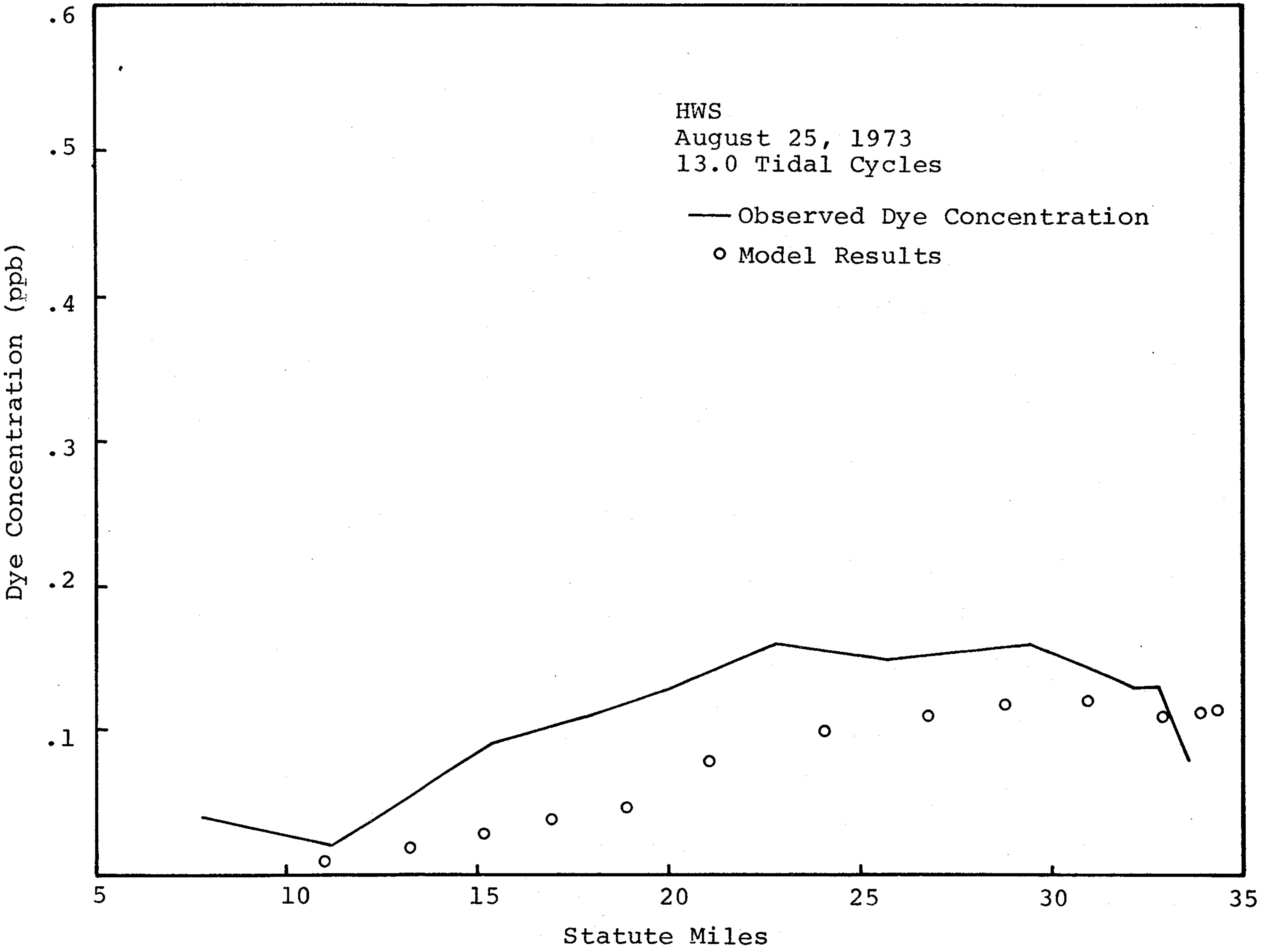


Figure 24. Observed dye distribution, August 25, 1973 with corresponding model result.

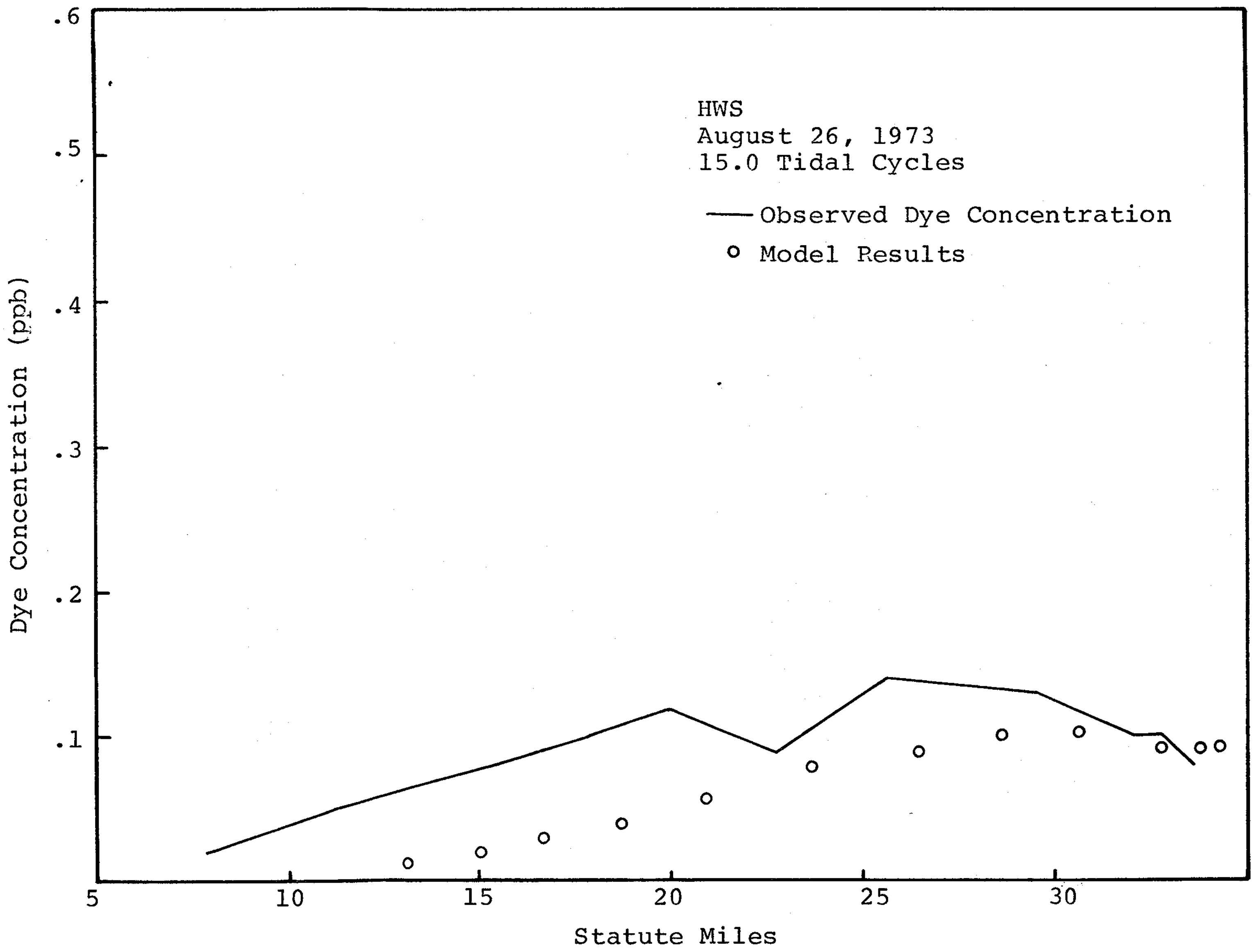


Figure 25. Observed dye distribution, August 26, 1973 with corresponding model result.

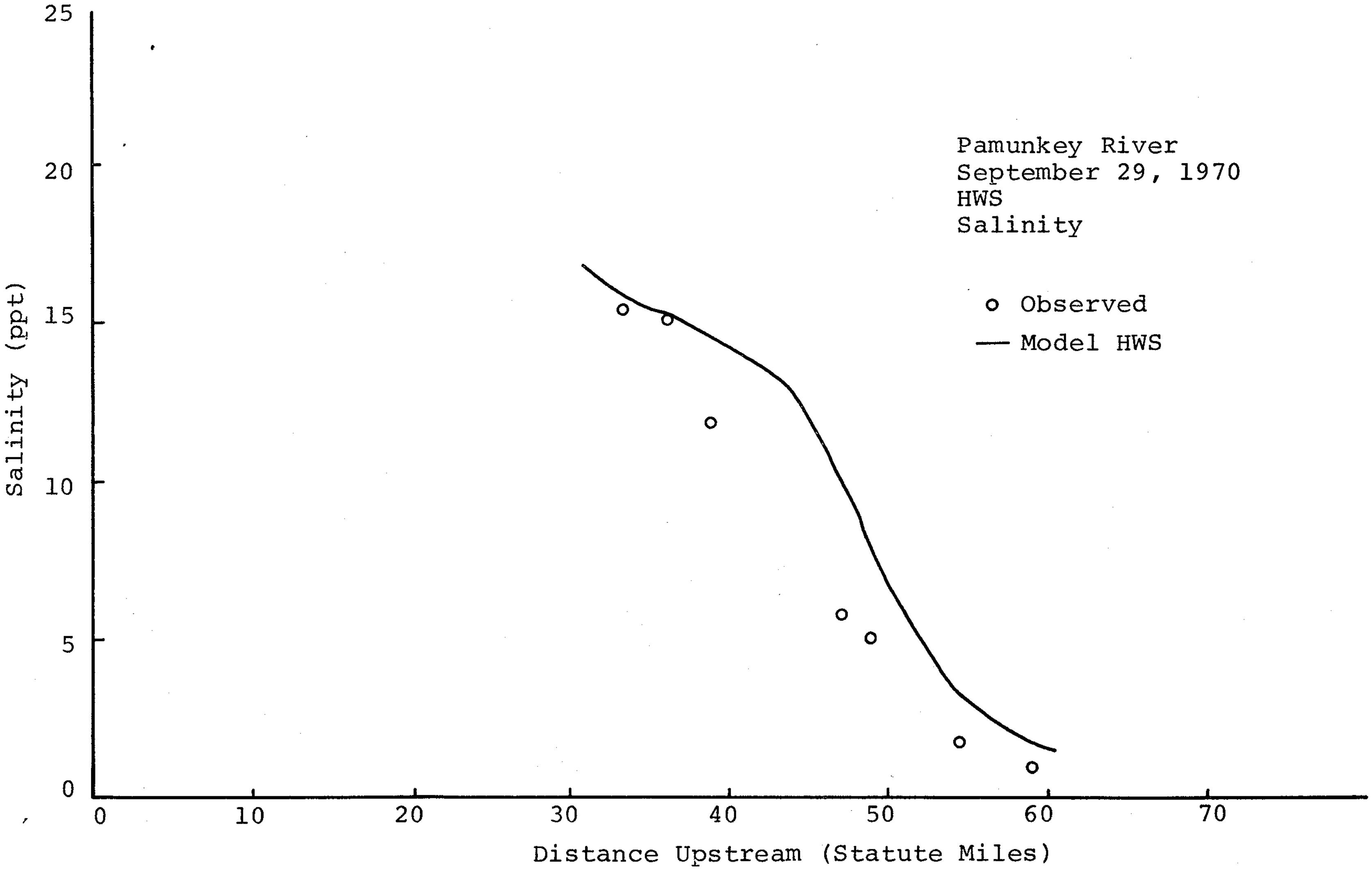


Figure 26. Comparison of model results with slack before ebb salinity, September 29, 1970.

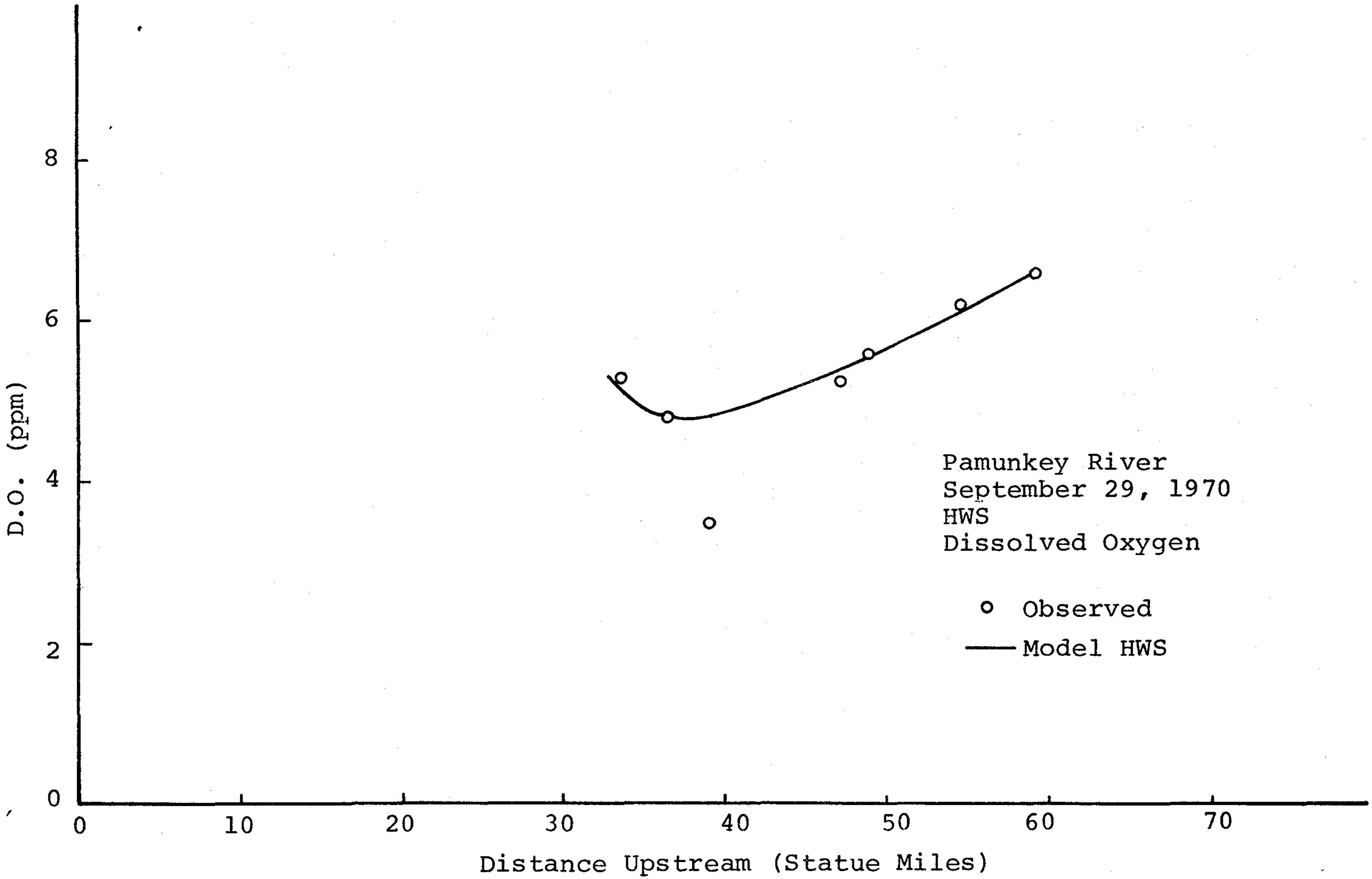


Figure 27. Comparison of model results with slack before ebb dissolved oxygen, September 29, 1970.

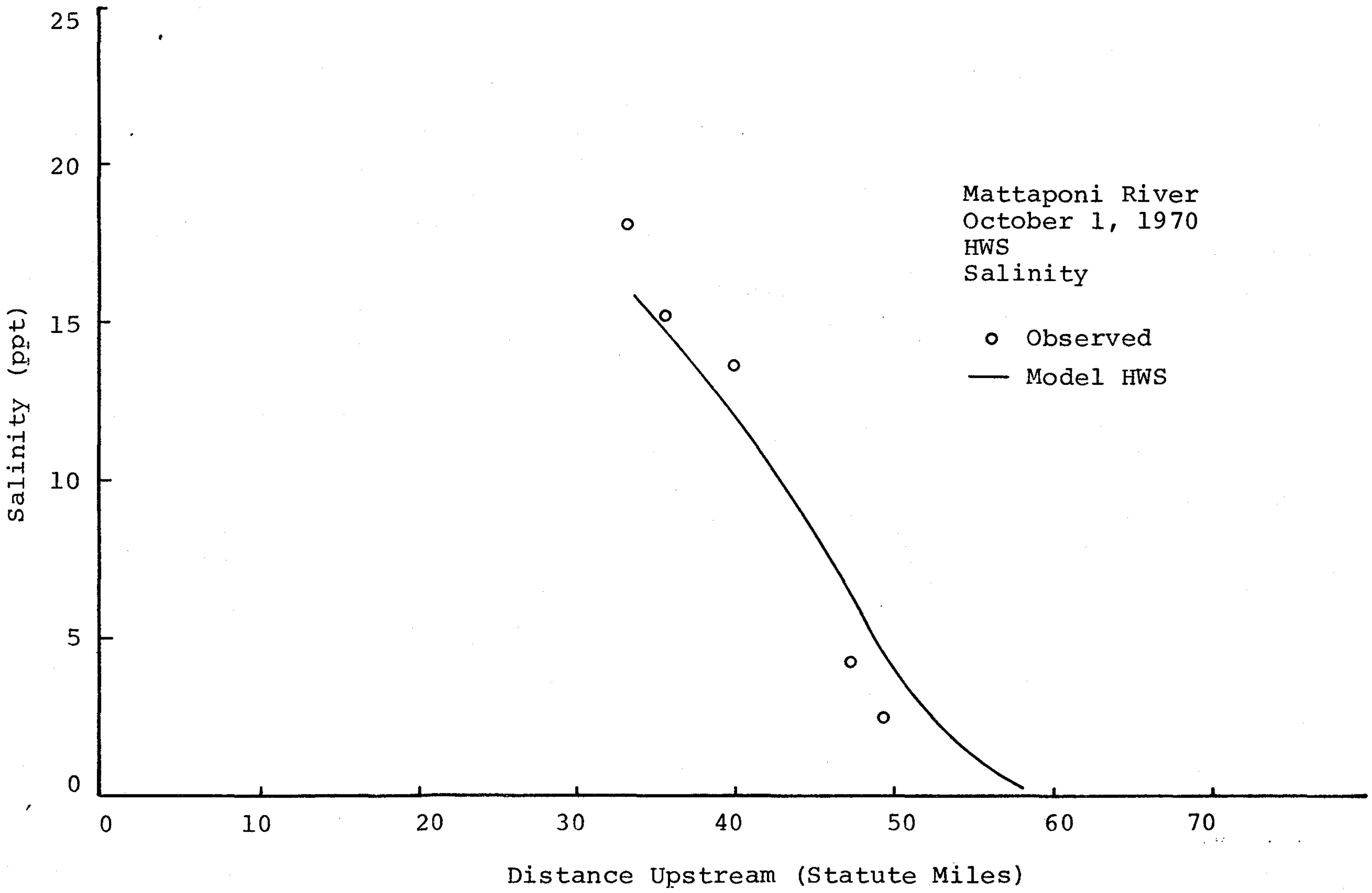


Figure 28. Comparison of model results with slack before ebb salinity, October 1, 1970.

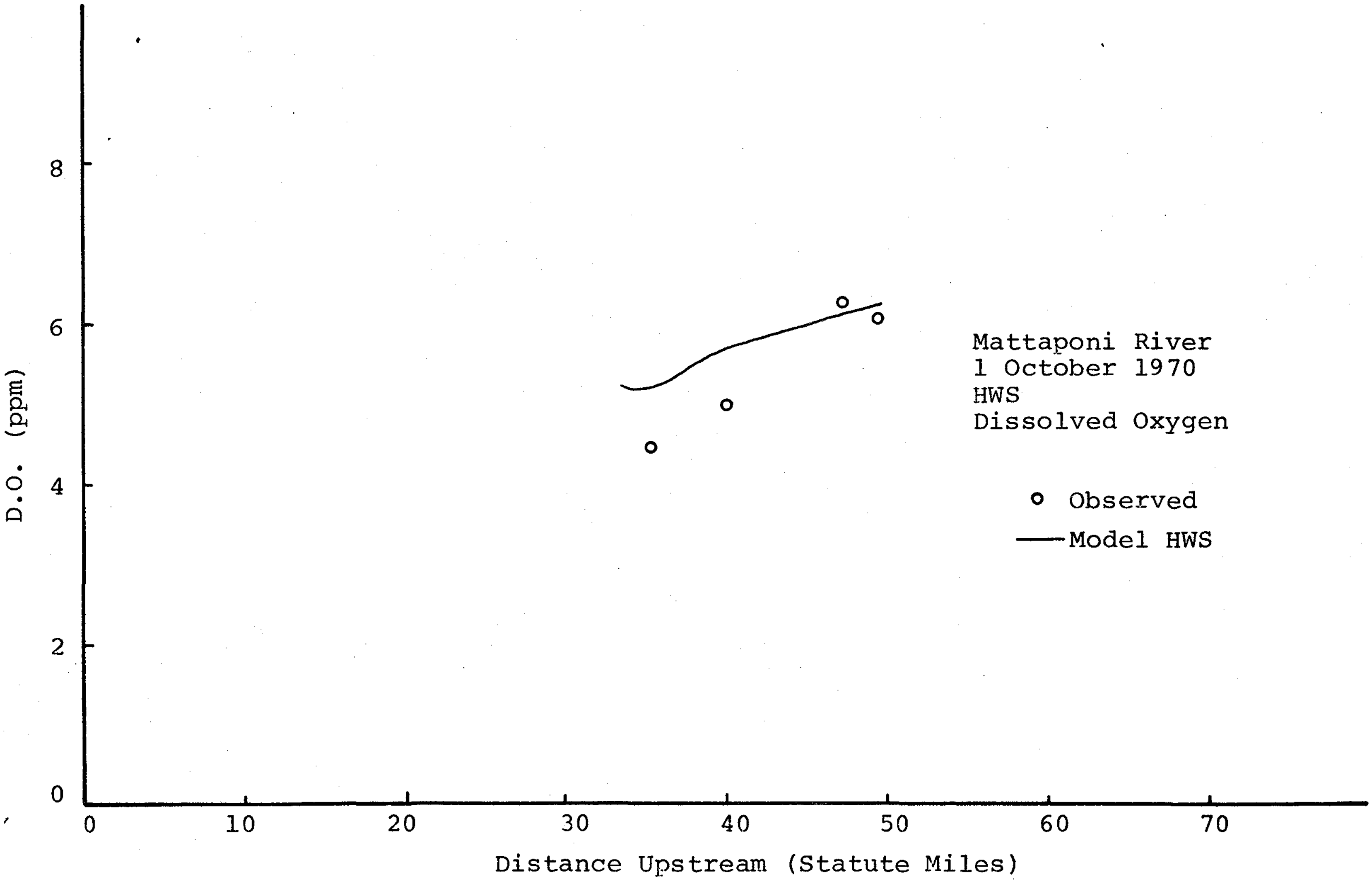


Figure 29. Comparison of model results with slack before ebb dissolved oxygen, October 1, 1970.

C. Manual for Program Users

The following is a list of all the input data needed to be specified to run the model. The values of those variables designated by asterisk are constant for a particular estuary and therefore, should not be altered from run to run.

Main Program

(1a) ML, MU: station numbers of upstream boundary and downstream boundary respectively, ML<MU.

(1b) DRAIN: total drainage area, in square miles, at transect ML.

Format: (2I10, F10.0)

(2a) TMAX: the integral number of tidal cycles the program is to be run; in general, 40 tidal cycles will be sufficient to reach an equilibrium state.

*(2b) DTT: the time increment in tidal cycle.

(2c) NRNM: the number of freshwater discharges under which the program is to be run, NRNM $\geq$ 1.

(2d) NTPRIN: the number of times the calculated concentration field is to be printed.

Format: (2F10.0,2I5)

(3) TT(I), I=1, NTPRIN: number of tidal cycles after computation begins at which the computation fields are to be printed. All numbers should be integral multiples of DTT, and TT(NTPRIN) should equal TMAX.

Format: (7F10.0)

(4a) DNB: the number of hours from 0600 to computation starting time; DNB is to take into account the phase of diurnal variation in photosynthesis and respiration.

(4b) TB: the number of hours from low water slack at the most upstream transect to computation starting time; TB may be set to zero for most cases.

Format: (7F10.0)

*(5a) BETA: weighting factor for advection of sea salt.

*(5b) ALPHA: weighting factor for advection of oxygen and biochemical oxygen demand (BOD).

Format: (7F10.0)

*(6a) FC: Manning friction coefficient.

*(6b) AK, TK: empirical constants relating dispersion coefficient to the salinity and the salinity gradient respectively; AK $\geq$ 0; TK $\geq$ 0

Format: (7F10.0)

(7) TCCKC, TCCKN, TCBEN: the exponential base for temperature dependence of CBOD and NBOD decay rates and benthic oxygen demand.

Format: (7F10.0)

(8) CBODBG, NBODBG, DOBG, SBG: background concentration of carbonaceous BOD, nitrogenous BOD, dissolved oxygen, and salinity respectively in freshwater inflow; in milligrams per liter for BOD and DO; in parts per thousand for salinity.

Format: (7F10.0)

(9) CBODU, CBODD: carbonaceous BOD levels of reaches ML and MU, respectively, in milligrams per liter.

Format: (7F10.0)

(10) NBODU, NBODD: nitrogenous BOD levels of reaches ML and MU, respectively, in milligrams per liter.

Format: (7F10.0)

(11) DOU, DOD: dissolved oxygen concentrations of reaches ML and MU, respectively in milligrams per liter.

Format: (7F10.0)

(12) SU, SD: salinity of reach ML and estimated maximum salinity of reach MU respectively, in parts per thousand.

Format: (7F10.0)

(13) NTRIB: number of tributaries.

Format: (I10)

(14a) K: the tributary number

(14b) MLT(K): the most upstream reach of the Kth tributary.

(14c) MUT(K): the most downstream reach of the Kth tributary.

(14d) JN(K): the reach number of the main estuary to which the Kth tributary is connected.

(14e) DRAINT(K): total drainage area, in square miles, at transect MLT(K).

Format: (4I5, F10.0)

These data should be repeated for each of the tributaries and K=1, NTRIB.

(15) SUT(I), CBODUT(I), NBODUT(I), DOUT(I), I=1, NTRIB: the tributary upstream boundary conditions for salinity, CBOD, NBOD and DO respectively.

Format: (4F10.0)

Hydral Subroutine

The following data should be repeated for each of the tributaries.

(1) TITLE: a title describing the following geometric and hydraulic data.

Format: (1X, 35A2)

(2) NDG, NS, NAME: data group number, number of points in the group, and some description of the contents. In order to exit the subroutine set NDG $\geq$ 99.

Format: (2I5, 30A2)

* (a) Data Group 1.

NS is the number of transects of interest starting with transect number 1, NS $\geq$ MU+1.

(i) DIST(I), I=1, NS: distance of transect from mouth, in statute miles.

(ii) ARCO(I), I=1, NS: conveyance area or cross-sectional area of the transect in the main channel of flow, in square feet.

Format: (7F10.0)

(iii) ART(I), I=1, NS: total cross-sectional area of the transect including stagnant shoals which merely store water, in square feet.

Format: (7F10.0)

(iv) VOL(I), I=1, NS: volume of reach at mean tide level, in cubic feet; VOL (NS) may be arbitrarily specified.

Format: (6E12.4)

(v) H1(I), I=1, NS: transect depth, in feet.

Format: (7F10.0)

(vi) HA(I), I=1, NS: average reach depth in feet. HA(NS) may be arbitrarily specified.

Format: (7F10.0)

(vii) ARD(I), I=1, NS: drainage area increment over the Ith reach, in square miles. ARD (NS) may be arbitrarily specified.

Format: (7F10.0)

* (b) Data Group 2

NS is the number of transects of interest starting with transect 1, NS $\geq$ MU+1.

(i) PHA(I), I=1, NS: phase difference of tide at Ith transect relative to transect 1, in hours.

Format: (7F10.0)

(ii) UT(I), I=1, NS: tidal velocity at each transect, in feet per second.

Format: (7F10.0)

(iii) S(I), I=1, NS: initial salinity of each reach, in parts per thousand.

Format: (7F10.0)

(c) Data Group 3.

NS is the number of freshwater discharge conditions to be tested in the run; NS=NRNM

DISCH(I), I=1, NS: freshwater discharge at transect ML, in cubic feet per second. NS should be equal to or greater than NRNM (2C of main program).

Format: (7F10.0)

Input Subroutine

The following data should be repeated for each tributary.

(1) TITLE: a title describing the following water quality data.

Format: (1X, 35A2)

(2) NDG, NS, NAME: input data group number, number of points in the group, and some description of the contents. In order to exit the subroutine set NDG $\geq$ 99.

Format: (2I5, 30A2)

(a) Data Group 1

. NS is the number of reaches of interest starting with reach 1.

(i) CBOD(I), I=1, NS: the initial carbonaceous BOD concentrations in each reach, in milligrams per liter.

Format: (14F5.0)

(ii) NBOD(I), I=1, NS: the initial nitrogenous BOD concentrations in each reach, in mg/liter.

Format: (14F5.0)

(iii) DO(I), I=1, NS: the initial dissolved oxygen concentrations in each reach, in mg/liter.

Format: (14F5.0)

NOTE: This data group need not be specified by the user. Default values are as follows:

CBOD(I), I=1, NS: 1.5
NBOD(I), I=1, NS: 1.5
DO(I), I=1, NS: 7.0

(b) Data Group 2.

NS is the number of reaches into which point sources of wastewater are introduced.

K, QWAST(K), CBODP(K), NBODP(K), DOWAST(K), SP(K): reach number, flow rate of wastewater in cubic feet per second, flow rate of carbonaceous BOD in pounds per day, flow rate of nitrogenous BOD in pounds per day, concentration of dissolved oxygen in wastewater in mg/liter, salinity concentration in wastewater in parts per thousand.

Format: (I5, 5X, 5F10.0)

NOTE: This data group need not be specified, or data may be specified for any subset of reaches. Default values are zero for each QWAST(I), CBODP(I), NBOD(I), DOWAST(I).

(c) Data Group 3.

NS is the number of reaches of interest starting with reach 1 <u>or</u> NS is 1 if values are to be uniform throughout the estuary.

TEMP(I), I=1, NS: water temperature of reach in degrees centigrade.

Format: (14F5.0)

NOTE: This data group must always be immediately followed by data groups 5 and 6, respectively.

(d) Data Group 4.

NS is the number of reaches of interest starting with reach 1 <u>or</u> NS is 1 if values are to be uniform throughout the estuary.

(i) CKC(I), I=1, NS: decay coefficient of carbonaceous BOD at 20° centigrade in each reach (base e), in unit of 1/day.

(ii) CKN(I), I=1, NS: decay coefficient of nitrogenous BOD at 20° centigrade in each reach (base e), in unit of 1/day.

Format: (14F5.0)

NOTE: This data group must always be immediately followed by data group 6.

(e) Data Group 5.

NS is the number of reaches of interest starting with reach 1 <u>or</u> NS is 1 if values of both sub-groups are to be uniform throughout the estuary.

(i) CBODNP(I), I=1, NS

Format: (14F5.0)

(ii) NBODNP(I), I=1, NS

Format: (14F5.0)

The CBOD and NBOD concentrations in each reach, resulting from non-point sources, in mg/liter.

(f) Data Group 6.

NS is the number of reaches of interest, starting with reach 1.

PHOTO(I), I=1, NS: the rate of photosynthetic-respiration in each reach, in grams of dissolved oxygen per square meter per day.

Format: (7F10.0)

NOTE: This data group need not be specified.
Default values are 0.0 for each reach.

(g) Data Group 7.

NS is the number of reaches of interest starting with reach 1.

BEN(I), I=1, NS: the benthic oxygen demand in each reach in grams per square meter per day.

Format: (14F5.0)

NOTE: This data group need not be specified. Default values are 0.0 for each reach.

NOTE: In Data Groups 2 through 8, the variables with I<ML (or MLT, in case of tributaries) may be specified arbitrarily.

In case more than one freshwater discharge condition is to be executed in one run, i.e., NRNM $\geq$ 2, the input data for INPUT Subroutine may be repeated. Only those data groups for which the values are to be altered need to be specified, with the following exceptions: If data group 4 is specified, groups 5 and 6, respectively must immediately follow or if group 5 is specified, group 6 must immediately follow. In any case, after data for the first freshwater flow, TITLE for the INPUT subroutine and an NDG $\geq$ 99 must be specified for the main stream and each tributary to exit the subroutine. Therefore, for each freshwater flow after the first a minimum of 2(n+1) data cards are required, where n is the number of tributaries.

NOTE: All BOD values are ultimate BOD values, rather than 5-day.

VI. Salt Intrusion Model Study

A mathematical model was developed and verified for use in predicting the salt intrusion in the York River System, including the tidal portions of the Pamunkey and the Mattaponi. The model is an inter-tidal model designed to simulate the intrusion of salt water over a several-month period under the actions of mean advection by freshwater runoff and dispersion by tidal currents. The model is based on the one-dimensional mass-balance equation averaged over a tidal cycle. The equation is applied to each branch of the river system and coupled together at the confluence of the branches.

A. Mathematical Formulation

The transport of salt in a roughly sectionally homogeneous estuarine river may be described by the one-dimensional mass balance equation

$$\frac{\partial}{\partial t}(AS) + \frac{\partial}{\partial x}(AUS) = \frac{\partial}{\partial x}\left(AE_s \frac{\partial S}{\partial x}\right) \qquad (1)$$

where t is time, x is the distance along river, A is the cross-sectional area, E_s is the dispersion coefficient, U and S are the cross-sectional mean velocity and salinity, respectively. The lateral variation of axial velocity and the transport of salt due to lateral convection and diffusion are not explicitly represented in equation (1), but are lumped into a single dispersion term. The concept of dispersion in a shear flow was first illustrated by Taylor (1953, 1954), both theoretically and experimentally. Aris (1956) gave a rigorous mathematical proof of the dispersion representation of the transport due to interaction between lateral diffusion and velocity shear. Harleman (1971) has given a brief account of the subsequent extensions of the dispersion concept to natural bodies of water.

To describe the long term, such as seasonal, variation of salinity intrusion, a time increment of numerical computation larger than a tidal cycle is desirable. This large time increment can not be applied to equation (1) directly; it has to be applied to the equation averaged over a tidal cycle. Okubo (1964) performed the time average of equation (1) and arrived at

$$\frac{\partial}{\partial t}(\bar{A}\bar{S}) + \frac{\partial}{\partial x}(\bar{A}U_f\bar{S}) = \frac{\partial}{\partial x}\left(E\bar{A}\frac{\partial \bar{S}}{\partial x}\right) \qquad (2)$$

where the overbars represent the average over a tidal cycle, and U_f is the velocity due to freshwater discharge Q, given by

$$U_f = \frac{Q}{\bar{A}} \qquad (3)$$

E is a dispersion coefficient including the time average of E_s and the effect of transport by oscillating tidal currents, or phase effect.

In practical applications, it is often the maximum salinity in a tidal cycle which is of most interest. Equations similar to equation (2) may be derived by expressing the variation of parameters within a tidal cycle as

$$A = \bar{A} + A' \qquad (4)$$

$$U = \bar{U} + U' \qquad (5)$$

$$S = S_h + S' \qquad (6)$$

$$E_s = \bar{E}_s + E' \qquad (7)$$

where A', U' and E' are the deviation from the respective quantities averaged over tidal cycle, S_h is the salinity at slack water before ebb and S' is the deviation from S_h. Substituting equations (4), (5), (6) and (7) into equation (1) and averaging over a tidal cycle, the equation becomes

$$\frac{\partial}{\partial t} (\bar{A}S_h) + \frac{\partial}{\partial x} (\bar{A}U_f S_h) = \frac{\partial}{\partial x} (\bar{A}E \frac{\partial S_h}{\partial x}) \qquad (8)$$

with

$$E = \bar{E}_s + E_t \qquad (9)$$

where

$$E_t = - \frac{\overline{S'U'}}{\frac{\partial S_h}{\partial x}} \qquad (10)$$

The one-dimensional continuity equation may be written as

$$\frac{\partial}{\partial t} A + \frac{\partial}{\partial x} (AU) = q \qquad (11)$$

where q is the lateral freshwater inflow along a unit length of estuary. Averaging over a tidal cycle, equation (11) becomes

$$\frac{\partial}{\partial t} \bar{A} + \frac{\partial}{\partial x} (\bar{A}U_f) = \bar{q} \qquad (12)$$

Substituting equation (12) into equation (8), the mass balance equation becomes

$$\frac{\partial}{\partial t} S_h + U_f \frac{\partial}{\partial x} S_h = \frac{1}{\bar{A}} \frac{\partial}{\partial x} \left(\bar{A} E \frac{\partial S_h}{\partial x} \right) - \frac{\bar{q}}{\bar{A}} S_h \qquad (13)$$

B. Finite Difference Approximation

Equation (13) was applied to the York River System, between transects upstream of the limits of salt intrusion in the Pamunkey and Mattaponi and a transect near the York River Bridge at Yorktown. The equation was solved numerically with an implicit finite difference scheme. 48, 44 and 11 transects were chosen for the Pamunkey, Mattaponi, and York Rivers respectively. Except for the end transects of the three rivers, equation (13) was approximated by the following finite difference form for each of the transects, (for simplicity the subscript h for S_h and the over-bars for A and q are dropped in the following equations)

$$\begin{aligned}
&\frac{S_m' - S_m}{\Delta t} + \frac{1}{2(\Delta x_{m-1} + \Delta x_m)} \left[U'_{f,m} (S'_{m+1} - S'_{m-1}) \right. \\
&\quad \left. + U_{f,m} (S_{m+1} - S_{m-1}) \right] \\
&\quad = \frac{1}{\Delta x_{m-1} + \Delta x_m} \left\{ \frac{1}{A'_m} \left[\left(\frac{A'_m E'_m + A'_{m+1} E'_{m+1}}{2} \right) \frac{S'_{m+1} - S'_m}{\Delta x_m} \right. \right. \\
&\quad \left. - \left(\frac{A'_{m-1} E'_{m-1} + A'_m E'_m}{2} \right) \frac{S'_m - S'_{m-1}}{\Delta x_{m-1}} \right] \\
&\quad + \frac{1}{A_m} \left[\left(\frac{A_m E_m + A_{m+1} E_{m+1}}{2} \right) \frac{S_{m+1} - S_m}{\Delta x_m} \right. \qquad (14) \\
&\quad \left. \left. - \left(\frac{A_{m-1} E_{m-1} + A_m E_m}{2} \right) \frac{S_m - S_{m-1}}{\Delta x_{m-1}} \right] \right\} - \frac{q_m}{A_m} S_m
\end{aligned}$$

where the subscript m designates the quantities at the mth transect, subscripts m-1 and m+1 designate the adjacent upstream and downstream transects respectively, the primed quantities are evaluated at the end of time step Δt, unprimed quantities are evaluated at the beginning of the time step, Δx_m is the distance between the (m-1)th and the mth transects.

With salinities at the end of time step as unknowns, equation (14) may be simplified by grouping all the known quantities together, as

$$S'_m = -a_m S'_{m+1} + b_m S'_{m-1} + C_m \tag{15}$$

where

$$a_m = \delta_m \left[U'_m - \left(E'_m + \frac{A'_{m+1}}{A'_m} E'_{m+1}\right)/\Delta x_m\right]/d_m$$

$$b_m = \delta_m \left[U'_m + \left(E'_m + \frac{A'_{m-1}}{A'_m} E'_{m-1}\right)/\Delta x_{m-1}\right]/d_m$$

$$\begin{aligned} c_m = \{S_m - \delta_m U_m (S_{m+1} - S_{m-1}) + \delta_m \Big[\Big(E_m + {}&\\ \frac{A_{m+1}}{A_m} E_{m+1}\Big)(S_{m+1} - S_m)/\Delta x_m - \Big(E_m + {}&\\ \frac{A_{m-1}}{A_m} E_{m-1}\Big)(S_m - S_{m-1})/\Delta x_{m-1}\Big]&\\ - \frac{q_m}{A_m} S_m \cdot \Delta t\}/d_m& \end{aligned}$$

and

$$\begin{aligned} d_m = 1 + \delta_m \left(E'_m + \frac{A'_{m+1}}{A'_m} E'_{m+1}\right)/\Delta x_m &\\ + \delta_m \left(E'_m + \frac{A'_{m-1}}{A'_m} E'_{m-1}\right)/\Delta x_{m-1}& \end{aligned}$$

$$\delta_m = \frac{1}{2} \frac{\Delta t}{\Delta x_{m-1} + \Delta x_m}$$

C. Boundary Conditions

The finite difference approximation of the mass balance equation transforms the differential equation into a system of algebraic equations. In this model, there are three systems of simultaneous equations, corresponding to the three branches of the estuarine river, the Pamunkey, the Mattaponi and the York. These three systems of equations are coupled with a mass balance equation for the element including the confluence. The salinity is assumed homogeneous within the water body circumscribed by the three transects bounding the confluence. This leaves two upper and one lower boundary condition to be established to close the whole system of equations. The two furthest upstream transects are located far beyond the salt intrusion limits in the Pamunkey and Mattaponi, hence their boundary conditions may safely be taken as zero salinity. The boundary condition at the downstream end in the York River imposes some difficulty.

The York River System contributes about only 3.2% of the total freshwater runoff of the Chesapeake Bay drainage basin (Bue, 1968). The salinity near the York River mouth is controlled more by the freshwater runoff of the other major tributaries than by the runoff of the York. It is unfeasible to develop any scheme estimating the downstream boundary condition without information from other tributaries of the Bay. Therefore, the downstream boundary condition must be specified a priori. For the model simulation run, the actual field data at station near the most downstream transect are used.

D. Method of Solution

Three sets of simultaneous equations arise from the application of equation (15) to the interior transects of the Pamunkey, Mattaponi and York Rivers. These equations are solved by the Gaussian elimination method and condition matched at the confluence of the three rivers.

Let the $m\ell$th transect be the most upstream one in the Pamunkey or Mattaponi River and applying equation (15) to the $(m\ell+1)$th transect, it is obtained

$$S'_{m\ell+1} = -a_{m\ell+1}S'_{m\ell+2} + b'_{m\ell+1}S'_{m\ell} + C_{m\ell+1} \qquad (16)$$

Since the boundary condition $S'_{m\ell}$ is specified, there are only two unknowns, $S'_{m\ell+1}$ and $S'_{m\ell+2}$ in equation (16). Substituting equation (16) into equation (15) with $m = m\ell+2$, $S'_{m\ell+2}$ may be written in terms of $S'_{m\ell+3}$. In general, there exists the following recursion relationship

$$S'_m = -P_mS'_{m+1} + O_m \qquad (17)$$

or

$$S'_{m-1} = -P_{m-1}S'_m - O_{m-1} \qquad (18)$$

Substituting equation (18) into equation (15), it is obtained

$$S'_m = -a_mS'_{m+1} + b_m\,(-P_{m-1}S'_m + O_{m-1}) + c_m$$

or

$$S'_m = -\frac{a_m}{1 + b_mP_{m-1}}\,S'_{m+1} + \frac{b_mO_{m-1} + C_m}{1 + b_mP_{m-1}}$$

comparing with equation (17), gives

$$\left.\begin{aligned} P_m &= \frac{a_m}{1 + b_m P_{m-1}} \\ O_m &= \frac{c_m + b_m O_{m-1}}{1 + b_m P_{m-1}} \end{aligned}\right\} \quad m=m\ell+1,\ldots,m_{j-1} \qquad (19)$$

where mjth transect is the transect bounding the confluence of the three rivers.

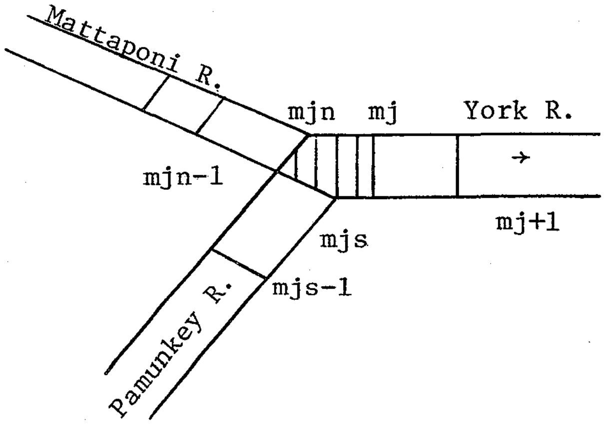
Comparing equation (16) and equation (17) with $m=m\ell+1$, gives

$$P_{m\ell+1} = a_{m\ell+1}, \quad O_{m\ell+1} = b_{m\ell+1} S'_{m\ell} + c_{m\ell+1}$$

or, from equation (19)

$$P_{m\ell} = 0, \; O_{m\ell} = S'_{m\ell}$$

Equation (19) may be applied to the Pamunkey and Mattaponi Rivers to calculate the recursion coefficients P_m and O_m for transect $m\ell+1 \le m \le mj-1$. At the confluence of the rivers, as shown in the sketch, the mass balance of water and salt for the reached bounded by transects mjn, mjs and mj may be written as



$$\frac{\partial V}{\partial t} = Q_{mjs} + Q_{mjn} + Q_{mj} + Q_1 \qquad (20)$$

$$\frac{\partial}{\partial t}(VS) = Q_{mjs}S_{mjs} + Q_{mjn}S_{mjn} + Q_{mj}S_{mj} \qquad (21)$$

$$+ \text{ dispersion across the transects.}$$

where V is the volume of the reach, Q_{mjs}, Q_{mjn}, Q_{mj} are flow rates into the reach across transects mjs, mjn, and mj respectively, Q_1 is lateral inflow.

If it is assumed that salinity is uniform in the reach, i.e.

$$S_{mjs} = S_{mjn} = S_{mj}$$

it may be obtained from equations (20) and (21) that

$$V\frac{\partial S_{mj}}{\partial t} = -Q_1S_{mj} - \left(AE\frac{\partial S}{\partial x}\right)_{mjn} + \left(AE\frac{\partial S}{\partial x}\right)_{mj} - \left(AE\frac{\partial S}{\partial x}\right)_{mjs}$$

where $AE\frac{\partial S}{\partial x}$ is salt flux due to dispersion.

The finite difference form is

$$\frac{1}{2}(V + V')\frac{1}{\Delta t}(S'_{mj} - S_{mj}) = \frac{1}{2}\Big[A'_{mjs}E'_{mjs}\frac{-S'_{mj} + S'_{mjs-1}}{\Delta x_{mjs-1}}$$

$$+ A_{mjs}E_{mjs}\frac{-S_{mj} + S_{mjs-1}}{\Delta x_{mjs-1}} + A'_{mjn}E'_{mjn}\frac{-S'_{mj} + S'_{mjn-1}}{\Delta x_{mjn-1}}$$

$$+ A_{mjn}E_{mjn}\frac{-S_{mj} + S_{mjn-1}}{\Delta x_{mjn-1}} + A'_{mj}E'_{mj}\frac{S'_{mj+1} - S'_{mj}}{\Delta x_{mj}}$$

$$+ A_{mj}E_{mj}\frac{S_{mj+1} - S_{mj}}{\Delta x_{mj}}\Big] - Q_1S_{mj}$$

Let $$a = \frac{\Delta t}{\Delta x_{mj}} A_{mj}E_{mj}$$

$$bs = \frac{\Delta t}{\Delta x_{mjs-1}} A_{mjs}E_{mjs}$$

$$bn = \frac{\Delta t}{\Delta x_{mjn-1}} A_{mjn}E_{mjn}$$

then

$$\begin{aligned} S'_{mj}(V + V' + a' + bs' + bn') &= a'S'_{mj+1} + bs'S'_{mjs-1} \\ &+ bn'S'_{mjn-1} + a(S_{mj+1} - S_{mj}) \\ &+ bs(S_{mjs-1} - S_{mj}) + bn(S_{mjn-1} - S_{mj}) \\ &+ (V + V')S_{mj} - Q_1S_{mj} \end{aligned}$$

or $$S'_{mj} = -AS'_{mj+1} + BsS'_{mjs-1} + BnS'_{mjn-1} + C \qquad (22)$$

where

$$A = -\frac{a'}{V + V' + a' + bs' + bn'}$$

$$B_s = \frac{bs'}{V + V' + a' + bs' + bn'}$$

$$B_n = \frac{bn'}{V + V' + a' + bs' + bn'}$$

$$\begin{aligned} C = {} & \left[a(S_{mj+1} - S_{mj}) + bs(S_{mjs-1} - S_{mj}) \right. \\ & \left. + bn(S_{mjn-1} - S_{mj}) + (V+V')S_{mj} - Q_1S_{mj}\right] / \\ & (V+V' + a' + bs' + bn') \end{aligned}$$

Equation (17) gives

$$S'_{mjs-1} = -P_{mjs-1}S'_{mjs} + O_{mjs-1}$$

$$S'_{mjn-1} = -P_{mjn-1}S'_{mjn} + O_{mjn-1}$$

Substituting into equation (22) it is obtained

$$S'_{mj}(1 + B_s P_{mjs-1} + B_n P_{mjn-1})$$

$$= -AS'_{mj+1} + B_s O_{mjs-1} + B_n \cdot O_{mjn-1} + C$$

since $S'_{mj} = S'_{mjs} = S'_{mjn}$

$$\therefore S'_{mj} = -P_{mj} S'_{mj+1} + O_{mj}$$

with

$$P_{mj} = \frac{A}{1 + B_s\ P_{mjs-1} + B_n P_{mjn-1}}$$

$$O_{mj} = \frac{C + B_s\ O_{mjs-1} + B_n O_{mjn-1}}{1 + B_s\ P_{mjs-1} + B_n P_{mjn-1}} \qquad (23)$$

After calculating P_{mj} and O_{mj}, equation (19) may be applied to the York River to calculate the recursion coefficients for $m_{j+1} \leq m \leq mu-1$, where mu is the most downstream transect. With all the recursion coefficient calculated up to m = mu-1 and the boundary condition S'_{mu} specified, S'_{mu-1} may be calculated with equation (17), and then S'_{mu-2}, S'_{mu-3} and so forth.

