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Hydrography and Hydrodynamics of Virginia Estuaries XIV: Mathematical Model Studies of Water Quality of the Chickahominy Estuary

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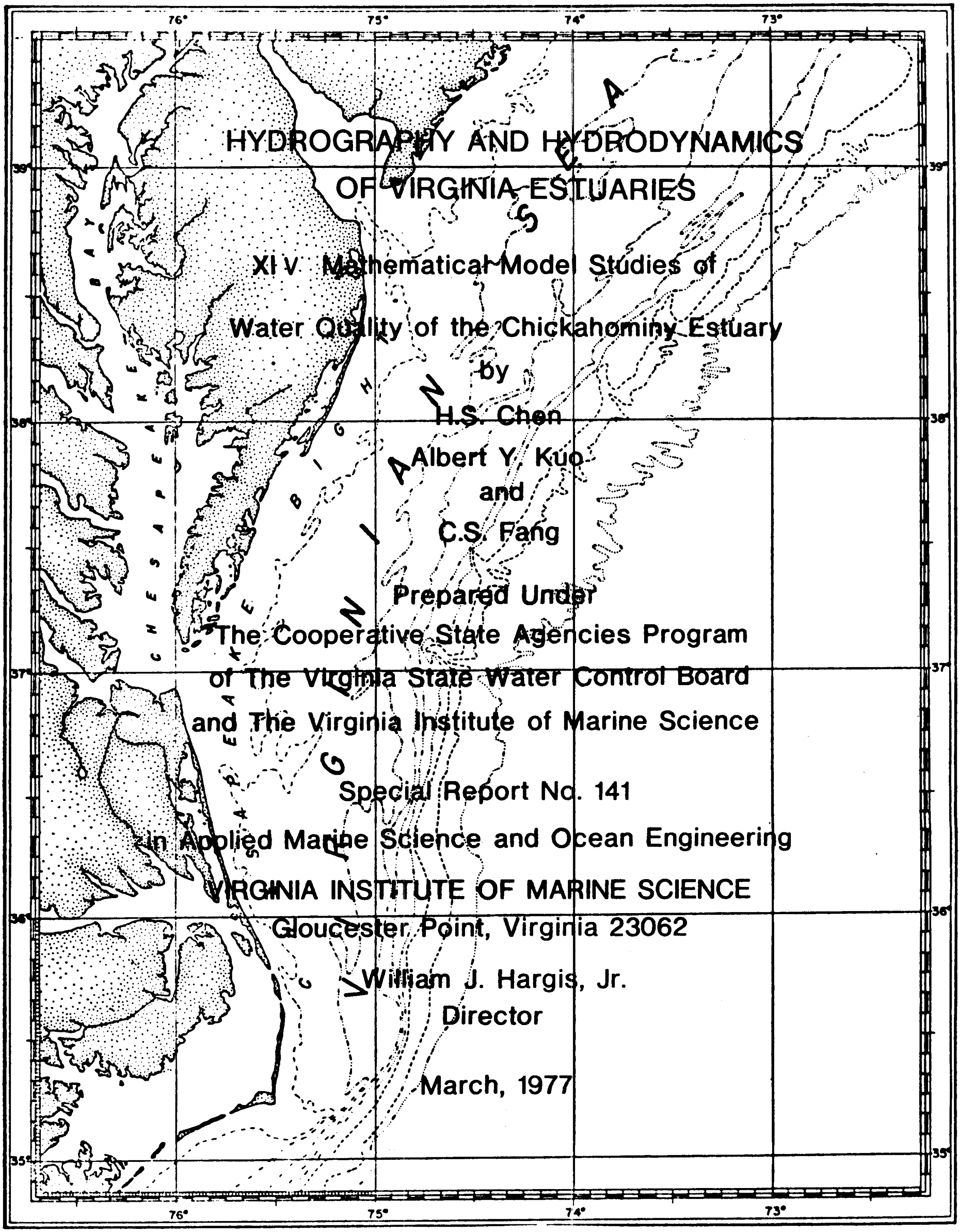

HYDROGRAPHY AND HYDRODYNAMICS OF VIRGINIA ESTUARIES

XIV. Mathematical Model Studies of Water Quality of the Chickahominy Estuary

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

Special Report No. 141
in Applied Marine Science and Ocean Engineering

VIRGINIA INSTITUTE OF MARINE SCIENCE
Gloucester Point, Virginia 23062

William J. Hargis, Jr.
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ABSTRACT

This report summarizes the water quality and the hydrographical data of the Chickahominy estuary obtained from the intensive field survey in June and July, 1975. A field dye study was also summarized. The sampled water quality includes temperature, conductivity, salinity, DO, BOD and TKN. A mathematical water quality numerical model study was also conducted. The numerical model developed by Kuo (1975) was employed for this study area. The model simulates the distribution of dye, CBOD, NBOD and DO.

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1. SUMMARY AND CONCLUSIONS

(1) The Chickahominy River (Figs. 2.1 and 2.2) serves a water supply for the lower peninsula. Water is drawn from the Chickahominy Lake at Walkers Dam which is a tidal dam, primarily serving as a salt water barrier. The upper reaches of the Chickahominy are heavily urbanized with the bulk of major waste discharges. In the lower reaches, downstream from Bottoms Bridge, there is no known major waste discharges other than those from campgrounds. The Chickahominy also provides a good area for fishing and recreation. The climate of the Chickahominy basin is classified as humid and subtropical.

(2) In June and July 1975, an intensive field survey was conducted in the Chickahominy estuary, namely downstream from Walkers Dam (Figs. 2.3 and 3.1). Two tide gages were installed for 9 days. The recorded tide ranges are approximately 2 ft. (0.61 m) at Chickahominy Bridge and 3 ft. (0.91 m) near Walkers Dam. Six sets of current meters were deployed at 6 anchor stations to measure current speed and direction at several depths for 4 days. The current data indicated that the current decreased toward upstream and a local maximum current speed was observed 2.4 fps (0.65 m/sec) at the river mouth. Time series data of salinity, dissolved oxygen (DO) and temperature were sampled at several depths at anchor stations for 2 successive days. Four slack water surveys were made, collecting data on salinity, temperature, DO biochemical oxygen demand (BOD) and total Kjehldahl nitrogen (TKN). A field dye study was conducted starting on June 25, 1975 and over the next 23 days monitored by 12 slack water runs.