E. Computation Procedure

The following are the principal steps in the computer program:

(1) Read the geometric and hydraulic data of the estuarine system.

(2) Rearrange the data to fit the finite difference scheme.

(3) Calculate the freshwater flow rate and dispersion coefficient for each transect at initial time.

(4) Calculate the freshwater flow rate and dispersion coefficient for each transect at new time step.

(5) Calculate a_m, b_m, c_m of equation (15) and P_m, O_m of equation (19) or (23).

(6) Compute concentration for new time steps with equation (17).

(7) Shift the freshwater flow rate and dispersion coefficient calculated in step (4) and concentration calculated in step (6) to initial condition.

(8) Repeat (4), (5), (6) and (7).

F. Evaluation of Parameters

(1) Advective Velocity. In this model, the advective velocity includes only the non-tidal component, which is given by

$$U_f(x,t) = \frac{Q(x,t)}{\bar{A}(x,t)} \tag{24}$$

$Q(x,t)$ is the freshwater discharge from the drainage area upstream of the transect at distance x. This is estimated from the record of stream gauge stations located upstream from the tidal limits. At the mth transect, the freshwater discharge at the kth day is estimated by

$$Q_m(k) = Q_{m-1}(k-j) + I_{m-1,m}(k) \tag{25}$$

where $I_{m-1,m}$ is the total lateral freshwater inflow between the (m-1)th and mth transects, and assumed to be proportional to the drainage area increment between the two transects. A delay time of j days is allowed for the discharge Q_{m-1} to travel from (m-1)th transect to mth transect. This travel time is estimated from the average drifting velocity suggested by Pritchard (1958) as

$$U_d = \frac{Q}{\bar{A}} - \gamma U_t A_t \qquad (26)$$

where U_t and A_t are amplitudes of tidal current and cross-sectional area fluctuations, γ is proportional to the correlation coefficient between the variations of tidal velocity and cross-sectional area.

The cross-sectional area averaged over a tidal cycle, $\bar{A}$, is the cross-sectional area corresponding to the freshwater discharge Q. Due to the large volume of average tidal discharge Q_t, $\bar{A}$ is a very weak function of Q except at the transects near tidal limits and at the time of flood. $\bar{A}$ is computed by the hypothetical formula

$$\bar{A} = A_r(1 + \frac{Q}{Q_t})^b \qquad (27)$$

where

$$Q_t = \frac{2}{\pi} U_t A_r$$

A_r is the cross-sectional area at zero freshwater discharge, and b is a constant less than unity. It may be inferred from calculations of Gallagher and Munk (1971) on the spectrum of tides in shallow water that A_r should be greater than the cross-sectional area below mean-sea level by less than 1% for the York River system.

(2) Dispersion Coefficient. As shown in equation (9), the dispersion coefficient includes two components: one is $\bar{E}_s$, the time average of dispersion due to shear effect and the other is E_t, the dispersion due to the oscillating tidal current or phase effect.

(a) Shear Effect

For a homogeneous estuarine river with a large width to depth ratio, Harleman (1971) suggested that

$$E_s = 77\ n\ h^{5/6}|U| \tag{28}$$

where n is the Manning friction coefficient, h is the hydraulic mean depth. If equation (28) is substituted into the dispersion term in equation (1) and averaged over a tidal cycle, it is determined that

$$\bar{E}_s = 77\ n\ \bar{h}^{5/6}\overline{|U|} \tag{29}$$

to the first order approximation. The equation needs to be modified in case the estuarine river is not well mixed. The York River is a partially mixed estuary except at times when prolonged low freshwater inflow prevails. The degree of stratification depends on the complicated interaction of tidal mixing, freshwater runoff and salinity intrusion. Paulson (1970) concluded from the study of salt intrusion in the Delaware Estuary that the dispersion coefficient increased with freshwater runoff under steady state condition. Kuo, et al., (1975) studied the transient response of salinity structure in the Chesapeake Bay to the Agnes flood. They suggested that the transient response may be divided into four stages. The third stage marks the rebound of salinity after it was depressed by flood water. It is therefore expected that the increase in the one-dimensional dispersion coefficient with freshwater runoff only occurs at the third stage which commences after flood crest past out of the estuary. In this York River model, equation (29) is modified as follows:

$$\bar{E}_s = 77n\, \bar{h}^{5/6}\overline{|U|}\, (1 + \alpha S\sqrt{Q_r/Q_t}) \qquad (30)$$

where

$Q_r = Q$, if

$Q < Q_{ref}$, or

Q decreases with time.

and

$Q_r = Q_{ref}$, if

$Q > Q_{ref}$, and

Q increases with time,

α is numerical constant and Q_{ref} is some reference magnitude of freshwater discharge.

(b) Phase Effect

A simple dimensional argument was used to formulate the dispersion due to the oscillating tidal current. Dimensionally, the dispersion coefficient may be written as

$$E_t = \beta u \ell \qquad (31)$$

where u and ℓ are the velocity and length scales of the transport mechanism involved, β is a coefficient of order of unity. The apparent choice of the velocity scale would be the amplitude of oscillating tidal current U_t. There are several possible choices of length scale. The tidal excursion seems to be the obvious one. In most estuarine rivers of the Chesapeake Bay, including the York River System, the amplitude of the tidal current averages about 1.5 fps, which gives an excursion of 20,000 ft., and $u\ell$ roughly equal to 100 square miles per day, which is an order of magnitude larger than empirical values. Furthermore, if the tidal current is uniform throughout every cross-section of the river, the salt transported upstream during the flood tide will be carried downstream to the original longitudinal position in the ebb tide, even if some may have been diffused laterally or vertically. Thus, neglecting the freshwater flow and longitudinal turbulent diffusion, the same amount of salt will return to the original transect after a complete tidal cycle, resulting in no dispersion regardless of the tidal excursion. It is the non-uniformity of the tidal current within a cross-section which induces longitudinal dispersion. Saline water is carried upstream faster in the mid-channel and part of it diffuses vertically or laterally. Those diffused out of mid-channel will not be carried downstream to the original longitudinal position because of slower currents outside the mid-channel. Therefore, after a complete tidal cycle, salt originally in one transect will be spread out to other transects, resulting in longitudinal dispersion. For a straight estuarine river with large width-to-depth ratio, Holley et al. (1970) showed that the time scale of lateral mixing due to turbulent diffusion is much larger than a tidal cycle while that of vertical mixing is much smaller. Therefore, the depth will be the choice of length scale. The depth averages 20 ft. for the York River and gives

$$u\ell \approx 0.1 \text{ mi}^2/\text{day}$$

an order of magnitude smaller than empirical data. In reality, in an estuarine river with large curvatures, secondary flows always exist; the time scale of lateral mixing may have the same order of magnitude as the vertical one. In this case, the choice of length scale would be the characteristic length of the cross-section such as the square root of the cross-sectional area. In this model, E_t was computed as:

$$E_t = \beta U_t \sqrt{\bar{A}} \qquad (32)$$

G. Model Calibration and Verification

Dispersion coefficient is the main parameter to be calibrated. The model was run to simulate the variation of salinity distribution in the York River system for a period from August 1970 to May 1971. The slack water run data of August 14, 1970 (Figure 30) were used as initial condition of the model. The empirical constants α (Eqn. (30)) and

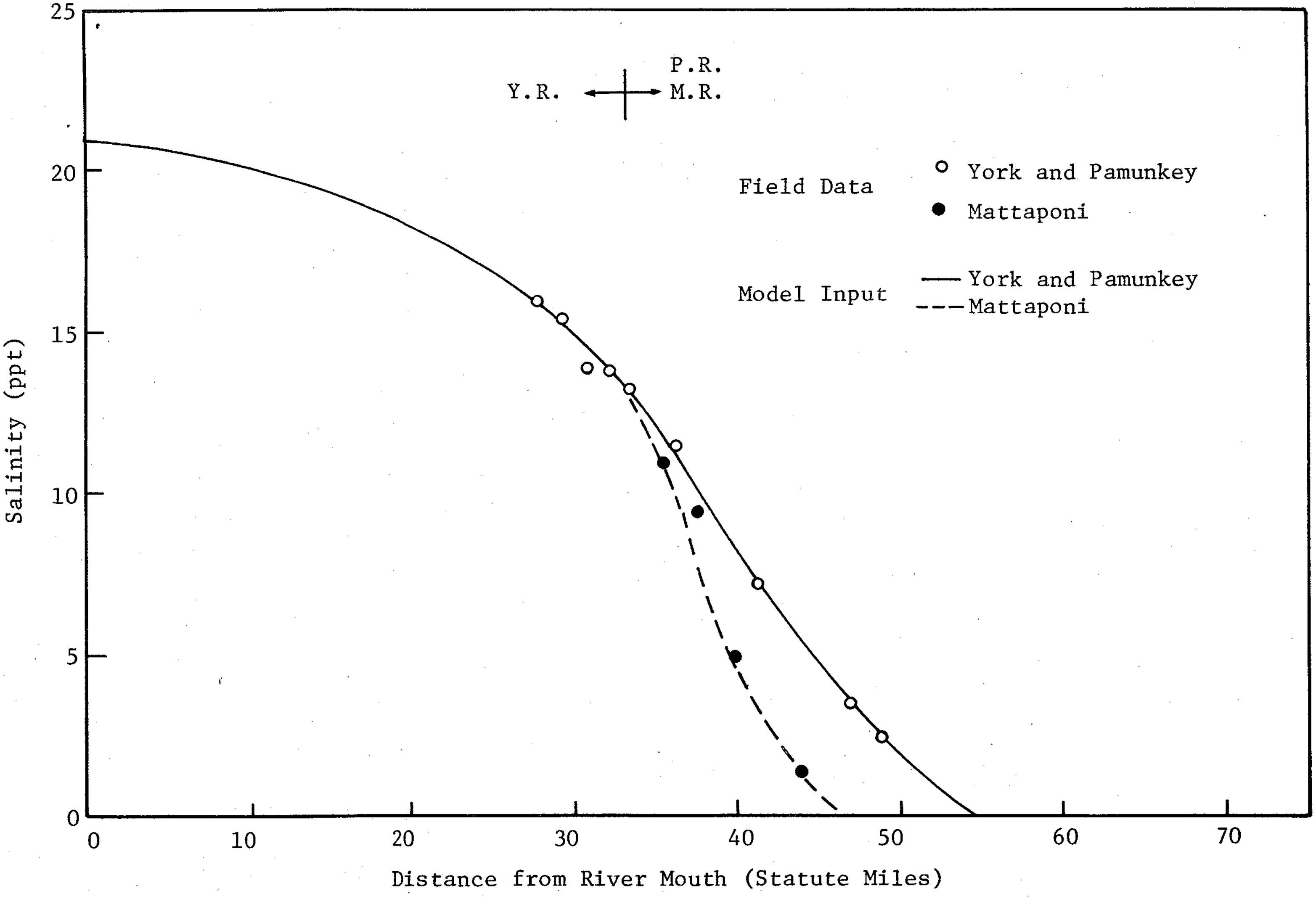


Figure 30. Longitudinal salinity distribution, August 14, 1970.

β (Eqn. (32)) were adjusted until the best agreement between model results and field data was obtained.

The model results are compared with slack water run data in Figures 31-36. Since the hydrograph of monthly average discharge, instead of daily discharge, is used as input data to the model, it is expected that the model only predicts the long-term salinity variation from month to month. The comparison of the field data collected at a particular date with model results has to take this fact into account. The results show that saline water intrudes farther upstream in dry season as indicated by the model output and field data of late September and mid-November (Figures 31, 32, 33 and 34). Figures 35 and 36 show the flushing of sea salt by the high freshwater runoff in the spring.

H. Manual for Program Users

The following is a list of all the input data needed to be specified to run the model. The values of those variables designated by an asterisk are constant and therefore, should not be altered from run to run.

Main Program

*(1a) MLS, MLN, MJ: the transect numbers of the most upstream transect of the Pamunkey, Mattaponi and York respectively.

*(1b) MU: the transect number of the most downstream transect in the York River.

(1c) KW: the number of dates on which the calculated salinity is to be printed.

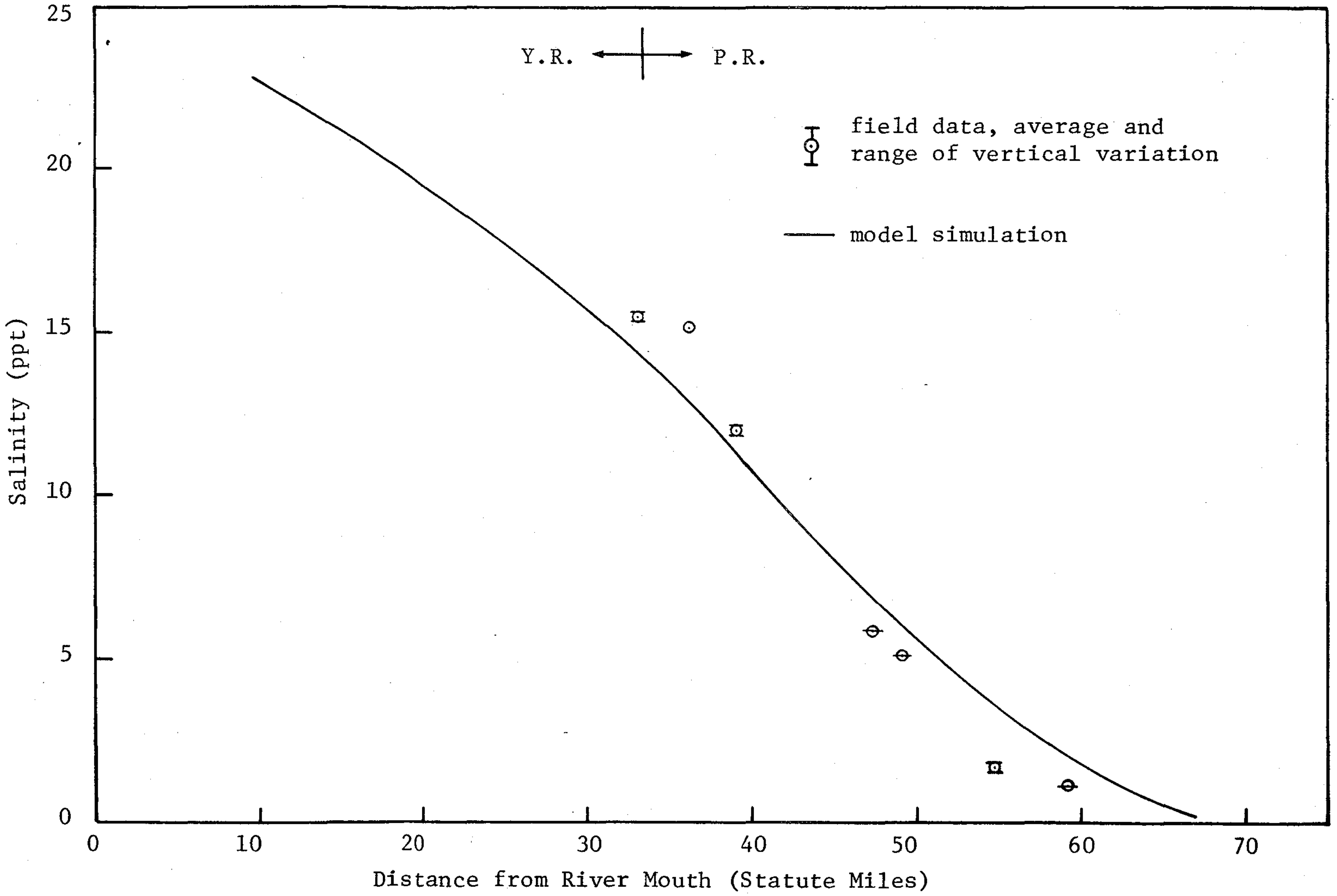


Figure 31. Longitudinal salinity distribution, September 29, 1970.

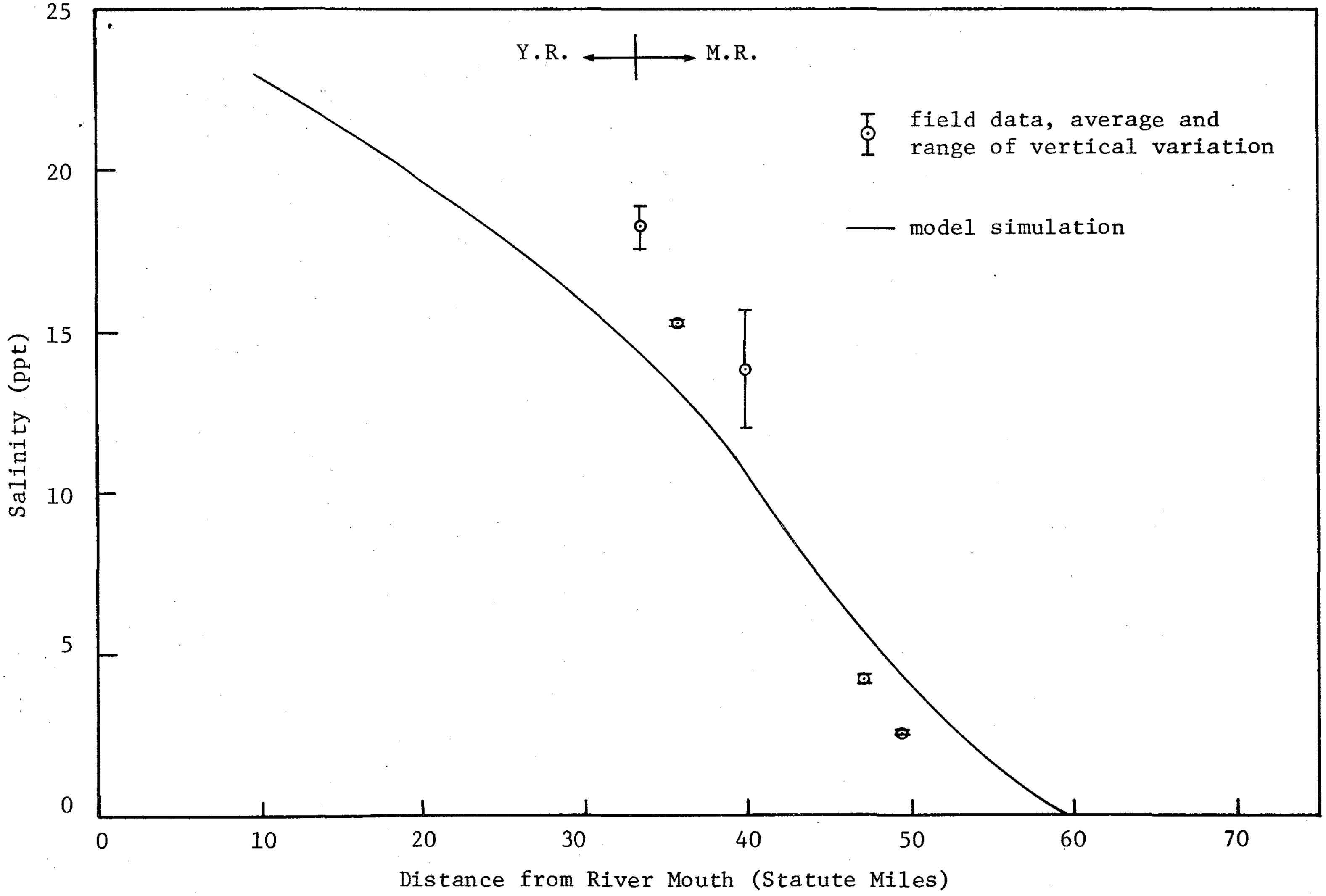


Figure 32. Longitudinal salinity distribution, October 1, 1970.

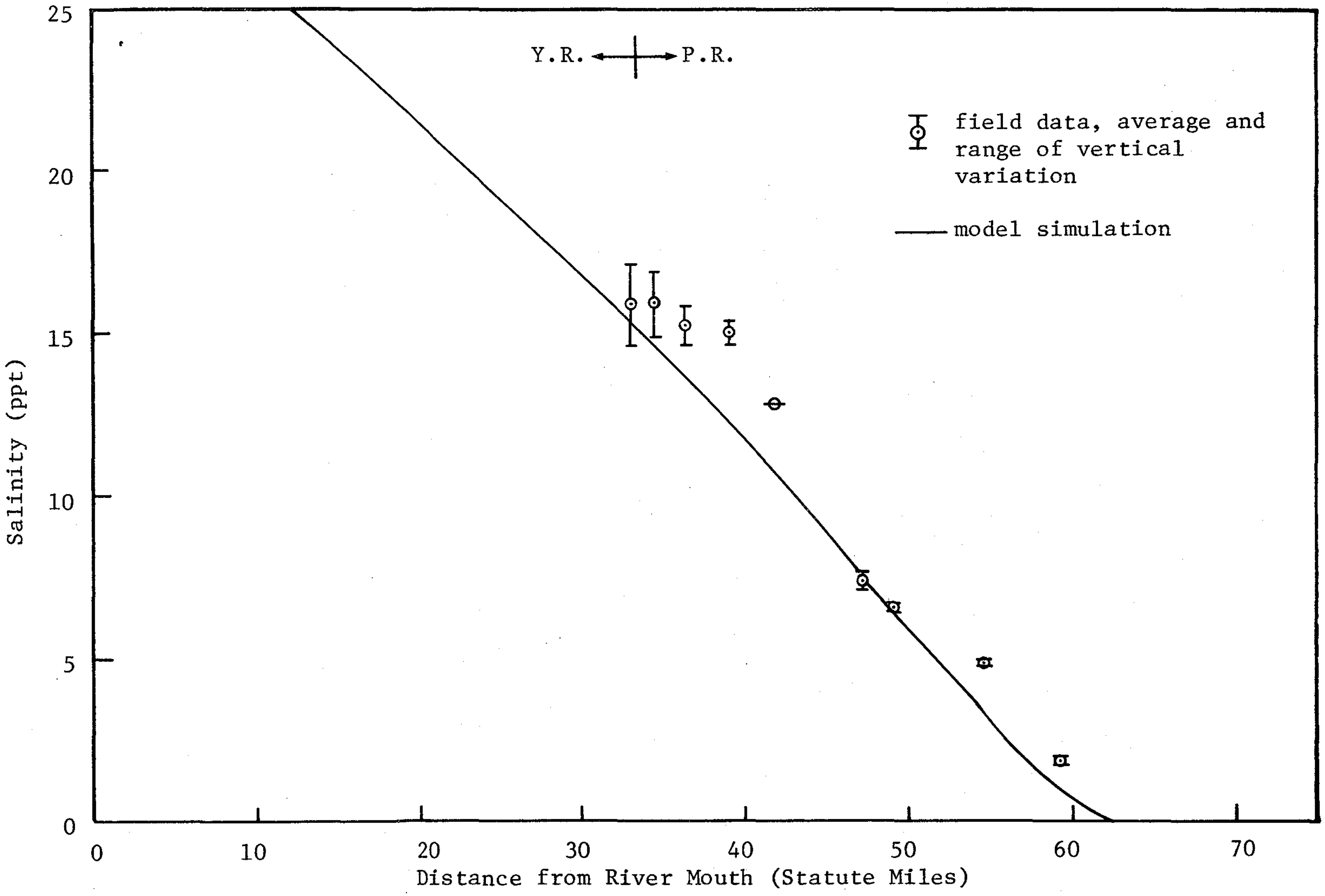


Figure 33. Longitudinal salinity distribution, November 12, 1970.

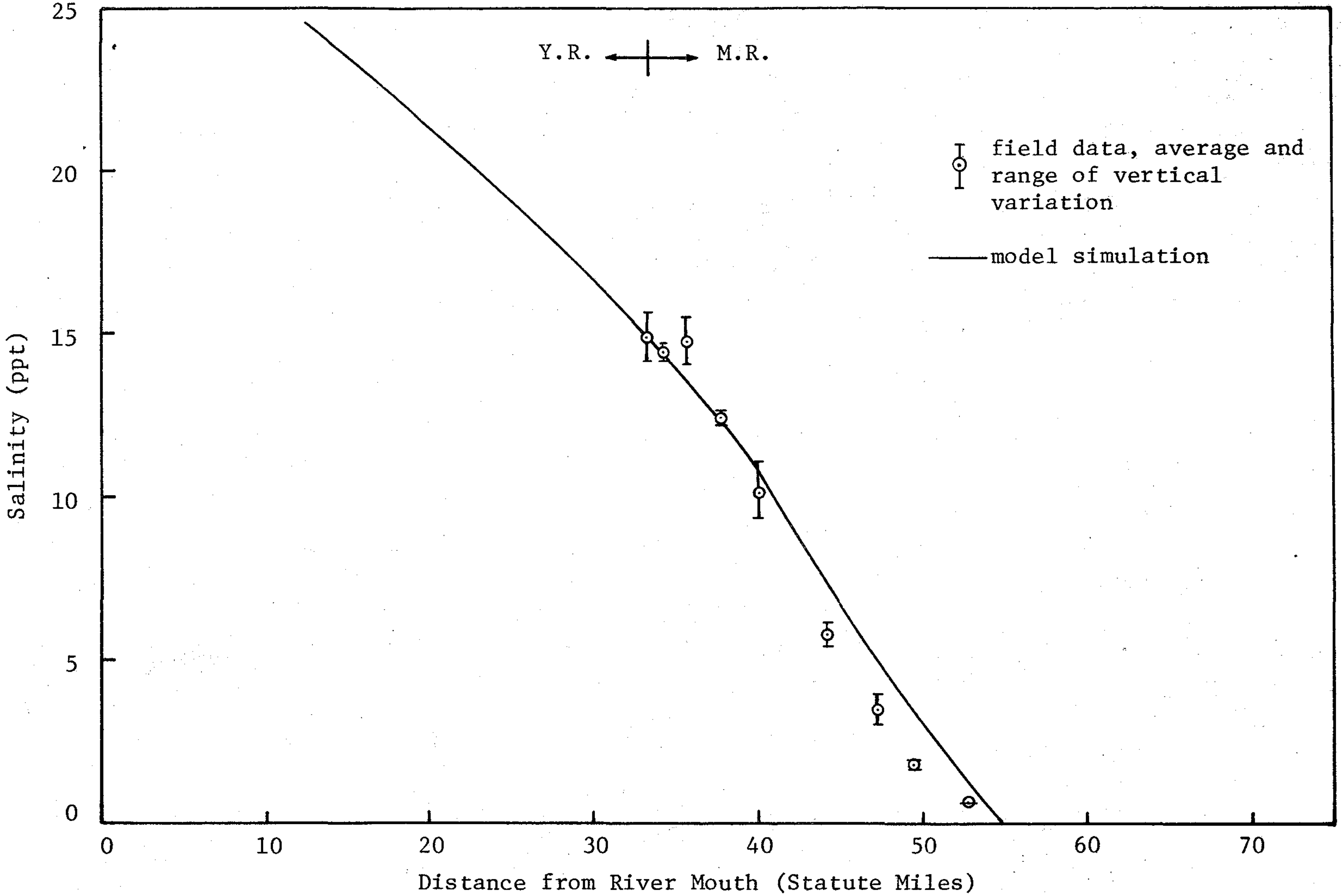


Figure 34. Longitudinal salinity distribution, November 15, 1970.

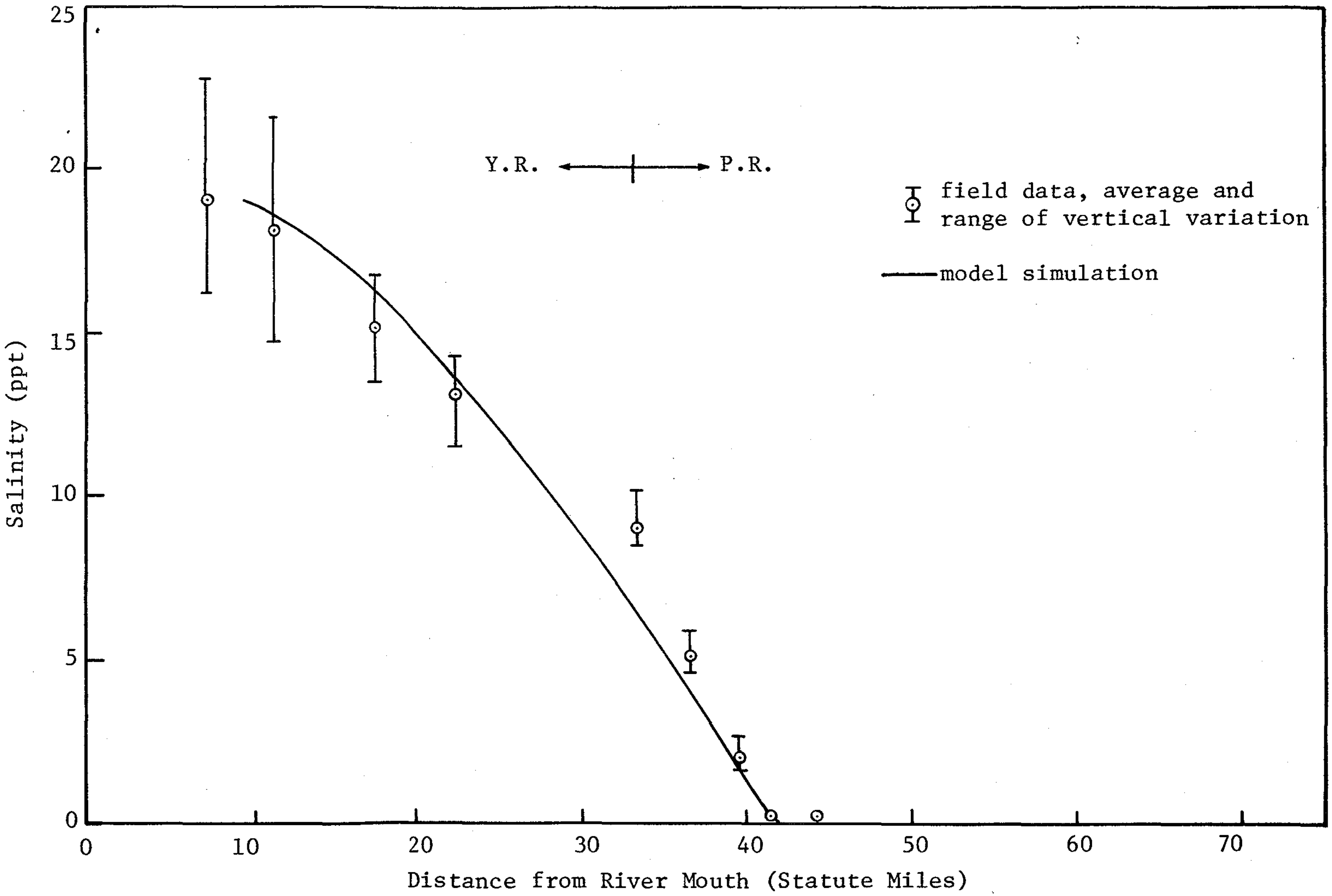


Figure 35. Longitudinal salinity distribution, April 9, 1971.

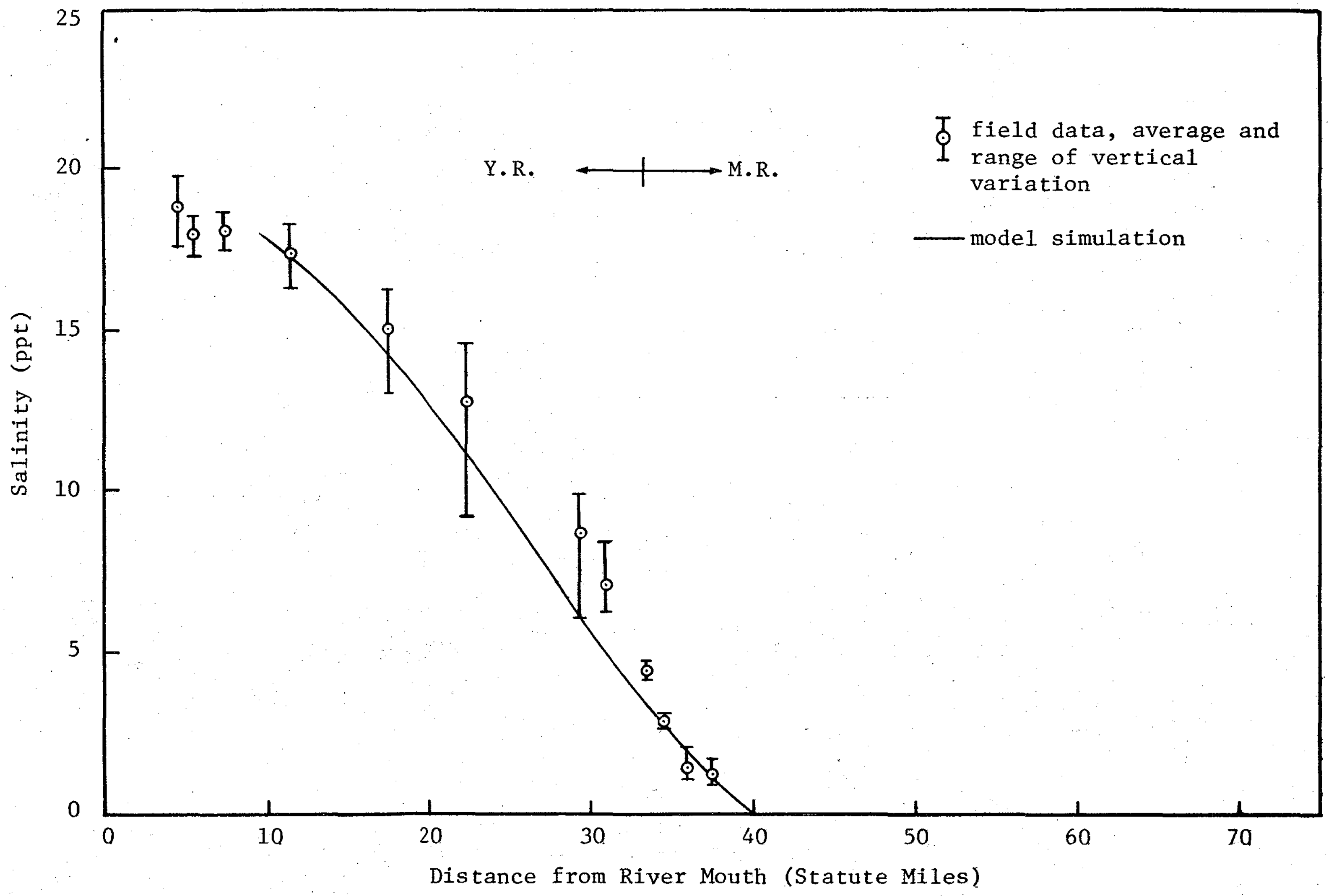


Figure 36. Longitudinal salinity distribution, May 19, 1971.

(1d) ITMAX: the number of days the program is to be run.

(1e) NRNM: the number of hydrographs (history of freshwater discharge at upstream gauging stations) to be run.

*(1f) DT: time increment in days.

*(1g) DXNS: the reach length, in miles, of the confluence reach.

Format: (7I5, 2F10.0)

(2) ITT(I), I=1, KW: the number of days after computation starts on which the calculated salinity to be printed, ITT(KW) should equal to ITMAX.

Format: (10I5)

*(3) JBW: the length, in days, of hydrographic record to be stored in the program memory.

Format: (10I5)

*(4a) COE: the constant for the dependence of cross-sectional area on the freshwater discharge.

*(4b) COR: the constant relating the drifting velocity to tidal current.

Format: (7F10.0)

Input Subroutine

(1) Title: a title describing the particular run of the program.

Format: (1X, 35A2)

(2) NDG, NS, NAME: data group number, number of data in the group and some description of the data. In order to exit the subroutine set NDG $\geq$ 99.

Format: (2I5, 30A2)

*(a) Data Group 1

NS is the number of transects including the Pamunkey and York.

(i) DP(I), I=1, NS: distances of the transects from the York River mouth, in statute miles.

Format: (7F10.0)

(ii) AP(I), I=1, NS: cross-sectional areas of the transects in square feet.

Format: (7F10.0)

(iii) BP(I), I=1, NS: mean depths of the transects in feet.

Format: (7F10.0)

(iv) UTP(I), I=1, NS: the amplitudes of the tidal current at the transects in feet per second.

Format: (7F10.0)

*(b) Data Group 2

NS is the number of transects in the Mattaponi.

(i) DM(I), I=1, NS: distances of the transects from the York River mouth, in statute miles.
Format: (7F10.0)

(ii) AM(I), I=1, NS: cross-sectional areas of the transects, in square feet.
Format: (7F10.0)

(iii) BM(I), I=1, NS: mean depths of the transects in feet.
Format: (7F10.0)

(iv) UTM(I), I=1, NS: the amplitudes of the tidal currents at the transects in feet per second.
Format: (7F10.0)

(c) Data Group Number 3

NS is the number of transects including the Pamunkey and York.

SP(I), I=1, NS: initial salinity, in parts per thousand.

Format: (7F10.0)

(d) Data Group Number 4

NS is the number of transects in the Mattaponi.

SM(I), I=1, NS: initial salinity in parts per thousand.

Format: (7F10.0)

(e) Data Group Number 5

NS is the number of freshwater discharges to be read. NS$\geq$ ITMAX/30+2.

QH(I), I=1, NS: monthly freshwater discharges, in cubic feet per second, at the most upstream transect in the Pamunkey.

Format: (7F10.0)

(f) Data Group Number 6

NS is the number of freshwater discharges to be read. NS$\geq$ ITMAX/30+2.

QB(I), I=1, NS: monthly freshwater discharges, in cubic feet per second, at the most upstream transect in the Mattaponi.

Format: (7F10.0)

*(g) Data Group Number 7

NS is the number of transects, including the Pamunkey and York.

DRAP(I), I=1, NS: the accumulated drainage areas upstream of the transects in square miles.

Format: (7F10.0)

*(h) Data Group Number 8

NS is the number of the transects in the Mattaponi.

DRAM(I), I=1, NS: the accumulated drainage areas upstream of the transects, in square miles.

Format: (7F10.0)

(i) Data Group Number 9

NS is the number of dates on which the downstream boundary conditions are to be specified. The program linearly interpolates the boundary conditions between successive specified dates.

KB(I), BC(I), I=1, NS: the number of days after computation starts and the salinity at the downstream boundary at that date respectively.

Format: (7F10.0)

*(j) Data Group Number 10

NS is the number of freshwater discharges to be read. NS≥ ITMAX/30+2.

ADICH(I), I=1, NS: monthly freshwater discharges, in cubic feet per second, at the most upstream transect in the Pamunkey. These data may be the same as data group number 5, the natural freshwater discharges, or any regulated freshwater discharges.

The freshwater discharges of data groups 5, 6 and 10 should start with the discharge in the month preceeding simulation and end with an arbitrary value for the month following simulation.

In case more than one simulation is to be executed in one run, i.e., NRNM $\geq$ 2, the input data for INPUT subroutine may be repeated. Only those data groups for which the values are to be altered need to be specified. After data for the first simulation, TITLE for the INPUT subroutine must be specified, an NDG $\geq$ 99 must be specified to exit the subroutine. Therefore, for each simulation after the first a minimum of two data cards are required.

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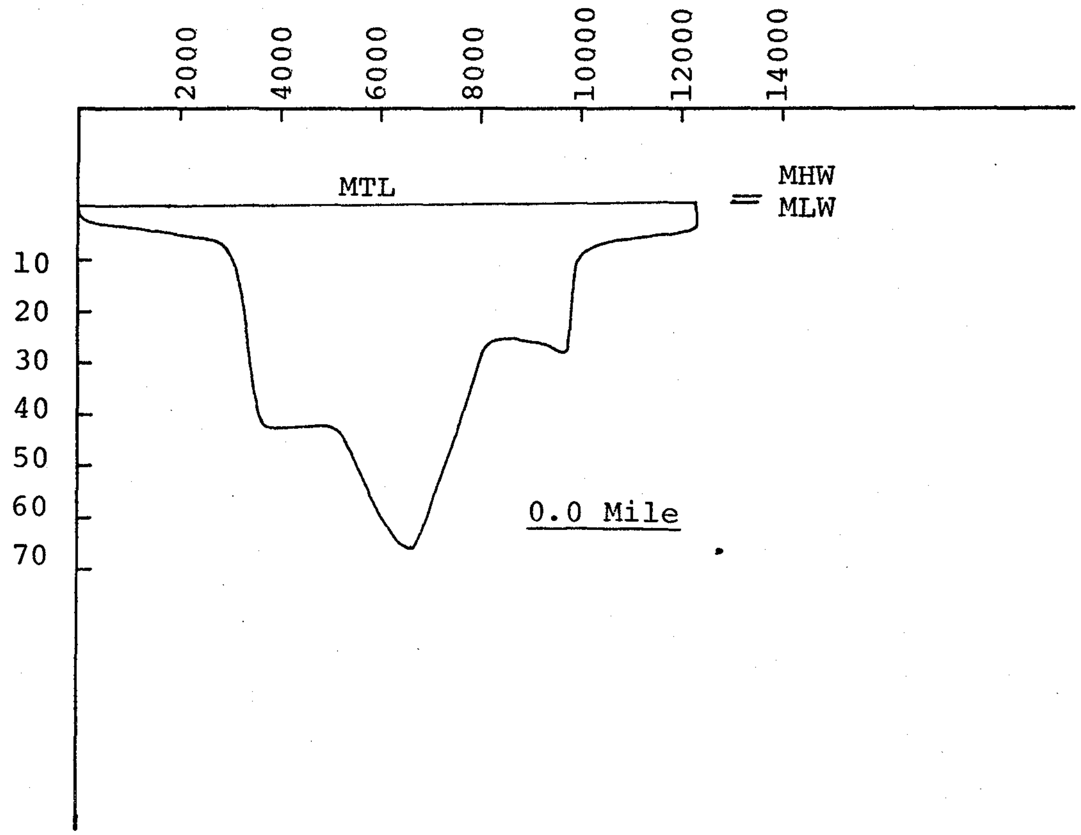
Appendix A

Bottom Profiles of Cross-Sections, 1973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MLW
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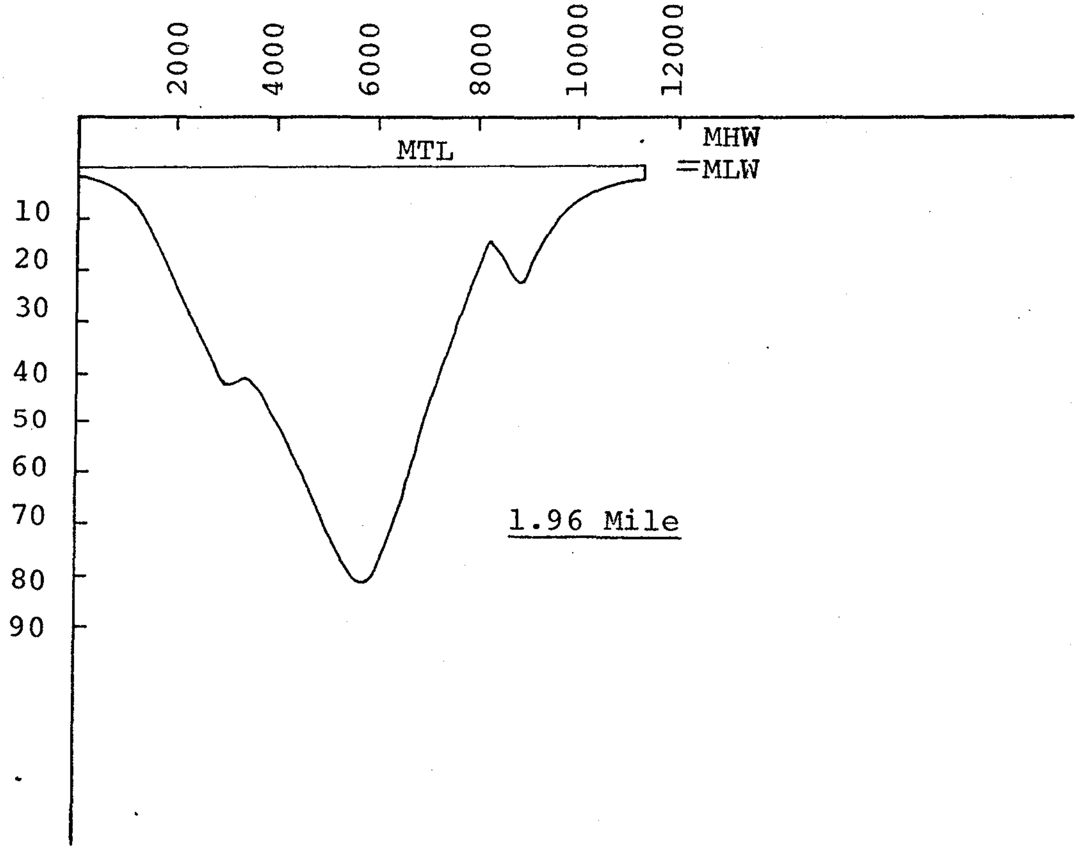
40
50
60
70
0.0 Mile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=MLW
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20
30
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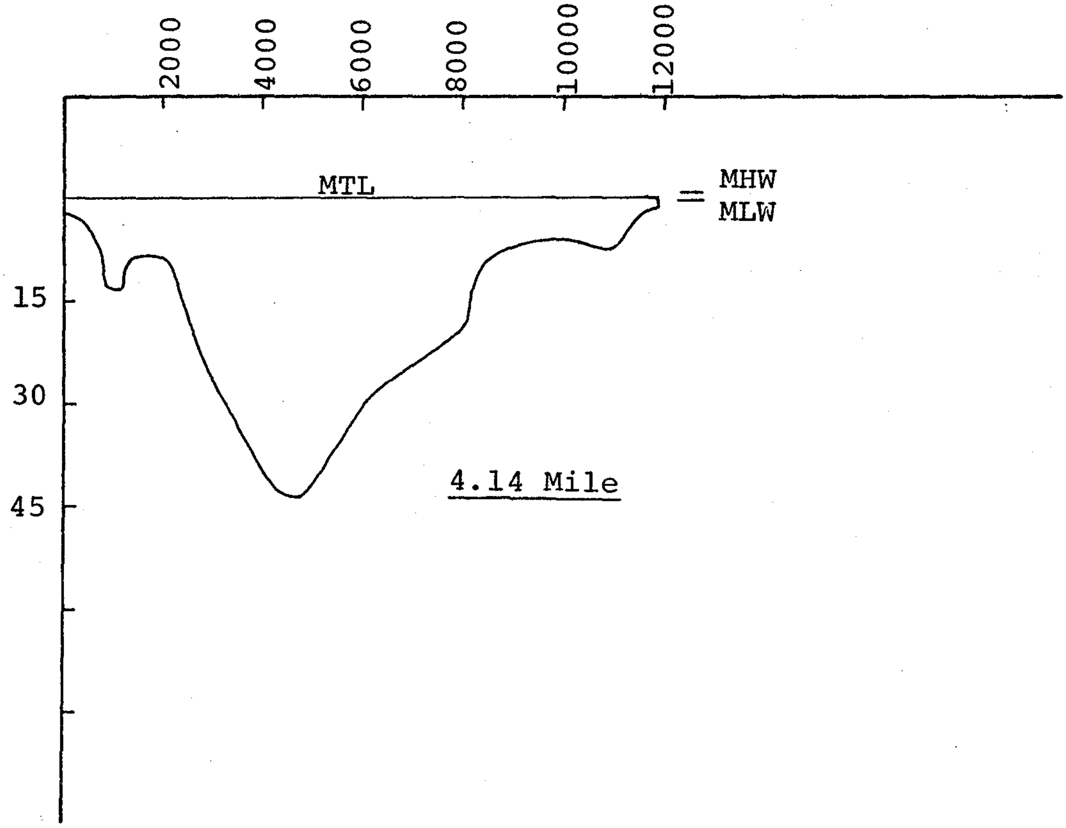
80
90
1.96 Mile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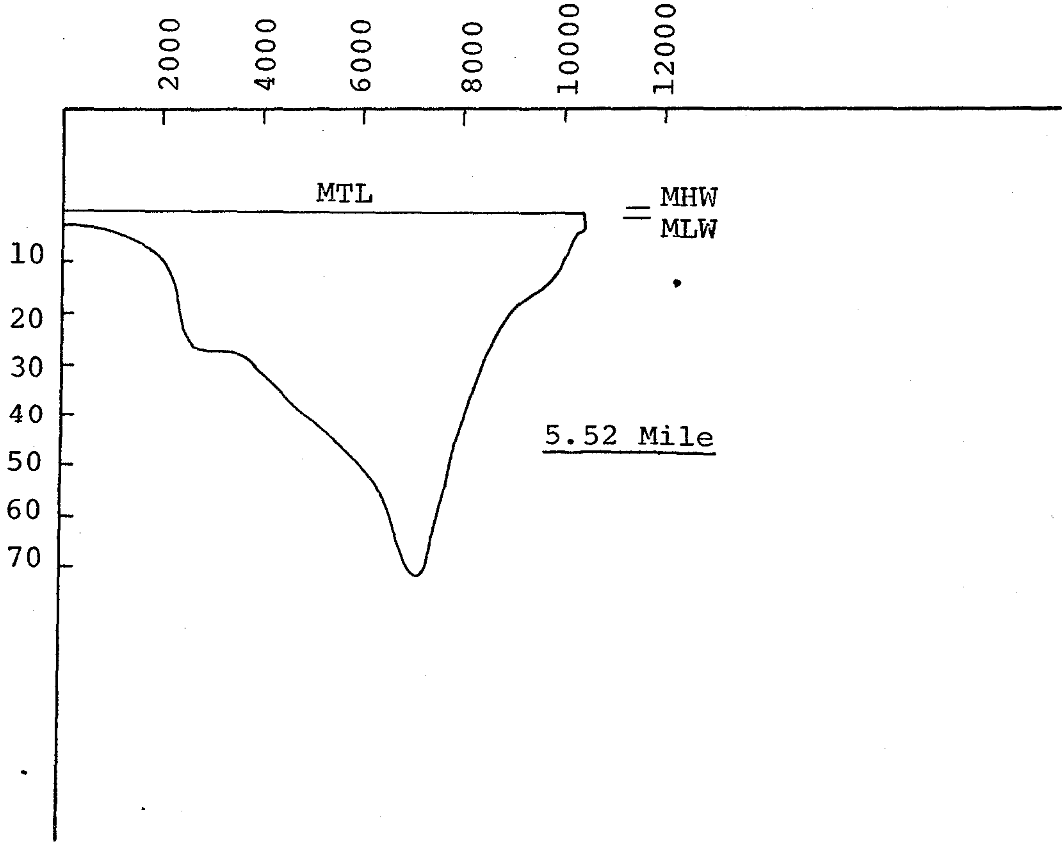
= MHW
MLW
15
30
45
4.14 Mile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MLW
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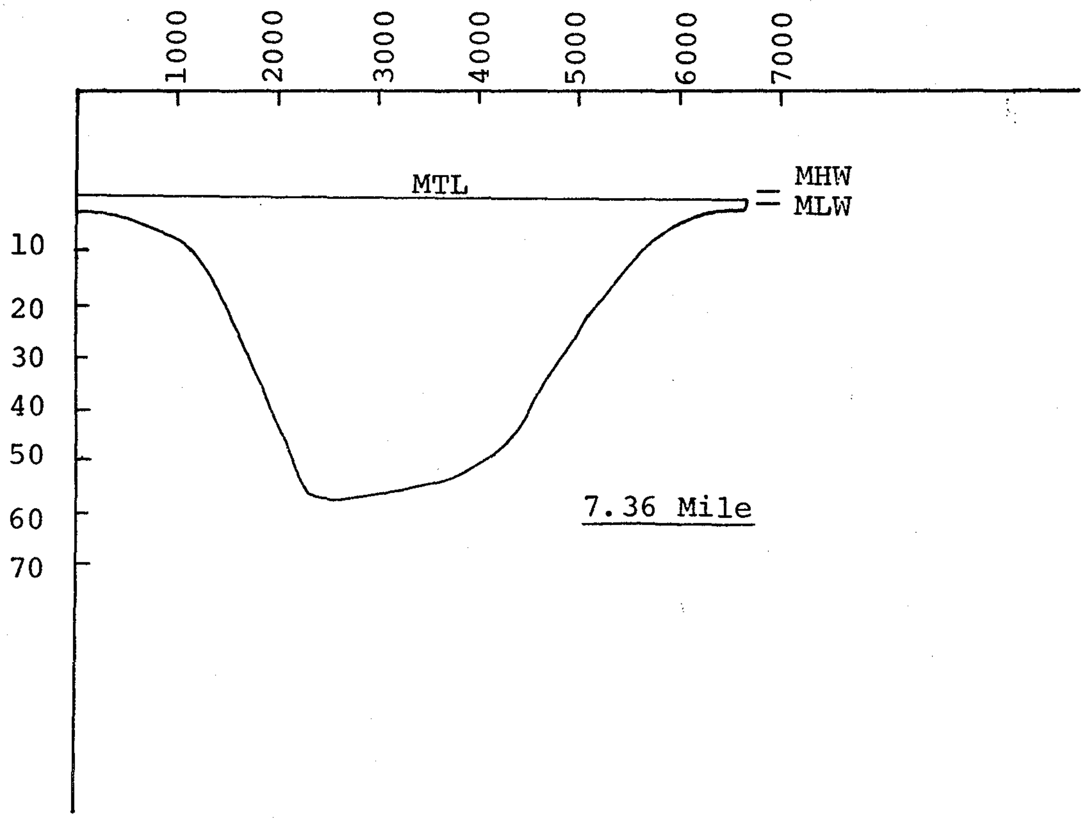
50
60
70
5.52 Mile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5000
6000
7000
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20
30
40
50
60
70
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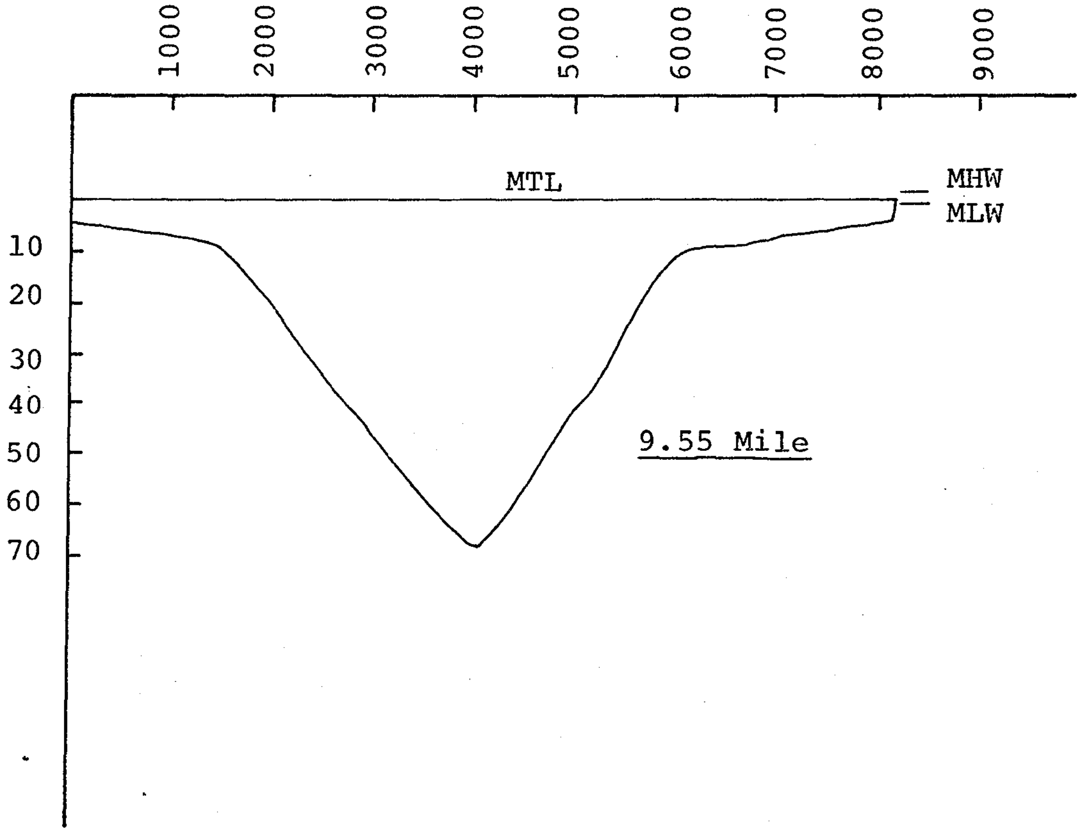
MHW
MLW
7.36 Mile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7000
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10
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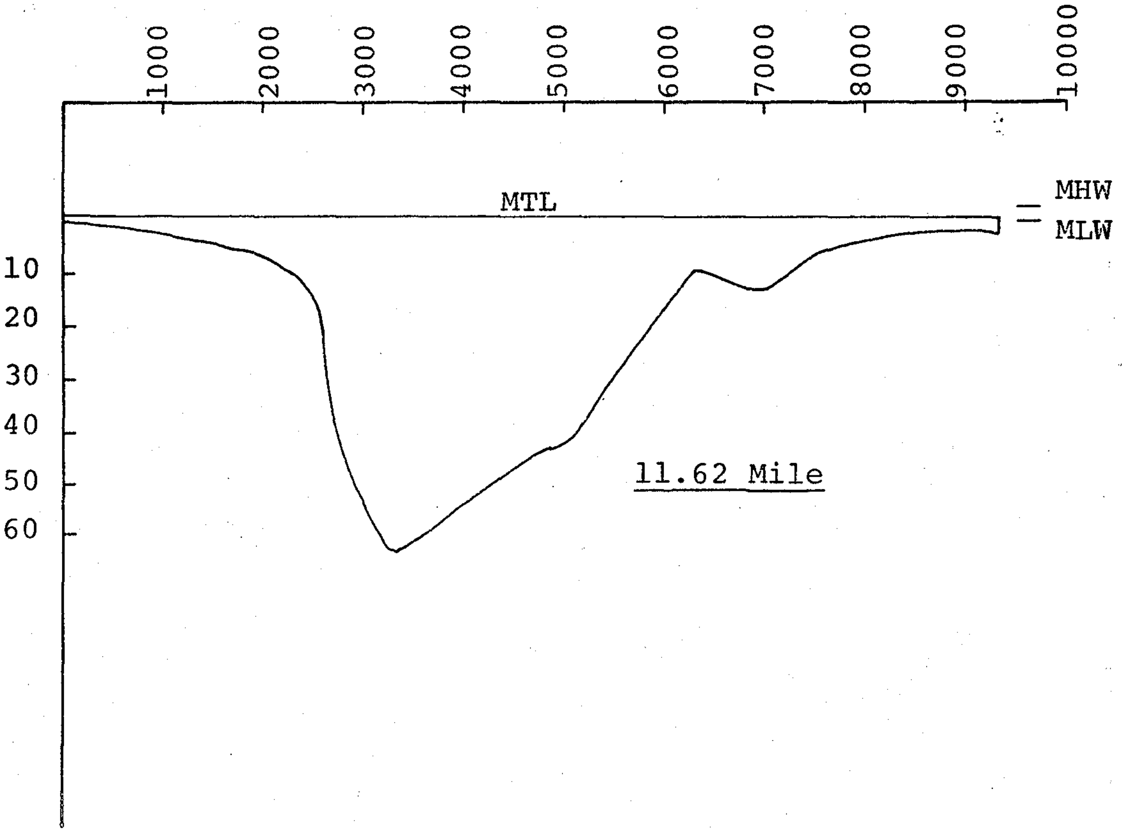
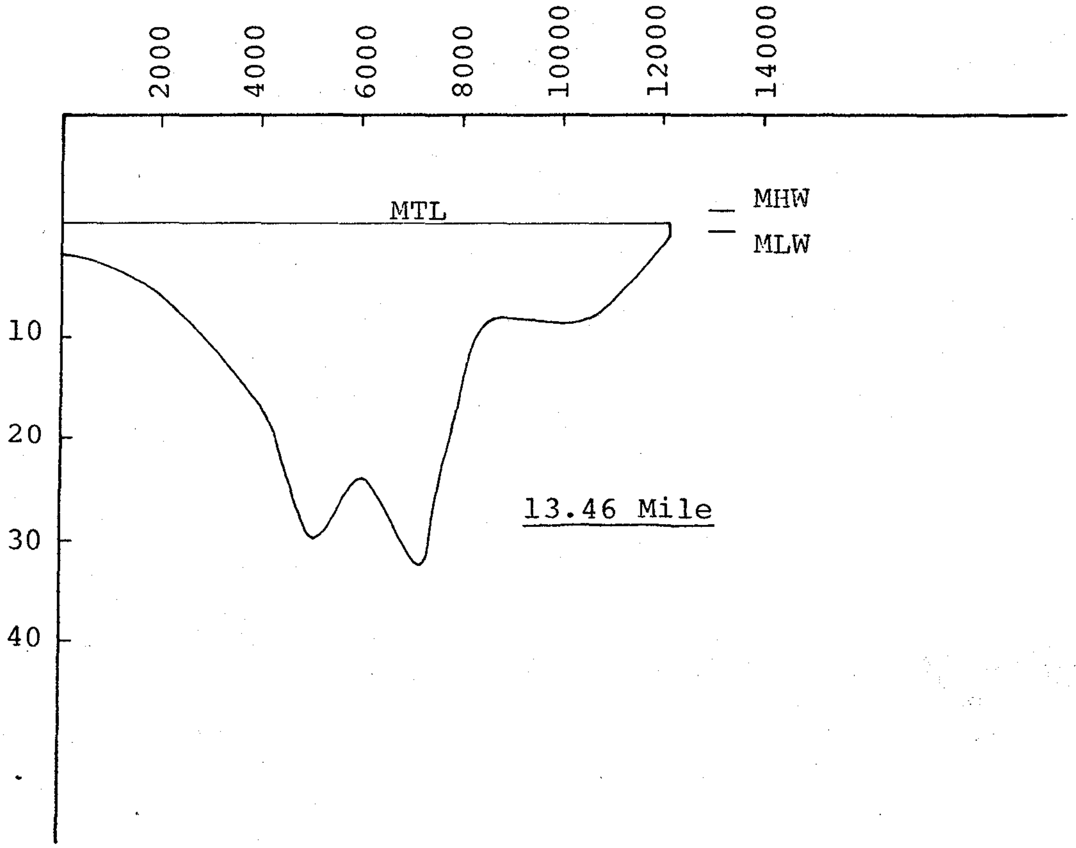
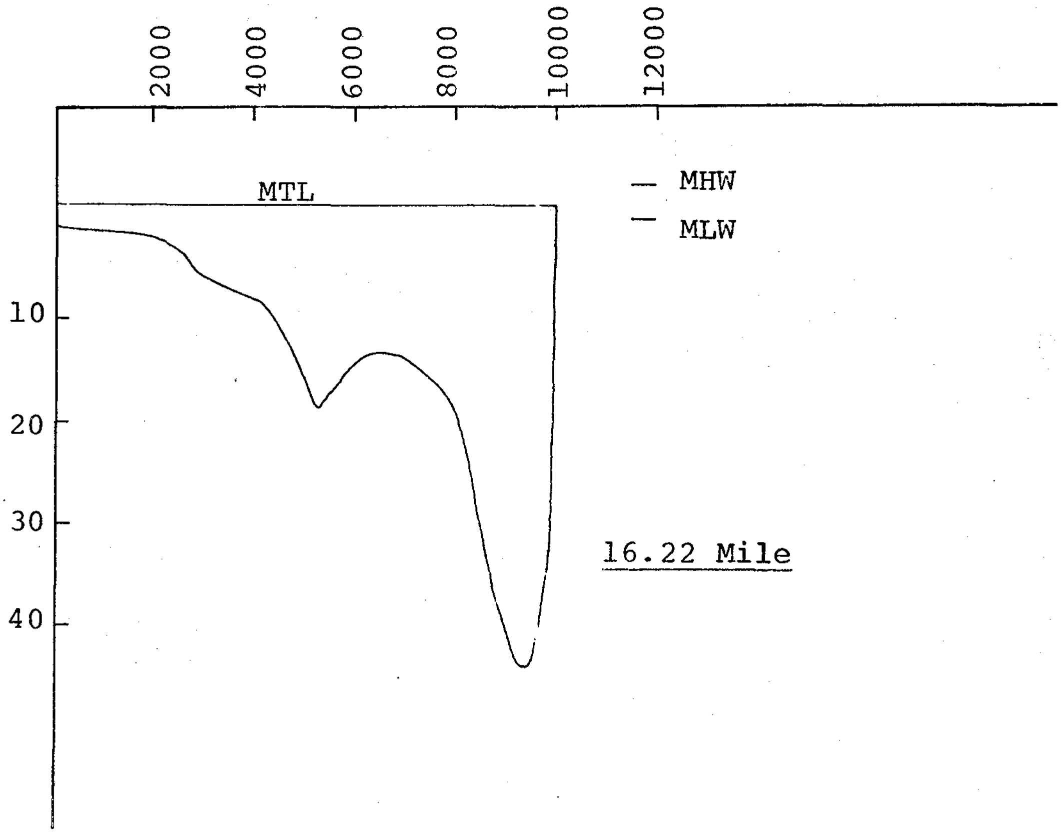
30
40
50
60
70
MTL
MHW
MLW
9.55 Mile



11.62 Mile



13.46 Mile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8000
10000
12000
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MHW
MLW
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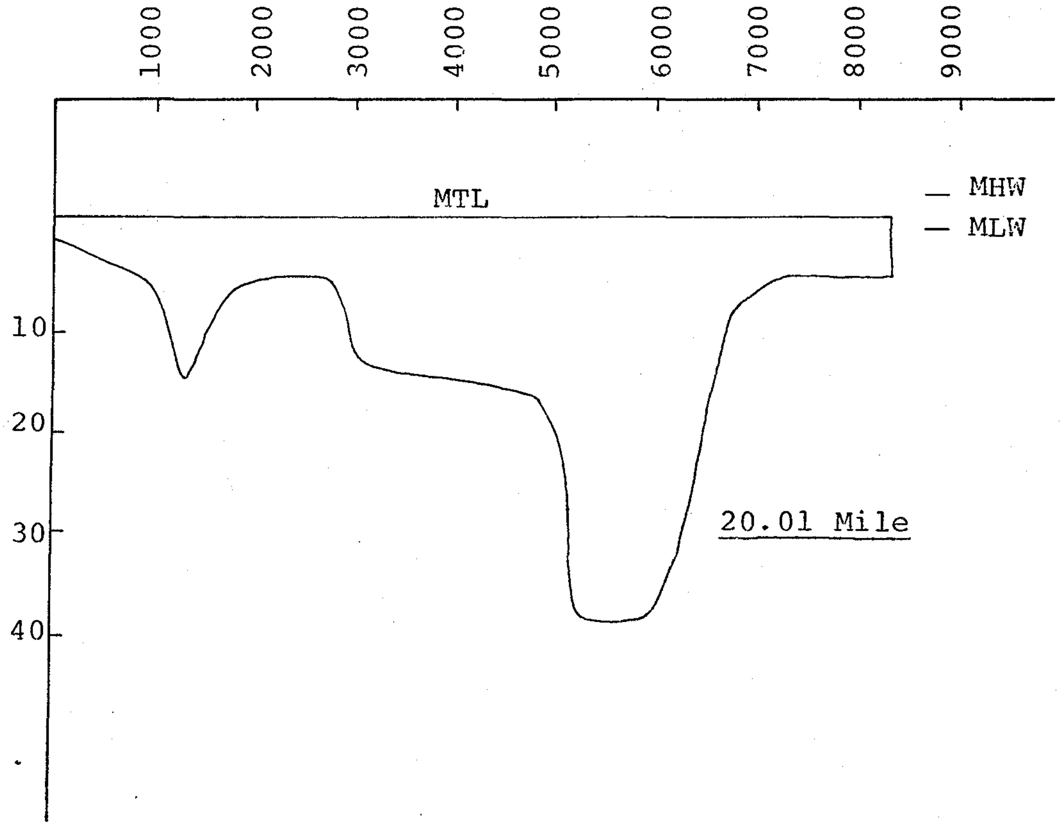
20
30
40
16.22 Mile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2000
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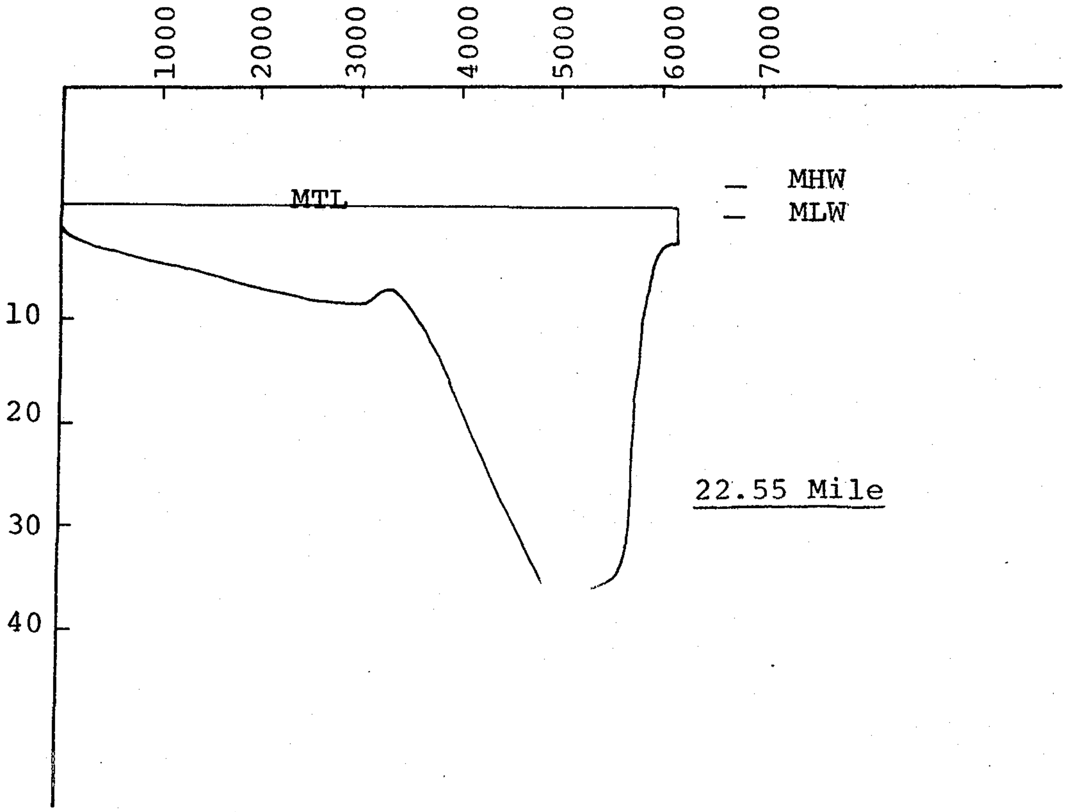
4000
5000
6000
7000
8000
9000
MTL
MHW
MLW
10
20
30
40
20.01 Mile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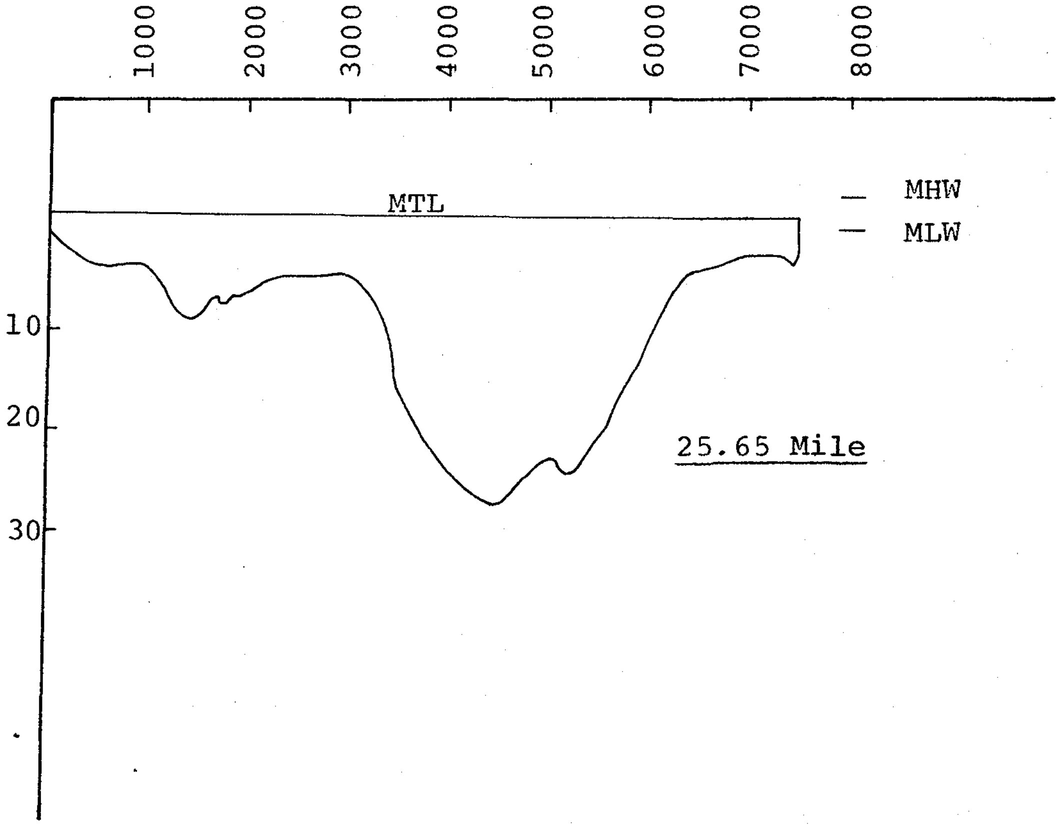
MHW
MLW
10
20
30
40
22.55 Mile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2000
3000
4000
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6000
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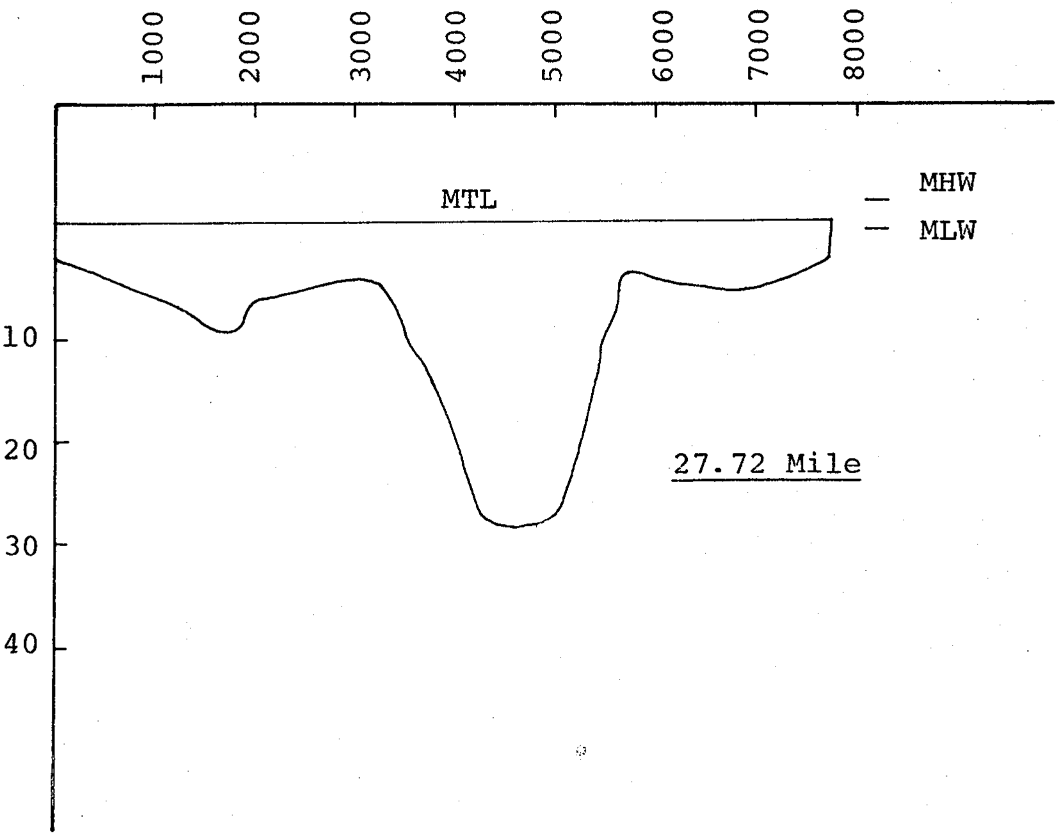
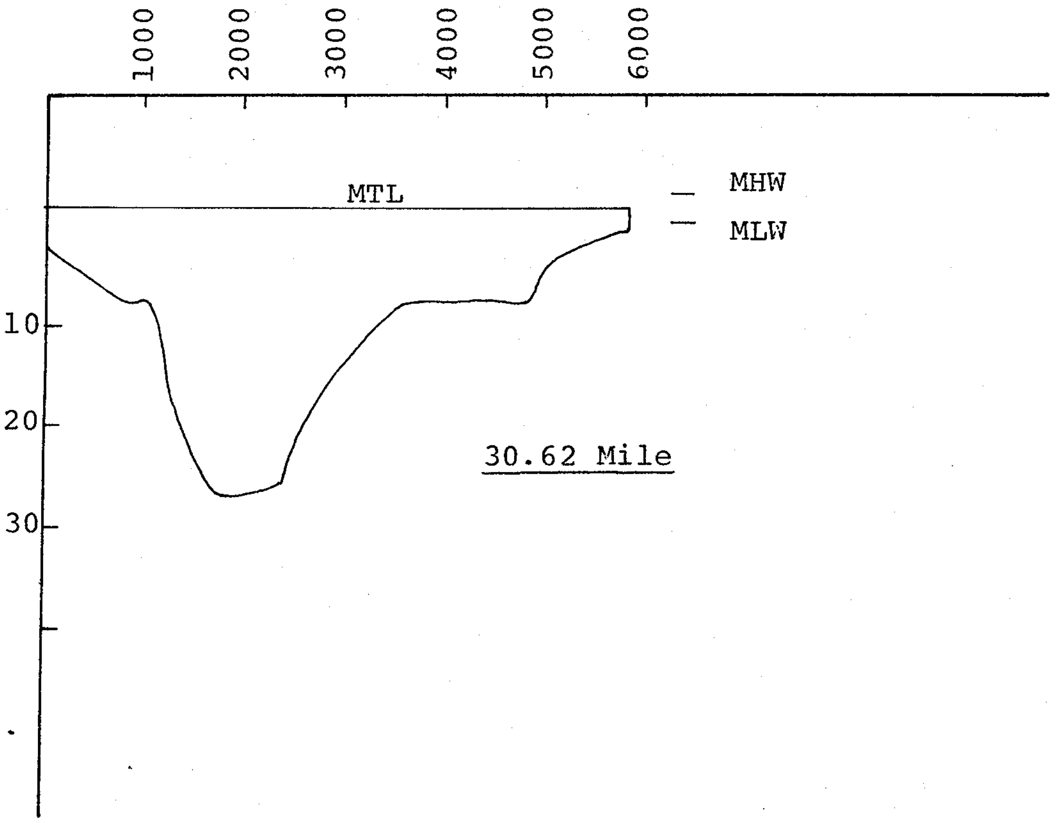
MTL
MHW
MLW
10
20
30
25.65 Mile



27.72 Mile



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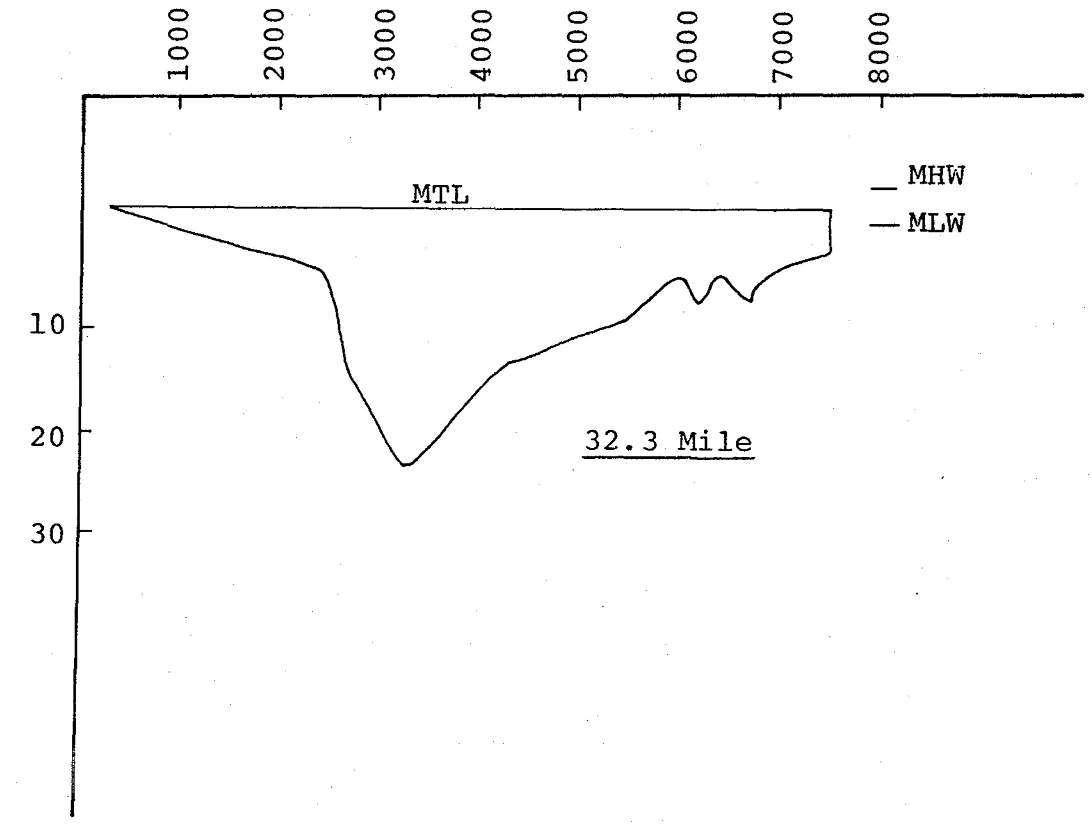
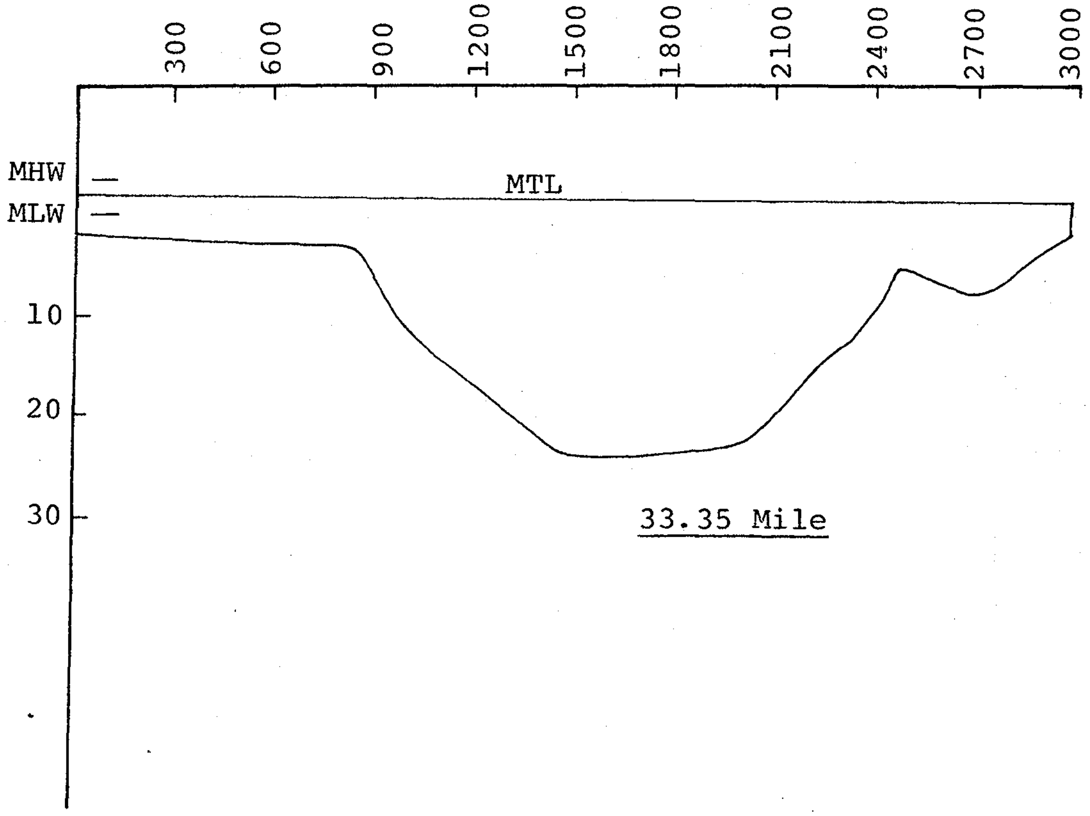
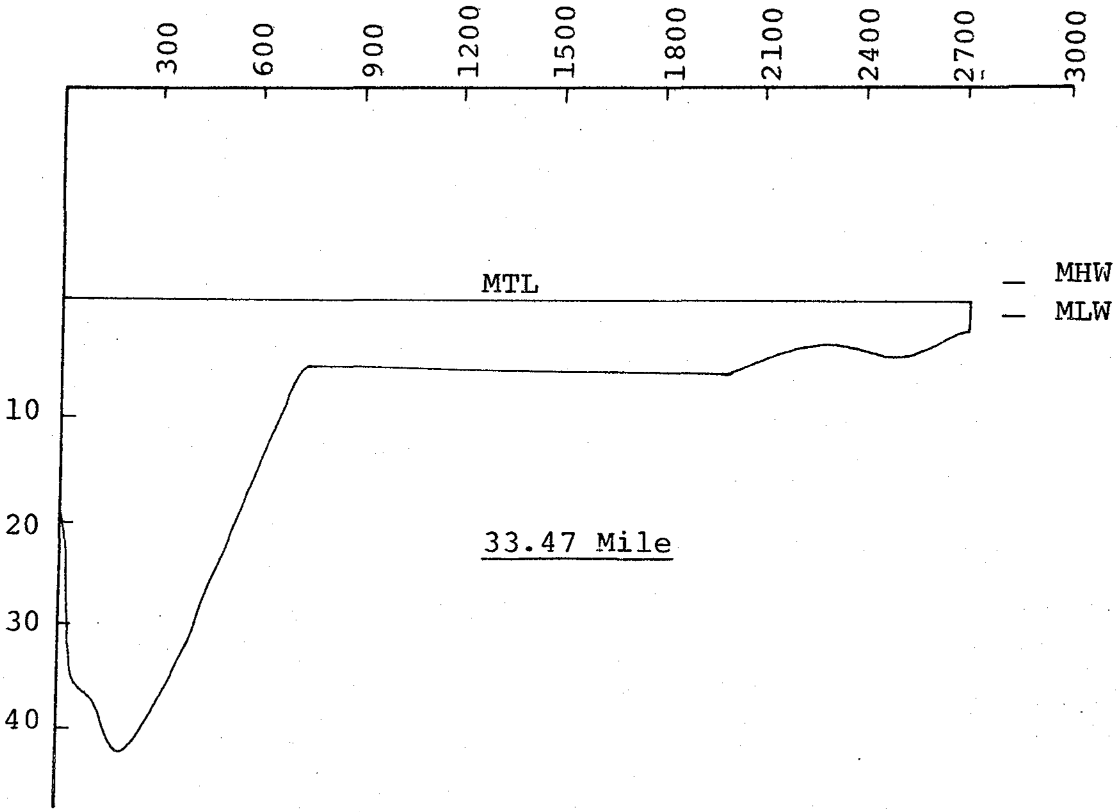