(3) The yearly average runoff near Providence Forge is about 14 inches (35.6 cm). The flushing and the dispersion of wastes are dominated by both freshwater discharge and tidal motion.

(4) The field data indicated that the salinity is less than 0.22 ppt in the entire estuary, making it a freshwater river.

The temporal average of CBOD and NBOD in general decreased gradually from 1.9 and 4.6 mg/ℓ respectively near Walkers Dam to 1.5 and 2.3 mg/ℓ at the river mouth, with the CBOD being 0.8 mg/ℓ at 5 miles (8.04 km) from the river mouth. The depth variations of CBOD and NBOD are significant. The difference between surface and bottom may reach as high as 2.5 for the CBOD and 1.5 mg/ℓ for the NBOD.

The DO data show a discernible temporal variation with respect to solar radiation and tidal motion. The temporal average DO was smoothly distributed along the estuary and was between 4.5 and 6.1 mg/ℓ. The depth distributions of DO illustrate little difference, except at the station near Walkers Dam where the surface DO was all above 4.5 mg/ℓ compared to an average value of approximately 6.0 mg/ℓ and the bottom DO might fall below 3 mg/ℓ. The surface DO in entire estuary was only 75% saturated with an approximately temporal average of 6 mg/ℓ.

(5) A water quality mathematical model in the Chickahominy estuary was constructed and calibrated. It is a real time model, including tidal motion, with time-integration carried out by an implicit scheme. The simulated variables include salinity (or dye), dissolved oxygen, and both nitrogenous and carbonaceous biochemical oxygen demand.

(6) The following coefficients were the simulated results from calibration: the Manning friction coefficient was 0.03. The weighting factor for advection were 0.5 for dye (or salinity) and 0.7 for others. The dispersion coefficient increases with the freshwater discharge. The decay rates were 0.1 for the CBOD and 0.05 1/day for the NBOD. The non-point sources for CBOD and NBOD and the photosynthesis-respiration DO and the bottom demand of DO were significant as compared to point sources.

2. INTRODUCTION

2.1 General Description of the Chickahominy Basin

The Chickahominy (see Figs. 2.1 and 2.2) is a meandering swampy river. It flows southeastward from its headwaters in western Henrico and Hanover counties some 70 river miles (113 km) to the James River, droping from an elevation of approximately 280 ft. (85 m) at its headwaters to sea level at its mouth. It is one of the major tributaries of the James River. This slow moving Chickahominy, with the main channel forming the boundary between Henrico-Hanover, Henrico-New Kent, Charles City-New Kent, and Charles City-James City counties, provides most of the raw water for the lower peninsula and delights sportsman with fishing and recreational opportunities. The river drains about 450 mi^2 (1165 km^2) of the James River basin. It drains large portions of Henrico, New Kent, Hanover, James City and Charles City counties and Richmond city.

Climatologically, the basin is humid-subtropical with some maritime influence. The annual mean temperature is 57°F (14°C) and the annual mean precipitation 43 inches (109 cm). Tables 2.1 and 2.2 illustrate the typical monthly mean temperatures and precipitation. Precipitation occurs in the form of frontal storms during most of the year but as thunderstorms in the summer. Additionally, tropical storms sometime strike the area. Snowfall averages 10 inches (25 cm) per year, but some years have seen much less than this amount. Near Providence Forge, the yearly average runoff is approximately 14 inches (36 cm), with the minimum daily flow being 1.53 cfs (0.04 m^3/s) on September 13, 1965 and the maximum flood peak discharge 7,710 cfs (218 m^3/s) on August 15, 1955, compared to the peak discharge of 2,820 cfs (80 m^3/s) during the Hurricane Agnes event, 1972.

The population in the area is over half a million and is still increasing as shown for example in Table 2.3. More than half of the basin is incorporated into agricultural and vacant use for cropland, pastureland, woodland and forestland. A detailed summary of land use is given in Tables 2.4a&b.

The upper reaches of the Chickahominy are heavily urbanized and are expected to be extensively developed in the near future. Table 2.5 shows the principal points of waste discharge. It is apparent that the major waste discharge and the principal urban areas are located upstream from Route 360 (Mechanicsville Turnpike) Bridge and the remainder are located nearly all upstream from Route 60 Bridge (Bottoms Bridge) (see Fig. 2.2).

2.2 The Chickahominy Estuary and the Intensive Field Survey

The Chickahominy serves a water supply for the lower peninsula. From the Chickahominy Lake at Walkers Dam water is pumped and drawn to the Newport News water system by the Walkers Dam pump station, which is recently expanded from 18 mgd (68,000 m^3/day) capacity to 40 mgd (151,000 m^3/day) to meet increasing water demand. Walkers Dam, located about 20 river miles (32 km) from the river mouth, is a tidal dam built by the Army during World War II to serve as a salt water barrier to prevent upstream intrusion of salt water. Its structure includes a fish ladder. The Chickahominy River downstream from Walkers Dam is subject to the effect of tidal motion and is referred to the Chickahominy estuary (see Fig. 2.3). Ecologically, the Chickahominy estuary is an ideal wildlife habitat, supporting a wide spectrum of recreational activities, such as fishing, boating, picnicing, hunting, and camping. The aquatic population, shellfish, finfish, and waterfowl, is abundant and diverse. Finfish include large-mouth bass, pickerel, catfish, sunfish, carp, spot, croaker and rock. Waterfowl are brant, coots, ducks, geese among others. The Chickahominy estuary is also a habitat for spawning anadromous fish species.

There is no known point source of waste downstream from Walkers Dam other than three campgrounds: Holiday Inn Trav-L Park at Chickahominy Bridge, Ed Allen's campground and Chickahominy Outpost campground near Walkers Dam which have 332, 200 and 200 campsites respectively and all use spetic systems. These waste sources are comparably small and were ignored in the model simulation.

An intensive field survey of water quality and hydrographic survey were conducted in June and July 1975. Salinity, temperature, dissolved oxygen (DO) and water conductivity were sampled at 6 anchor stations and for 4 slack water runs. In addition, biochemical oxygen demand (BOD) was determined and total Kjehldahl nitrogen (TKN) was also sampled for the 4 slack water runs. A field dye study was conducted over a period of more than 40 tidal cycles. The bathymetric profiles of the river transects at 16 locations were sounded. Two tide gages, one at Chickahominy Bridge and the other near Walkers Dam, were deployed for measuring tide stage. Six sets of current meters at the 6 anchor stations were also deployed for measuring current speed and direction at several depths.

This report summarizes the observational field work utilized in construction and calibration of the model, as well as the simulated results of the model. The mathematic water quality numerical model employed is a one-dimensional, real-time model with parameters including salinity (or dye), dissolved oxygen, and carbonaceous and nitrogenous biochemical oxygen demand.

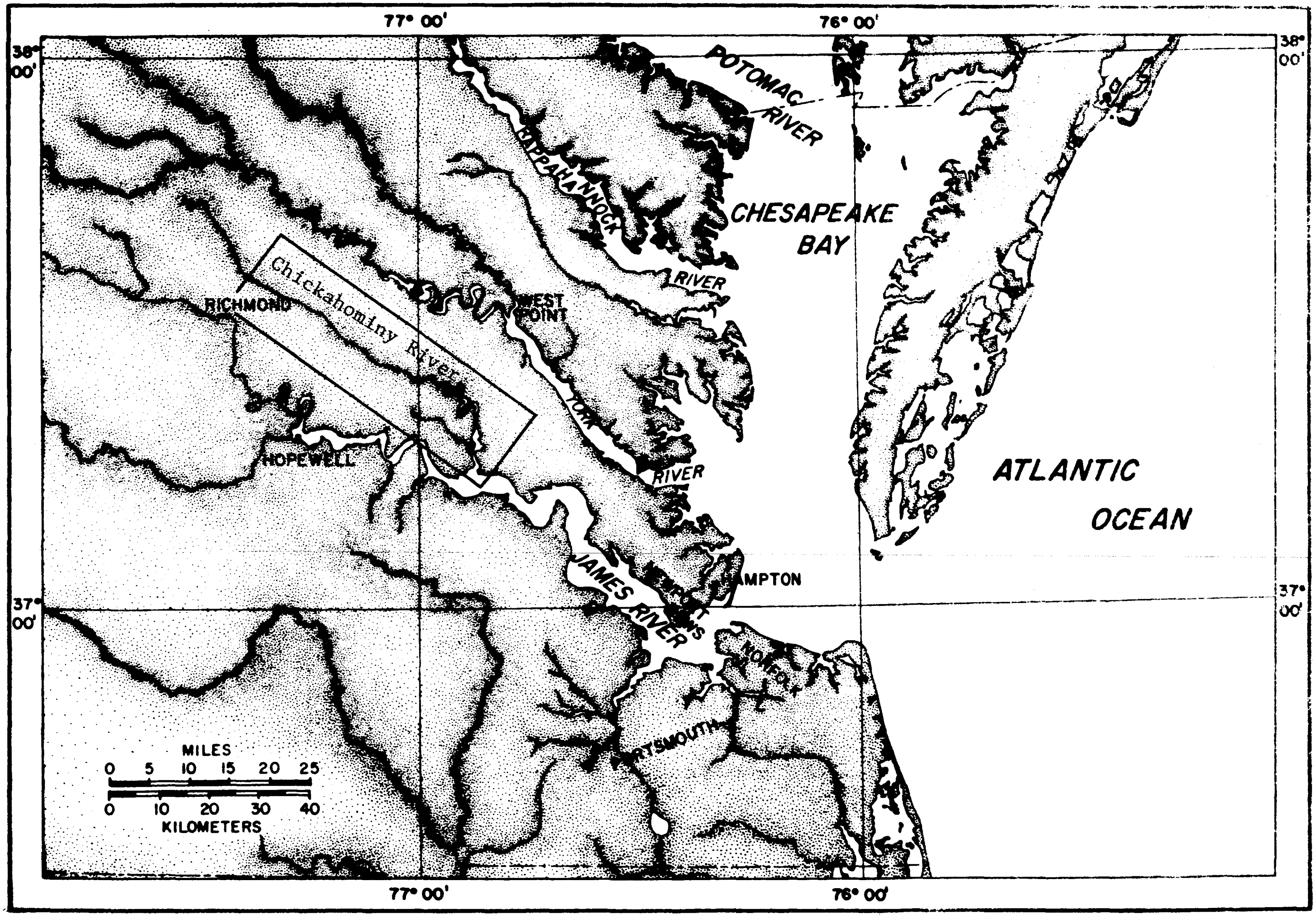

Figure 2.1. The location of the Chickahominy River.