32.3 Mile



33.35 Mile


33.47 Mile

300
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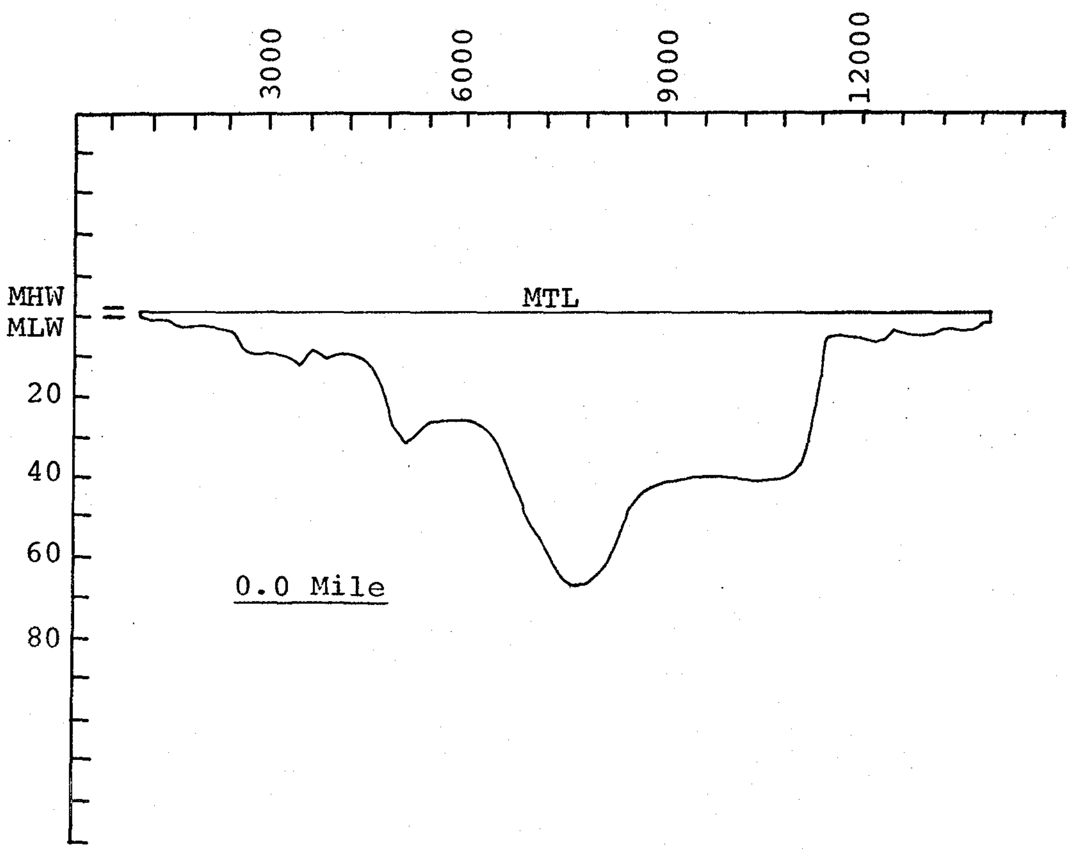
900
1200
1500
1800
2100
2400
2700
3000
MTL
MHW
MLW
10
20
30
40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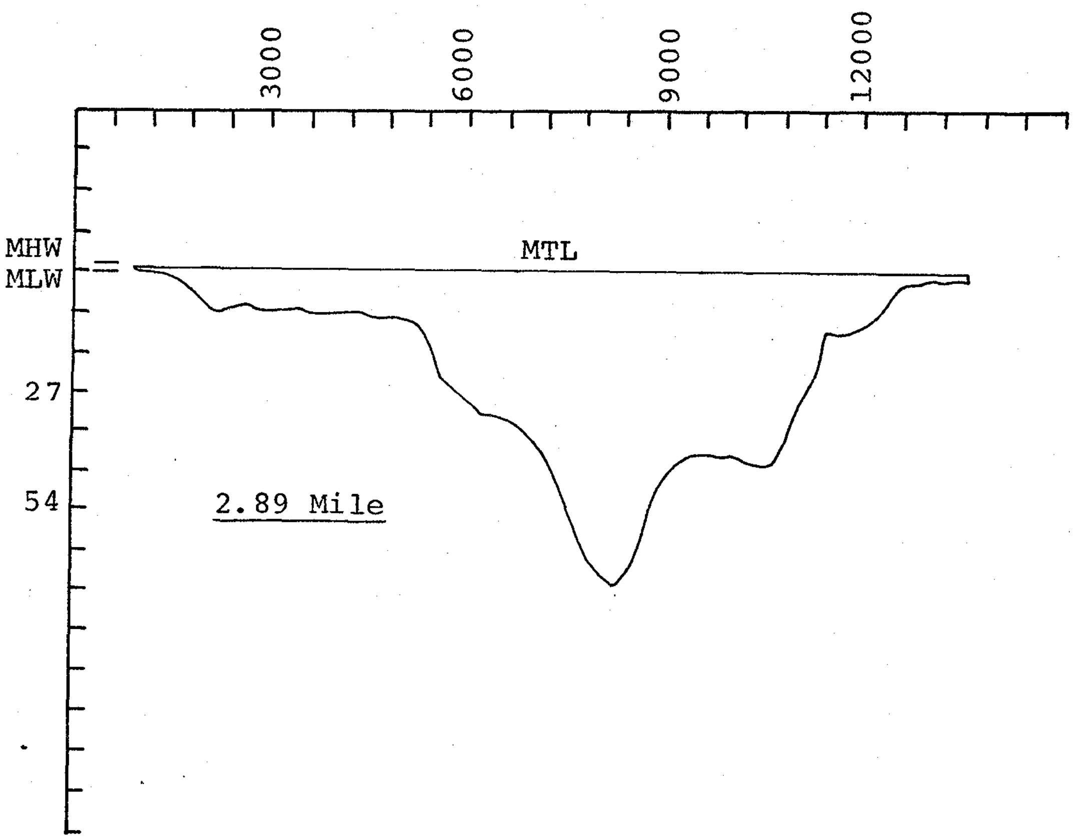
6000
9000
12000
MHW
MLW
=
MTL
20
40
60
80
0.0 Mile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9000
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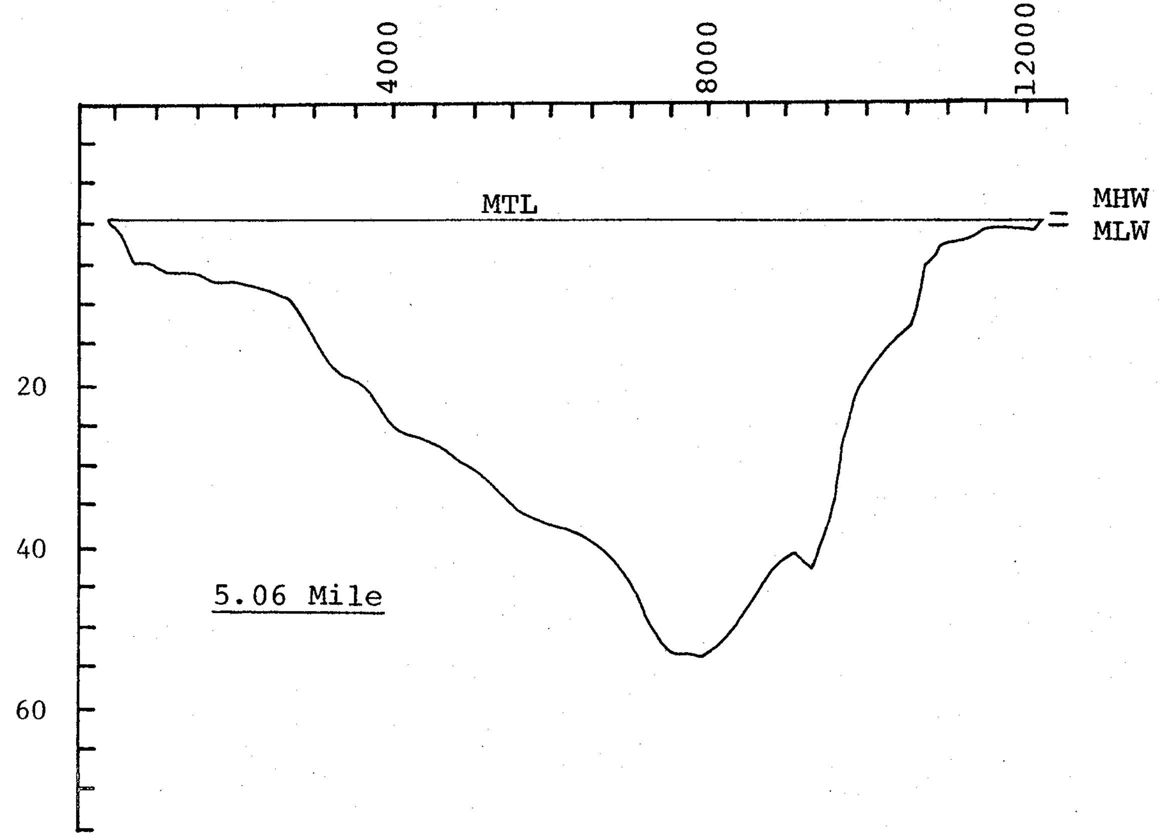
MHW
MLW
=
MTL
27
54
2.89 Mile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MLW
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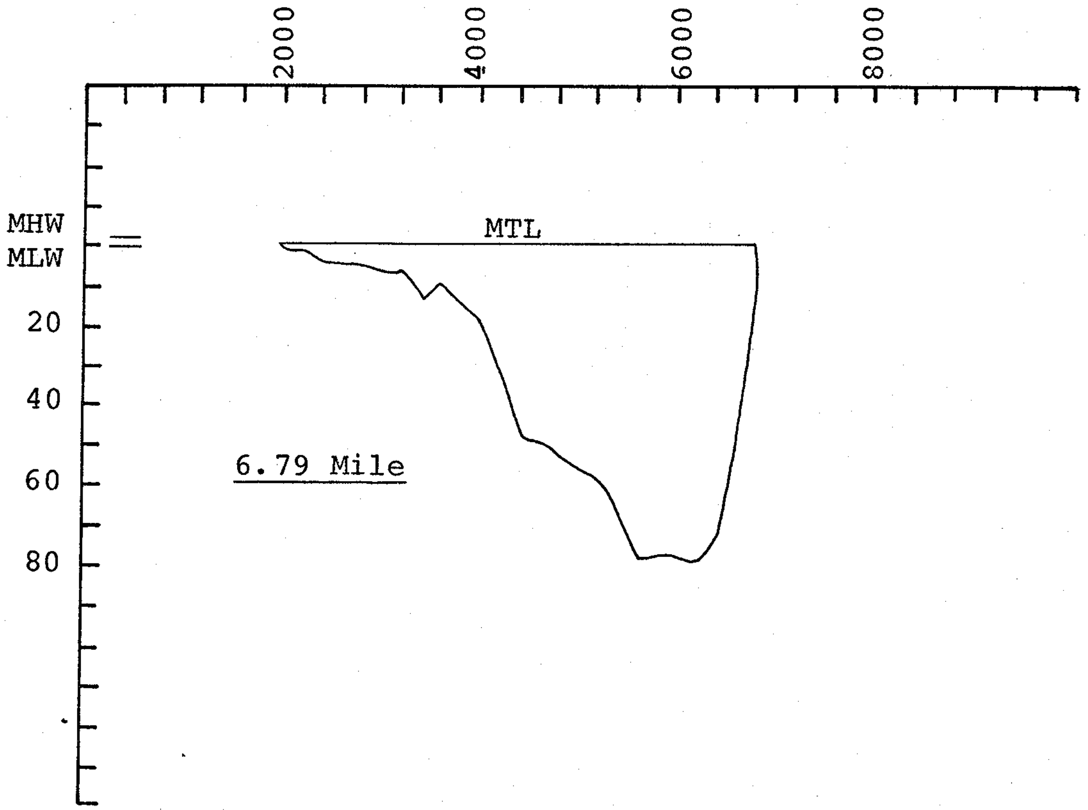
5.06 Mile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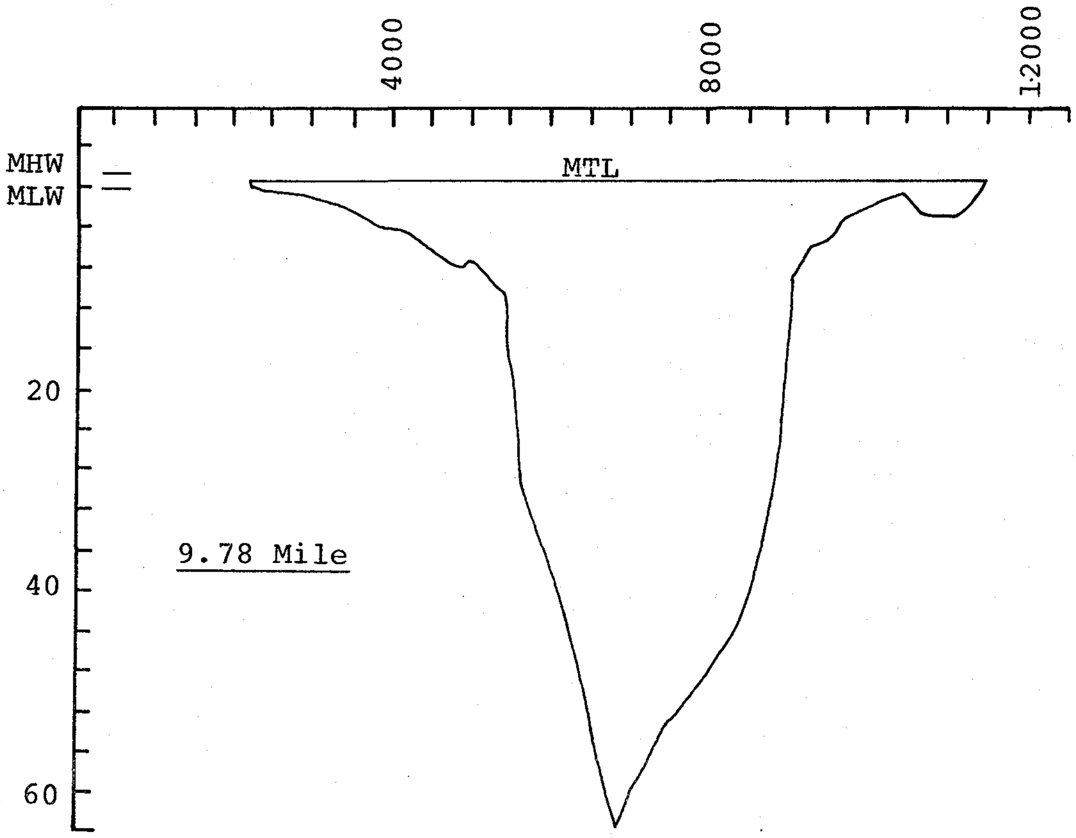
8000
MHW
MLW
MTL
20
40
60
80
6.79 Mile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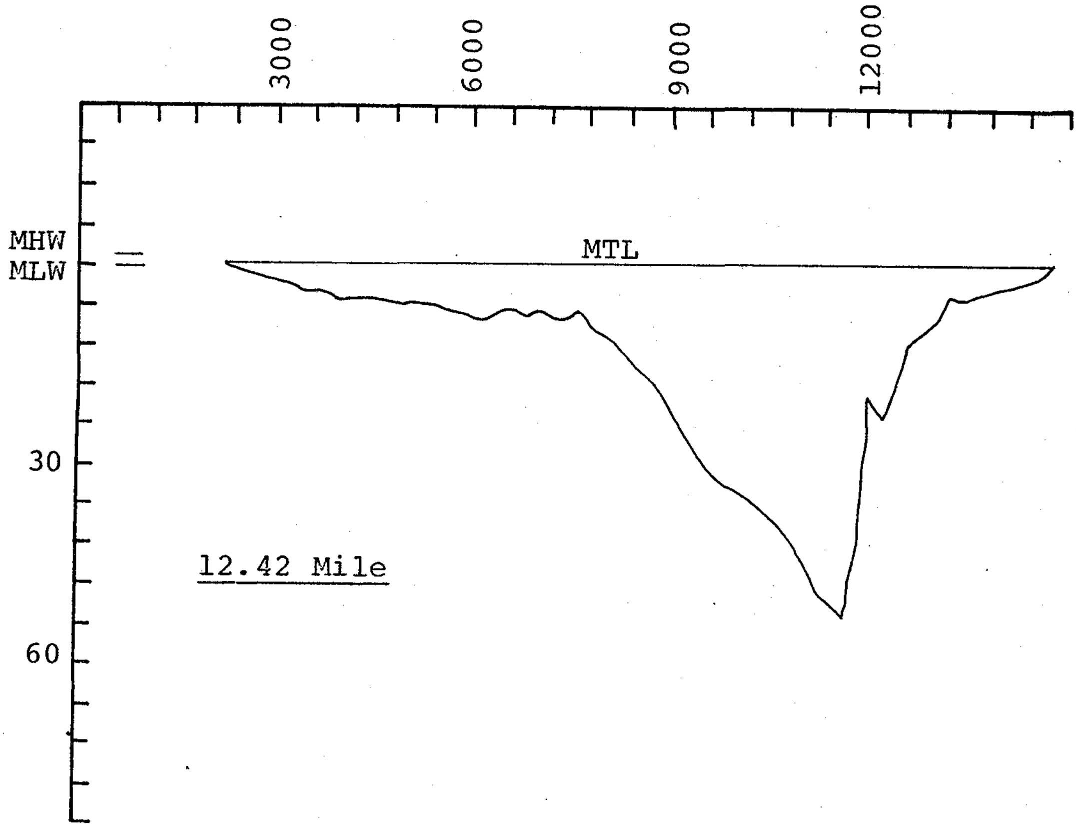
12000
MHW
MLW
MTL
20
40
60
9.78 Mile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6000
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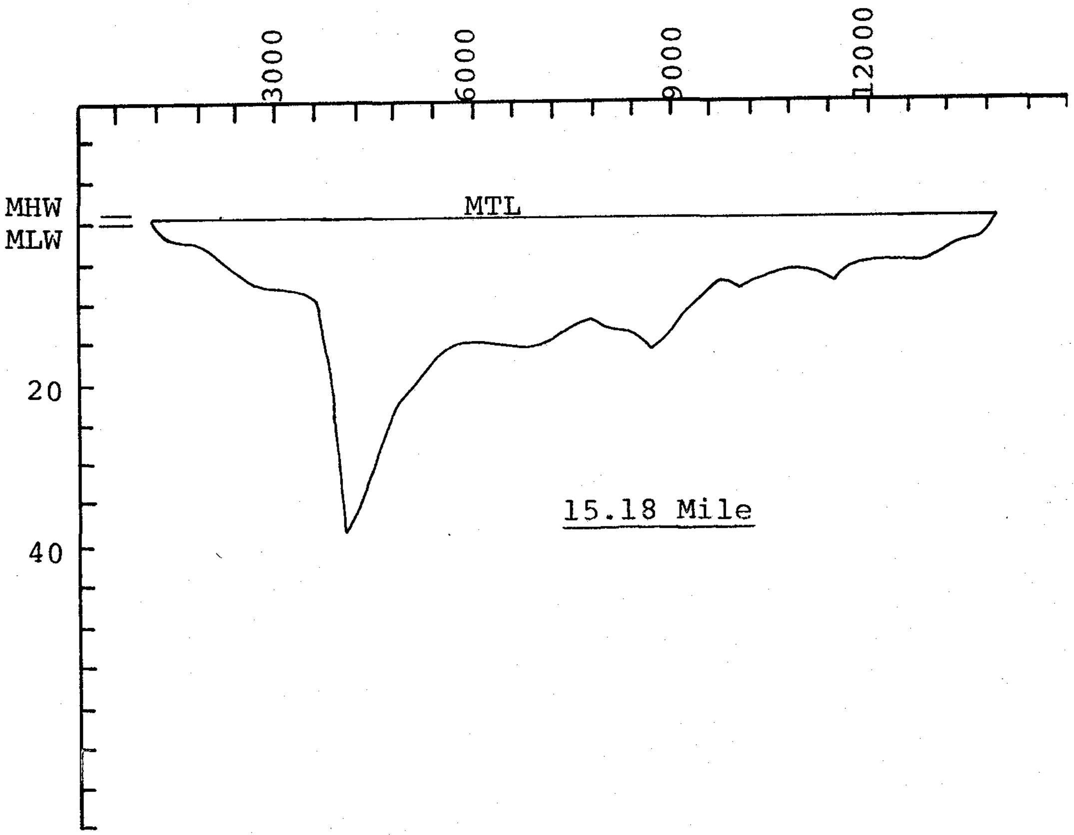
MHW
MLW
MTL
30
60
12.42 Mile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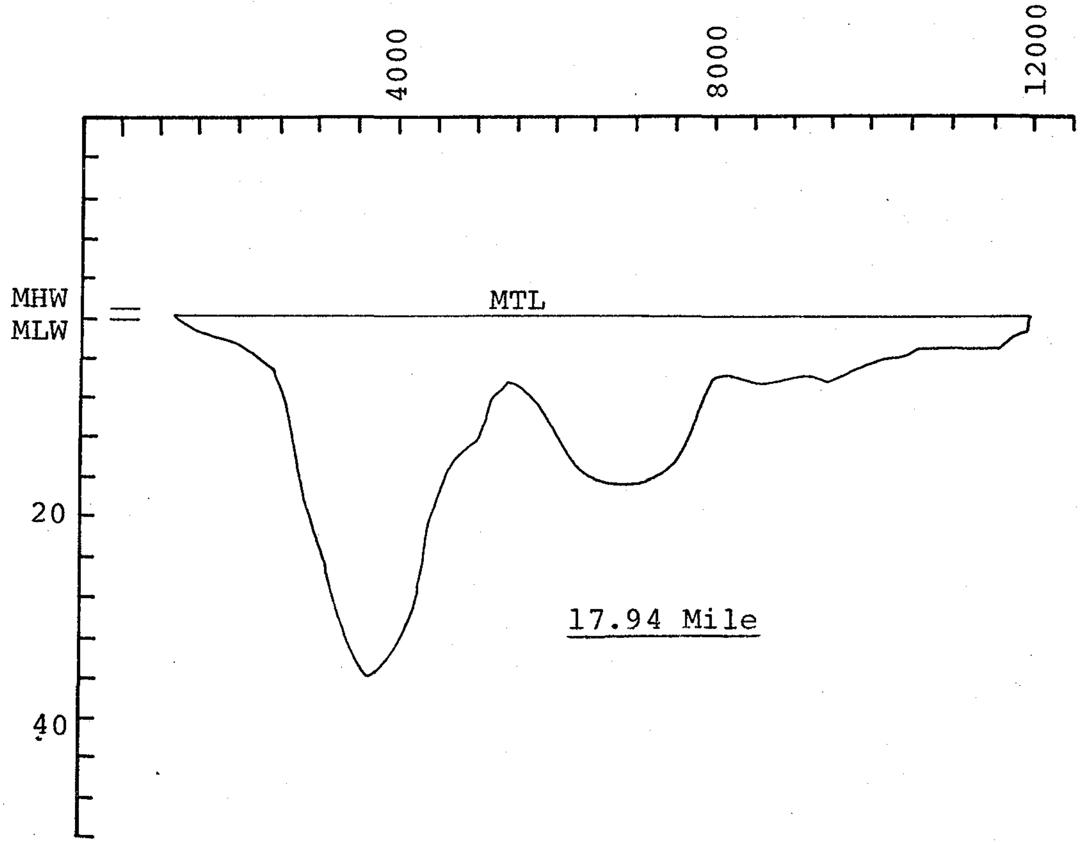
6000
9000
12000
MHW
MLW
MTL
20
40
15.18 Mile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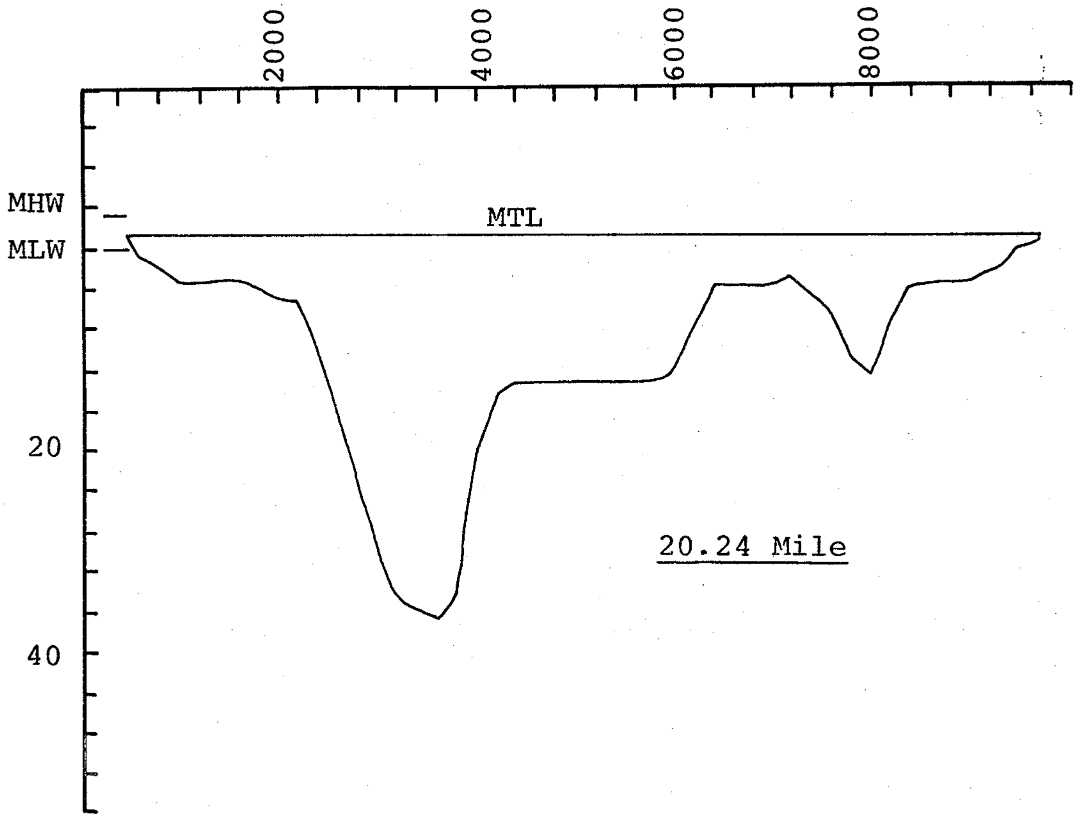
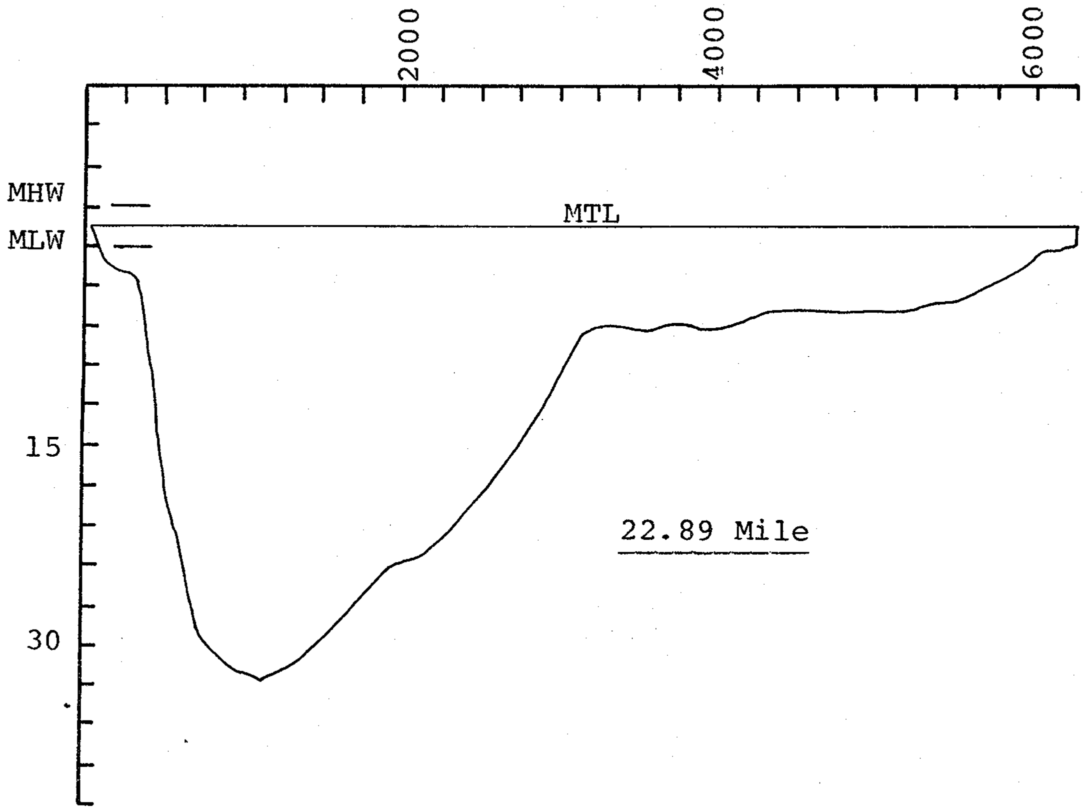
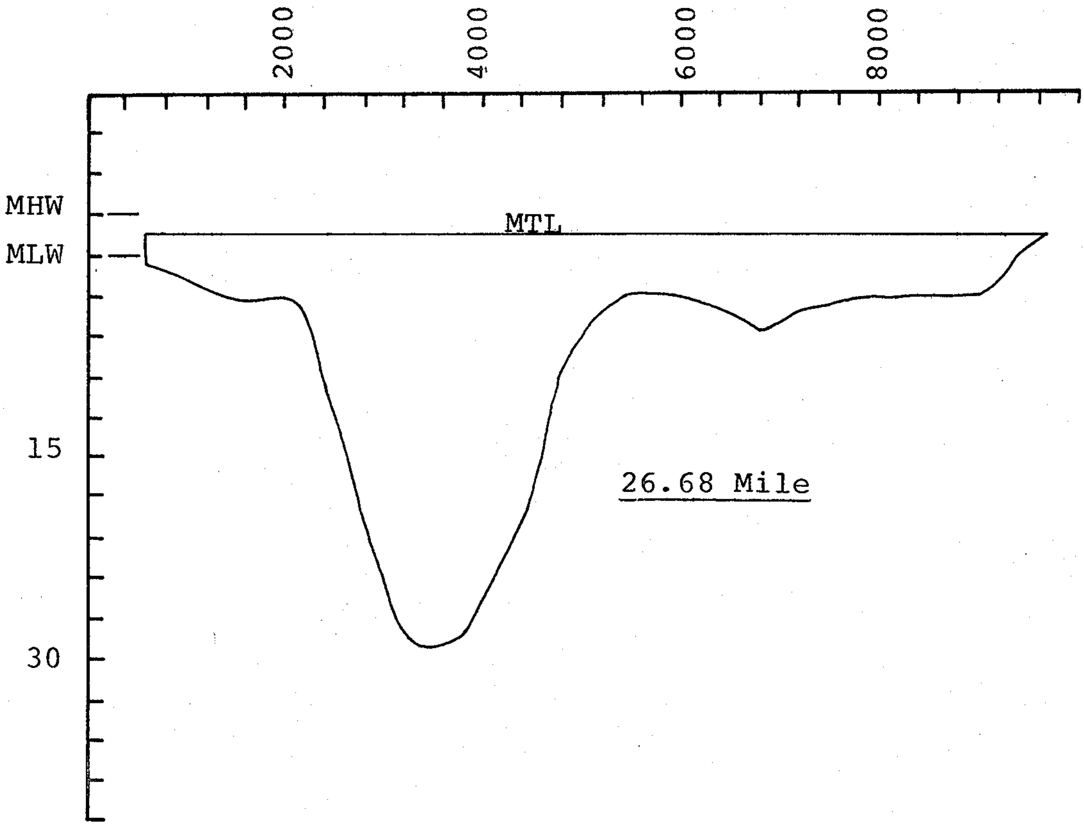
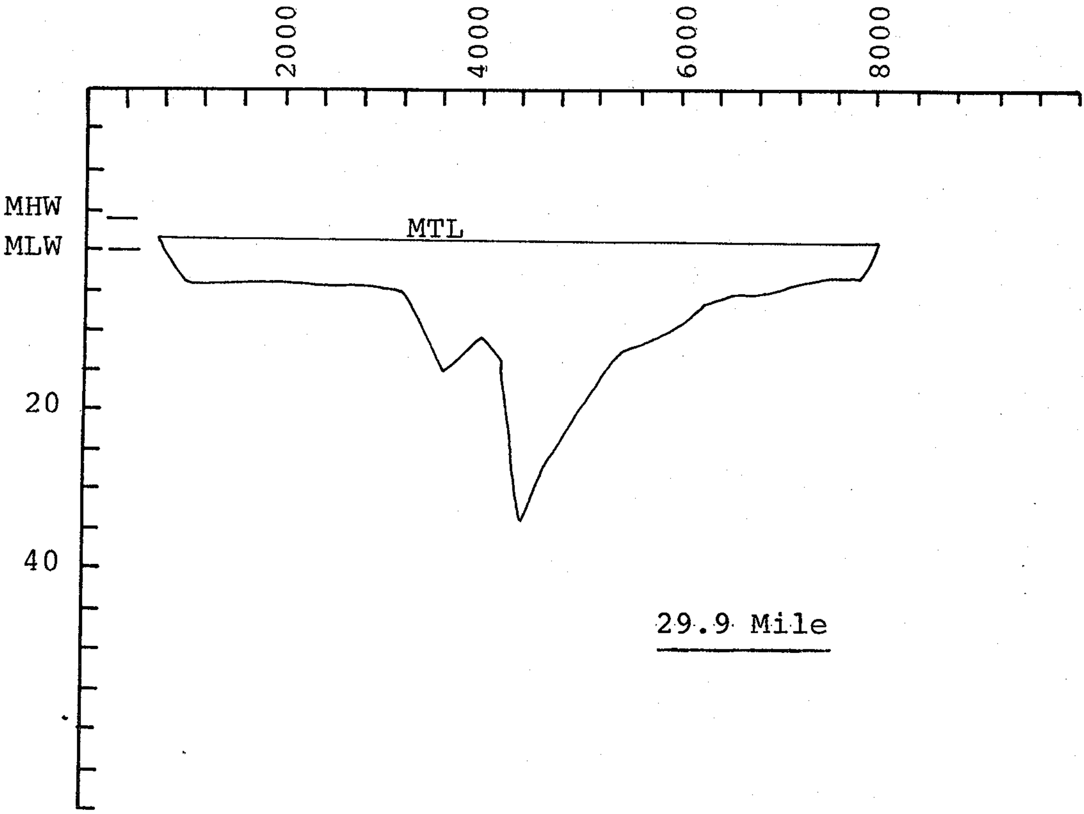
8000
12000
MHW
MLW
MTL
20
40
17.94 Mile


2000
4000
6000
8000
MHW
MLW
MTL
20
40
20.24 Mile

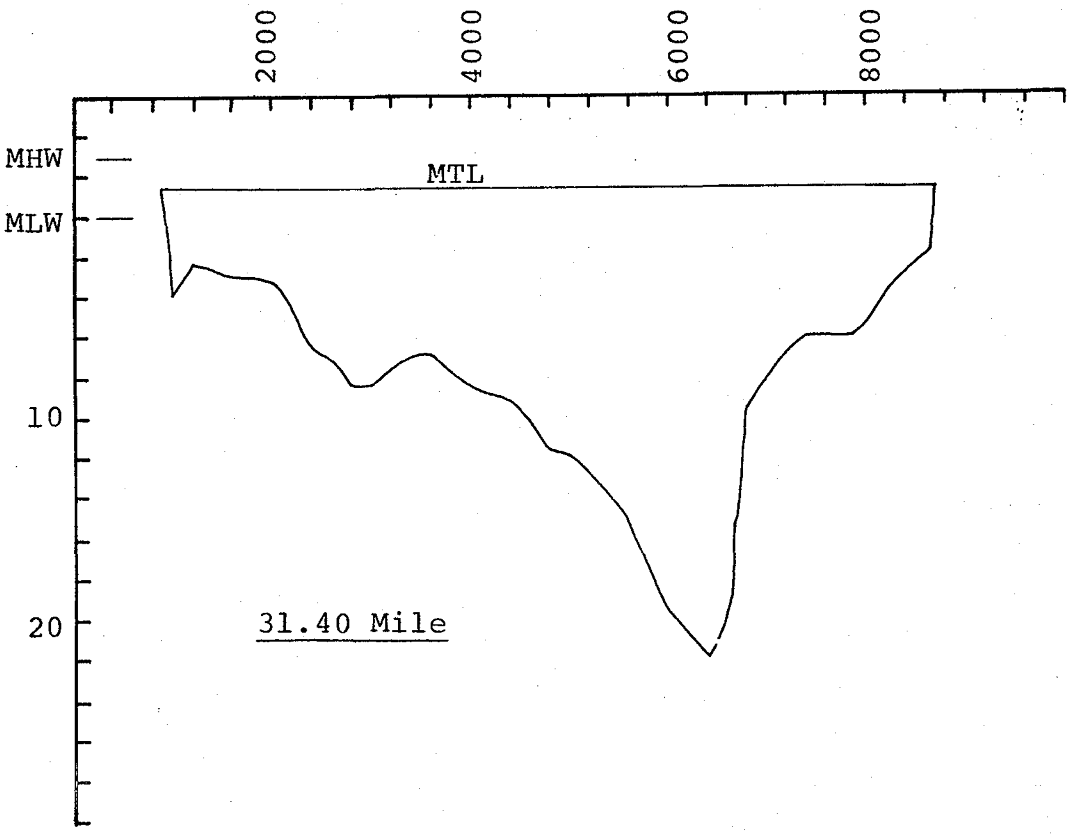

2000
4000
6000
MHW
MLW
MTL
15
30
22.89 Mile

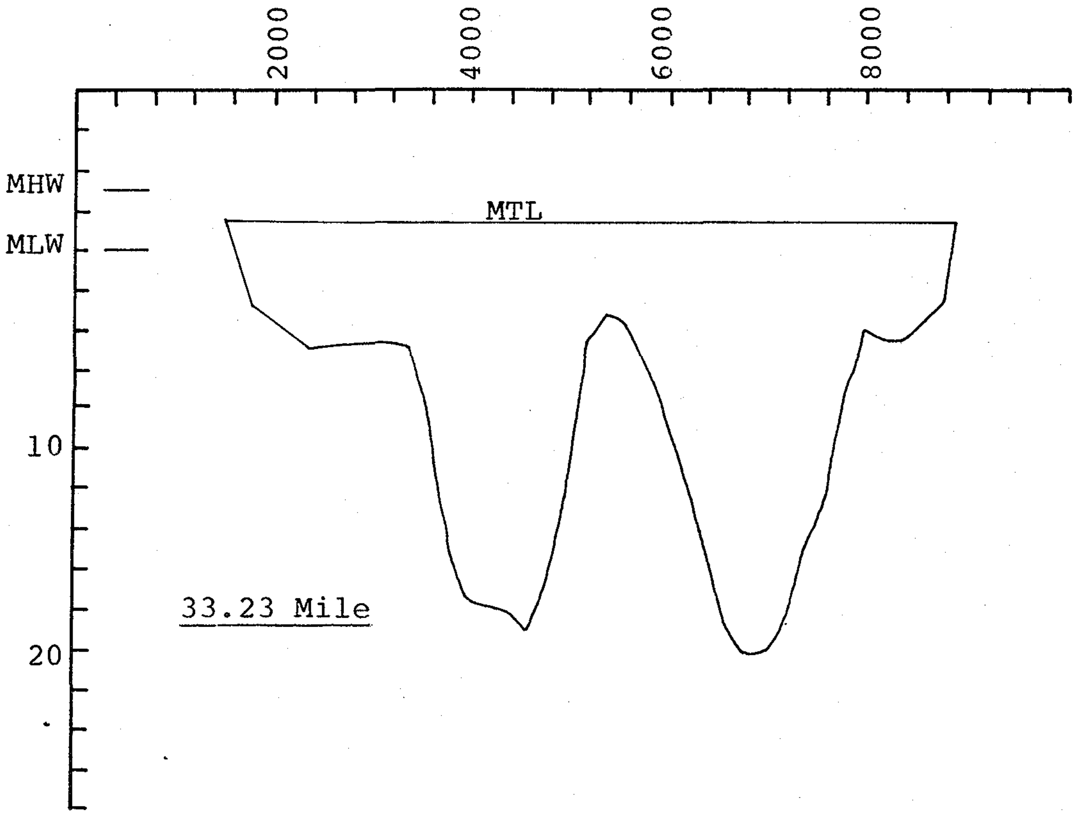


26.68 Mile



29.9 Mile

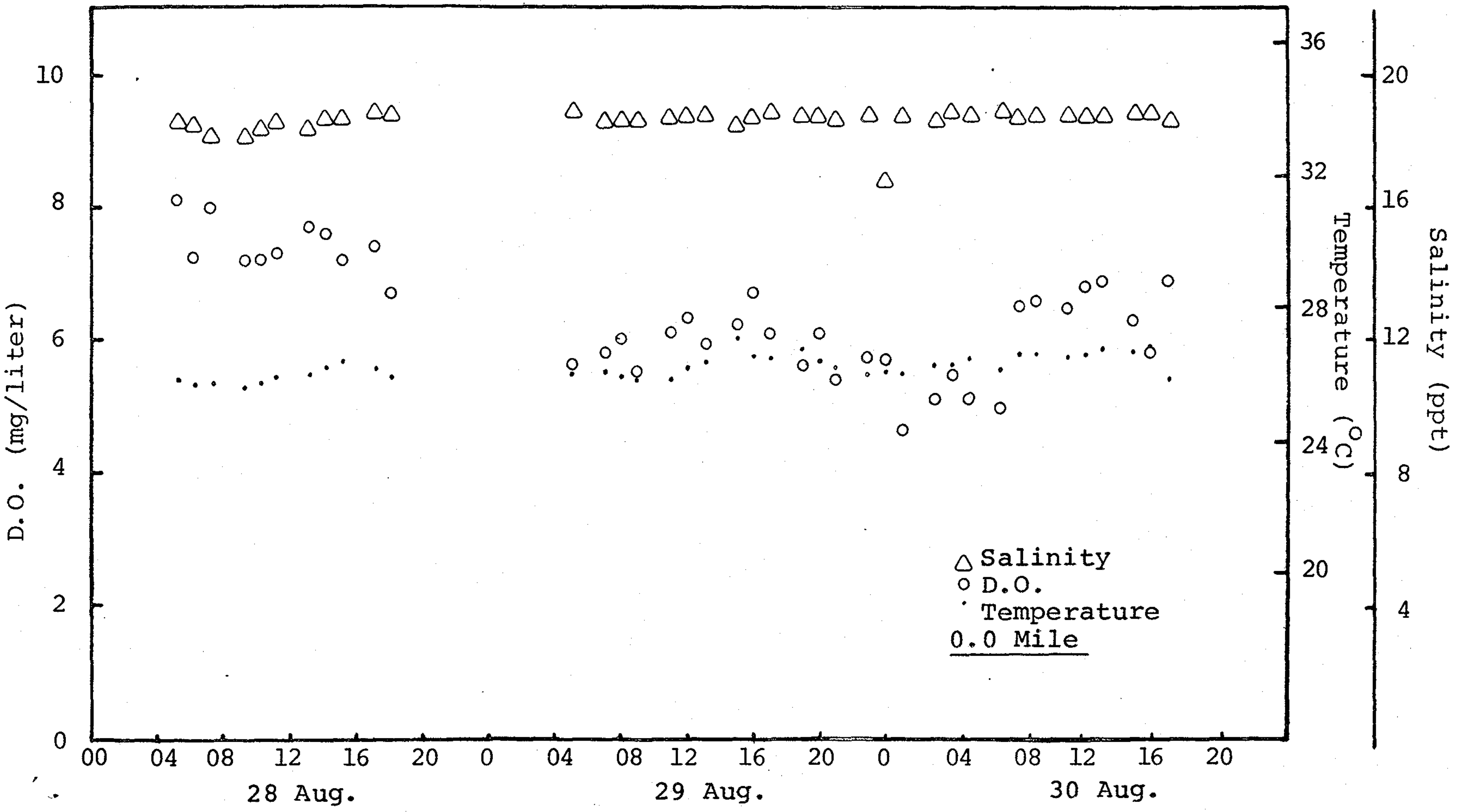

2000
4000
6000
8000
MHW
MTL
MLW
10
20
31.40 Mile


2000
4000
6000
8000
MHW
MTL
MLW
10
20
33.23 Mile

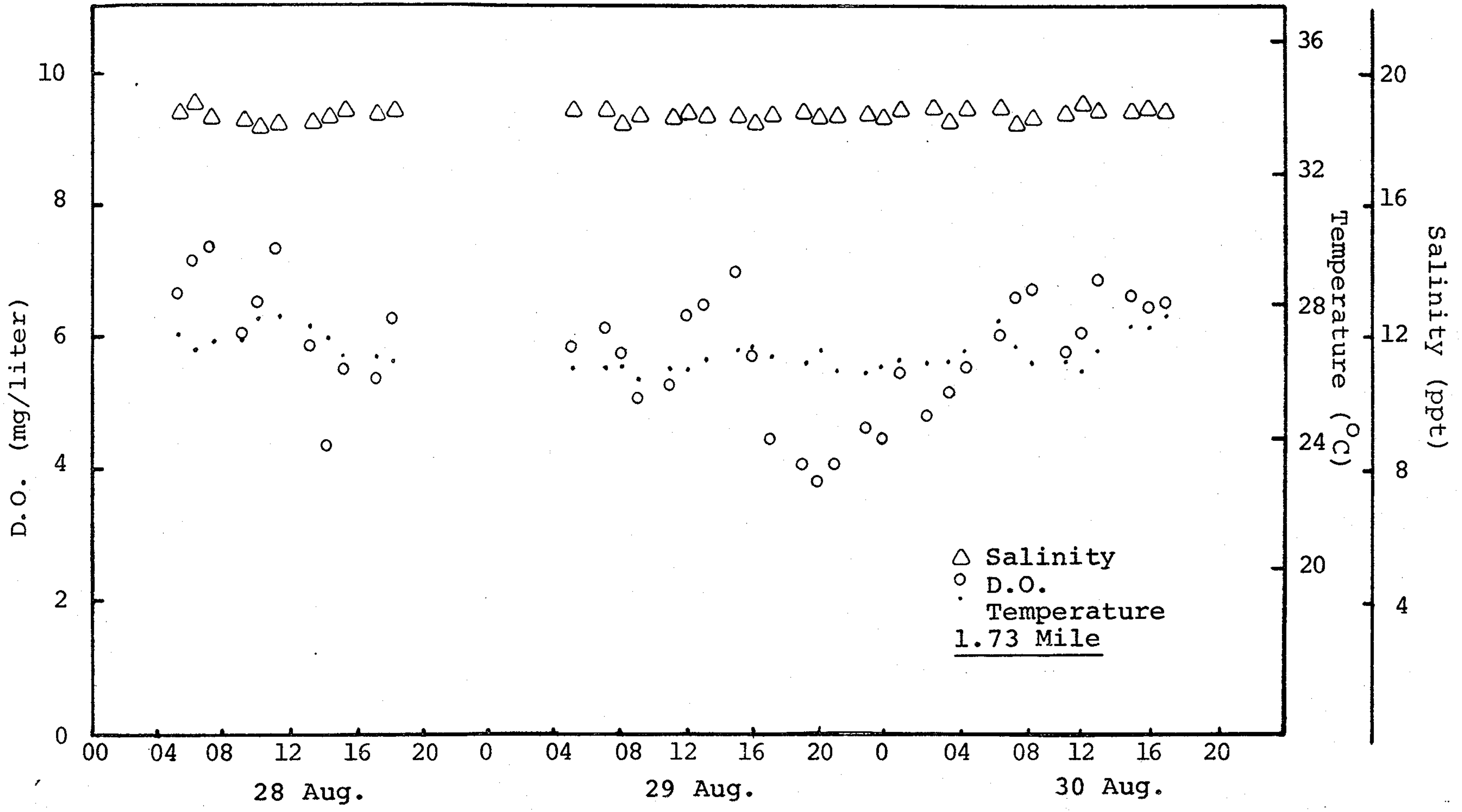
Appendix B

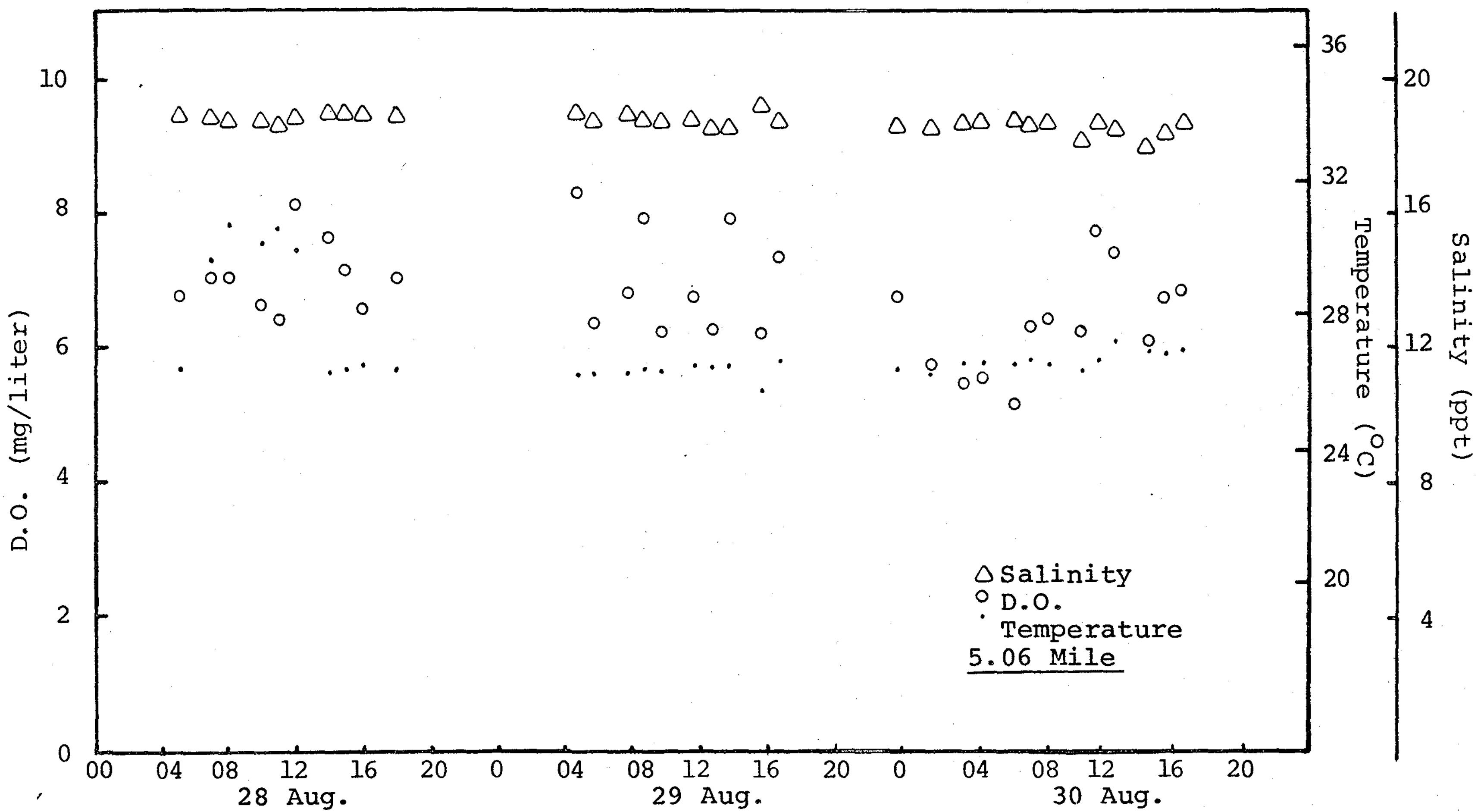
Graphical Summary of Time-Series Hydrographic Data York River

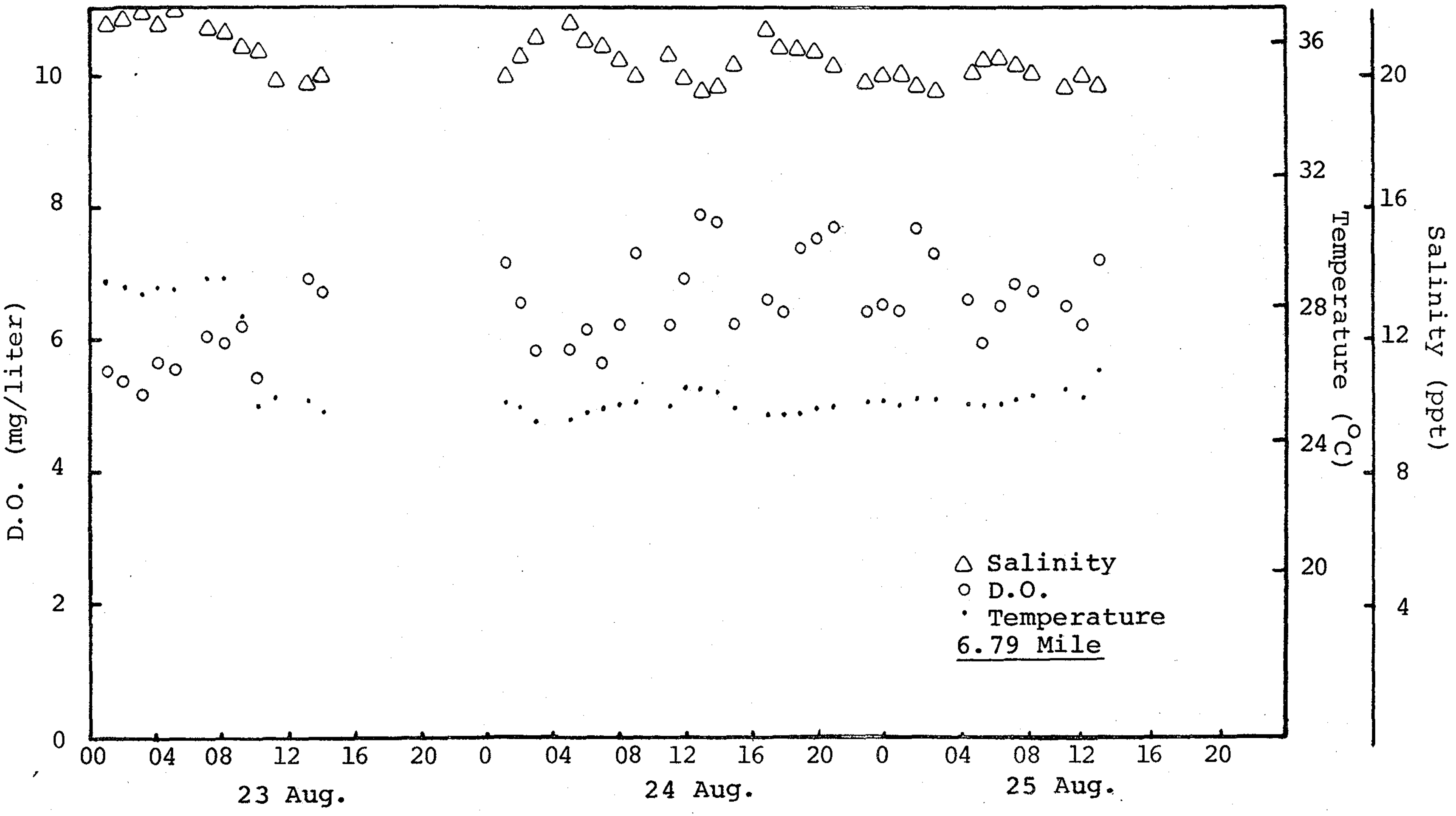
August 18 - 30, 1973
April 17 - 19, 1973
May 8 - 10, 1973

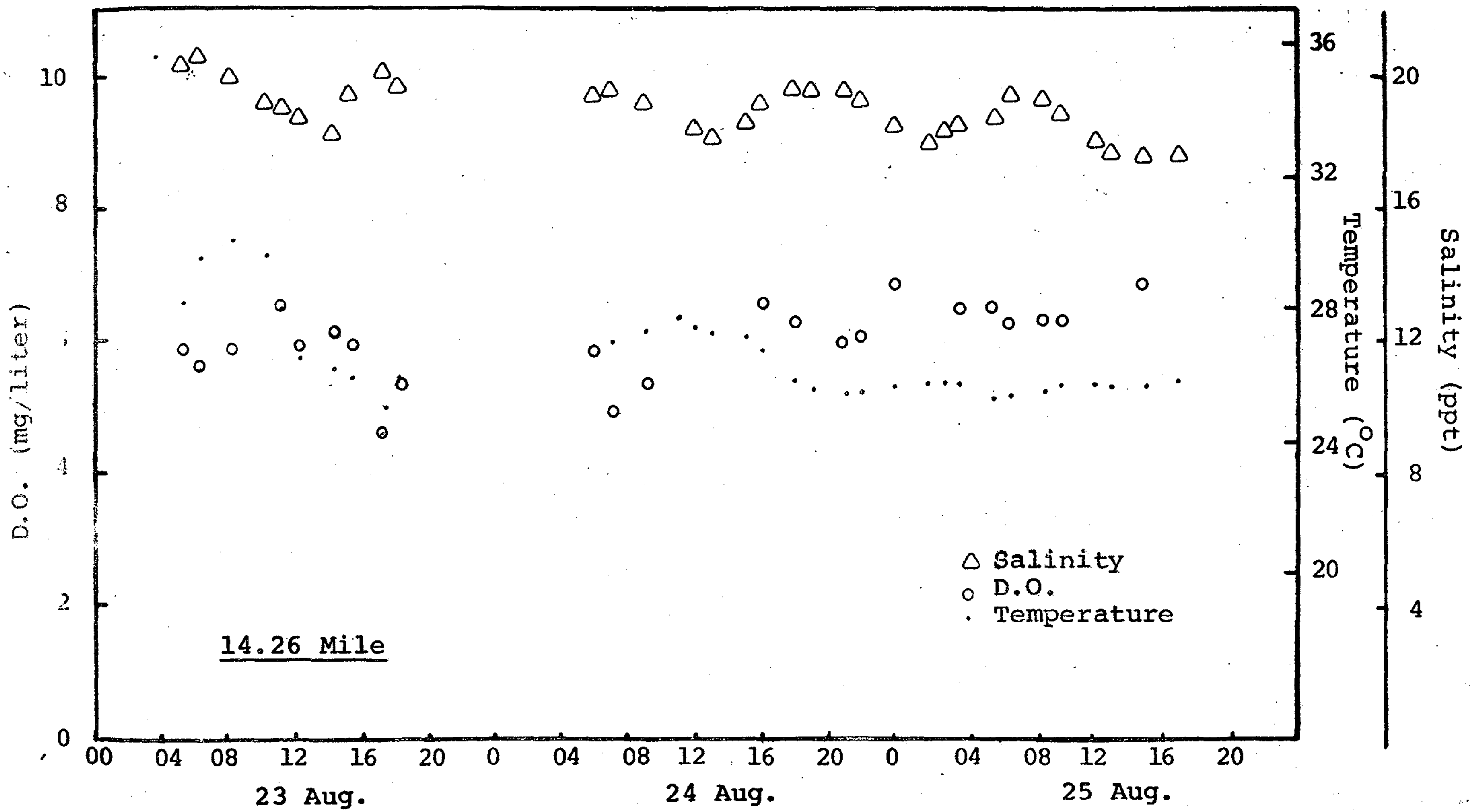


D.O. (mg/liter)
0
2
4
6
8
10
Temperature (°C)
20
24
28
32
36
Salinity (ppt)
4
8
12
16
20
00
04
08
12
16
20
0
04
08
12
16
20
0
04
08
12
16
20
28 Aug.
29 Aug.
30 Aug.
△ Salinity
○ D.O.
· Temperature
0.0 Mile

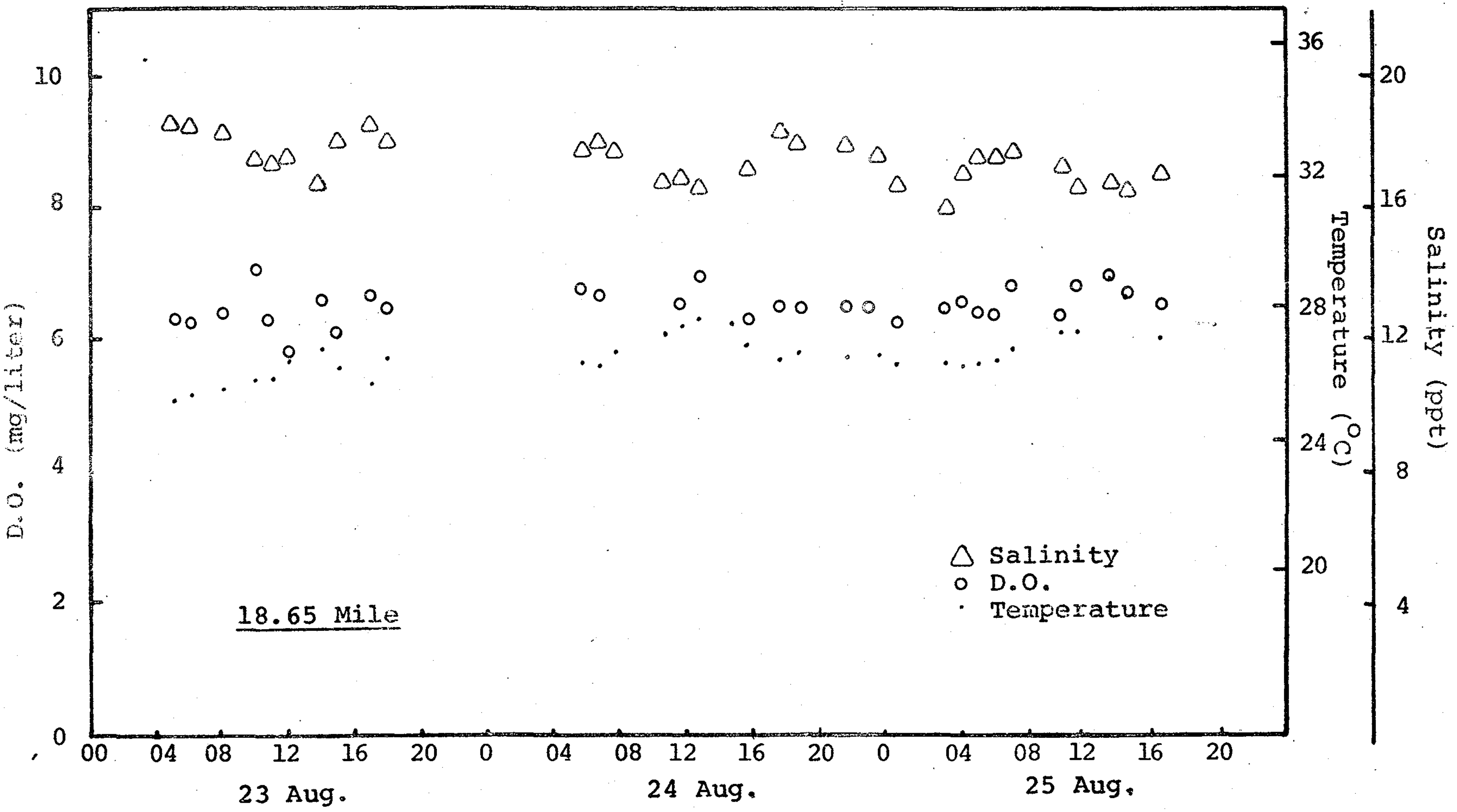

D.O. (mg/liter)
0
2
4
6
8
10
Temperature (°C)
20
24
28
32
36
Salinity (ppt)
4
8
12
16
20
00
04
08
12
16
20
0
04
08
12
16
20
0
04
08
12
16
20
28 Aug.
29 Aug.
30 Aug.
△ Salinity
○ D.O.
· Temperature
1.73 Mile

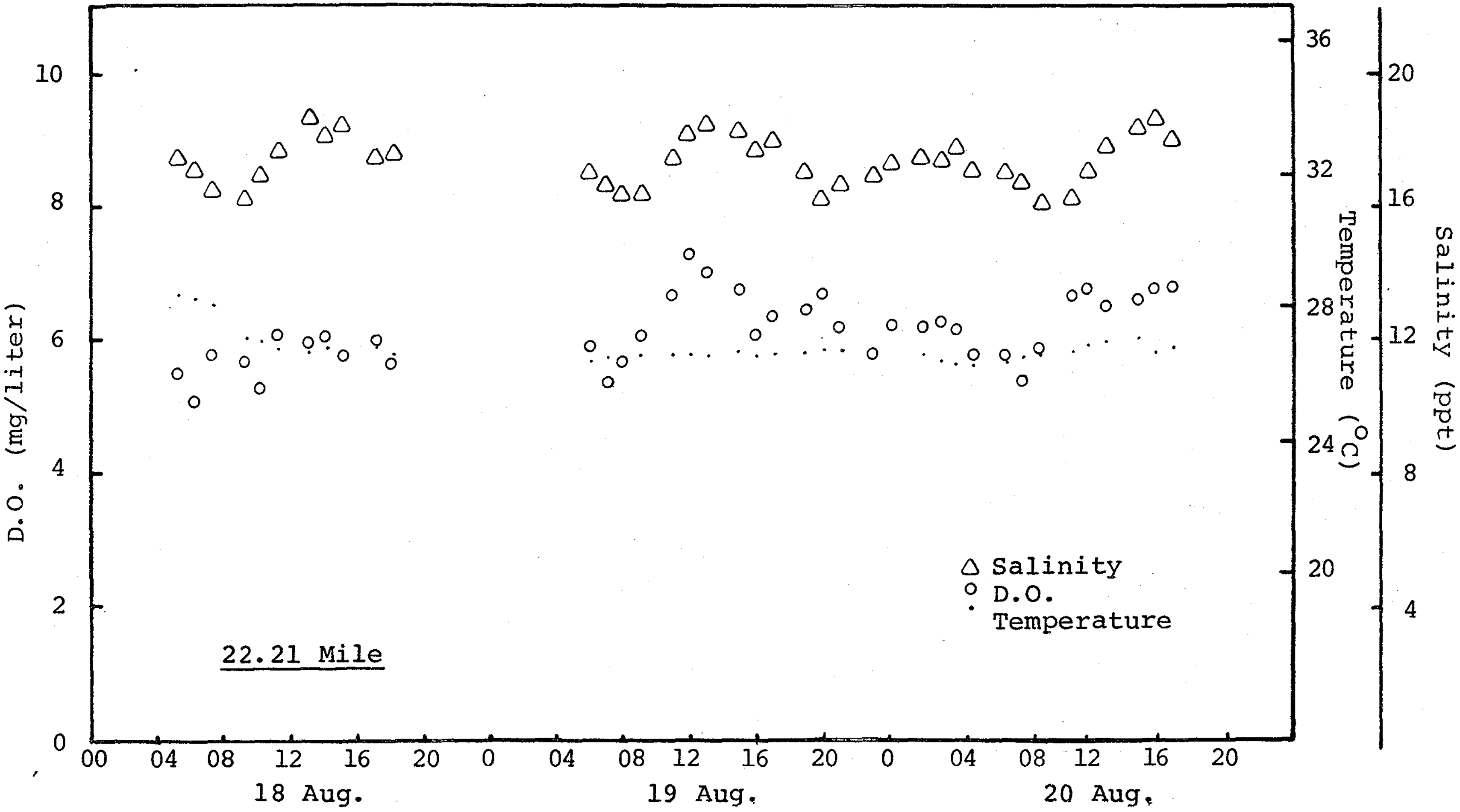

D.O. (mg/liter)
0
2
4
6
8
10
Temperature (°C)
20
24
28
32
36
Salinity (ppt)
4
8
12
16
20
00
04
08
12
16
20
0
04
08
12
16
20
0
04
08
12
16
20
28 Aug.
29 Aug.
30 Aug.
△ Salinity
○ D.O.
· Temperature
5.06 Mile

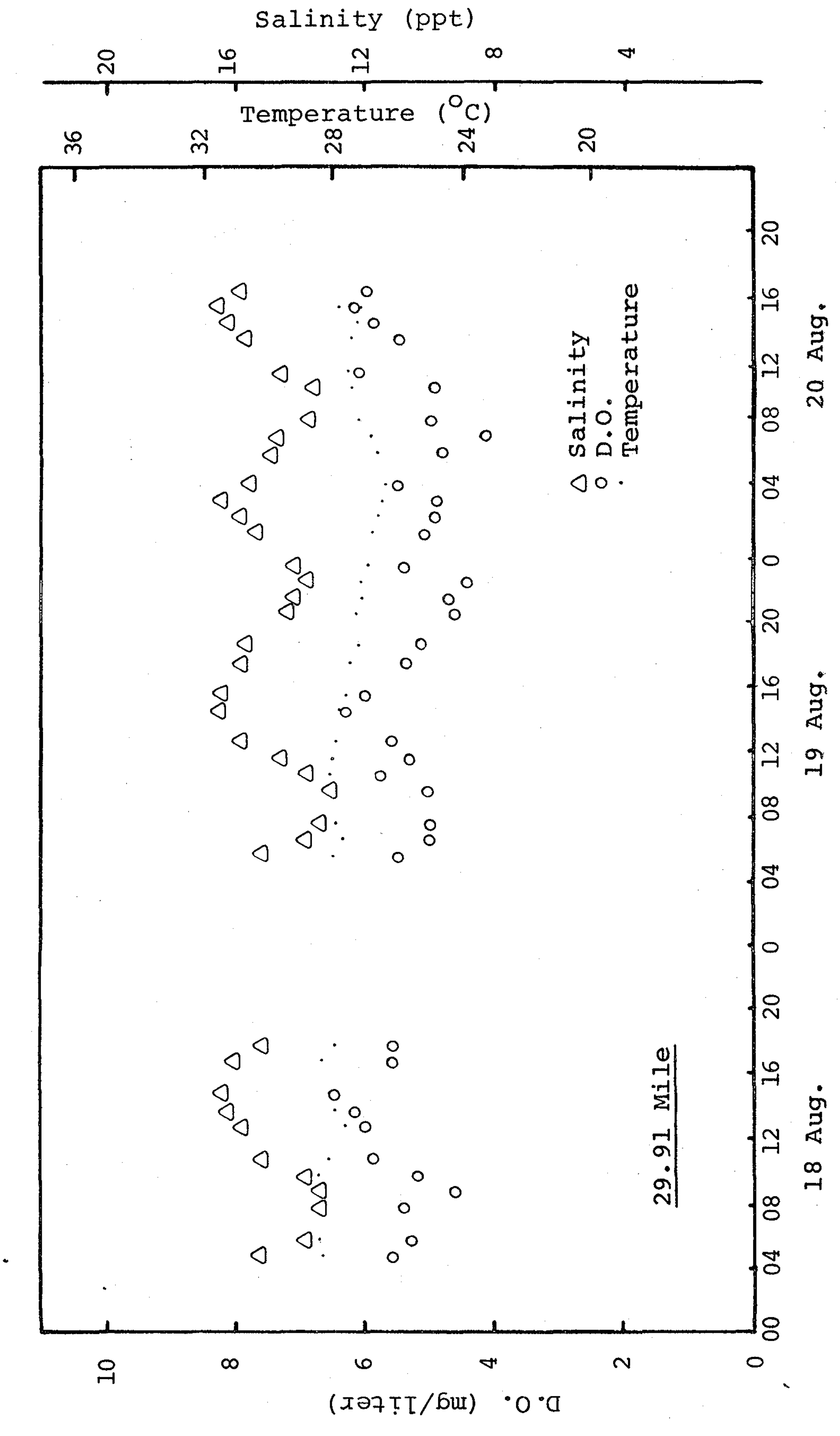

D.O. (mg/liter)
0
2
4
6
8
10
Temperature (°C)
20
24
28
32
36
Salinity (ppt)
4
8
12
16
20
00
04
08
12
16
20
0
04
08
12
16
20
0
04
08
12
16
20
23 Aug.
24 Aug.
25 Aug.
△ Salinity
○ D.O.
· Temperature
6.79 Mile

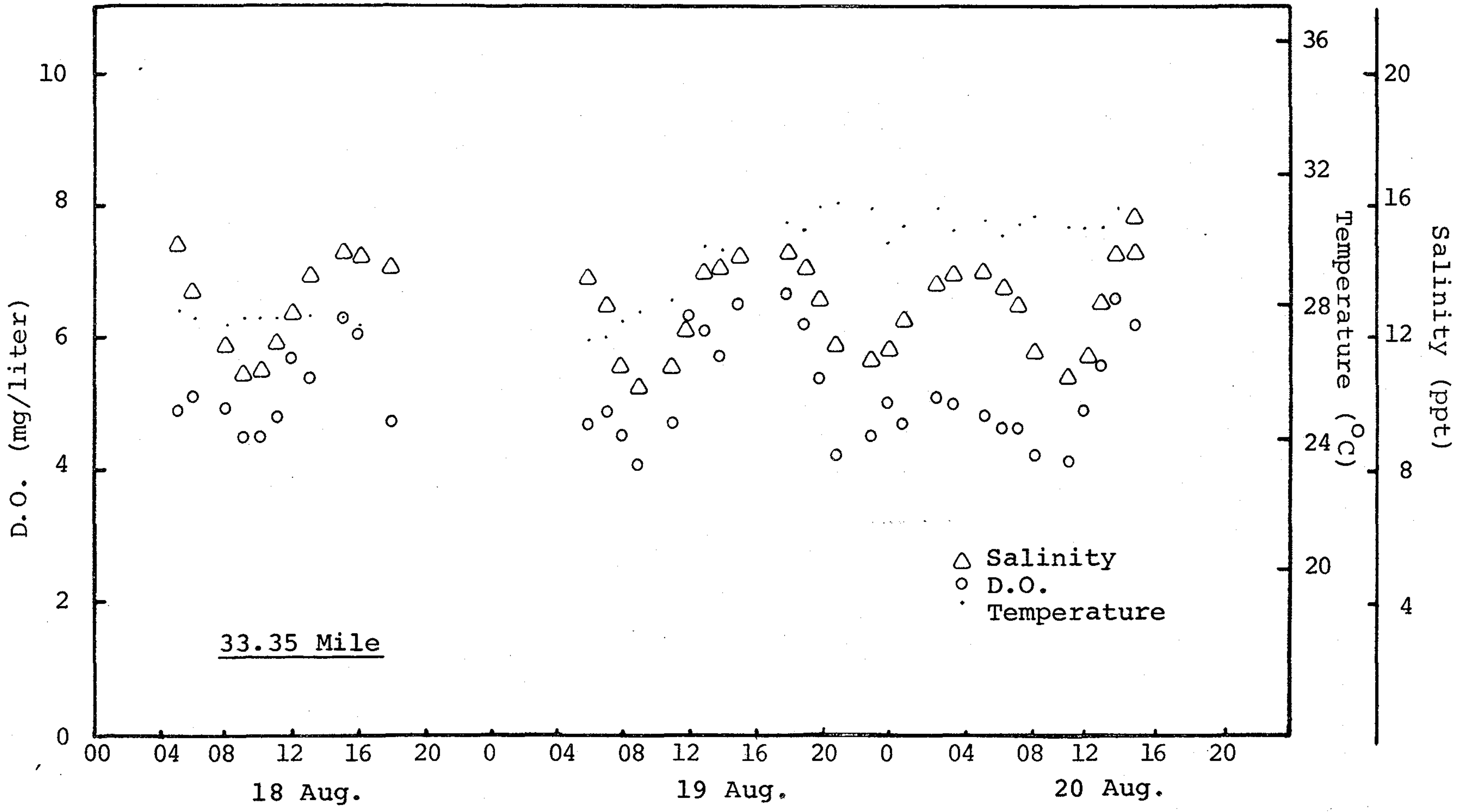


14.26 Mile
D.O. (mg/liter)
0
2
4
6
8
10
Temperature (°C)
20
24
28
32
36
Salinity (ppt)
4
8
12
16
20
00
04
08
12
16
20
0
04
08
12
16
20
0
04
08
12
16
20
23 Aug.
24 Aug.
25 Aug.
△ Salinity
○ D.O.
· Temperature


D.O. (mg/liter)
0
2
4
6
8
10
Temperature (°C)
20
24
28
32
36
Salinity (ppt)
4
8
12
16
20
00 04 08 12 16 20 0 04 08 12 16 20 0 04 08 12 16 20
23 Aug.
24 Aug.
25 Aug.
18.65 Mile
△ Salinity
○ D.O.
· Temperature


D.O. (mg/liter)
0
2
4
6
8
10
Temperature (°C)
20
24
28
32
36
Salinity (ppt)
4
8
12
16
20
00
04
08
12
16
20
0
04
08
12
16
20
0
04
08
12
16
20
18 Aug.
19 Aug.
20 Aug.
22.21 Mile
△ Salinity
○ D.O.
• Temperature


Salinity (ppt)
20
16
12
8
4
Temperature (°C)
36
32
28
24
20
D.O. (mg/Liter)
10
8
6
4
2
0
00
04
08
12
16
20
0
04
08
12
16
20
0
04
08
12
16
20
18 Aug.
19 Aug.
20 Aug.
△ Salinity
○ D.O.
· Temperature
29.91 Mile


D.O. (mg/liter)
0
2
4
6
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10
Temperature (°C)
20
24
28
32
36
Salinity (ppt)
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12
16
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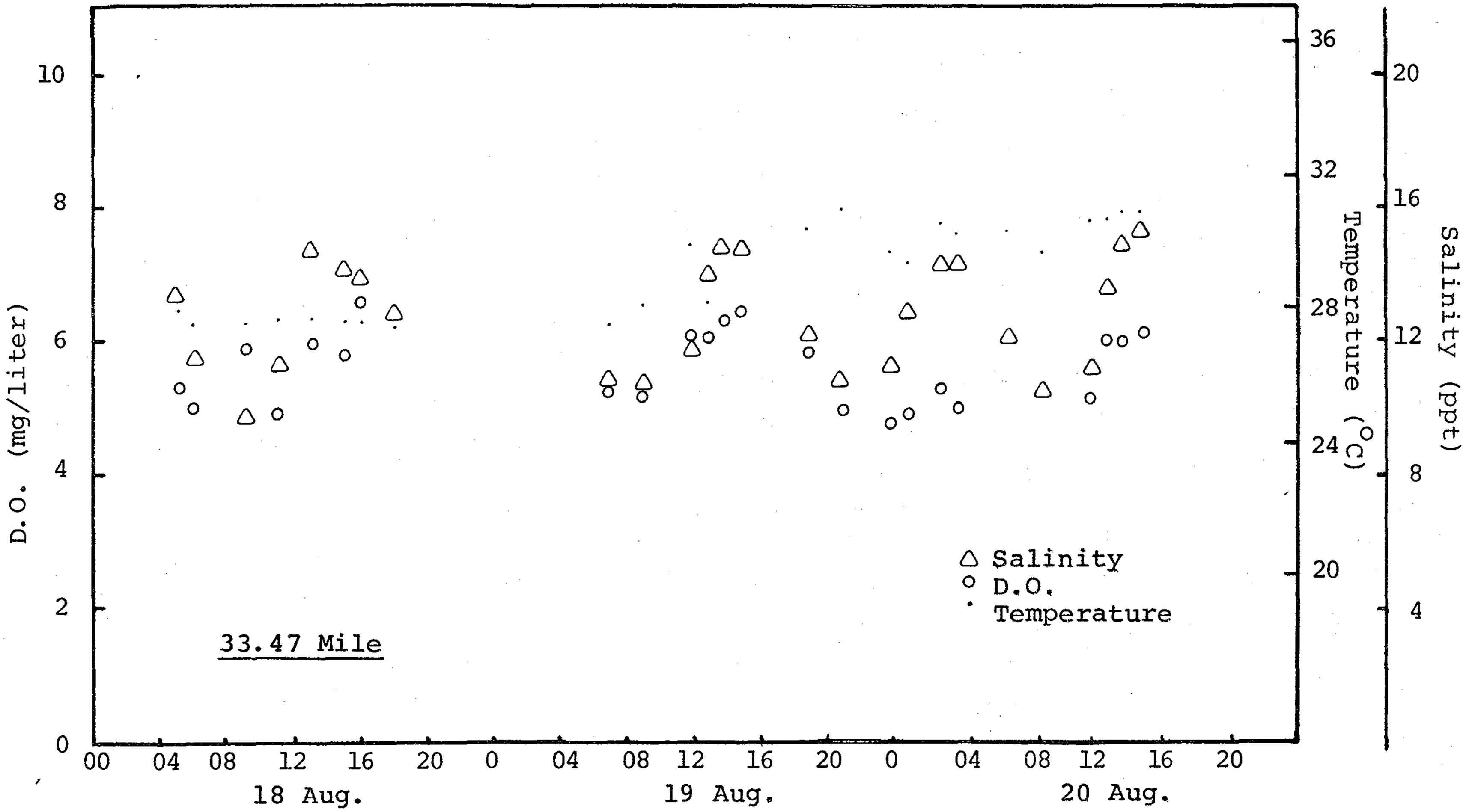
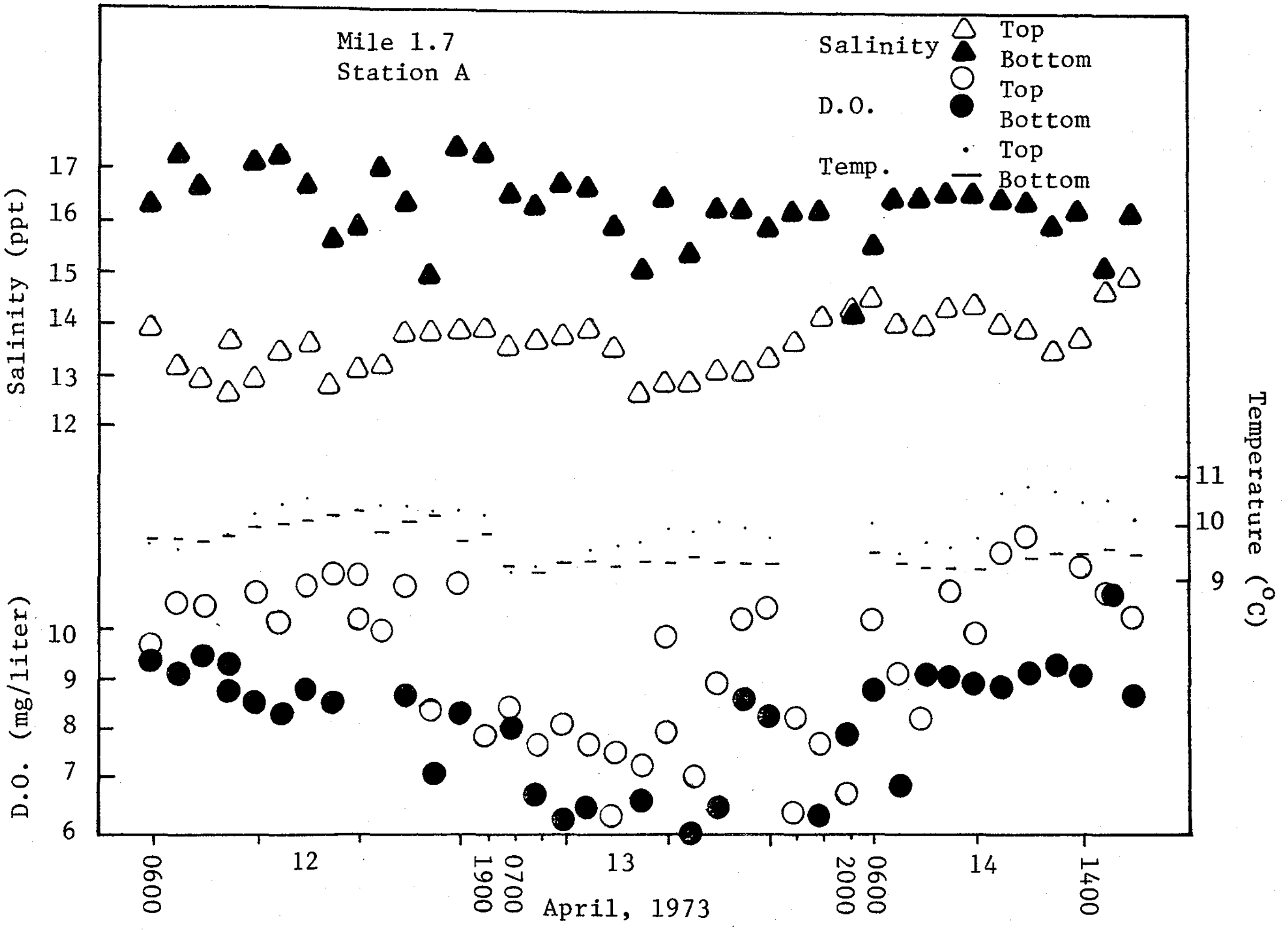
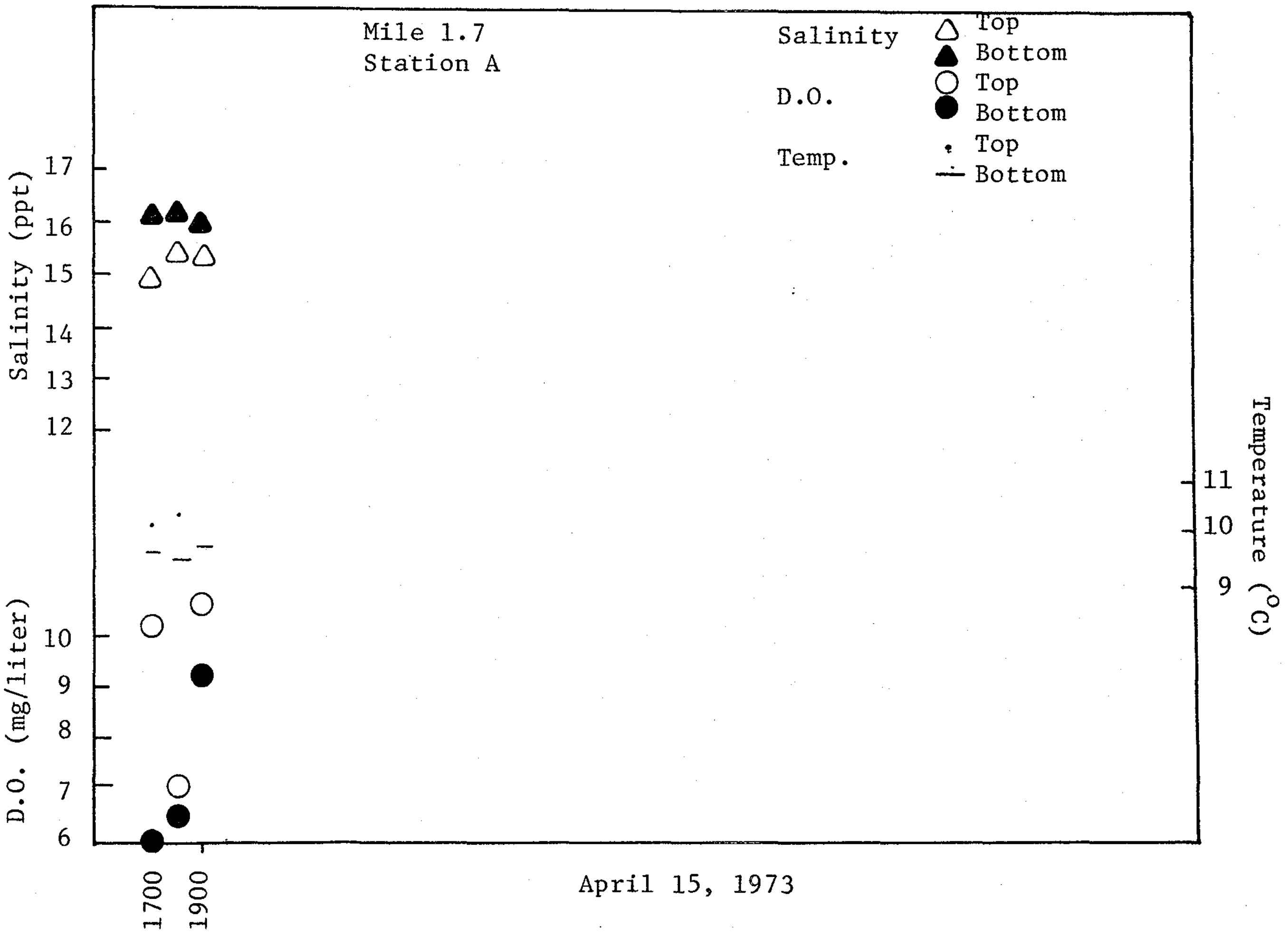
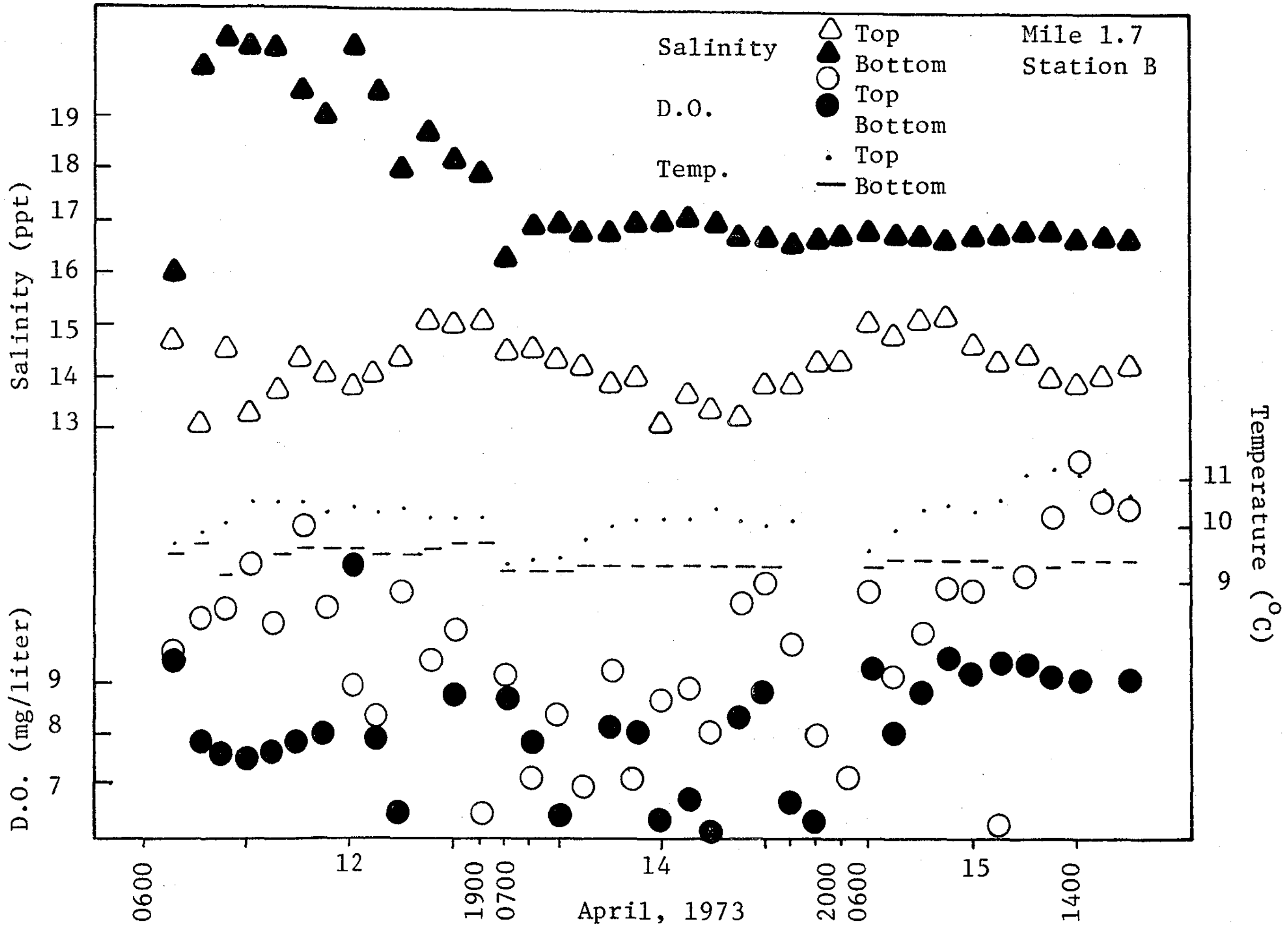
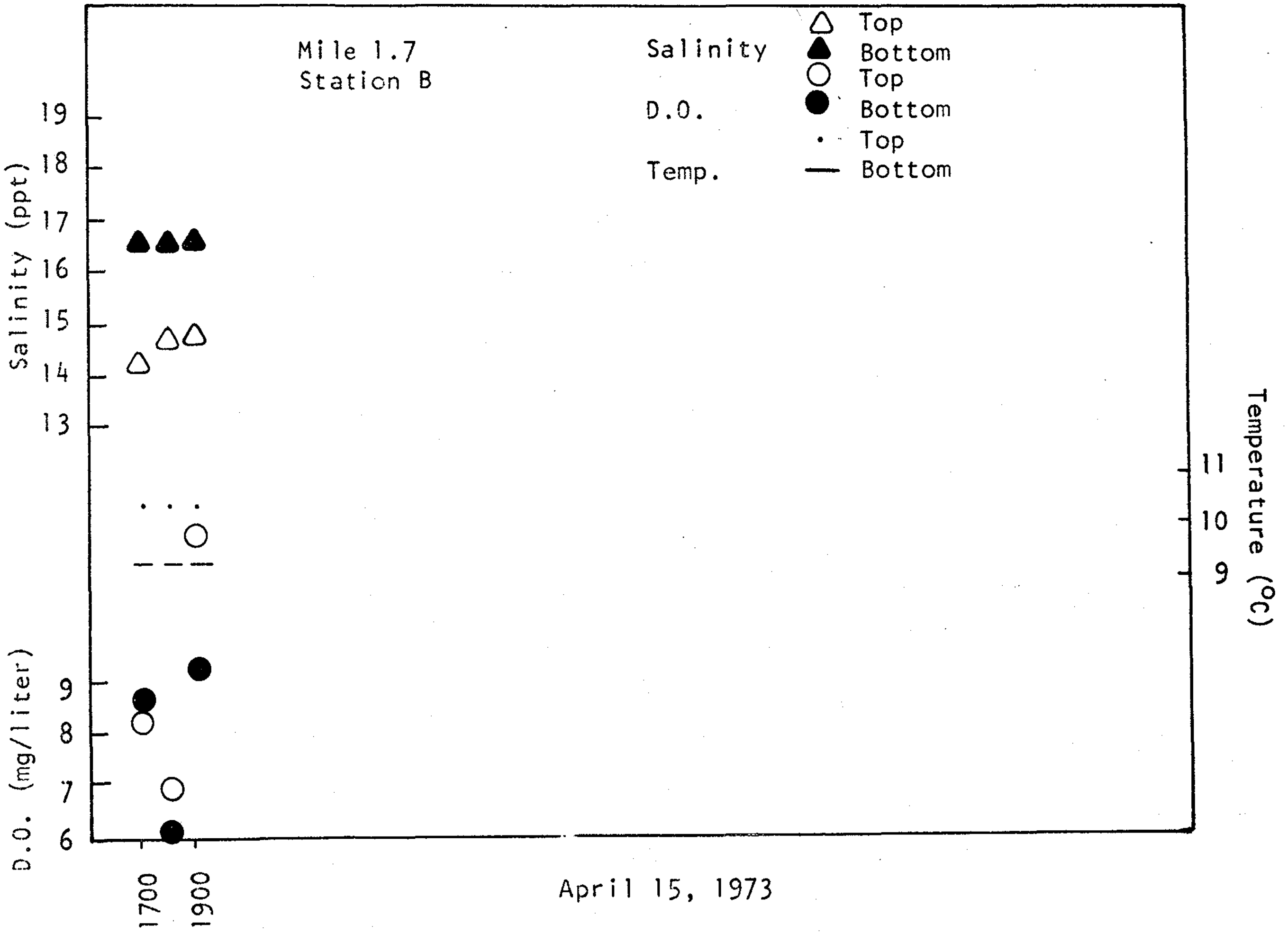
16
20
0
04
08
12
16
20
0
04
08
12
16
20
18 Aug.
19 Aug.
20 Aug.
33.35 Mile
Salinity
D.O.
Temperature

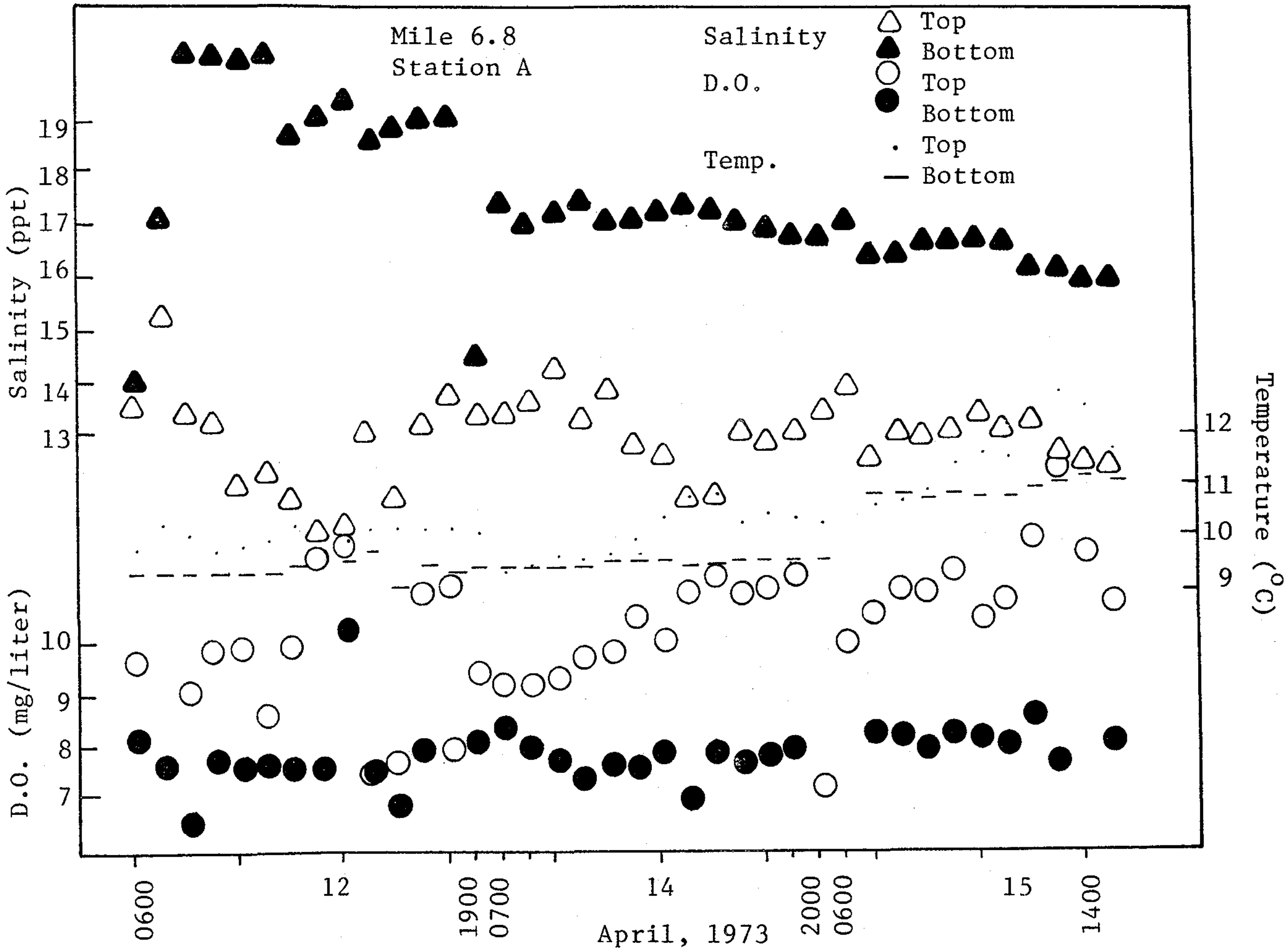

33.47 Mile
△ Salinity
○ D.O.
• Temperature
D.O. (mg/liter)
0
2
4
6
8
10
Temperature (°C)
20
24
28
32
36
Salinity (ppt)
4
8
12
16
20
00
04
08
12
16
20
0
04
08
12
16
20
0
04
08
12
16
20
18 Aug.
19 Aug.
20 Aug.

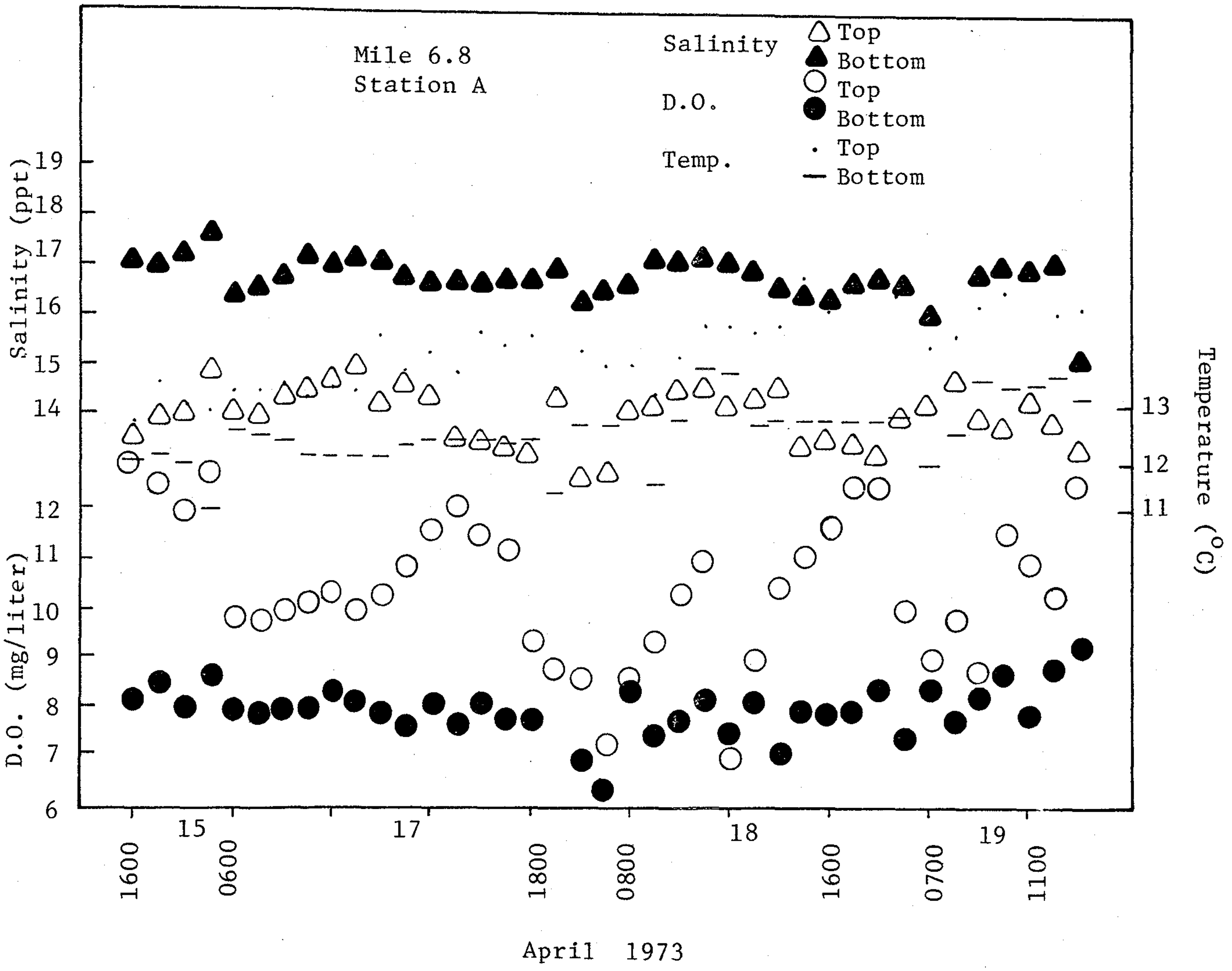

Mile 1.7
Station A
Salinity
Top
Bottom
D.O.
Top
Bottom
Temp.
Top
Bottom
Salinity (ppt)
17
16
15
14
13
12
D.O. (mg/liter)
10
9
8
7
6
Temperature (°C)
11
10
9
0600
12
1900
0700
13
2000
0600
14
1400
April, 1973

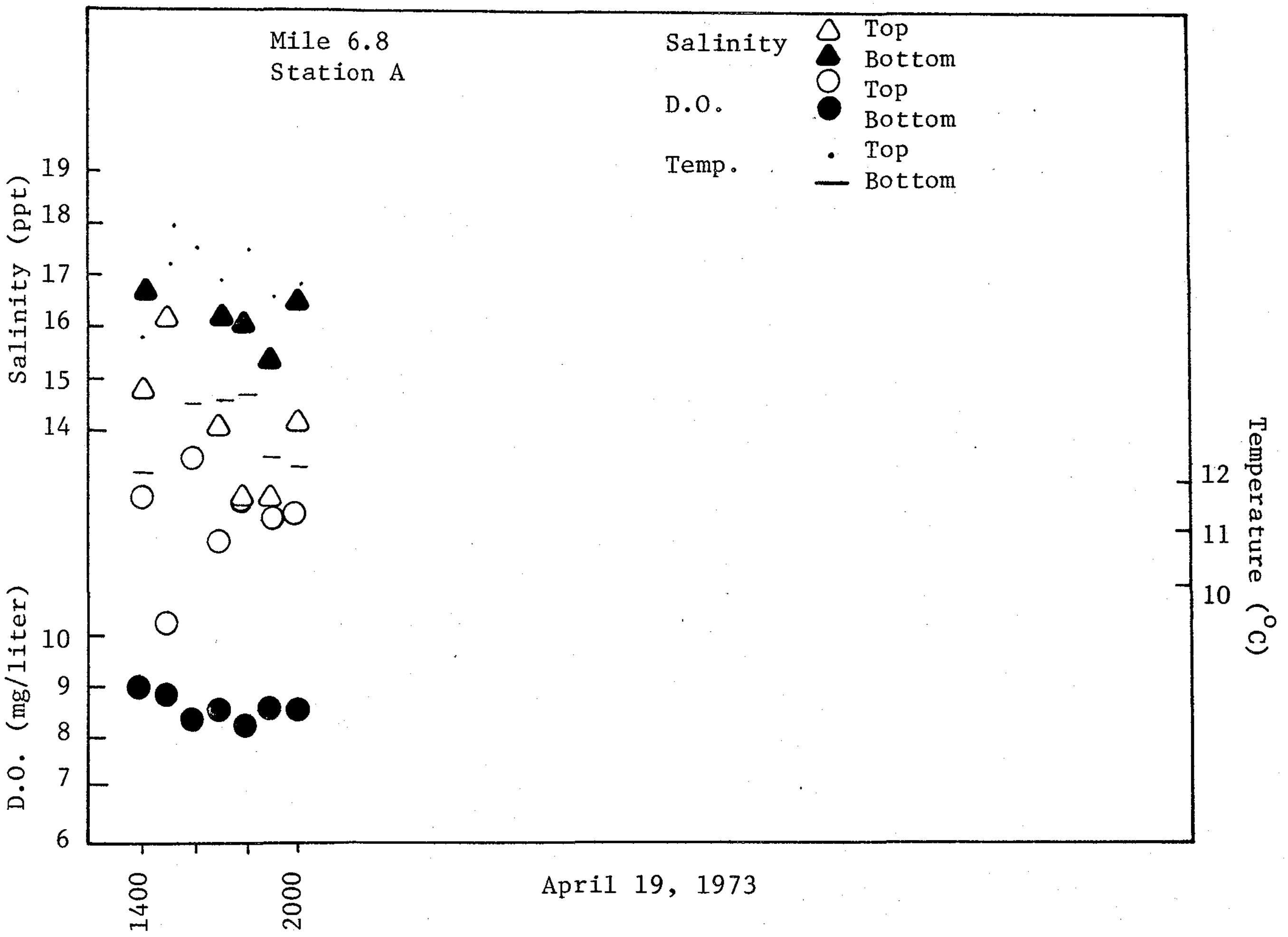

Mile 1.7
Station A
Salinity
△ Top
▲ Bottom
D.O.
○ Top
● Bottom
Temp.
• Top
– Bottom
Salinity (ppt)
17
16
15
14
13
12
D.O. (mg/liter)
10
9
8
7
6
Temperature (°C)
11
10
9
1700
1900
April 15, 1973


Salinity
D.O.
Temp.
△ Top
▲ Bottom
○ Top
● Bottom
· Top
— Bottom
Mile 1.7
Station B
Salinity (ppt)
13
14
15
16
17
18
19
D.O. (mg/liter)
7
8
9
Temperature (°C)
9
10
11
0600
12
1900
0700
14
2000
0600
15
1400
April, 1973