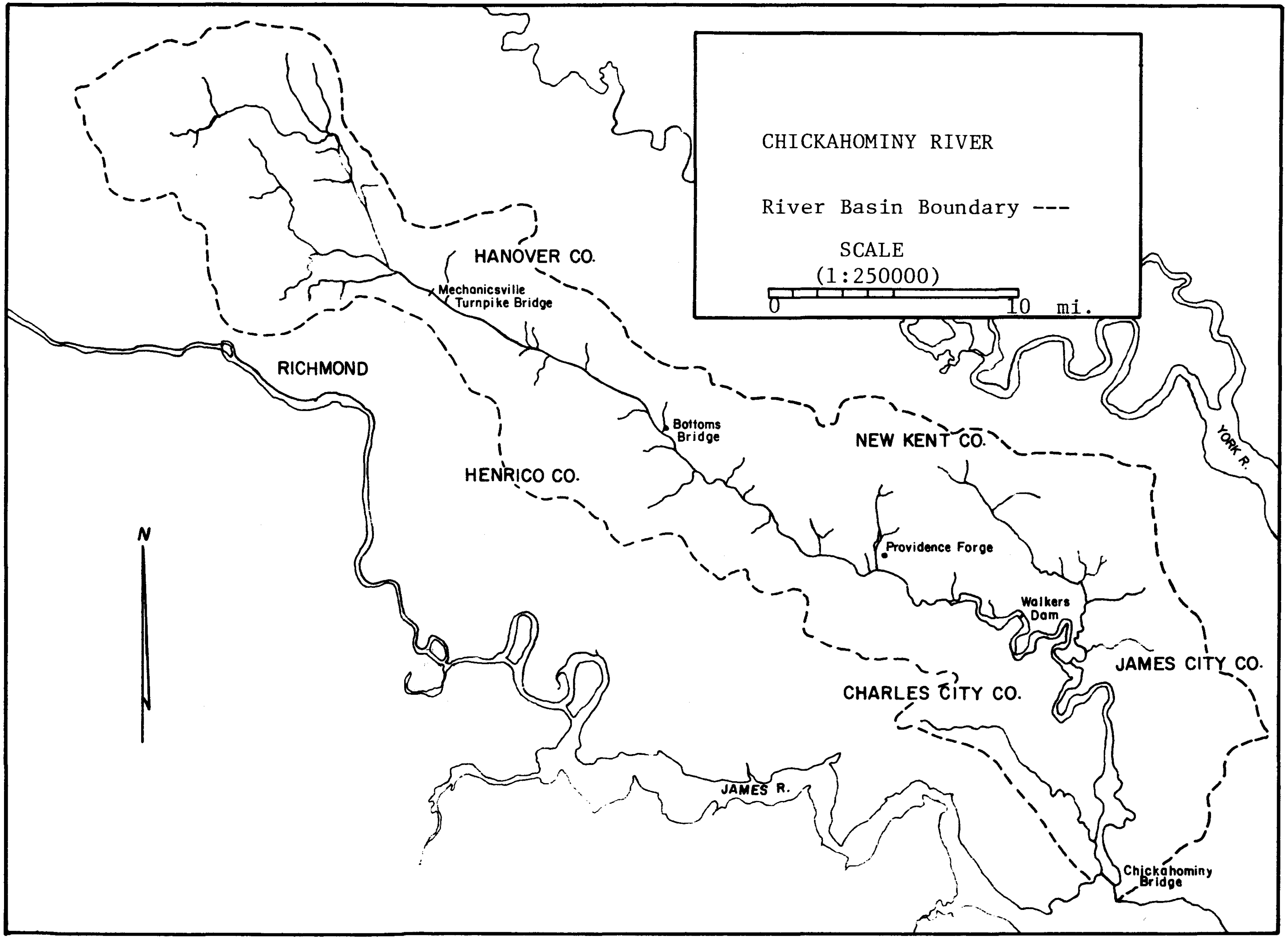

Figure 2.2. The Chickahominy and its basin.

Table 2.1 Monthly Mean Temperature ^oF (1931-1970) in the Chickahominy Basin. $^oC = \frac{5}{9}(^oF - 32)$

	Ashland	Columbia	Richmond	West Point	Williamsburg 2N
Jan	36.2	37.4	38.7	36.7	40.2
Feb	38.4	38.2	40.1	39.2	41.0
Mar	46.0	46.2	46.6	47.7	48.6
Apr	56.1	55.8	57.0	58.4	57.4
May	64.9	65.4	66.4	66.5	57.4
Jun	72.1	72.8	74.4	73.5	73.5
Jul	76.0	76.6	77.9	77.6	77.3
Aug	75.0	75.1	76.2	76.6	76.0
Sep	68.4	69.0	70.2	70.0	70.4
Oct	57.4	57.8	58.9	59.3	60.0
Nov	47.5	46.9	48.4	49.6	49.8
Dec	37.7	38.0	39.5	39.2	41.3
Annual	56.3	56.6	59.9	57.9	58.4
High	105	110	104	105	104
Low	-7	-15	-12	-3	-3
Years of Record	20	58	31	15	72

Data from Engineering Science Co. (1974)

Table 2.2 Monthly Mean Precipitation in inch (1931-1970) in the Chickahominy Basin. 1 inch = 2.54 cm

	Ashland 1 SW	Columbia	Richmond WB Airport	State Farm	West Point 2 SW
Jan	2.85	3.32	2.96	3.00	2.95
Feb	2.79	2.74	2.87	2.77	3.58
Mar	3.20	3.51	3.28	3.66	3.59
Apr	2.89	3.52	3.13	3.36	2.83
May	3.39	3.63	3.64	3.96	3.93
Jun	3.44	3.66	3.78	3.80	4.06
Jul	3.97	4.40	6.04	5.01	5.33
Aug	4.31	4.47	5.60	4.95	5.59
Sep	3.35	3.39	3.70	3.84	3.03
Oct	3.22	2.91	3.21	3.30	3.15
Nov	3.10	2.51	3.28	3.13	3.15
Dec	3.13	3.06	2.89	3.17	3.29
Annual	39.64	41.12	44.38	44.15	44.48
Years of Record	20	63	24	23	15

Data from Engineering Science Co. (1974)

Table 2.3 POPULATION IN THE CHICKAHOMINY BASIN, 1940 TO 1970

County or City	YEAR 1940	1950	1960	1970	Percentage Increase 1960-1970
Charles City County	4,275	4,676	5,492	6,158	12
Hanover County	18,500	21,985	27,550	37,479	36
Henrico County	41,960	57,340	117,339	154,364	32
New Kent County	4,092	5,556	4,504	5,300	18
Richmond	193,042	230,310	219,958	249,621	13
James City County	4,907	6,317	11,539	17,853	55
Williamsburg	3,982	6,735	6,832	9,069	33
TOTAL	270,758	332,919	393,214	479,844	22

Data from Engineering-Science Co. (1974)

Table 2.4a. Land Use in the Chickahominy Basin.

Use	Richmond	Henrico	Charles City	New Kent (Acres)	Hanover	Williamsburg	James City	Total Acres	Total Percent
Residential	18,700	19,981	1,460	1,836	8,038	461	1,616	52,092	6.0
Commercial	1,700	1,942	40	86	684	187	141	4,780	0.5
Industrial	6,000	12,371	55	635	2,239	88	368	21,756	2.5
Park & Rec.	1,700	740	183	540	327	839	5,497	9,826	1.1
Institut.	10,300	5,164	104	216	5,871	120	2,393	24,168	2.8
Tot. Develop.	38,400	40,198	1,842	3,313	17,159	1,695	10,015	112,622	12.9
Ag. & Vac.	--	112,172	115,918	132,367	282,625	1,558	86,512	731,152	84.0
Tot. Land	38,400	152,370	117,760	135,680	299,784	3,253	96,527	843,774	97.0
Water	1,920	4,118	12,800	3,840	3,200	19	500	26,397	3.0
Total	40,320	156,488	130,560	139,520	302,984	3,272	97,027	870,171	100.0

1 acre = 0.004 km^2

Data from Engineering-Science Co. (1974)