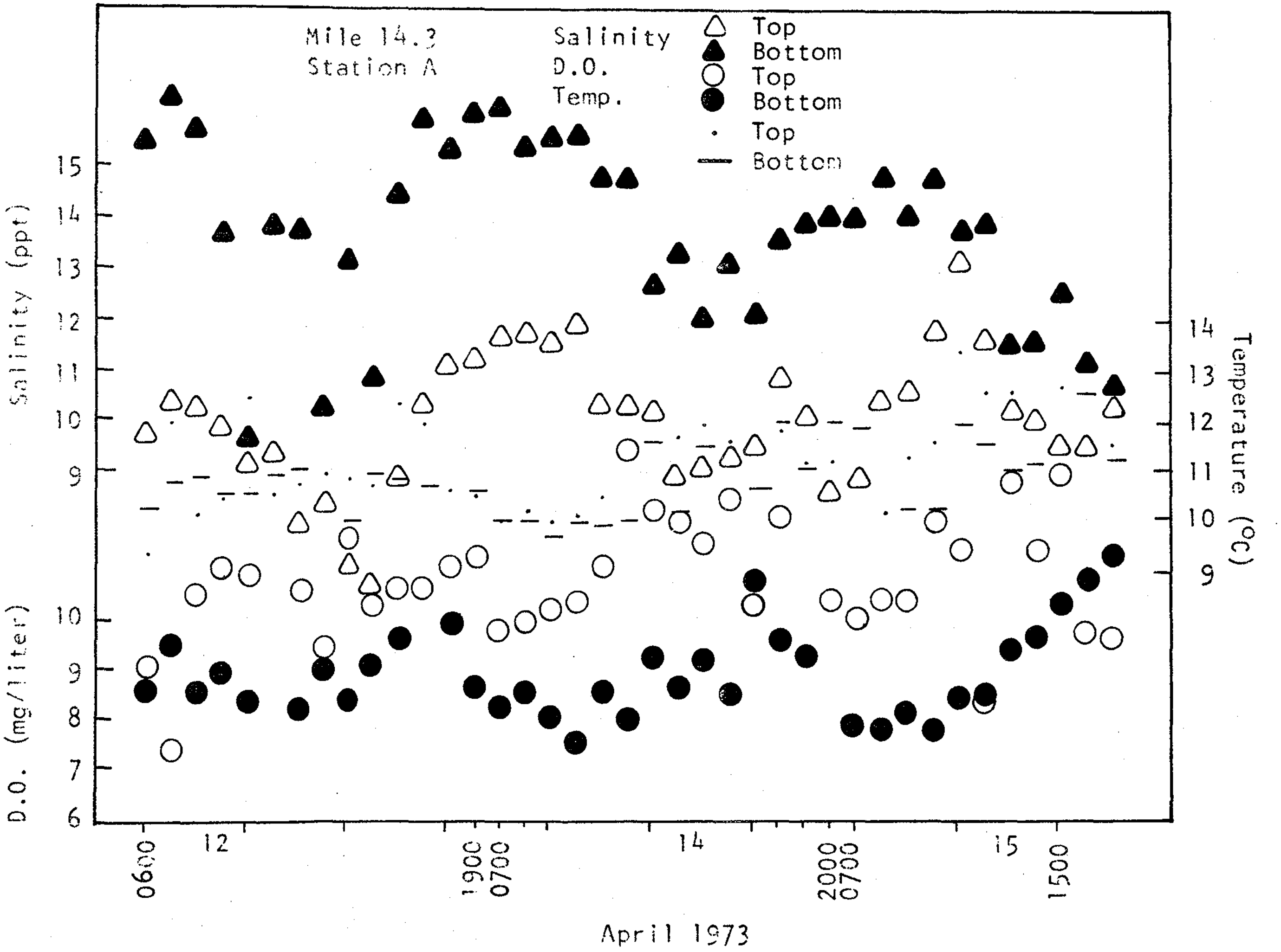

Mile 1.7
Station B
Salinity
△ Top
▲ Bottom
D.O.
○ Top
● Bottom
Temp.
· · Top
— Bottom
Salinity (ppt)
19
18
17
16
15
14
13
D.O. (mg/liter)
9
8
7
6
Temperature (°C)
11
10
9
1700
1900
April 15, 1973

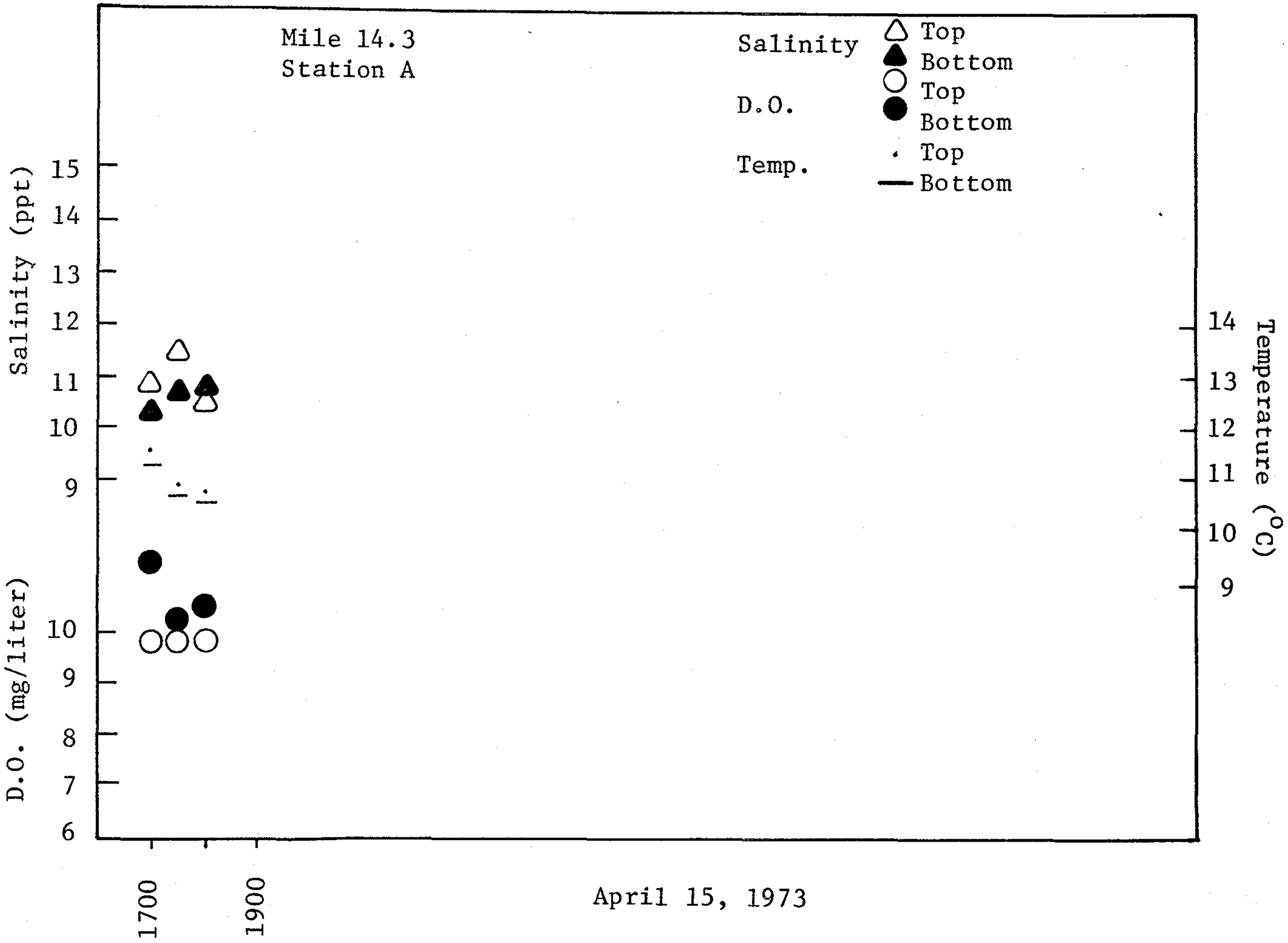

Mile 6.8
Station A
Salinity △ Top ▲ Bottom
D.O. ○ Top ● Bottom
Temp. · Top — Bottom
Salinity (ppt)
13
14
15
16
17
18
19
D.O. (mg/liter)
7
8
9
10
Temperature (°C)
9
10
11
12
0600
12
1900
0700
14
2000
0600
15
1400
April, 1973

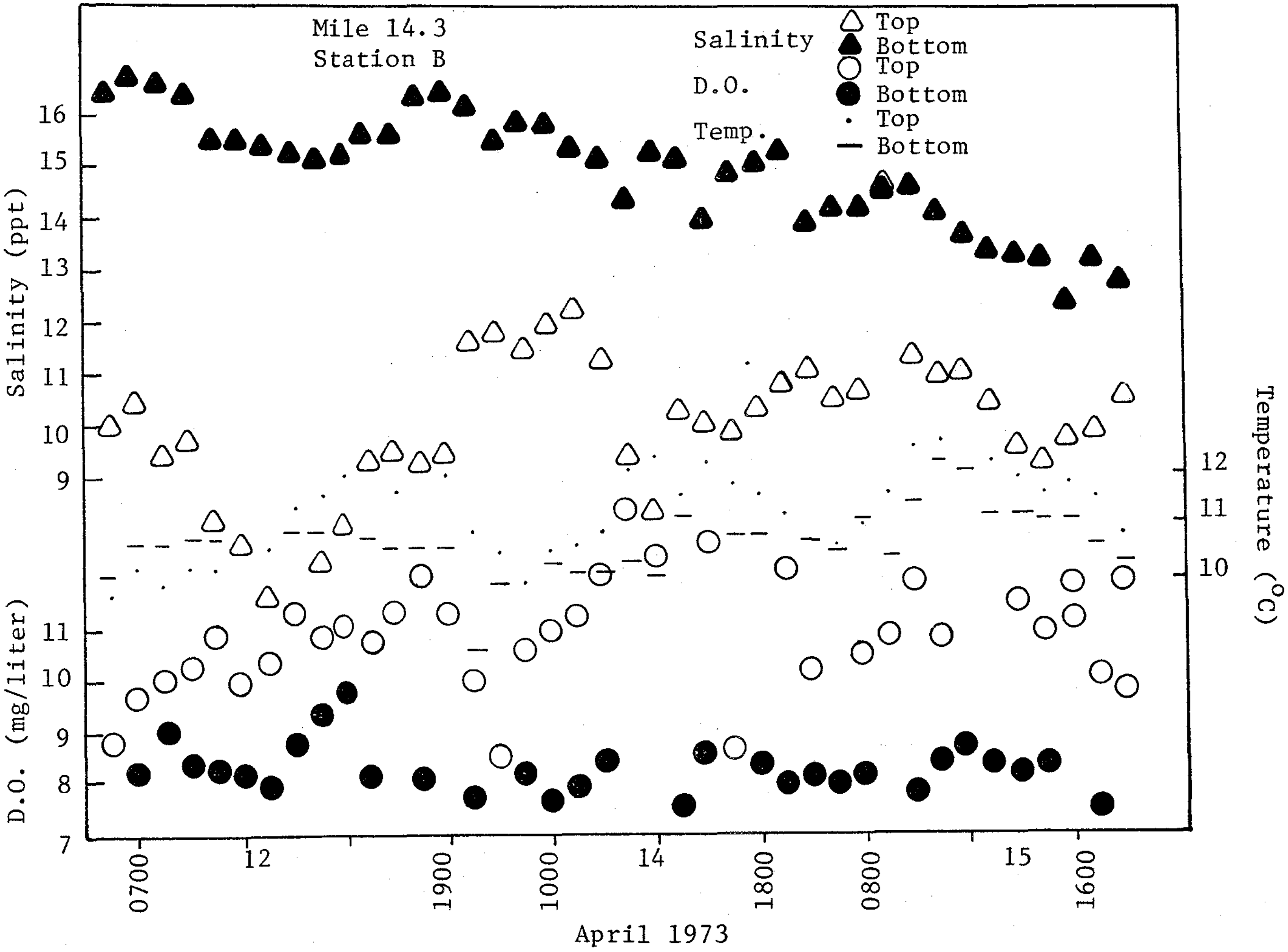

Mile 6.8
Station A
Salinity △ Top ▲ Bottom
D.O. ○ Top ● Bottom
Temp. · Top — Bottom
Salinity (ppt)
19
18
17
16
15
14
12
11
10
9
8
7
6
D.O. (mg/liter)
13
12
11
Temperature (°C)
1600
15
0600
17
1800
0800
18
1600
0700
19
1100
April 1973

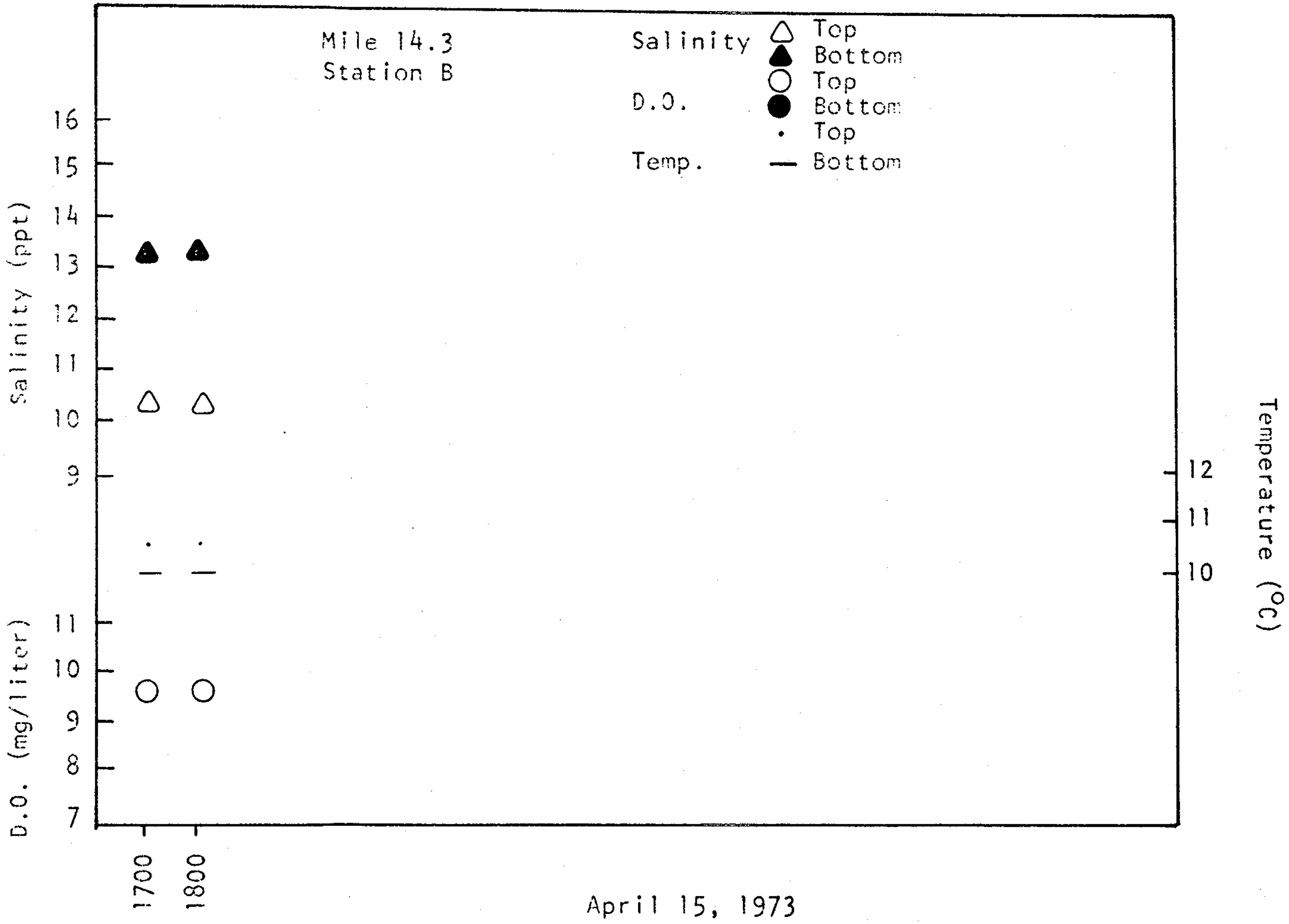


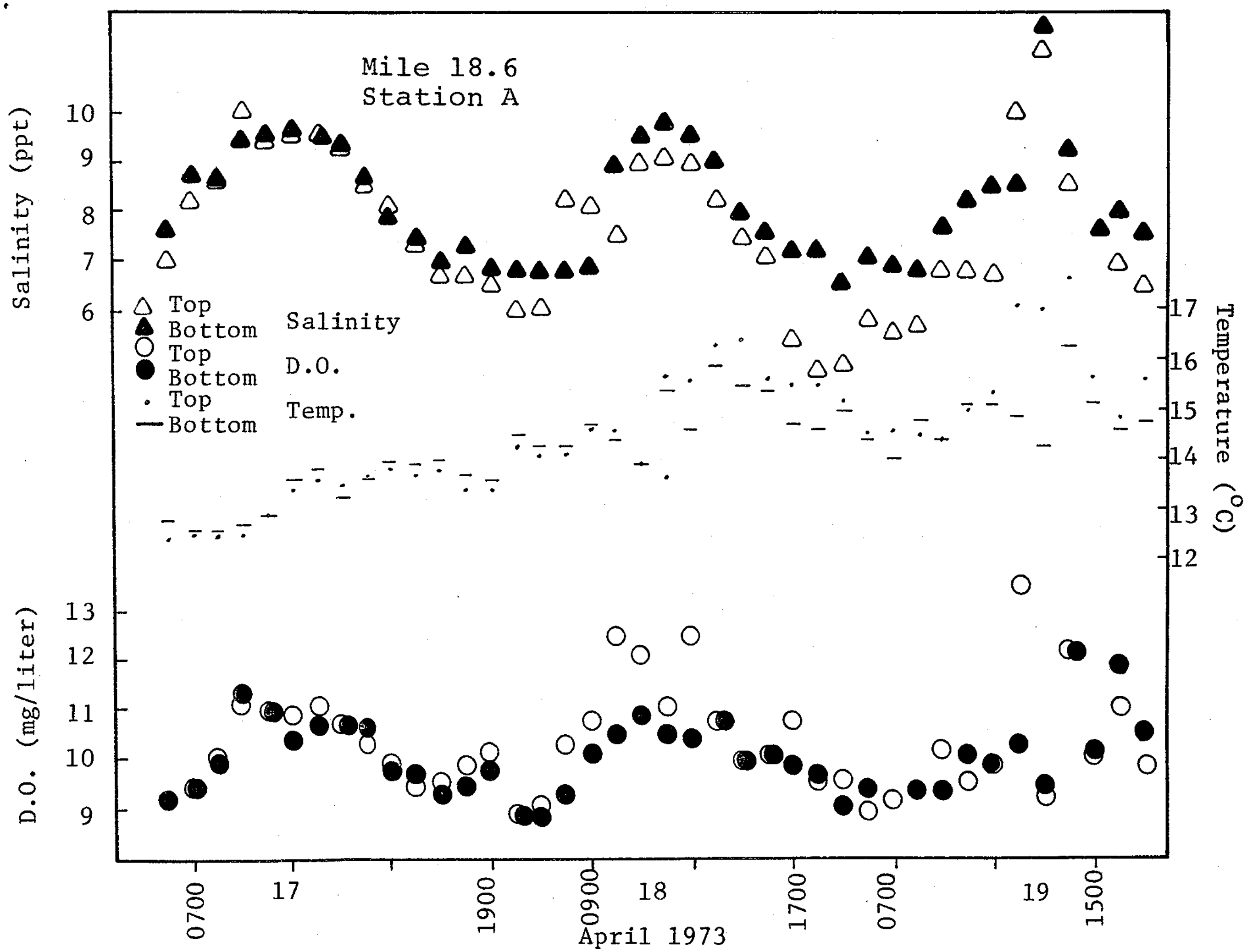
April 19, 1973

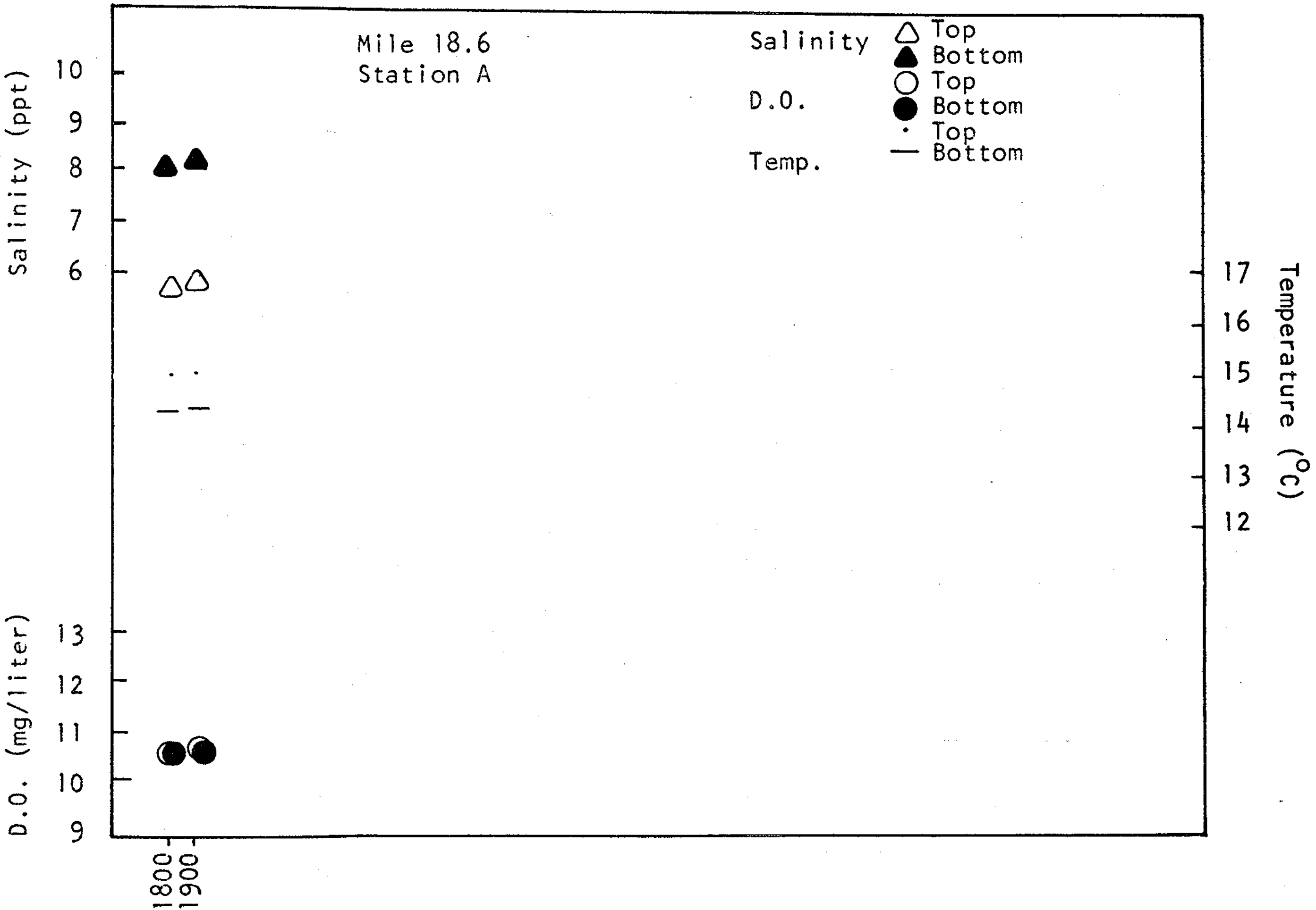

Mile 14.3
Station A
Salinity
D.O.
Temp.
△ Top
▲ Bottom
○ Top
● Bottom
· Top
— Bottom
Salinity (ppt)
9
10
11
12
13
14
15
D.O. (mg/liter)
6
7
8
9
10
Temperature (°C)
9
10
11
12
13
14
0600
12
1900
0700
14
2000
0700
15
1500
April 1973


Mile 14.3
Station A
Salinity △ Top ▲ Bottom
D.O. ○ Top ● Bottom
Temp. · Top — Bottom
Salinity (ppt)
15
14
13
12
11
10
9
D.O. (mg/liter)
10
9
8
7
6
Temperature (°C)
14
13
12
11
10
9
1700
1900
April 15, 1973

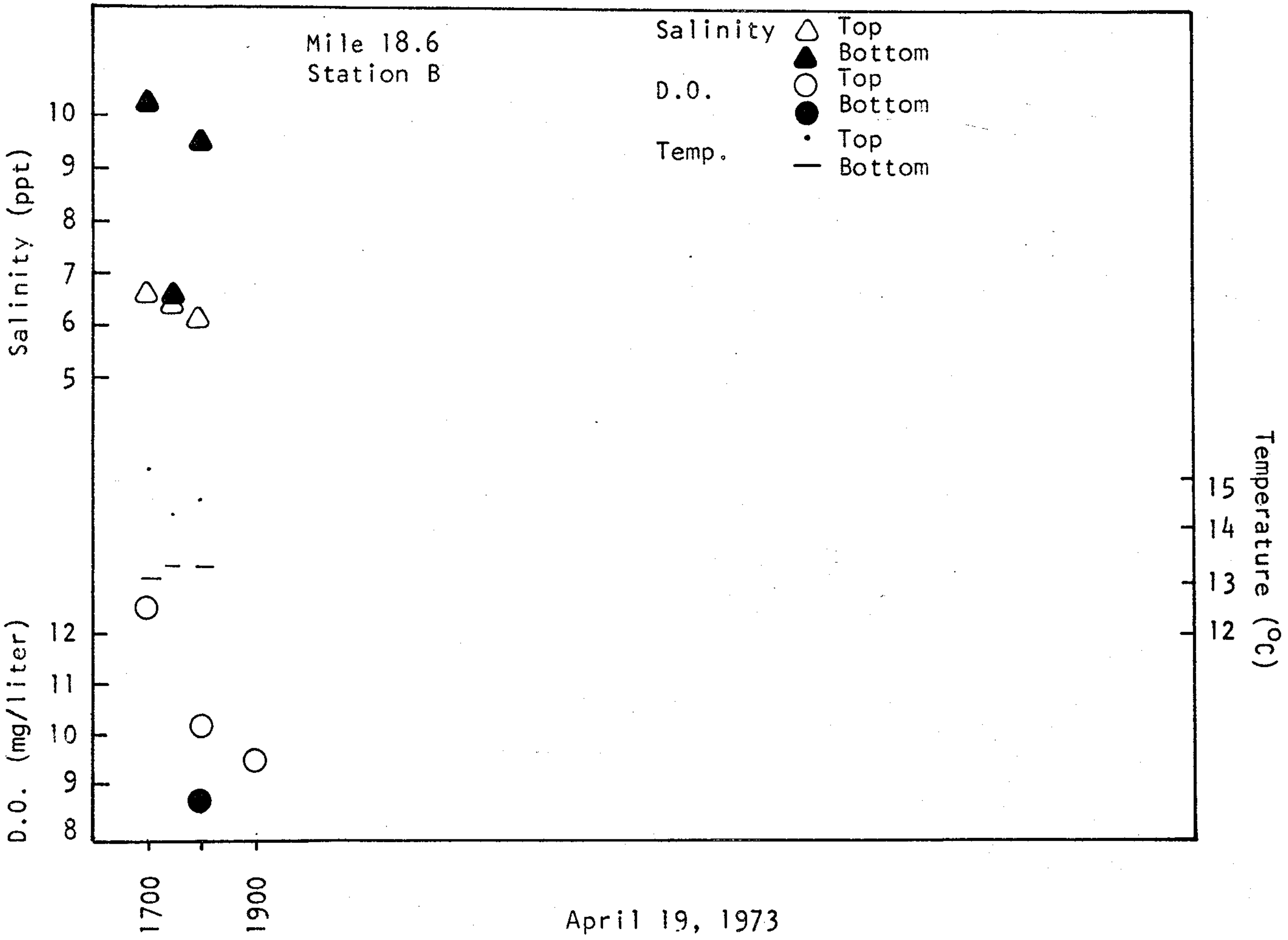

Mile 14.3
Station B
Salinity
D.O.
Temp.
△ Top
▲ Bottom
○ Top
● Bottom
· Top
— Bottom
Salinity (ppt)
16
15
14
13
12
11
10
9
D.O. (mg/liter)
11
10
9
8
7
Temperature (°C)
12
11
10
0700
12
1900
1000
14
1800
0800
15
1600
April 1973

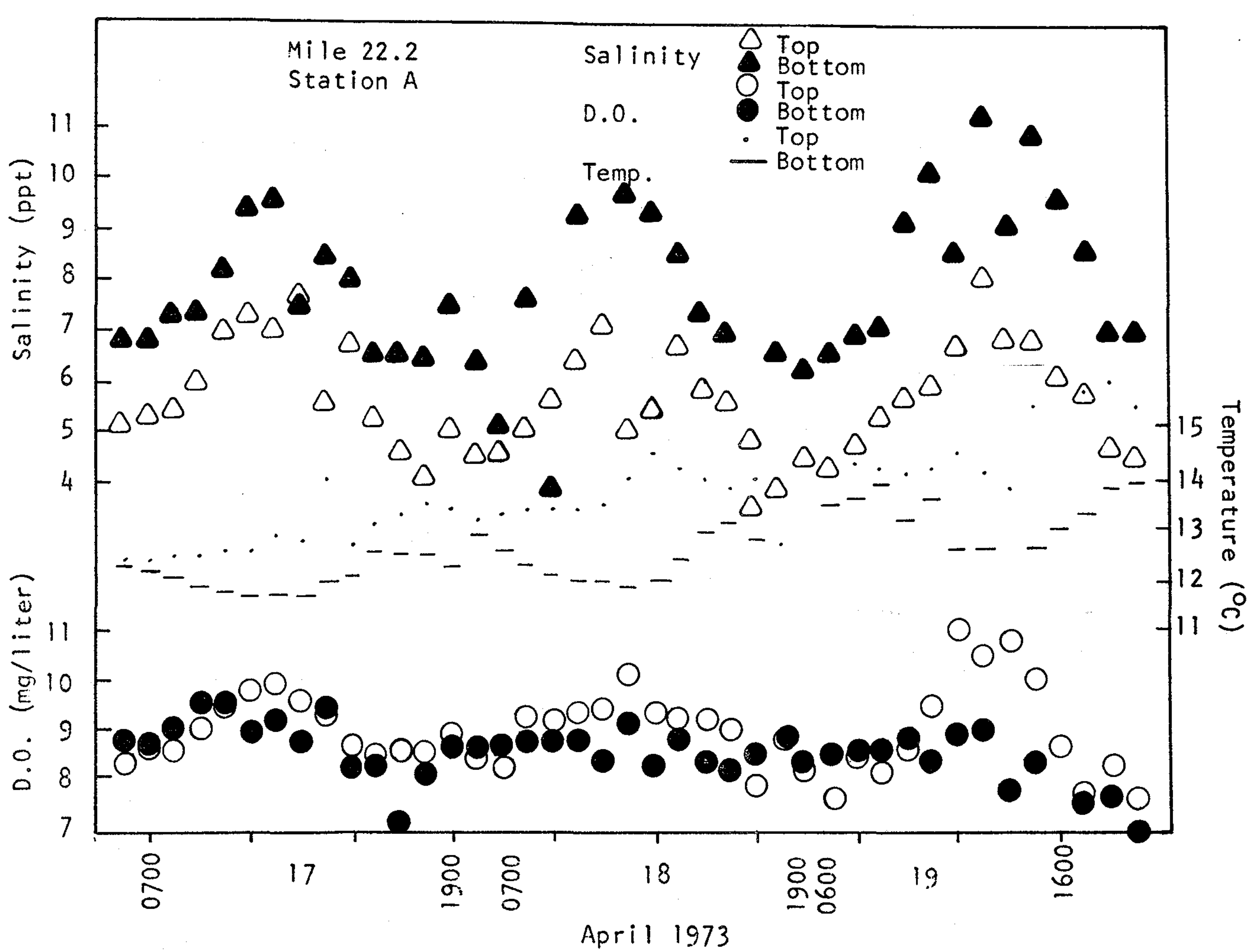

Mile 14.3
Station B
Salinity △ Top
▲ Bottom
D.O. ○ Top
● Bottom
Temp. · Top
— Bottom
Salinity (ppt)
16
15
14
13
12
11
10
9
D.O. (mg/liter)
11
10
9
8
7
1700
1800
April 15, 1973
Temperature (°C)
12
11
10

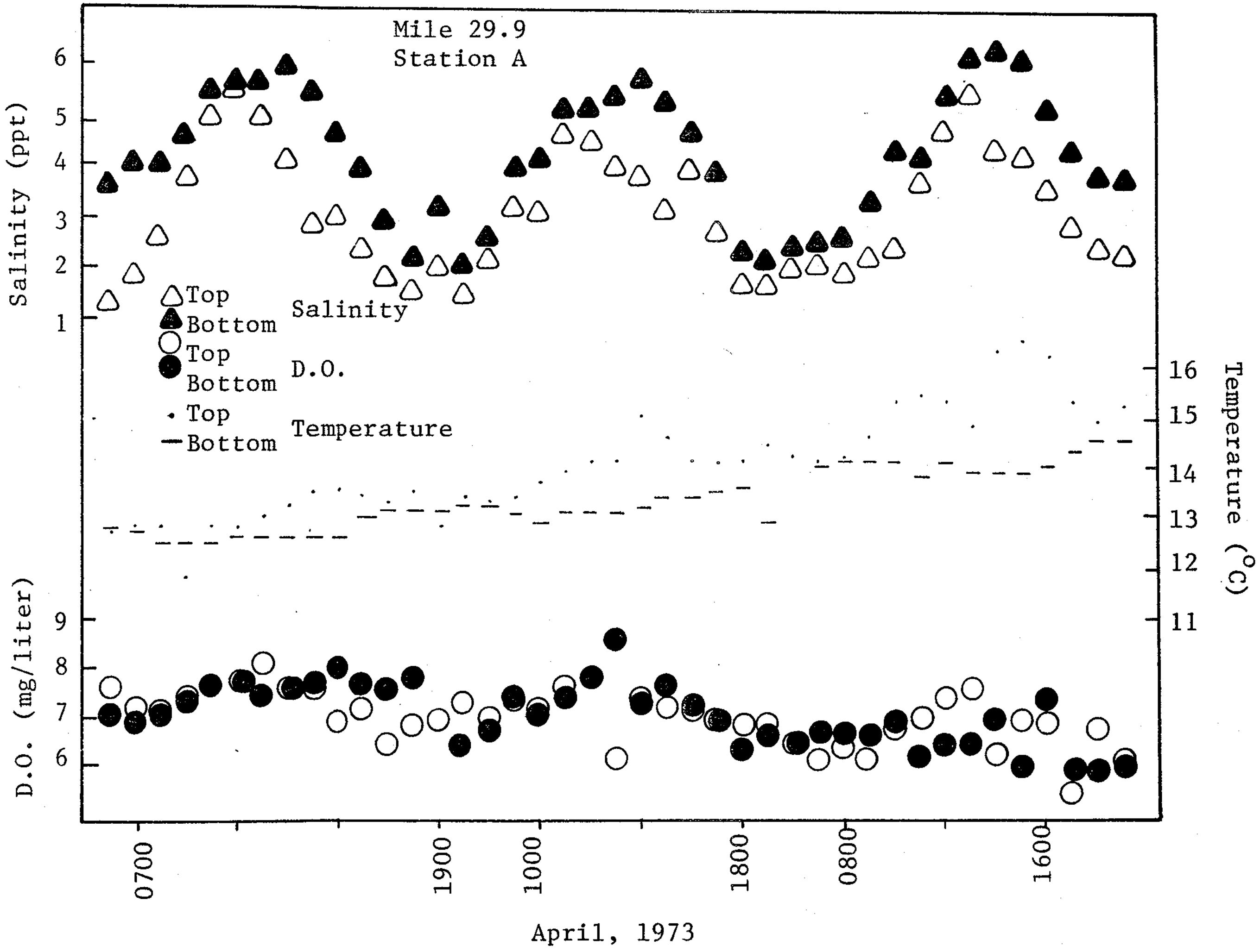

Mile 18.6
Station A
Salinity (ppt)
10
9
8
7
6
△ Top
▲ Bottom
Salinity
○ Top
● Bottom
D.O.
· Top
— Bottom
Temp.
17
16
15
14
13
12
Temperature (°C)
13
12
11
10
9
D.O. (mg/liter)
0700
17
1900
0900
18
1700
0700
19
1500
April 1973

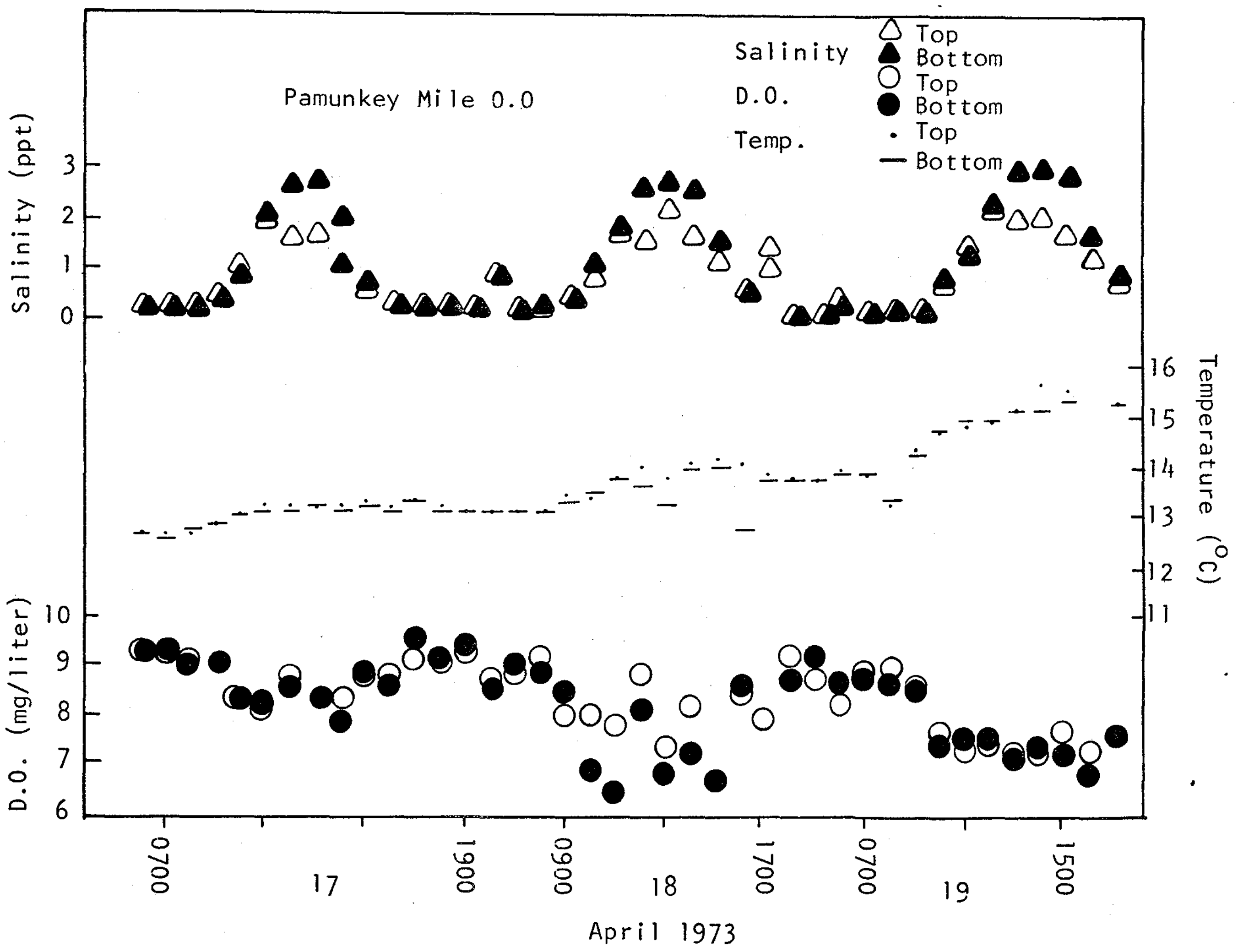


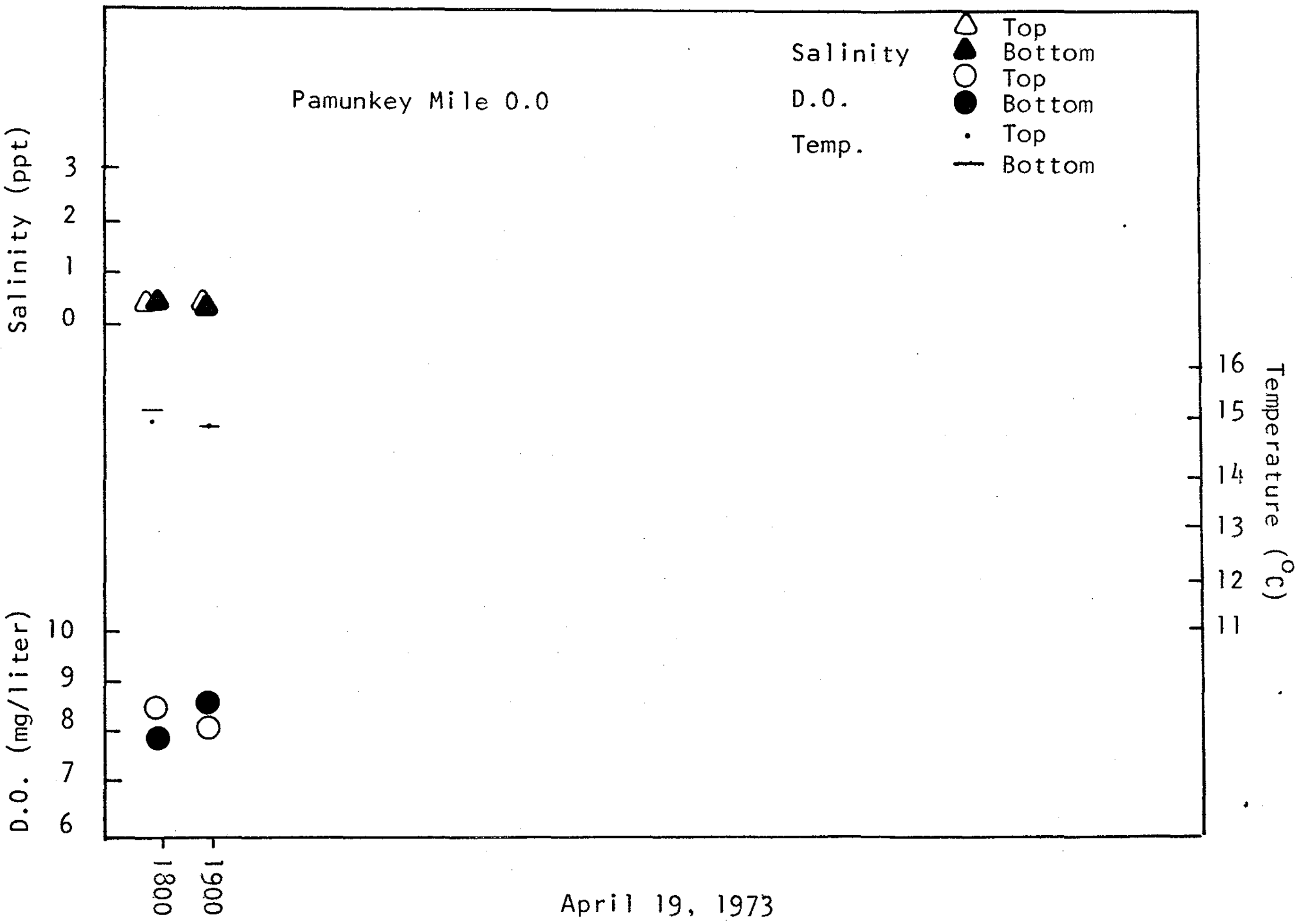
April 19, 1973

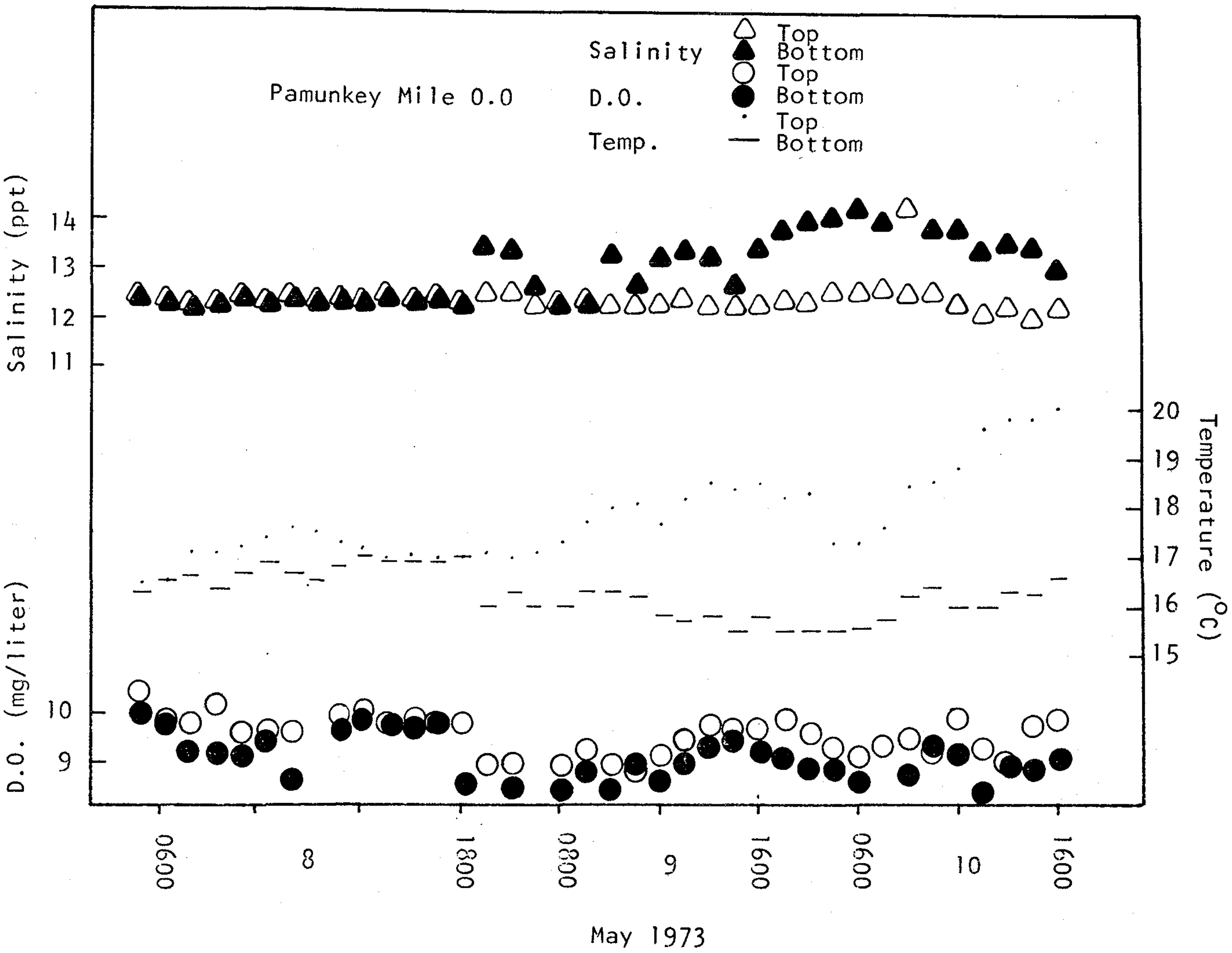

Mile 18.6
Station B
Salinity △ Top
▲ Bottom
D.O. ○ Top
● Bottom
Temp. · Top
— Bottom
Salinity (ppt)
10
9
8
7
6
5
D.O. (mg/liter)
12
11
10
9
8
Temperature (°C)
15
14
13
12
1700
1900
April 19, 1973

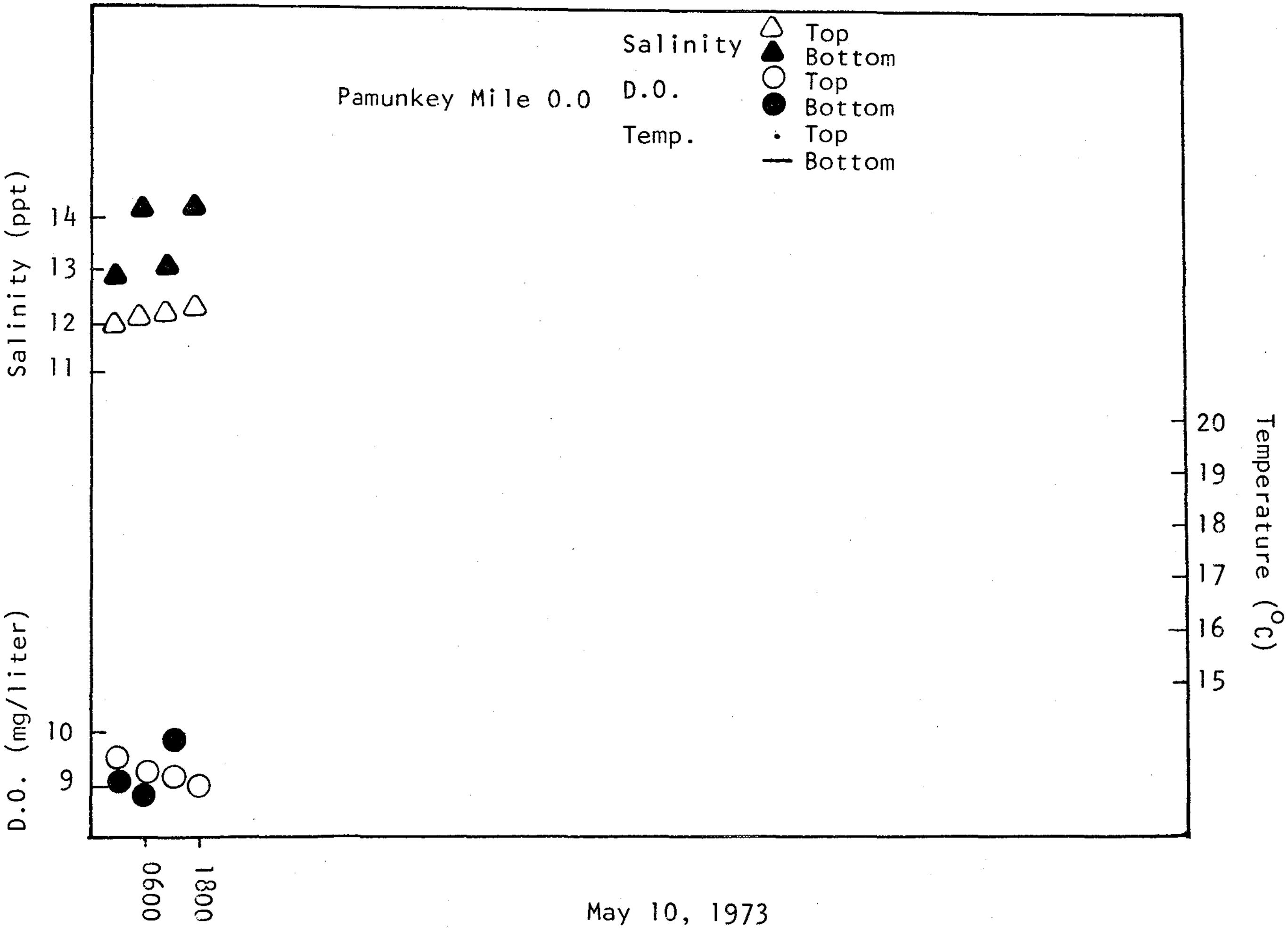

Mile 22.2
Station A
Salinity
D.O.
Temp.
Top
Bottom
Top
Bottom
Top
Bottom
Salinity (ppt)
11
10
9
8
7
6
5
4
D.O. (mg/liter)
11
10
9
8
7
Temperature (°C)
15
14
13
12
11
0700
17
1900
0700
18
1900
0600
19
1600
April 1973

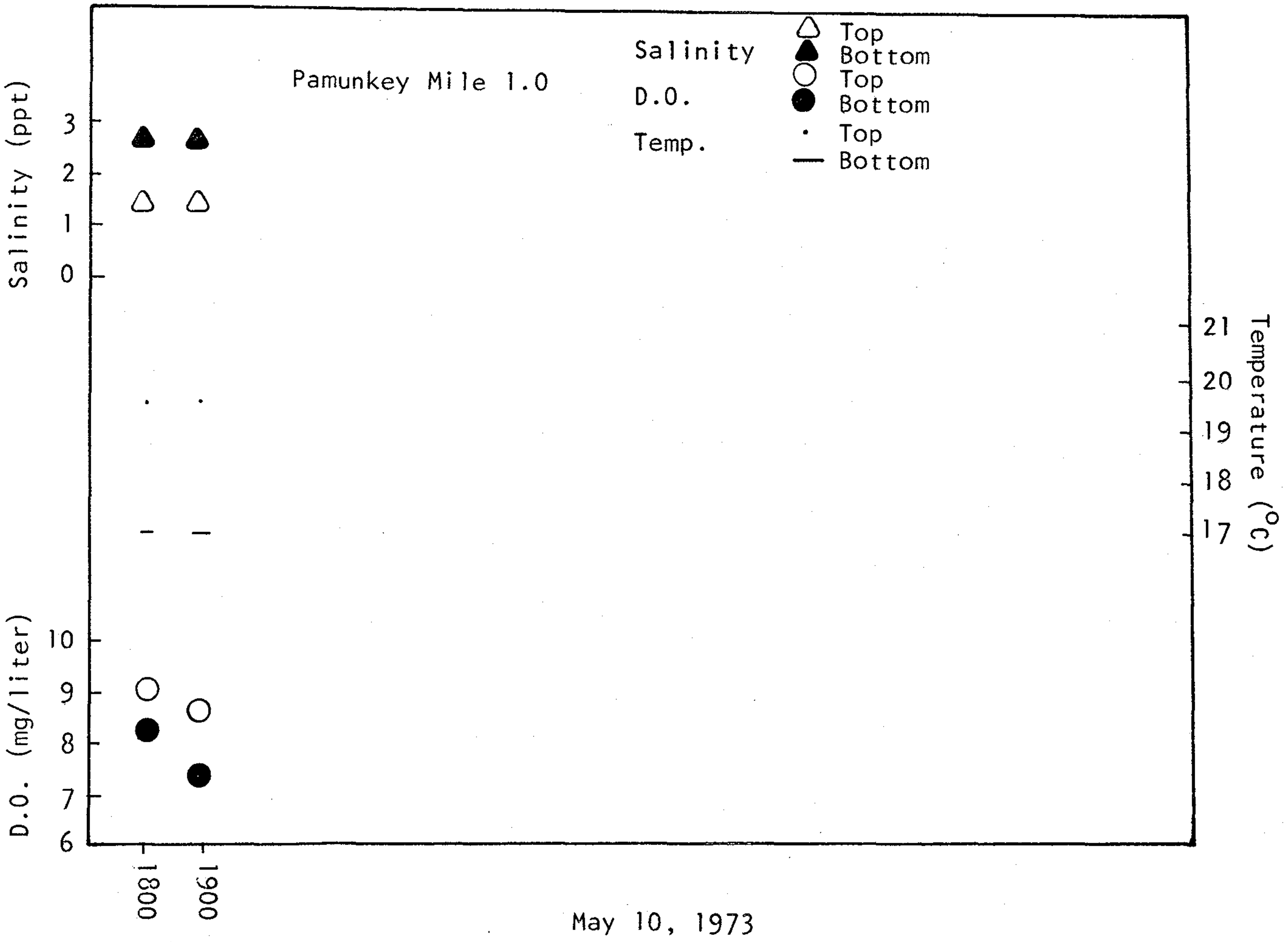

Mile 29.9
Station A
Salinity (ppt)
1
2
3
4
5
6
△ Top
▲ Bottom
Salinity
○ Top
● Bottom
D.O.
· Top
— Bottom
Temperature
Temperature (°C)
11
12
13
14
15
16
D.O. (mg/liter)
6
7
8
9
0700
1900
1000
1800
0800
1600
April, 1973

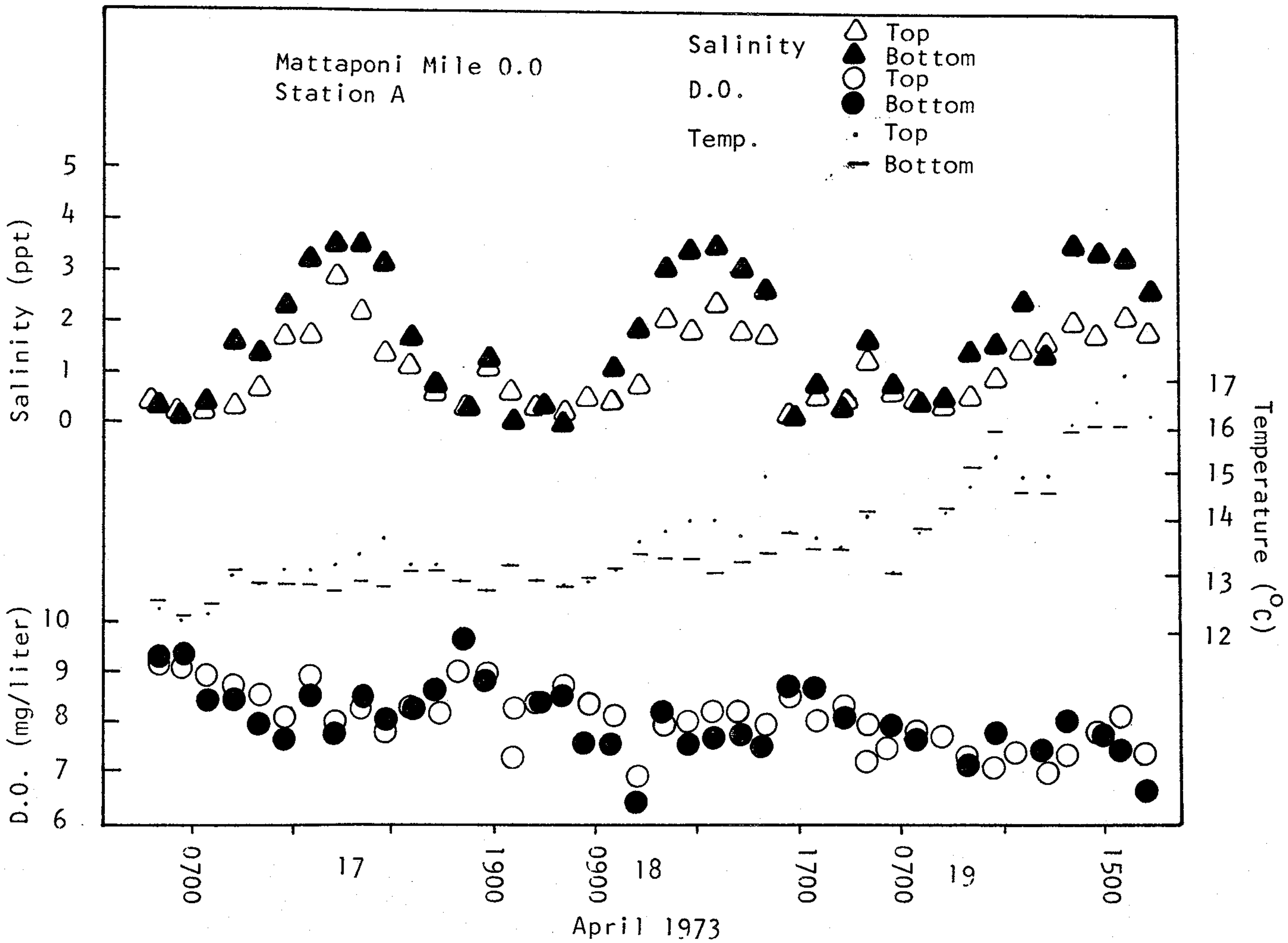

Pamunkey Mile 0.0
Salinity
△ Top
▲ Bottom
D.O.
○ Top
● Bottom
Temp.
• Top
— Bottom
Salinity (ppt)
0
1
2
3
Temperature (°C)
11
12
13
14
15
16
D.O. (mg/liter)
6
7
8
9
10
0700
17
1900
0900
18
1700
0700
19
1500
April 1973

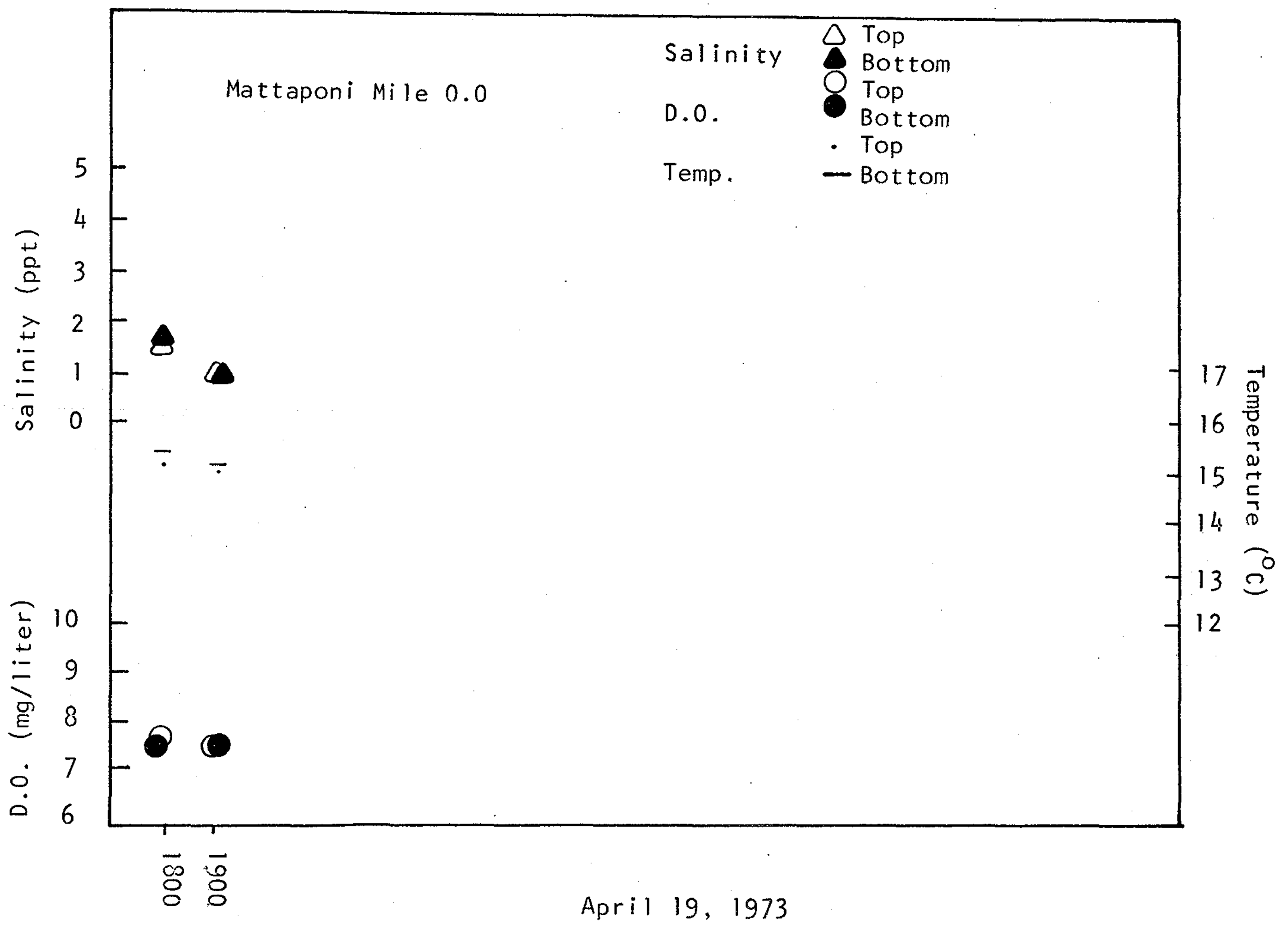

Pamunkey Mile 0.0
Salinity
△ Top
▲ Bottom
D.O.
○ Top
● Bottom
Temp.
· Top
— Bottom
Salinity (ppt)
3
2
1
0
D.O. (mg/liter)
10
9
8
7
6
Temperature (°C)
16
15
14
13
12
11
1800
1900
April 19, 1973


Pamunkey Mile 0.0
Salinity △ Top ▲ Bottom
D.O. ○ Top ● Bottom
Temp. · Top — Bottom
Salinity (ppt)
14
13
12
11
D.O. (mg/liter)
10
9
Temperature (°C)
20
19
18
17
16
15
0600
8
1800
0800
9
1600
0600
10
1600
May 1973


Pamunkey Mile 0.0
Salinity △ Top
▲ Bottom
D.O. ○ Top
● Bottom
Temp. · Top
— Bottom
Salinity (ppt)
14
13
12
11
D.O. (mg/liter)
10
9
Temperature (°C)
20
19
18
17
16
15
0600
1800
May 10, 1973


Pamunkey Mile 1.0
Salinity
△ Top
▲ Bottom
D.O.
○ Top
● Bottom
Temp.
· Top
— Bottom
Salinity (ppt)
3
2
1
0
D.O. (mg/liter)
10
9
8
7
6
Temperature (°C)
21
20
19
18
17
1800
1900
May 10, 1973

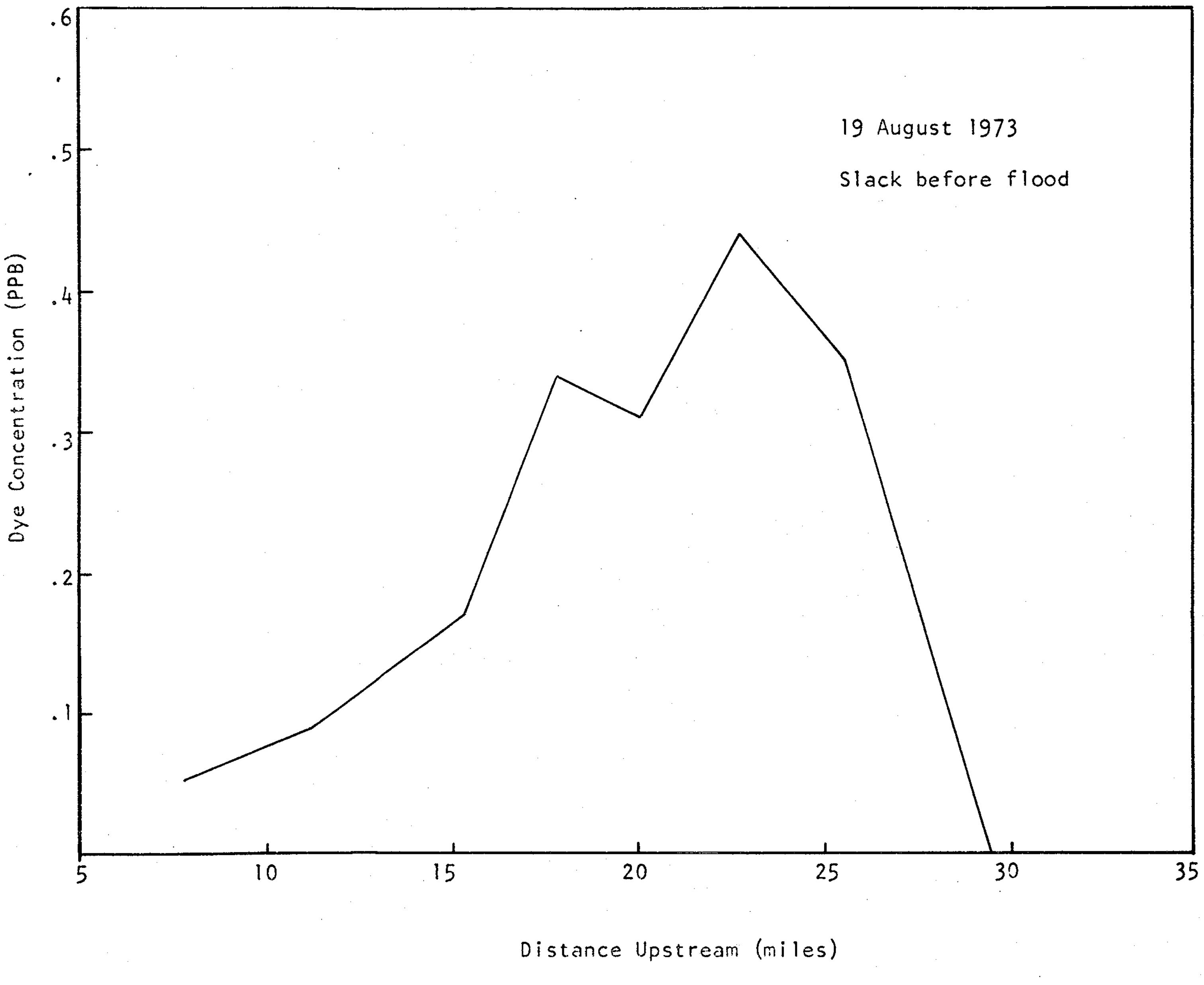

Mattaponi Mile 0.0
Station A
Salinity
D.O.
Temp.
Top
Bottom
Top
Bottom
Top
Bottom
Salinity (ppt)
5
4
3
2
1
0
D.O. (mg/liter)
10
9
8
7
6
Temperature (°C)
17
16
15
14
13
12
0700
17
1900
0900
18
1700
0700
19
1500
April 1973

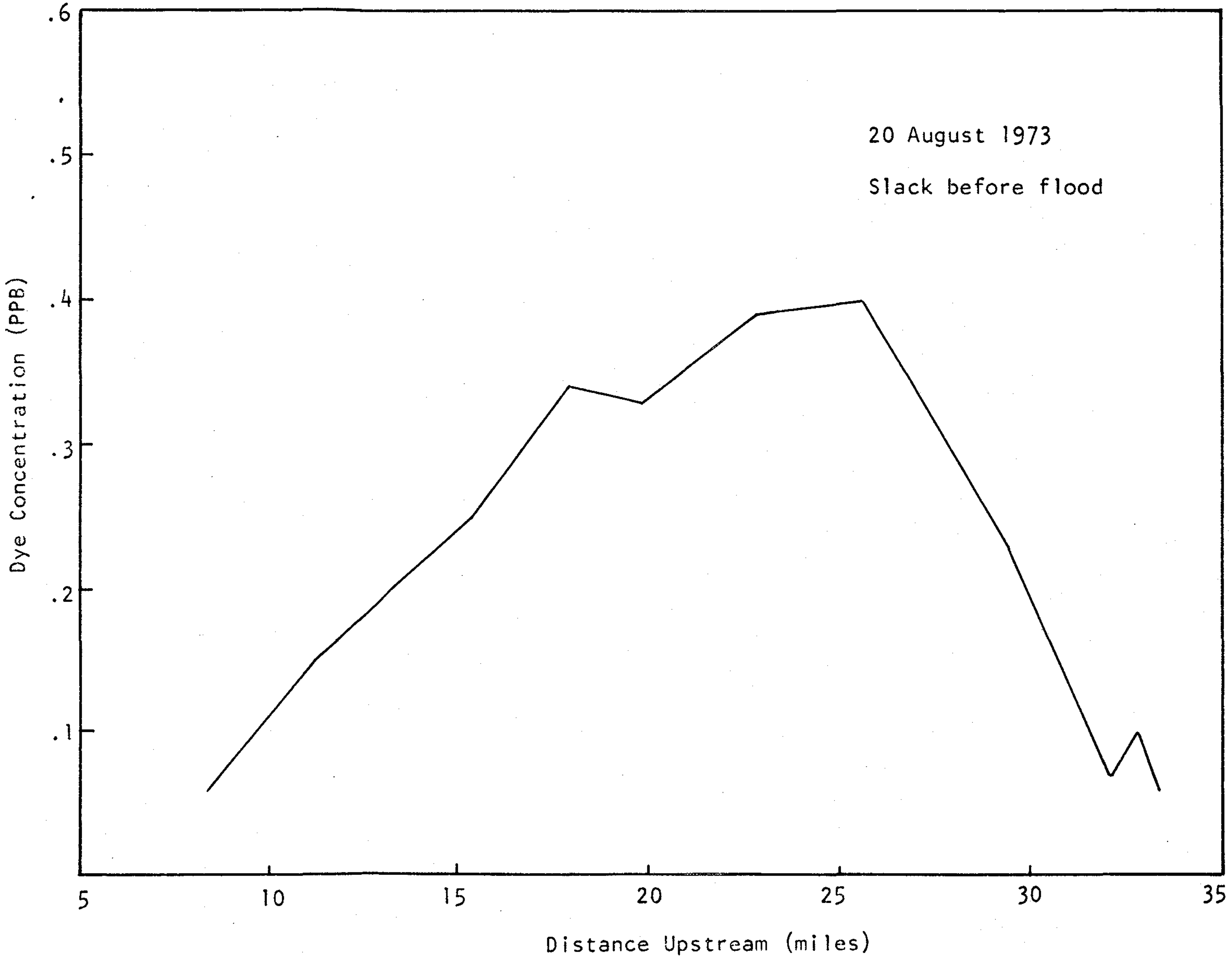

Mattaponi Mile 0.0
Salinity
△ Top
▲ Bottom
D.O.
○ Top
● Bottom
Temp.
· Top
— Bottom
Salinity (ppt)
5
4
3
2
1
0
D.O. (mg/liter)
10
9
8
7
6
Temperature (°C)
17
16
15
14
13
12
1800
1900
April 19, 1973

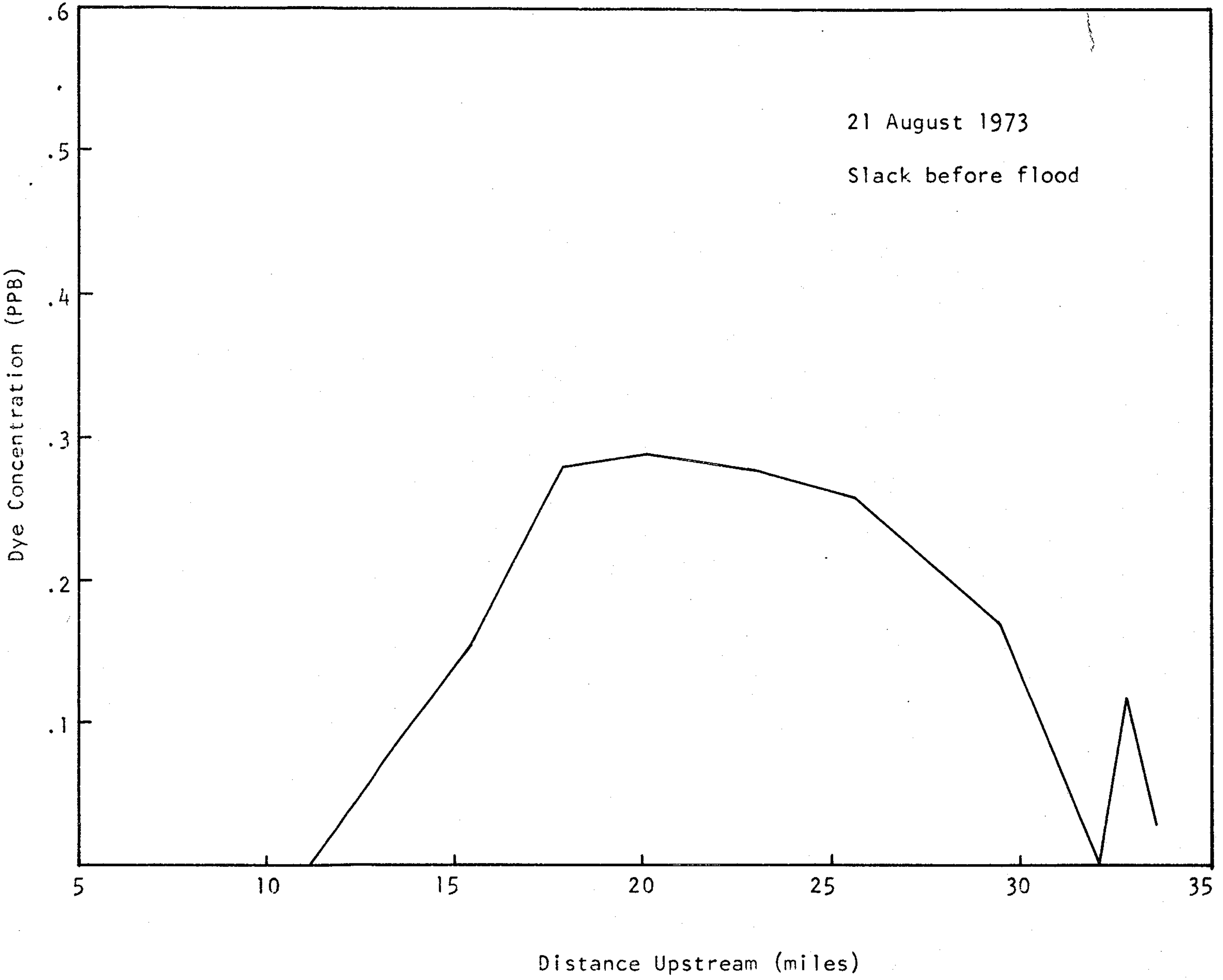
Appendix C

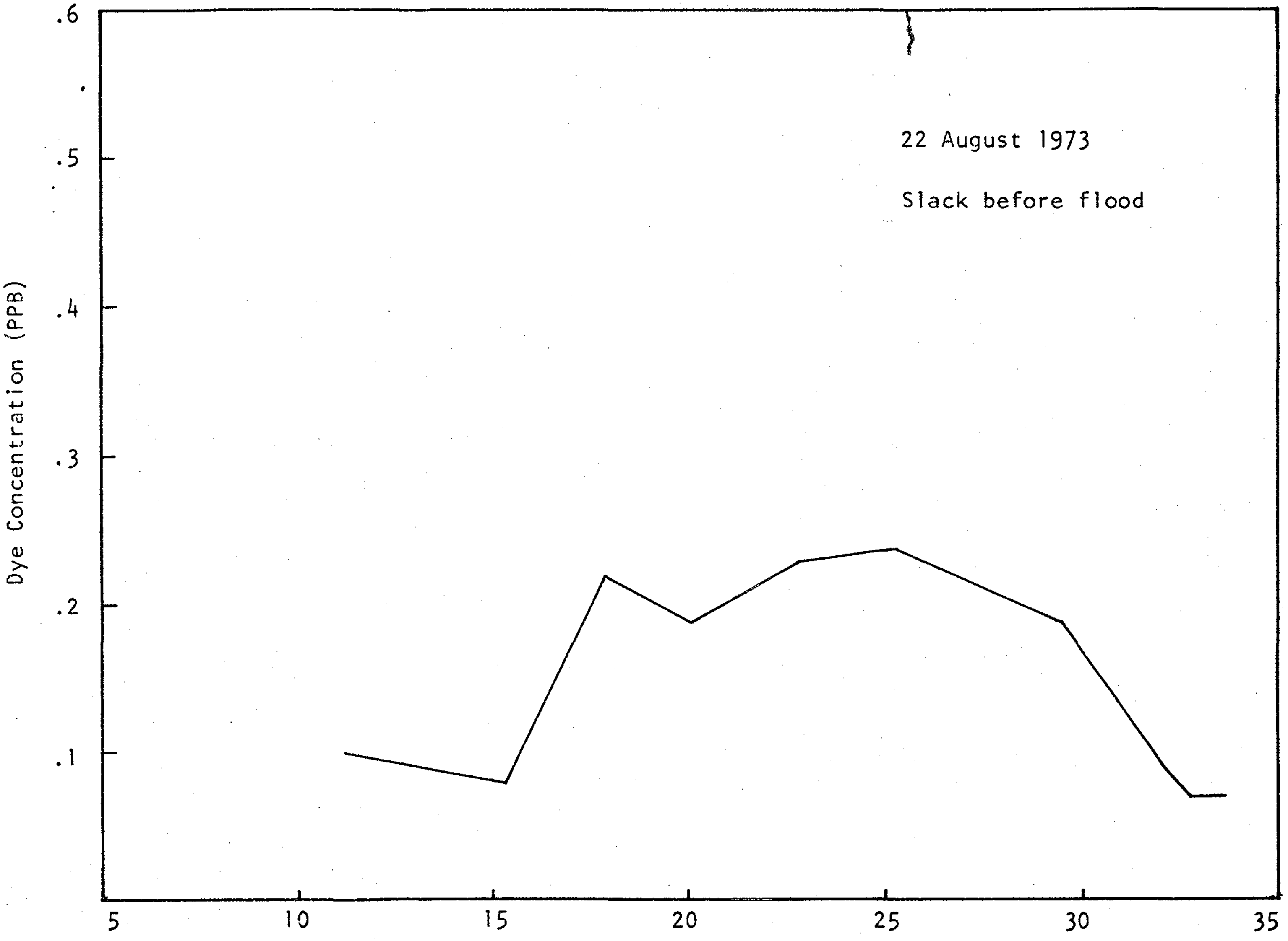
Graphical Summary of Observed Slack Water Dye Distribution

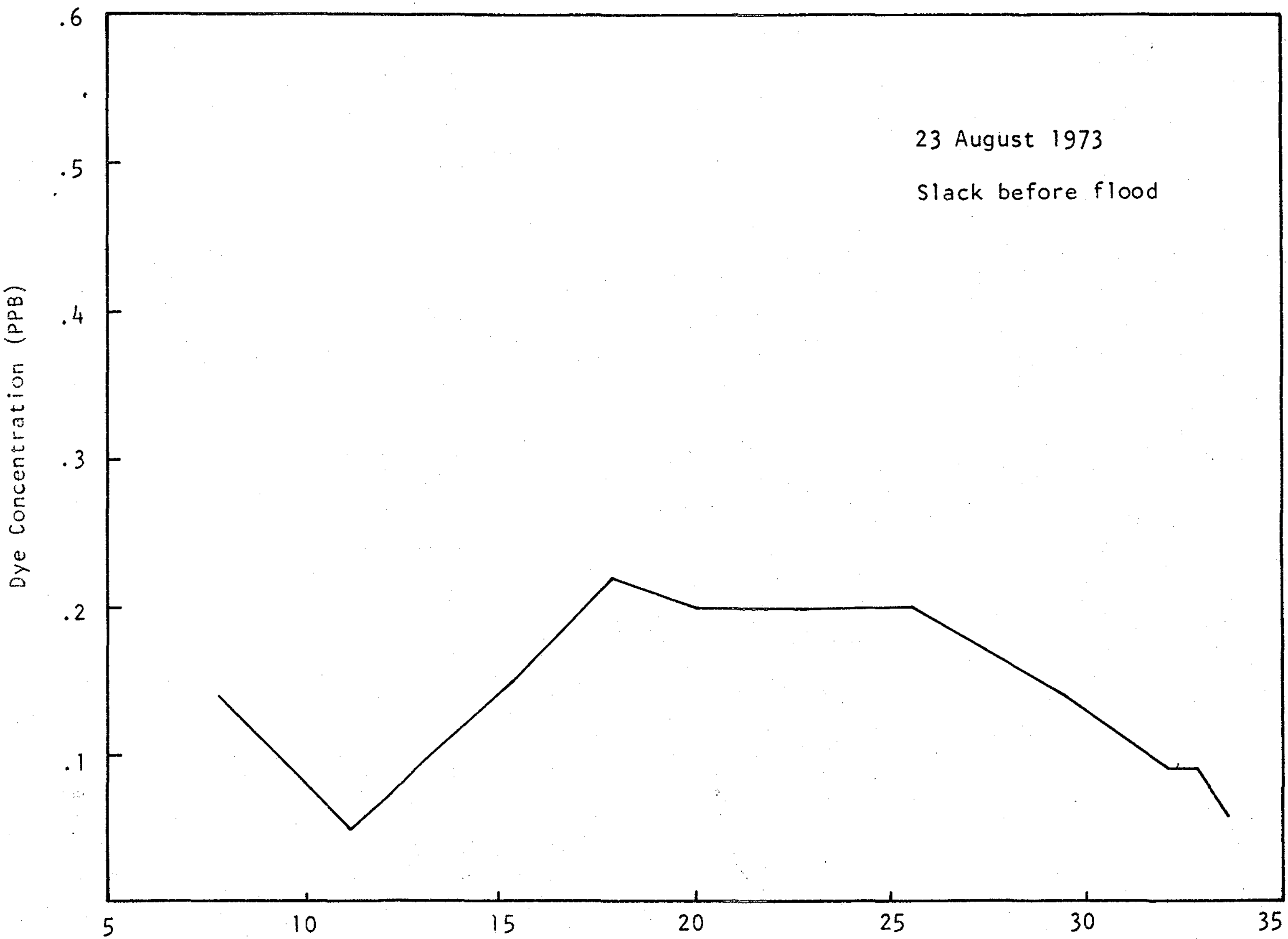
August 19 - 26, 1973

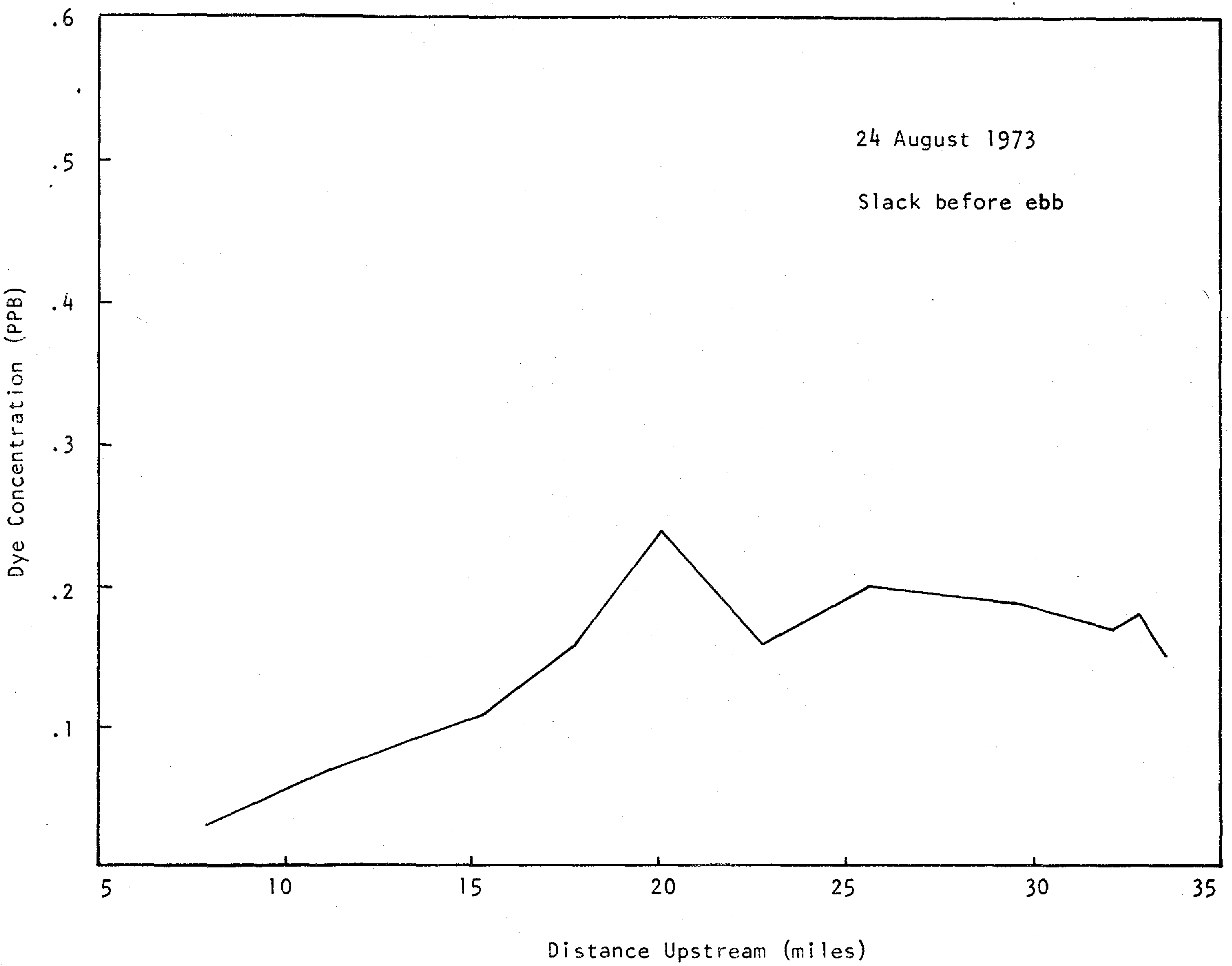

19 August 1973
Slack before flood
Dye Concentration (PPB)
.6
.5
.4
.3
.2
.1
5
10
15
20
25
30
35
Distance Upstream (miles)

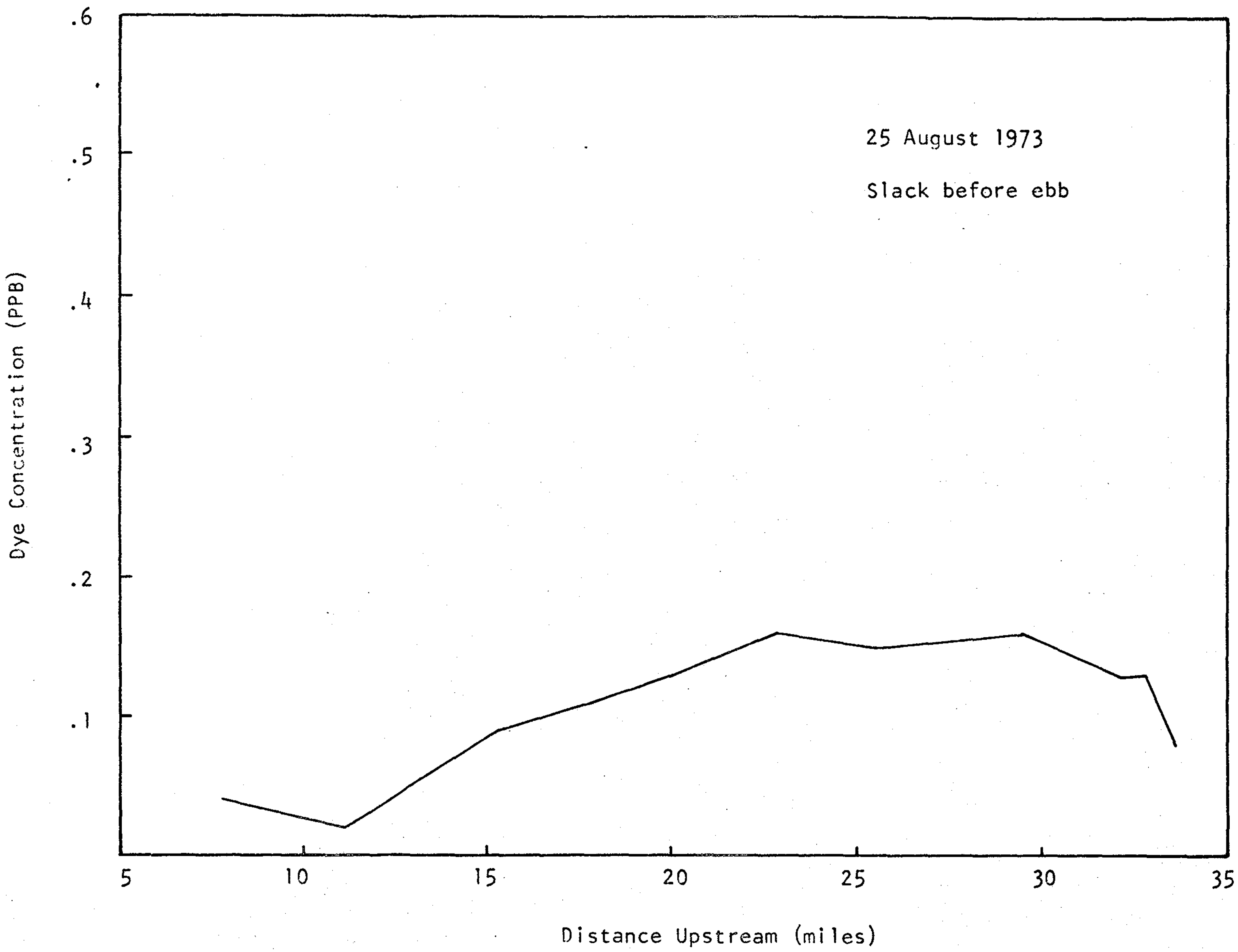

20 August 1973
Slack before flood
Dye Concentration (PPB)
.6
.5
.4
.3
.2
.1
5
10
15
20
25
30
35
Distance Upstream (miles)

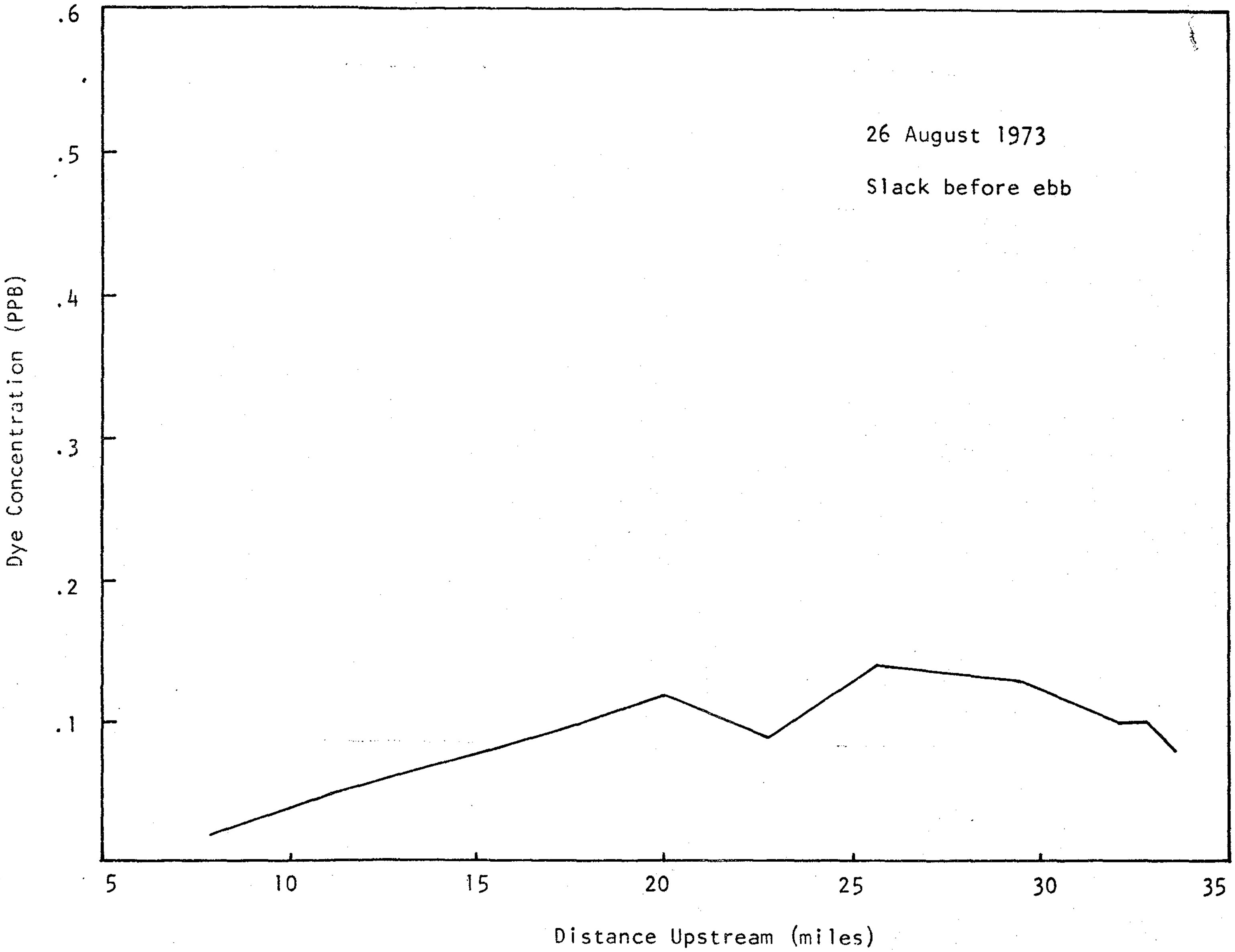

21 August 1973
Slack before flood
Dye Concentration (PPB)
.6
.5
.4
.3
.2
.1
5
10
15
20
25
30
35
Distance Upstream (miles)