Table 2.4b. Future Land Use in the Chickahominy Basin

Use	Richmond	Henrico	Charles City	New Kent (Acres)	Hanover	Williamsburg	James City	Total Acres	Total Percent
Residential	20,267	-	41,028	8,034	52,230	888	5,570	128,017	14.7
Commercial	2,661	-	-	436	3,550	334	238	7,219	0.8
Industrial	9,293	-	13,717	2,080	4,640	83	400	30,213	3.5
Park & Rec.	-	-	-	726	-	1,203	5,383	7,312	0.8
Institution	6,169	-	-	2,802	43,440	201	4,452	57,074	6.6
Total Develop.	38,400	-	54,745	14,078	103,860	2,709	16,043	229,835	26.5
Ag. & Vac.	-	-	63,015	121,602	195,924	548	80,483	461,572	53.0
Total Land	38,400	152,370	117,760	135,680	299,784	3,257	96,526	843,777	97.0
Total Water	1,920	4,118	12,800	3,840	3,200	19	500	26,397	3.0
Total Area	40,320	156,488	130,560	139,520	302,984	3,276	97,026	870,174	100.0

1 acre = 0.004 km^2

Data from Engineering-Science Co. (1974)

Table 2.5 Municipal Wastewater Loadings (1971) In The Chickahominy River. 1 lb = 0.454 kg, 1 MGD = 1.547 cfs = 0.0438 m^3/s

(Data from Engineering Science Co. 1971)

		West End Manor	Glennwood Farms	Sanitary District # 3 (Highland Springs)	Sanitary District # 2 (Sandston)	Byrd Airport
Ownership		West End Manor	Henrico County	Henrico County	Henrico County	City of Richmond
Service Area			Glennwood Farms Area of Henrico County	Highland Springs Area of Henrico County	Sandston Area of Henrico County	Byrd Airport Area
Population served		2,665	3,090	2,395	4,730	2,300
Average Daily Flow (MGD)		0.23	0.31	0.24	0.47	0.23
BOD (lbs/day)	Infl	1,940	430	516	860	58
	Effl	103	86	103	172	33
Total Suspended Solids (lbs/day)	Infl	750	625	750	1,250	107
	Effl	300	250	300	500	71
Ammonia Nitrogen (lbs/day)	Infl	75	63	75	125	58
	Effl	60	50	60	100	46
Ortho-Phosphate (lbs/day)	Infl	25	21	25	42	19
	Effl	20	17	20	33	12

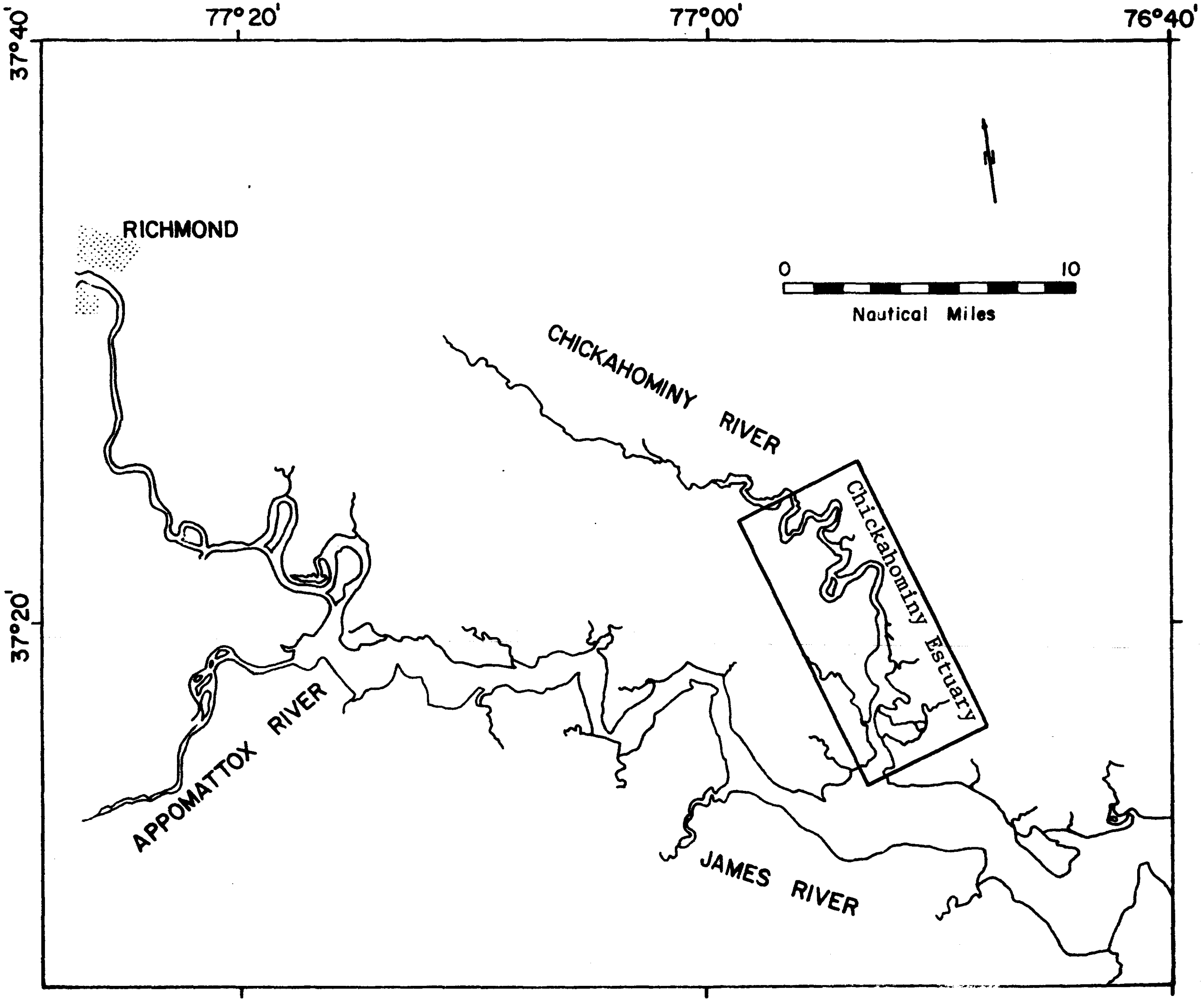

Figure 2.3. The Chickahominy estuary (1 n.m. = 1.852 km).

3. WATER QUALITY AND HYDROGRAPHIC SURVEY

3.1 Field Survey

In June and July 1975 an intensive field hydrographic survey was conducted in the Chickahominy estuary, including 6 anchor stations and 4 slack water runs. The 6 anchor stations for sampling are shown in Fig. 3.1 and Table 3.1.

On June 12 through 20, 1975, two tide gages were deployed at Chickahominy Bridge and Walkers Dam respectively. The recorded tidal ranges were approximately 2 ft. (0.61 m) at Chickahominy Bridge and 3 ft. (0.91 m) at Walkers Dam. On June 17 through 20, 1975 six sets of current meters were deployed at the 6 anchor stations to measure current speed and direction at 2 to 4 different depths, depending on the river depth, generally each current meter for every 10 ft. The maximum local current speed decreased gradually from 2.14 fps (0.65 m/s) at the river mouth, station JC1, to 0.54 fps (0.16 m/s) at station JC6 near Walkers Dam. The recorded tide stage and the current data are summarized in Appendix A.

On June 18 through 19, 1975 six current meter stations were anchored with small boats for sampling for a period of nearly 38 hours continuously on two successive days. Salinity, temperature, dissolved oxygen (DO) and water conductivity were sampled hourly. On June 4, 18 and 19, 1975 four slack water runs, three at high water and one at low water, were conducted to sample salinity, temperature, dissolved oxygen, biochemical oxygen demand (BOD), total Kjehldahl nitrogen (TKN) and conductivity. These data are illustrated in Appendix B.

On June 25 through July 18, 1975 a field study of dye was conducted. One and half barrels (47 gallons or 180 liters) of 20% solution Rhodamine WT were released at station JC6 near Walkers Dam at high water slack at 1630 on June 25. Dye concentration was sampled on June 25, 26, 27 and 30 and July 2-3, 8 and 18 at slack waters at 11 to 19 locations along the river where the peak and the distribution of the dye were significant. The background dye concentration, the dye concentration before dye released, was observed about 0.05 ppb in the river. The measured data are summarized and shown in Figs. 4.2 through 4.15.

On June 26, 1975 the bathymetric profiles of 16 transects were sounded to provide geometrical data for the model. The results are presented in Appendix D and interpolated in Table 4.1.

3.2 Instruments and Analysis

Conductivity and temperature were measured using an InterOcean Model 513 CTD instrument. Salinity was calculated from conductivity and temperature according to a regression formula based on laboratory calibration. Temperatures are accurate to $0.1^{\circ}C$; salinity is accurate to 0.1 parts per thousand (ppt). Dye concentration was measured in the laboratory using a modified Turner Associates model 10-000 fluorometer. Dye concentration is accurate to one percent of full scale or 0.05 parts per billion (ppb), whichever is greater.

Dissolved oxygen concentration was determined in the laboratory by means of titration (Winkler method, Azide modification). The accuracy of this method is considered to be 0.1 milligrams per liter. BOD was determined by the samples incubated at $20^{\circ}C$ for 5 or 6 days unseeded, with nitrification - inhibited with Hach Formula 2533, and analyzed for oxygen by the Azide modification of the Winkler titration. TKN was determined by the following procedure: the sample was digested with a solution containing sulfuric acid, potassium sulfate, and mercuric sulfate converting organic nitrogen to ammonium sulfate. The digested sample was steam-distilled into a saturated boric acid solution and titrated with standard hydrochloric acid.

Fischer-Porter Type 1550 punched tape tide gages were used to record tide stage. This tide gauge has a maximum operating range of 50.00 ft. and records level to the nearest 0.01 ft. Type 1381 Histogram current meters manufactured by Braincon Co. was used for current measurement. This Braincon current meter is a graphic photo-recording instrument which measures and records the speed and direction of water currents. Current speed range is 0-5 knots (8.44fps or 2.57 m/s) with accuracy of $\pm$ 3% full scale and current direction range is 0-360^{o} with accuracy of $\pm$ 10^{o}.

3.3 Field Results of Water Quality and Discussion

The sets of salinity data (see Appendix B) show that the salinity was nowhere greater than 0.22 ppt ; hence the Chickahominy estuary is in general a freshwater river, yet subject to tidal effects.

The sets of DO data indicate a discernible temporal variation in response to tidal motion and solar radiation. The depth distributions of DO show little difference, except at station JC6, just downstream from Walkers Dam where the bottom DO occasionally falls below 3 mg/ℓ. This might be caused by the combined effect of the benthic DO demand and the low mixing process due to the weak tidal motion here. The temporal average DO near the surface water was approximately 6 mg/ℓ. This is only 75% of saturated DO. This might speculate that the nitrogen and phosphate were not over enriched and no algal blooms have occurred, as reported by Malcolm Pirnie Engineering, Inc. (1974). The TKN data collected in 4 slack water runs partially support this speculation. Unfortunately, nitrite, nitrate, phosphate and phytoplankton were not sampled during the intensive survey and this speculation needs more study.