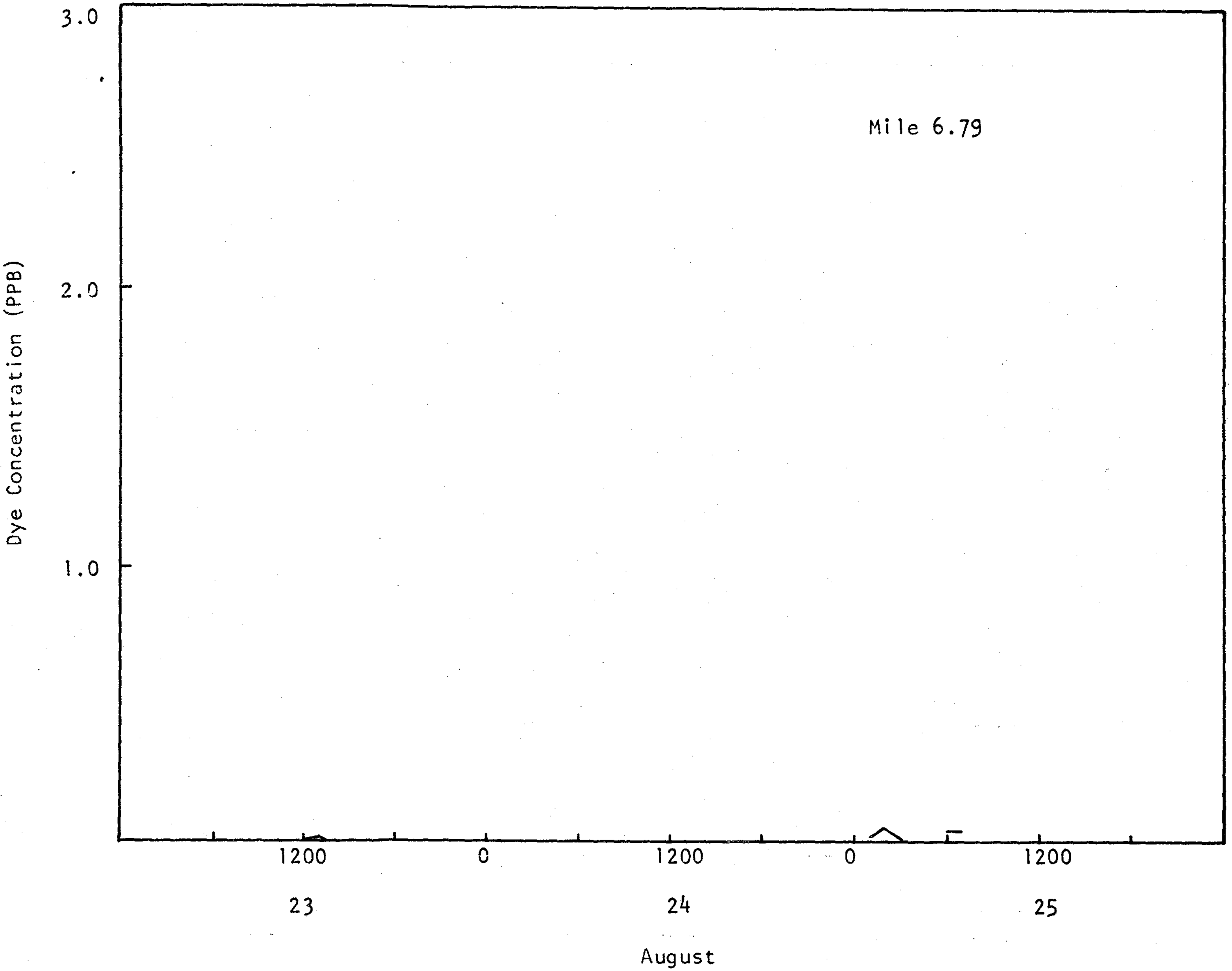

22 August 1973
Slack before flood
Dye Concentration (PPB)
.6
.5
.4
.3
.2
.1
5
10
15
20
25
30
35

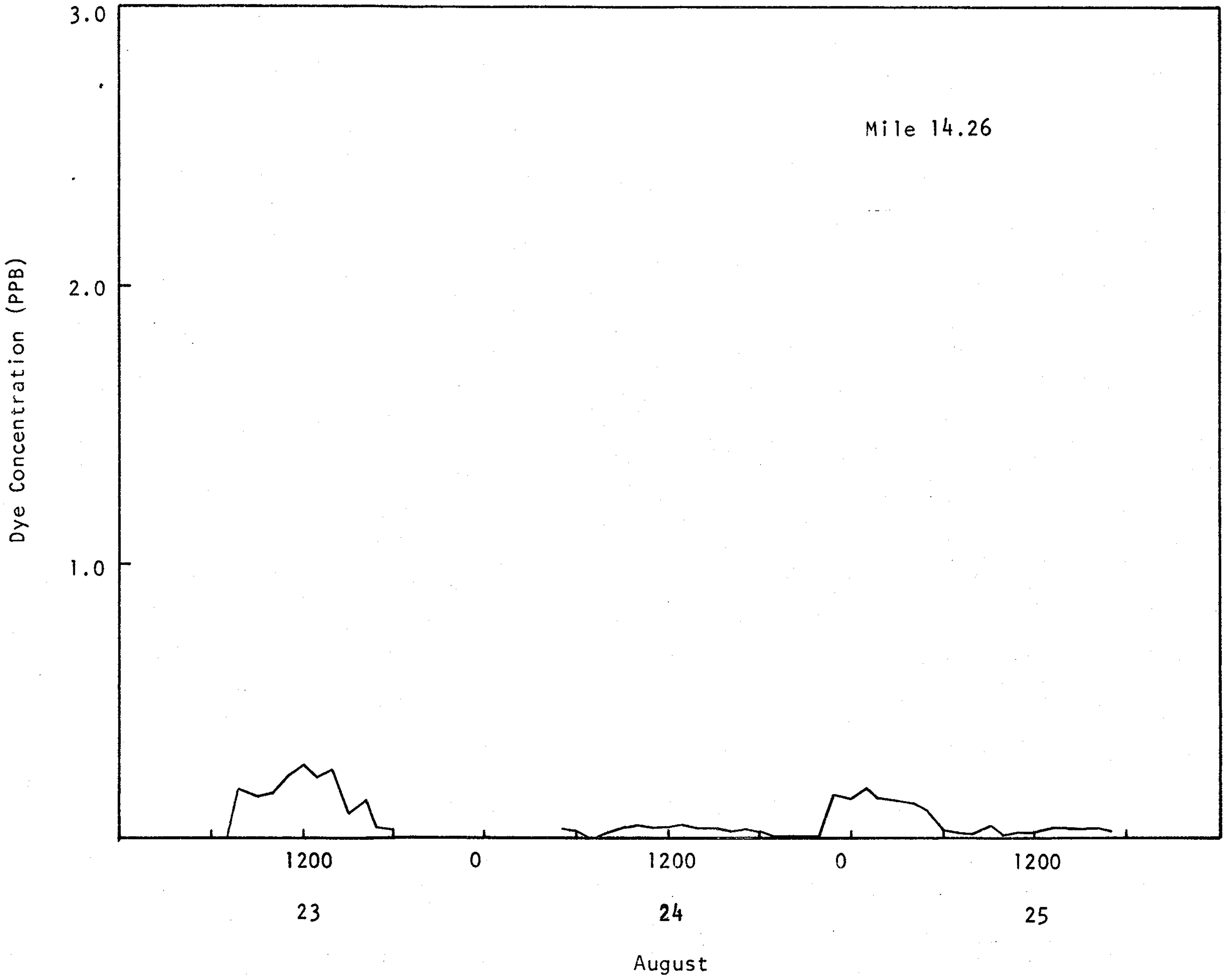

23 August 1973
Slack before flood
Dye Concentration (PPB)
.6
.5
.4
.3
.2
.1
5
10
15
20
25
30
35

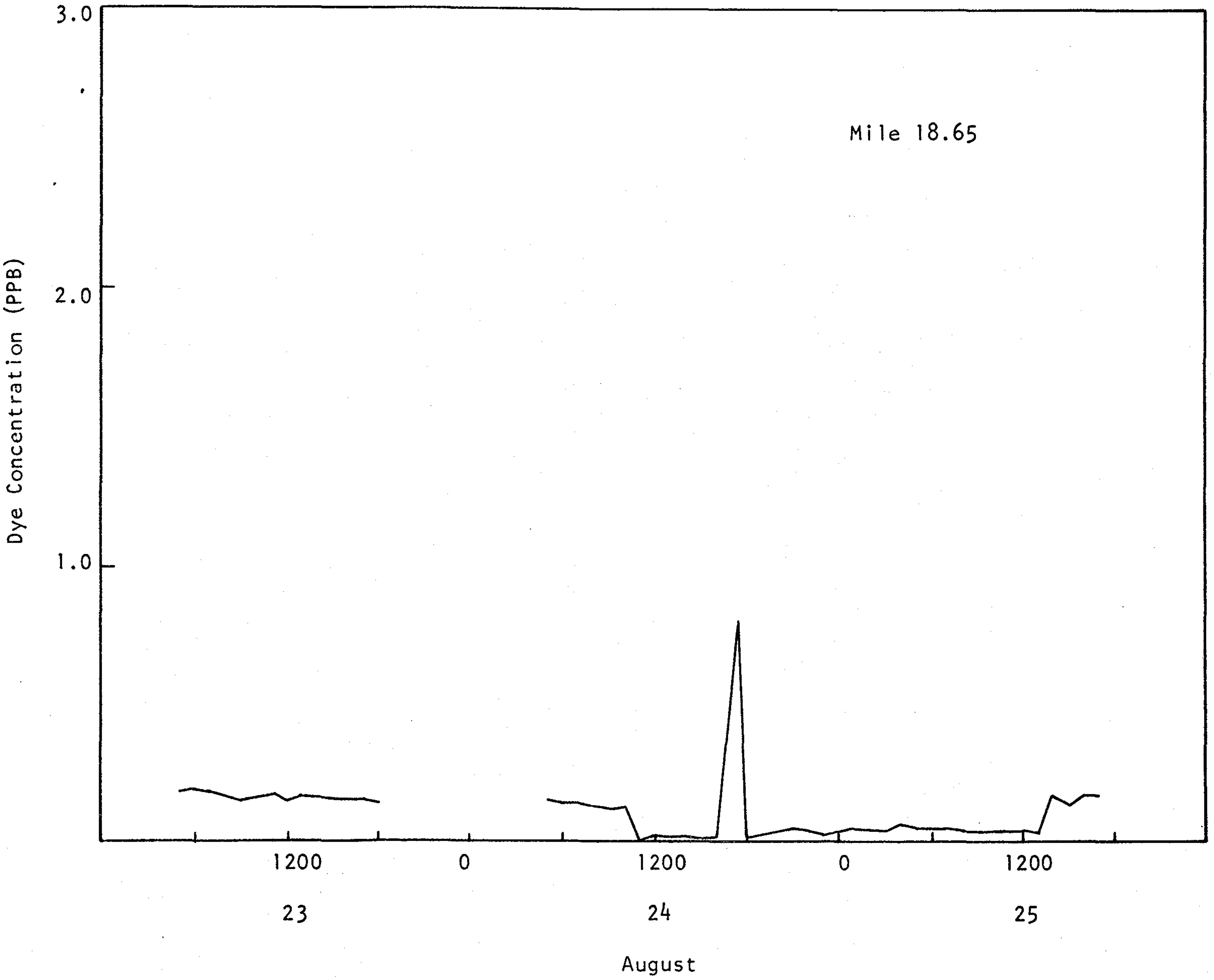

.6
.5
.4
.3
.2
.1
Dye Concentration (PPB)
5
10
15
20
25
30
35
Distance Upstream (miles)
24 August 1973
Slack before ebb

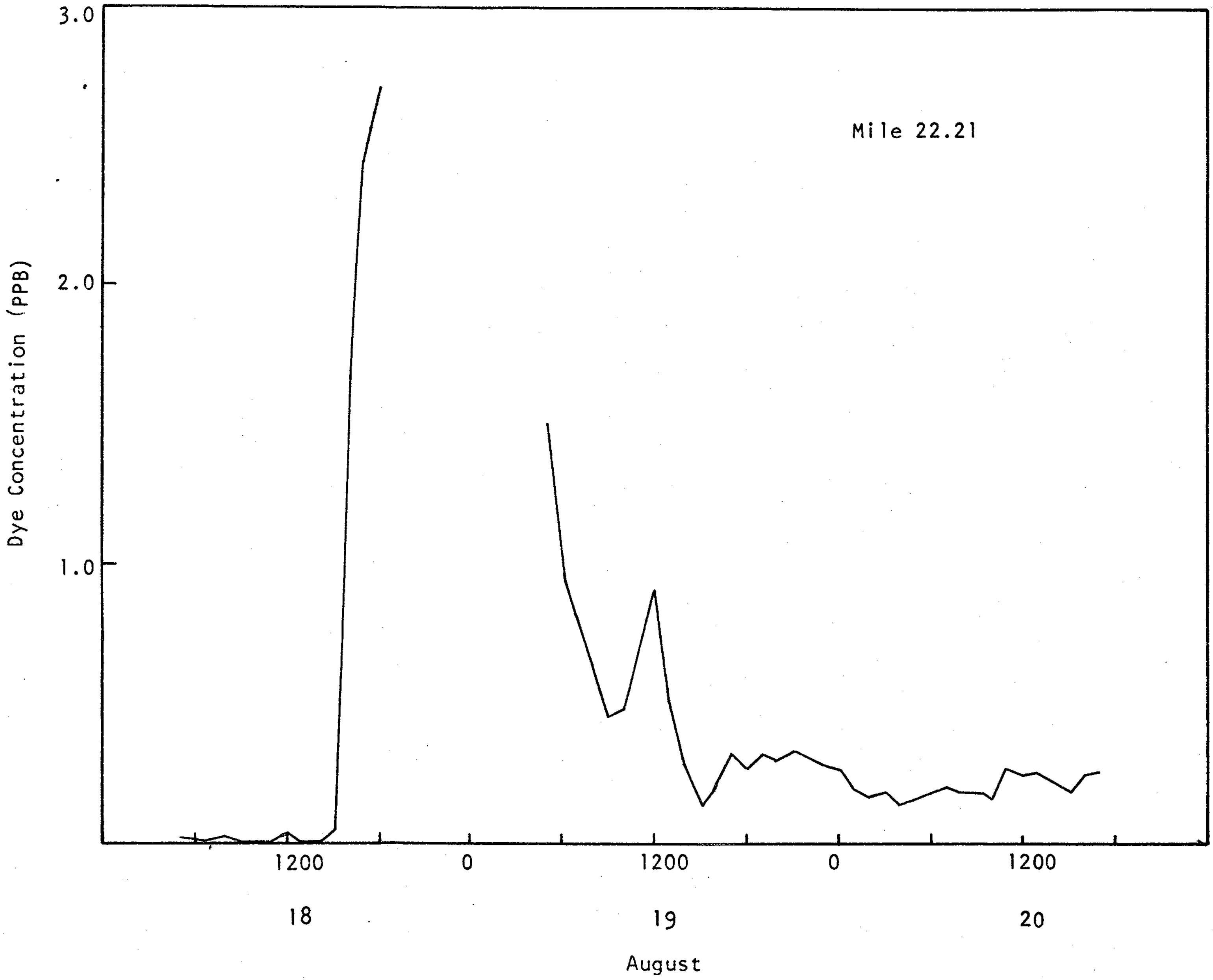

.6
.5
.4
.3
.2
.1
Dye Concentration (PPB)
25 August 1973
Slack before ebb
5
10
15
20
25
30
35
Distance Upstream (miles)

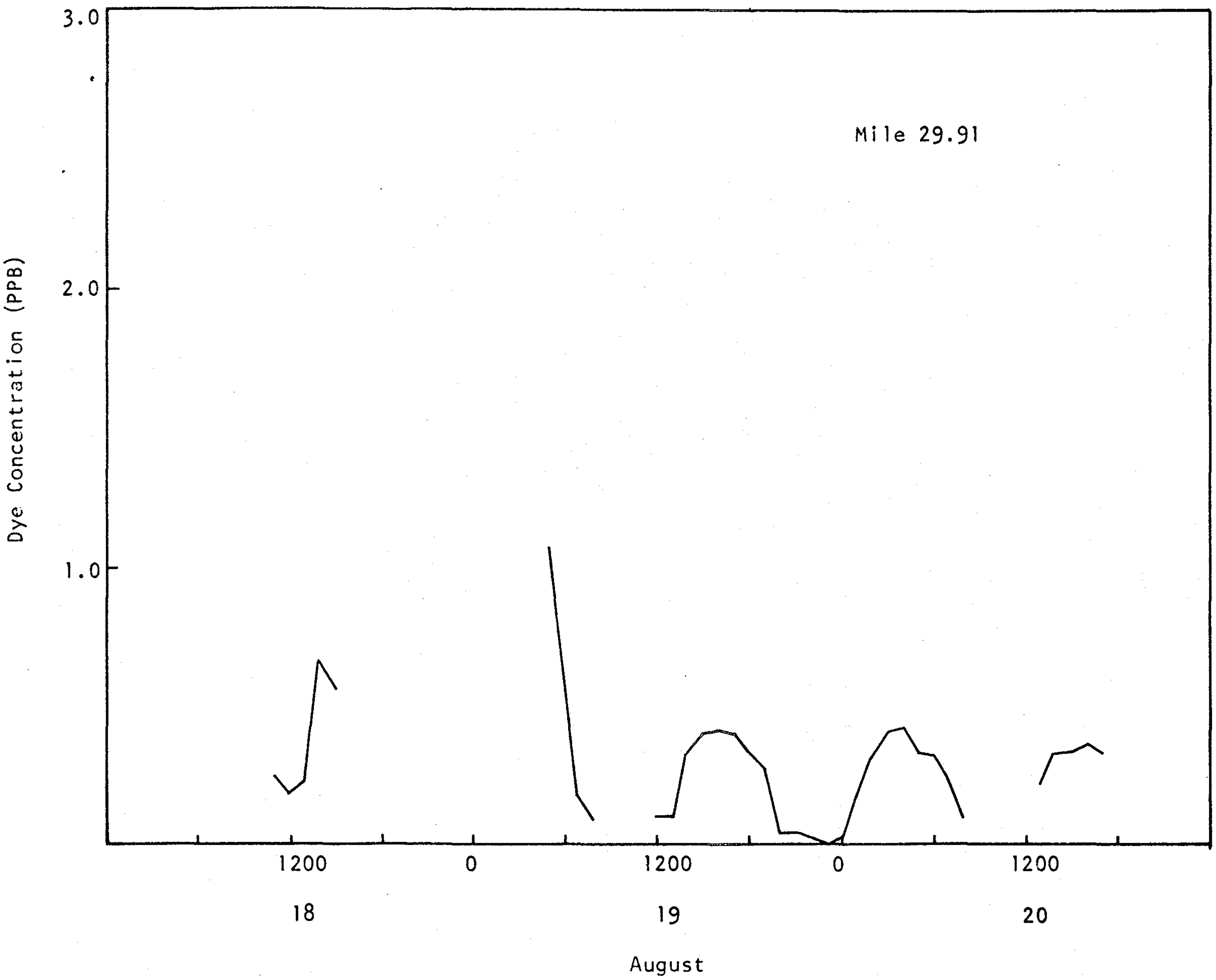

.6
.5
.4
.3
.2
.1
Dye Concentration (PPB)
5
10
15
20
25
30
35
Distance Upstream (miles)
26 August 1973
Slack before ebb

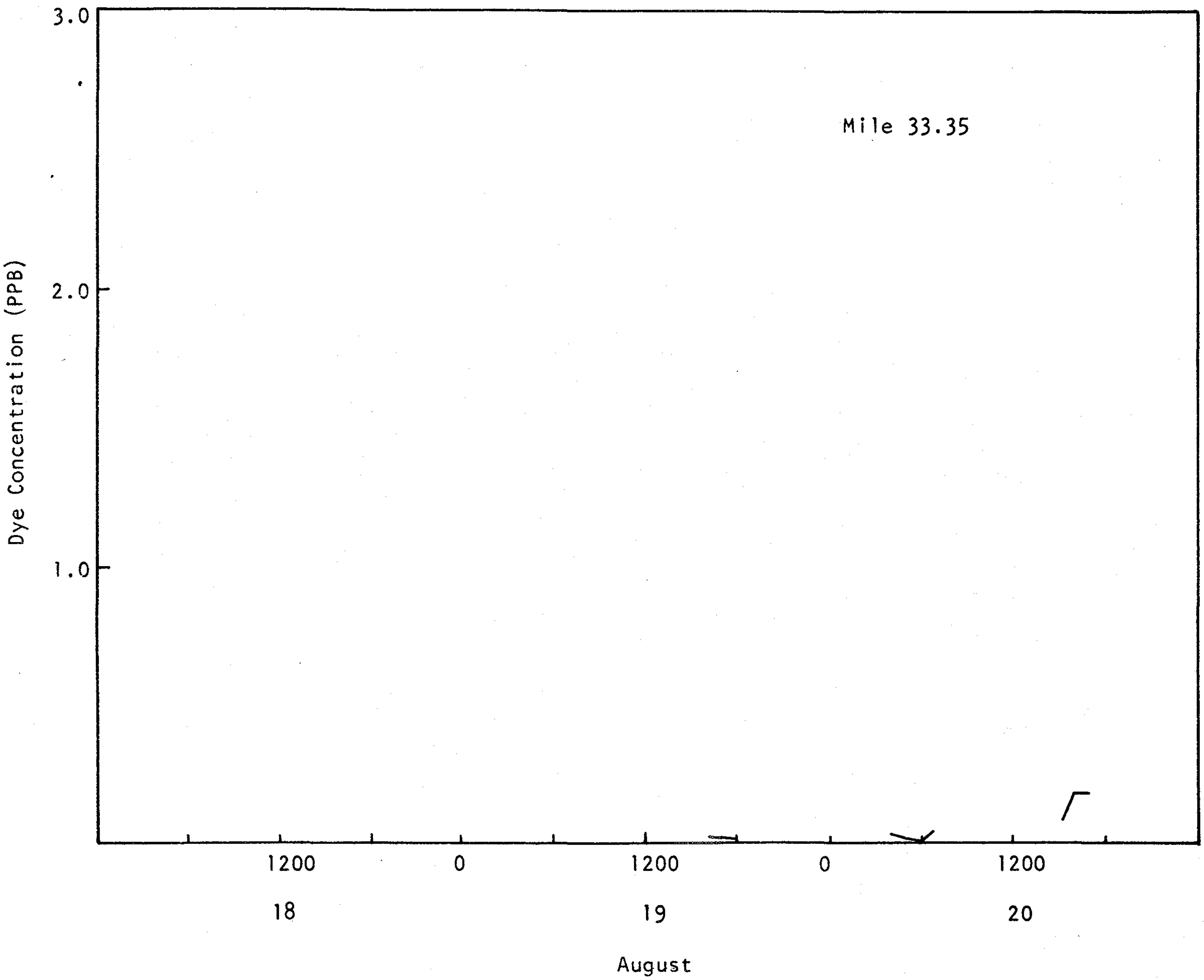

Mile 6.79
Dye Concentration (PPB)
3.0
2.0
1.0
1200
0
1200
0
1200
23
24
25
August

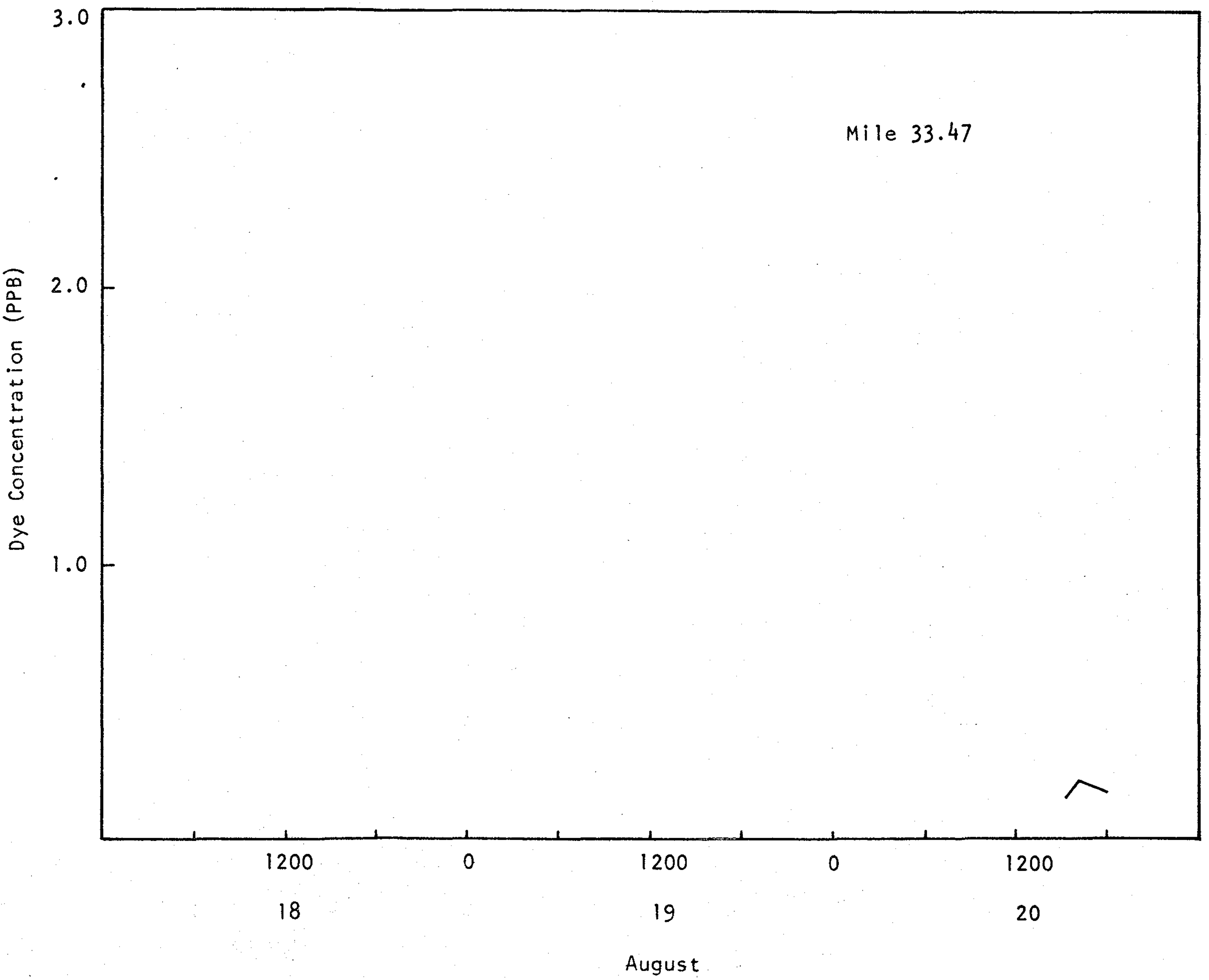

3.0
2.0
1.0
Dye Concentration (PPB)
Mile 14.26
1200
0
1200
0
1200
23
24
25
August


Mile 18.65
Dye Concentration (PPB)
3.0
2.0
1.0
1200
0
1200
0
1200
23
24
25
August


3.0
2.0
1.0
Dye Concentration (PPB)
Mile 22.21
1200
0
1200
0
1200
18
19
20
August


Mile 29.91
3.0
2.0
1.0
Dye Concentration (PPB)
1200
0
1200
0
1200
18
19
20
August

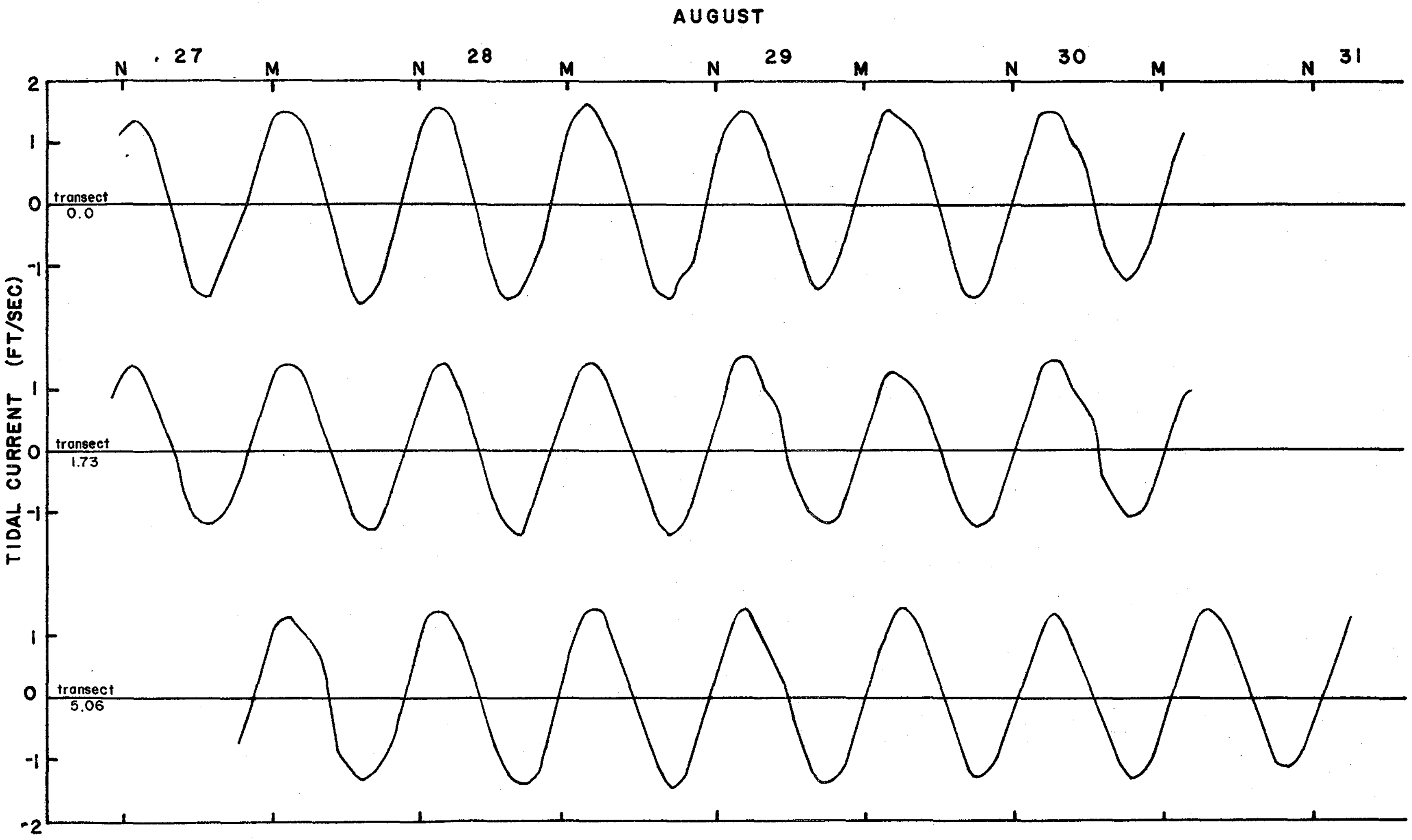

3.0
2.0
1.0
Dye Concentration (PPB)
Mile 33.35
1200
0
1200
0
1200
18
19
20
August

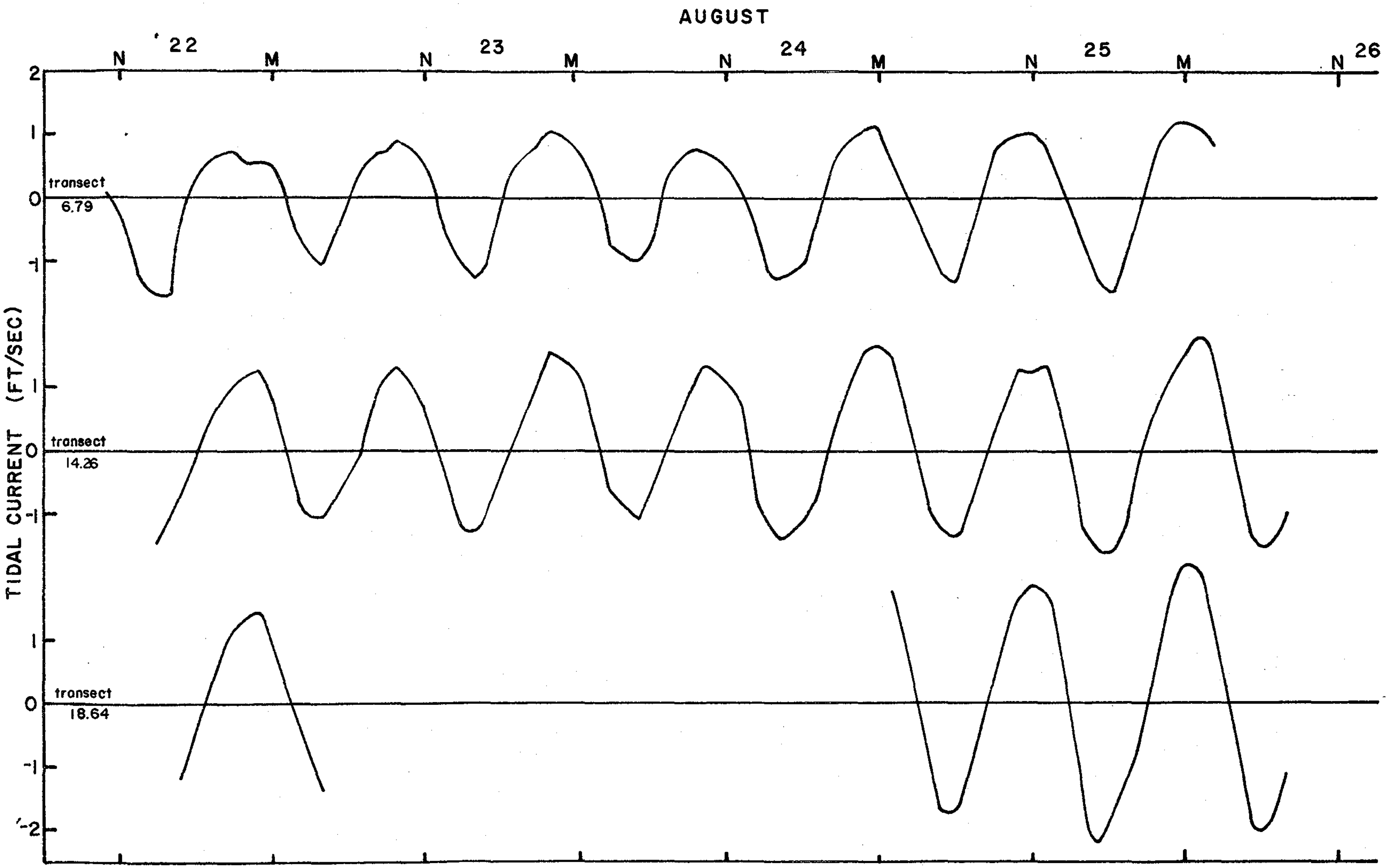

Mile 33.47
Dye Concentration (PPB)
3.0
2.0
1.0
1200
0
1200
0
1200
18
19
20
August

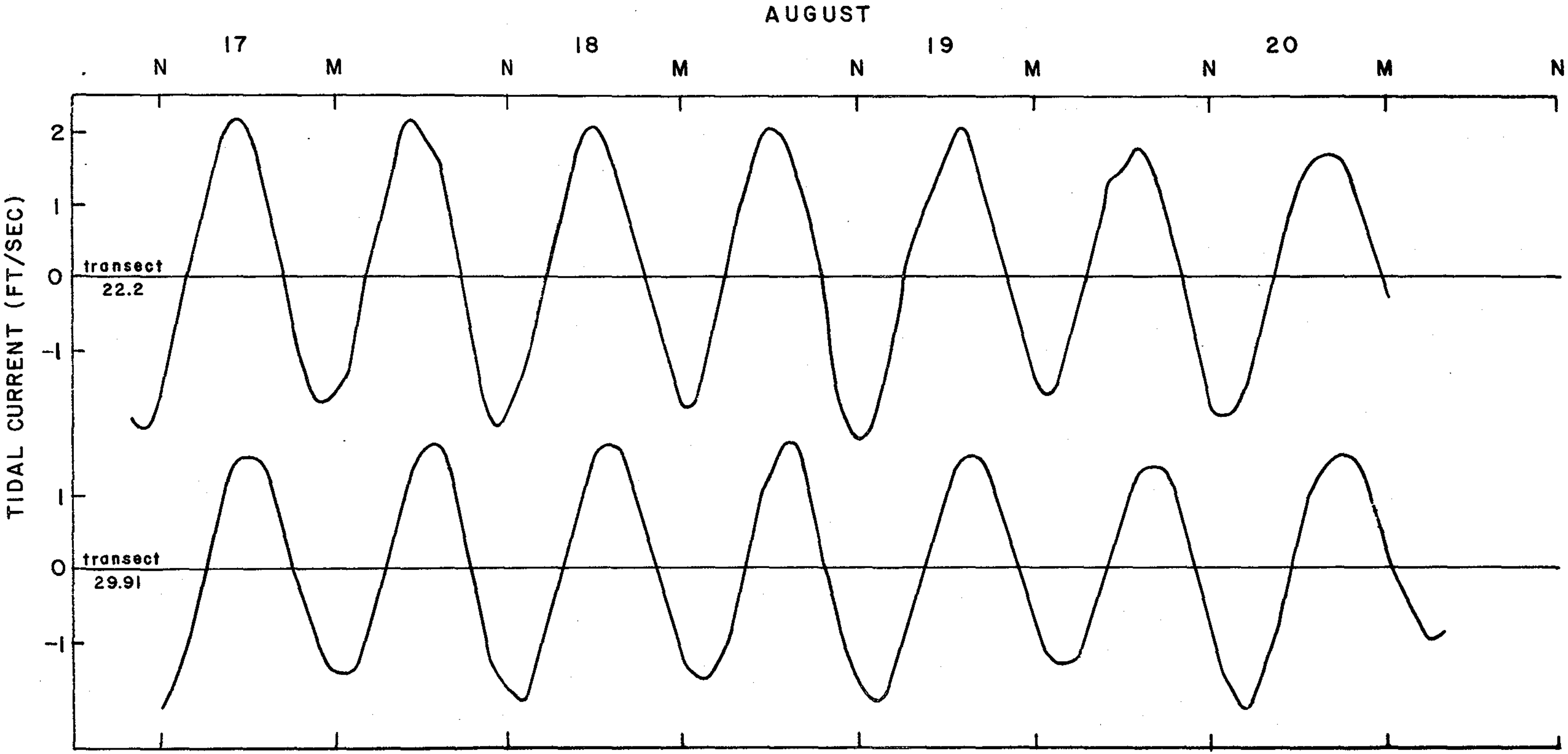
Appendix D

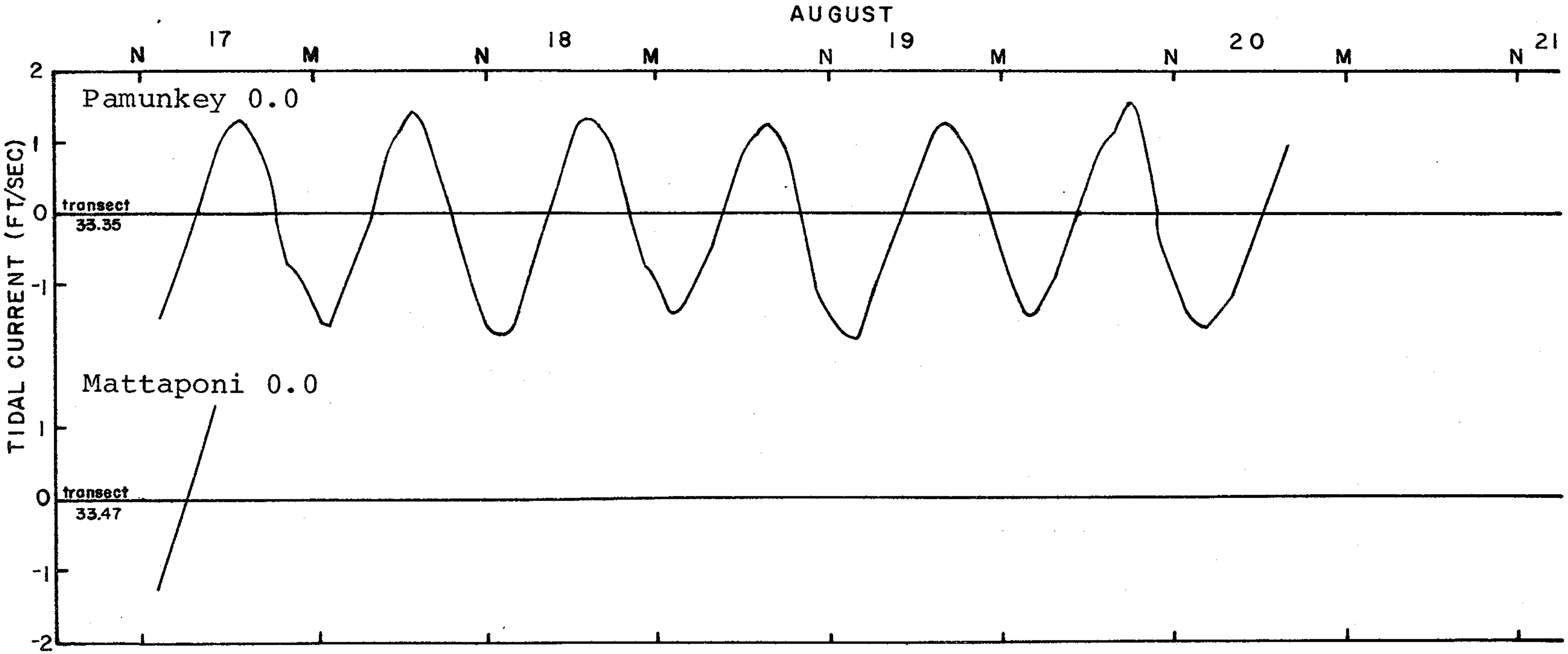
Graphical Summary of Observed Tidal Currents

August 1973


AUGUST
N
27
M
N
28
M
N
29
M
N
30
M
N
31
2
1
0
-1
1
0
-1
1
0
-1
-2
TIDAL CURRENT (FT/SEC)
transect 0.0
transect 1.73
transect 5.06


AUGUST
N
22
M
N
23
M
N
24
M
N
25
M
N
26
TIDAL CURRENT (FT/SEC)
2
1
0
-1
transect
6.79
1
0
-1
transect
14.26
1
0
-1
-2
transect
18.64

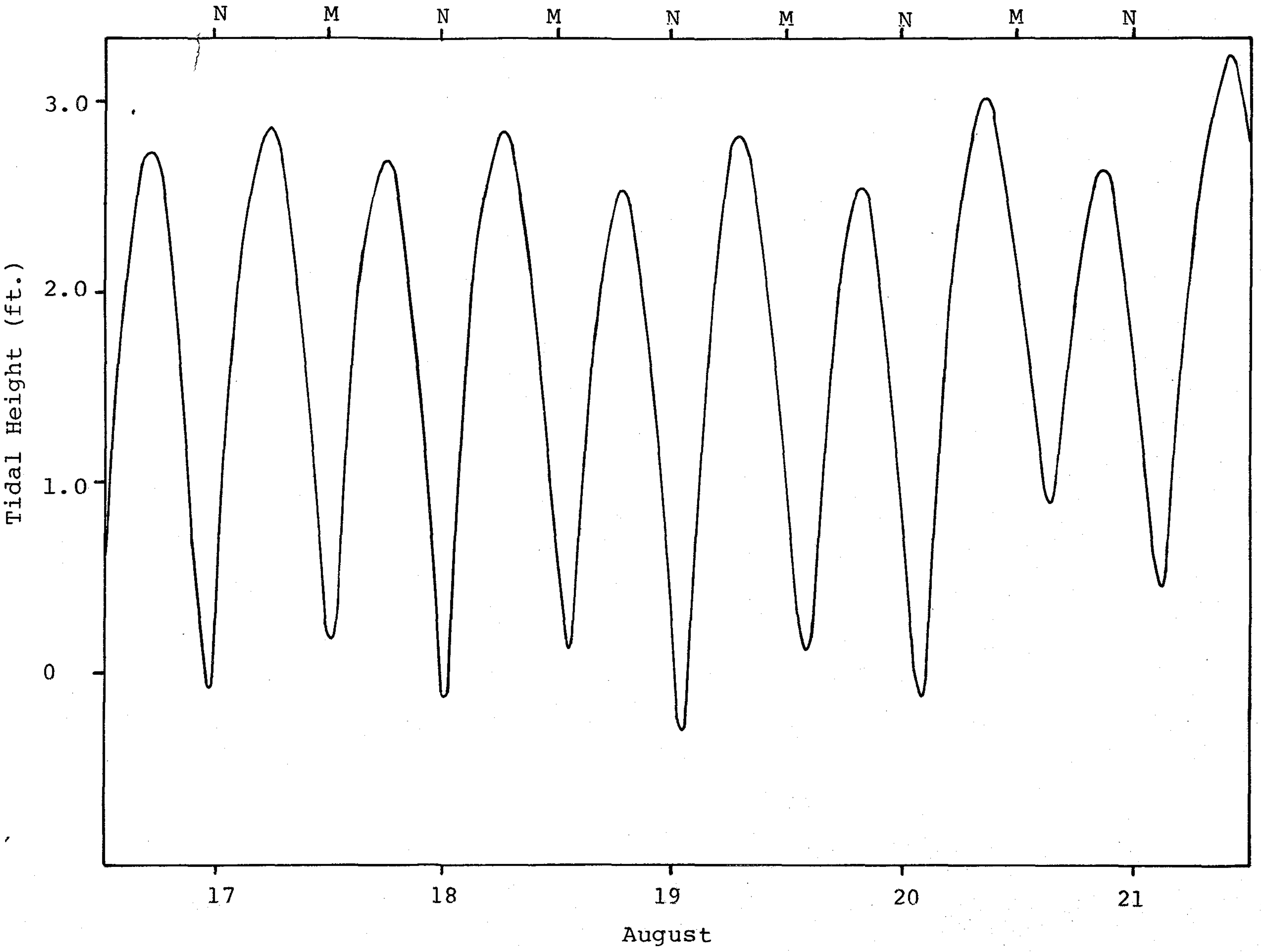

AUGUST
17
18
19
20
N
M
N
M
N
M
N
M
N
TIDAL CURRENT (FT/SEC)
2
1
0
-1
1
0
-1
transect
22.2
transect
29.91

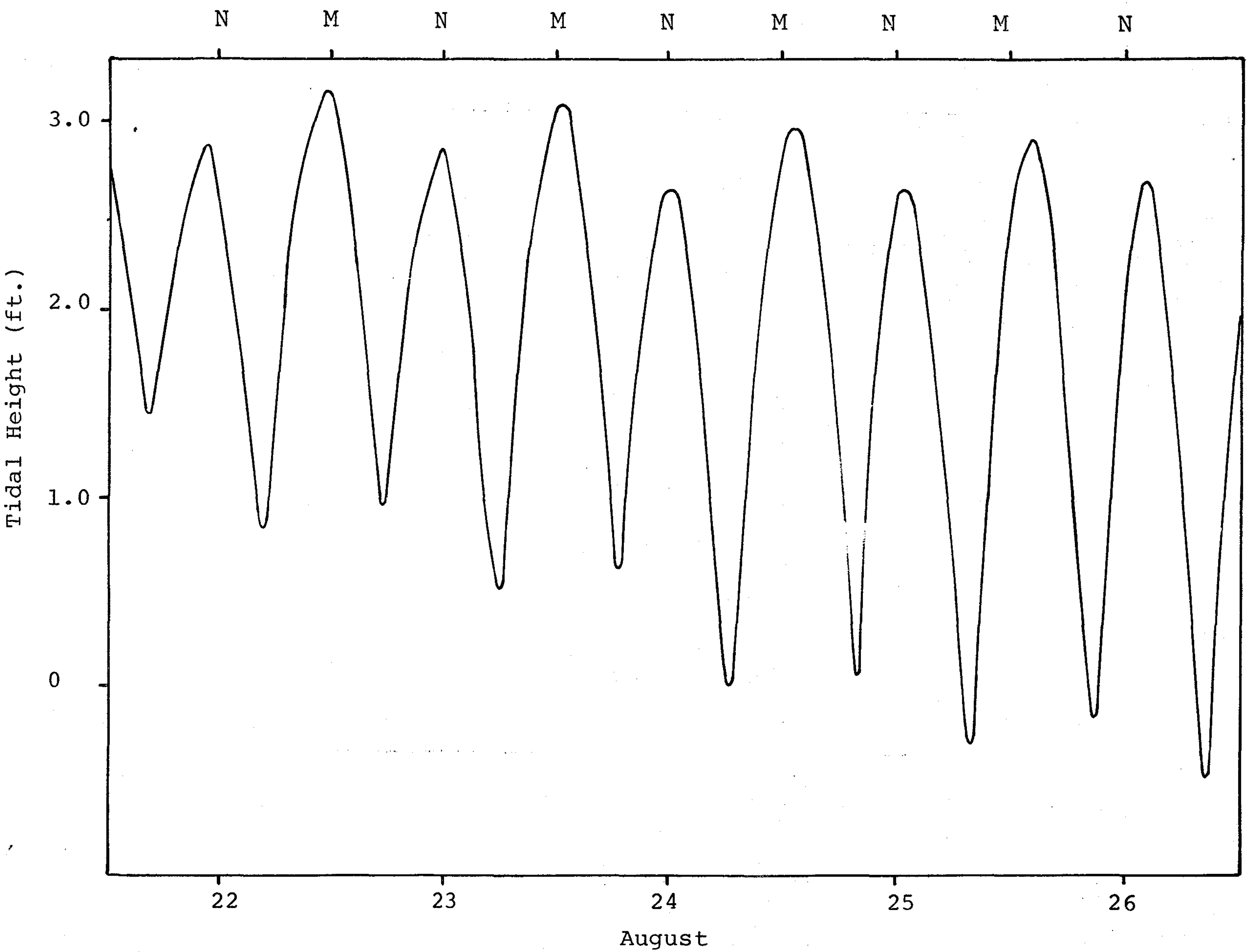

AUGUST
17
18
19
20
21
N
M
N
M
N
M
N
M
N
2
1
0
-1
1
0
-1
-2
TIDAL CURRENT (FT/SEC)
Pamunkey 0.0
transect
33.35
Mattaponi 0.0
transect
33.47

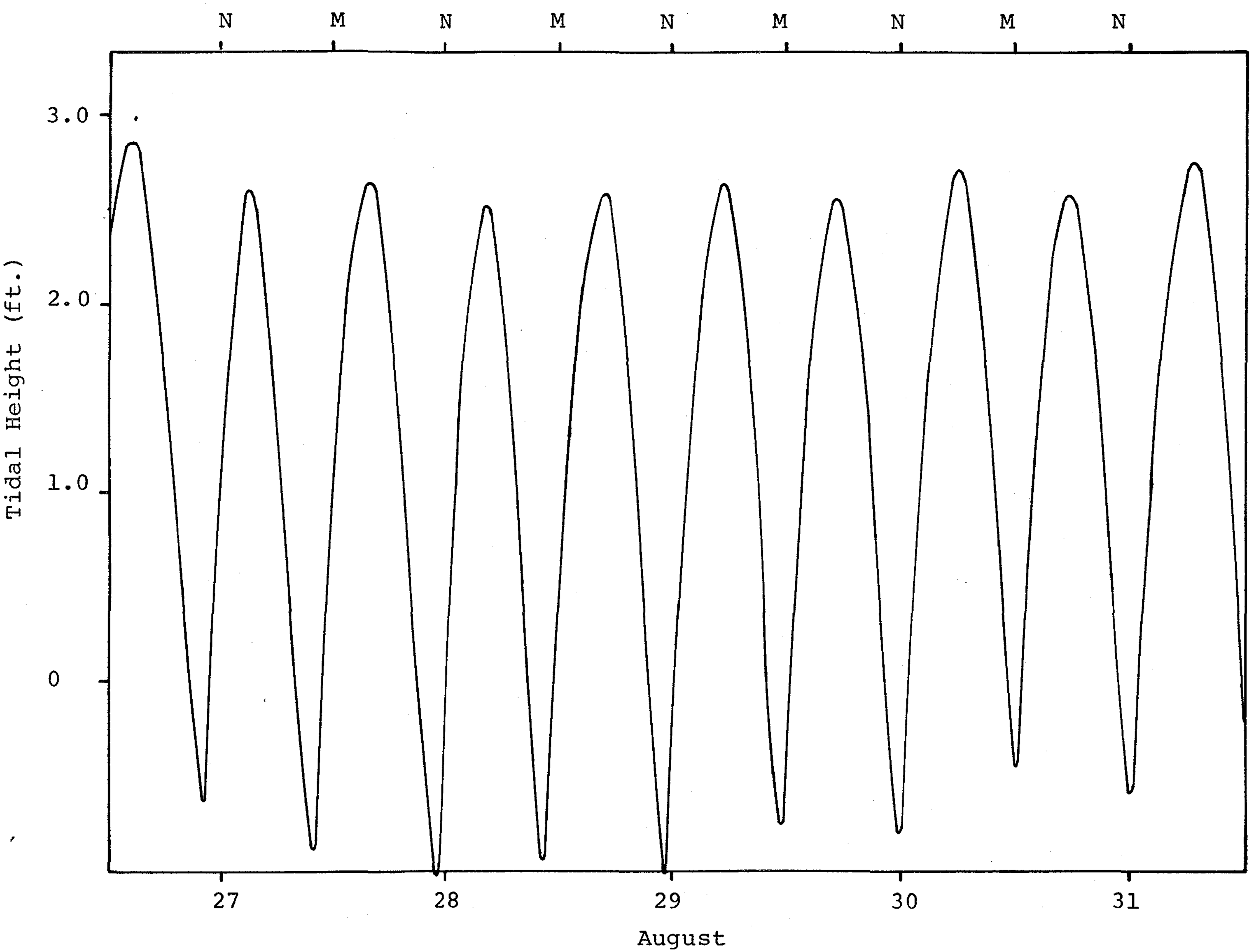
Appendix E

Tidal Height Observations Elsing Green, Va.

August, 1973


N
M
N
M
N
M
N
M
N
3.0
2.0
1.0
0
Tidal Height (ft.)
17
18
19
20
21
August


N
M
N
M
N
M
N
M
N
3.0
2.0
1.0
0
Tidal Height (ft.)
22
23
24
25
26
August


N
M
N
M
N
M
N
M
N
3.0
2.0
1.0
0
Tidal Height (ft.)
27
28
29
30
31
August