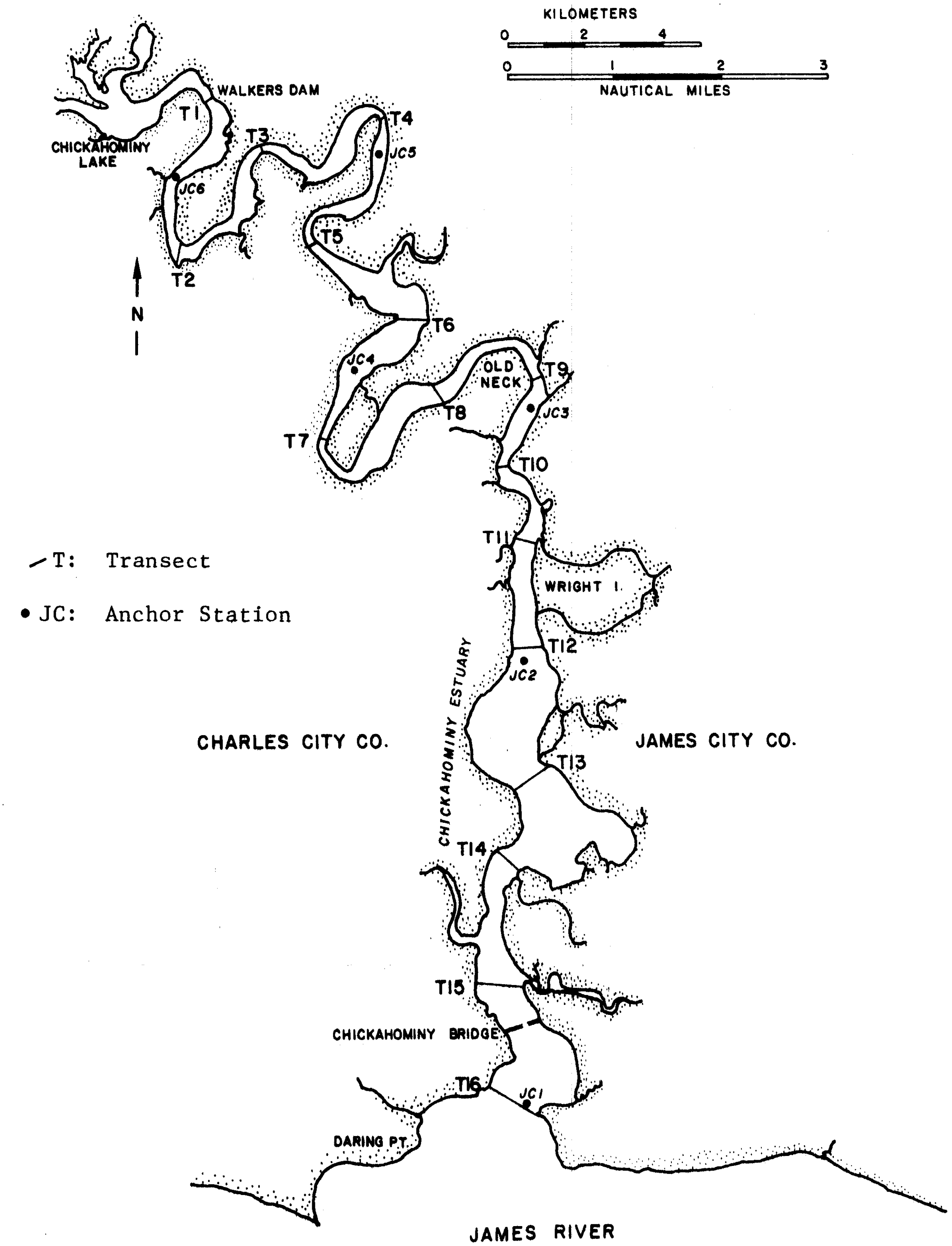

Figure 3.1. Locations of 6 anchor stations and 16 transects.

Table 3.1 Six Anchor Stations In The Chickahominy Estuary During The Intensive Field Survey in June 1975

Station	Location		Distance From River Mouth	
	Latitude	Longitude	mi	km
JC1	37°15'04"	76°52'36"	0.0	0.0
JC2	37°18'56"	76°52'38"	4.72	7.60
JC3	37°21'34"	76°52'29"	7.94	12.78
JC4	37°21'53"	76°54'40"	11.51	18.52
JC5	37°23'55"	76°54'16"	16.11	25.93
JC6	37°23'46"	76°56'37"	20.71	33.33

4. MATHEMATICAL MODEL STUDY

The one-dimensional estuarine water quality model, developed under the CSA program, was employed to simulate the water quality condition in the Chickahominy estuary, meaning the river downstream from Walkers Dam. The model is a numerical model based on the equation describing the mass balance of the dissolved or suspended substances in a water body. It is a real-time, intra-tidal model using the implicit finite difference scheme. For the description of the theory and the numerical scheme of the model, the reader is referred to the work by Kuo, et al. (1975).

4.1 Segmentation of the River

In order to facilitate the numerical computation, the river downstream from Walkers Dam, total 21.5 river miles (34.6 km), was divided into 15 reaches by 16 transects as shown in Fig. 3.1. Notice that the 16 transects in the model were chosen to coincide with those sounded in the field. The length of each reach is obtained by measuring along the navigable course in the USC & GS Map 530 (1970). The geometric parameters of the transects were obtained by calculating the field data of the 16 bathymetric profiles.

The drainage area near Providence Forge is 248 mi^2 (642 km^2) according to Water Resource Data for Virginia, Water Year 1975. The total drainage area and the drainage area of each reach were summarized and interpolated from Seitz (1971).

The amplitude of tidal velocity for each transect was obtained by either interpolating or extrapolating from the field tidal current. Instead of using the field tidal stage data from the intensive survey, which had only 2 tide gauge stations. The tidal phase differences at Chickahominy Bridge, Wright Island Loading, Mount Airy and Lanexa were obtained from Tide Table 1975 by taking the average phase lag of both high water and low water, then either interpolation or extrapolation to find the phase difference for each transect.

The geometric data of the river and the drainage area and the tidal data used in the model computation are shown in Tables 4.1 and 4.2.

4.2 Point Source of Wastes

Other than three campgrounds, one (Holiday Inn Trav-L Park) near the river entrance and two (Chickahominy Outpost Campground and Ed Allen's Campground) near Walkers Dam which use septic systems, there is no known point source of pollutants. These point sources were ignored in the model study, because of their small waste loadings.

4.3 Calibrations and Results

4.3.1 Dispersion Coefficient

Salinity field data was usually employed to calibrate the dispersion coefficient. However, the Chickahominy estuary is about 45 miles (70 km) away from the Chesapeake Bay, it contained salinity less than 0.22 ppt everywhere in the river, according to this intensive survey data. If the tolerance of accuracy of the instrument, which is $\pm$ 0.1 ppt, is considered, the salinity field data in this survey is not pertinent to calibration. Furthermore, the distribution of the salinity in certain small estuaries is usually very mild and smooth and the gradient of salinity is usually very small, so that there is low sensitivity to the changes in dispersion coefficient. Therefore, for a small estuary with low longitudinal salinity gradient, the calibration of the dispersion coefficient by using the salinity field data should proceed with caution.

The field data of dye concentration collected during the intensive survey was used mainly for the calibration of the dispersion coefficient.

In order to prevent mass transport of dye beyond the most upstream transect at Walkers Dam, a fictitious reach was added to become the new most upstream reach. This fictitious reach had zero values of flow discharge, flow velocity and drainage area increment, but had to have an arbitrary non-zero positive values of the distance, the volume and the average depth of the reach and an arbitrary non-zero positive value of the conveyance area, the total cross-sectional area and the depth at the upstream transect of this fictitious reach. The dye concentration at this new most upstream transect could be arbitrarily specified. Four numerical tests by specifying this boundary dye concentration = 0.05, 50 and 100 ppb gave identical results except the fictitious one where the results were redundant.

In the simulation of dye, an initial distribution of dye concentration of 15.85 ppb in the second reach and 0.05 ppb in the remaining reaches, was assumed to be released at high water slack on June 26 as shown in Fig. 4.3b. This was the initial condition. Notice that 0.05 ppb is the river background dye concentration and 15.85 ppb is the sum of the river background dye concentration, 0.05 ppb, and the dye concentration, 15.8 ppb, resulted from one and half barrels of dye being well mixed throughout in the second reach.

A dye transport is also subject to the variation of the freshwater discharge. The freshwater discharge at the station near Providence Forge (Water Resource Data for Virginia Water Year 1975) and the water stage at Walkers Dam (private communication with Mr. McGhee of the Water Works of Newport News in January 1977) are well-correlated, as shown in Fig. 4.1 and Table 4.3. An exact freshwater discharge for the model is difficult to obtain since Providence Forge is about 10 miles (16 km) away from Walkers Dam and Walkers Dam itself includes a fish ladder. However, the average freshwater discharges were used by assuming the same runoff per unit area and shown in column 4, Table 4.3.

The comparison of the field dye data and the model calibrated results are presented in Figs. 4.3b through 4.3ℓ. The results illustrate that the dispersion coefficient increases with increasing freshwater discharge (see Fig. 4.4). Notice that the model results in most cases are higher than the field data, probably because a significant amount of dye was lost to the river bottom and marsh areas. A slight inconsistency in Figure 4.3ℓ is due to the imposed boundary condition at the river mouth. Also notice that the dispersion coefficient is also effected by tidal motion and is a spatial function. Therefore Fig. 4.4 should be used with caution. The weighting factor for advection was 0.5 for dye.

4.3.2 CBOD, NBOD, DO and Decay Rates

The water quality field data collected during the same slack tide survey on June 4, 18 & 19, four slack water runs were used for calibration. During these 3 days the average natural freshwater discharge was 150 cfs according to Water Resource Data for Virginia and the stream fresh water was then assumed 188 cfs to include the added runoff area downstream of the flow gage. The corresponding dispersion coefficient, AK ≃ 4.8 from Fig. 4.4, was used.

The calibrated results of CBOD and NBOD are shown in Figs. 4.5 and 4.6. The weighting factor for advection was 0.7. The decay rates of CBOD and NBOD are 0.1 and 0.05 1/day respectively. The non-point sources of CBOD and NBOD are shown in Table 4.4.

The results of the calibrated DO are shown in Fig. 4.7. The photosynthesis and respiration for the DO is also shown in Table 4.4. In the table the benthic DO demand was interpolated from the field data (see Appendix C).

In all of the model calibration runs, the CBOD, NBOD and DO concentrations of lateral freshwater inflow were assumed 1.0, 1.0 and 6.0 mg/ℓ respectively. The boundary conditions of the water quality variables were assumed to be the average values of the four slack water field data at the boundary stations. The following values were used:

	At Upstream	At Downstream
CBOD (mg/ℓ)	2.400	1.245
NBOD (mg/ℓ)	4.296	2.376
DO (mg/ℓ)	4.620	5.520

Notice that in Fig. 4.5 the average CBOD at 3 mile (4.8 km) from the river mouth is relatively high and disagrees with the calibrated result. This probable discrepancy may result from a scarcity of field data in this area, or may indicate that CBOD runoff is actually occurring from the Holiday Inn Trav-L Park. However the exact reason is not known.

4.4 Sensitivity Analysis

4.4.1 Dye

The sensitivity of the distribution of dye concentration to the dispersion coefficient, while maintaining all other input data unchanged, was studied. Figs. 4.8 a&b are typical results, showing that there was a great effect of the dispersion coefficient on the distribution of dye concentration. The results in Figs. 4.8a and 4.8b agree with the theory, namely, the greater the dispersion coefficient, the wider the distribution and the lower the peak concentration.

4.4.2 Water Quality

The sensitivity of CBOD, NBOD and DO to the dispersion coefficient and the decay rates were also made by varying them singly while keeping all other input data unchanged. Table 4.5 shows that there was almost no effect of varying the dispersion coefficient on the distribution of CBOD, NBOD and DO. The insensitivity to the dispersion coefficient is due to smoothness and small gradient of the distribution of the water quality, making the dispersion term insignificant.

Figures 4.9 through 4.11 show the simulated CBOD, NBOD and DO profiles based on different BOD decay rates. The figures illustrate high sensitivity to the BOD decay rate, with BOD decreasing as the decay rate increases.

Table 4.1. Geometric and Tidal Data of 16 Transects

Transect	Distance		Cross-Sectional Area	Width	Tide Height Correction	MTL Cross-Sectional Area	Average Depth	Tide	
								Current Amplitude	Phase Difference
	mi.	(km)	ft^2	ft.	ft.	ft^2	ft.	ft.	hr.
T16	0.0	(0.0)	50867	2900	-1.78	45705	15.76	0.71	2.140
T15	1.343	(2.161)	39402	2900	-1.70	34472	11.89	0.80	1.998
T14	2.813	(4.526)	36337	2075	-1.63	26955	12.99	0.93	1.856
T13	3.772	(6.069)	30312	2415	-1.55	26569	11.00	0.82	1.715
T12	5.178	(8.331)	25169	1775	-1.48	22542	12.70	0.75	1.573
T11	6.265	(10.080)	18418	1215	-1.4	16717	13.76	0.88	1.432
T10	7.352	(11.829)	18774	615	-1.1	18097	29.43	0.74	1.305
T9	8.375	(13.475)	9670	600	-0.8	9190	15.32	1.40	1.178
T8	9.909	(15.943)	12993	1150	-0.5	12418	10.80	1.05	0.940
T7	11.827	(19.030)	13748	600	-0.2	13618	22.71	0.71	0.924
T6	13.426	(21.602)	17457	1835	-0.1	17273	9.41	0.46	0.770
T5	14.768	(23.762)	8480	560	0.0	8480	15.14	0.73	0.616
T4	16.686	(26.848)	6539	400	0.5	6559	16.40	0.72	0.464
T3	18.477	(29.729)	7409	515	0.5	7448	14.46	0.47	0.308
T2	19.883	(31.992)	11947	1150	0.5	12005	10.44	0.21	0.154
T1	21.544	(34.664)	8337	675	0.5	8371	12.40	0.0	0.0

1 ft. = 0.3048 m. 1 ft^2 = 0.0929 m^2 1 mi = 1.609 km

Table 4.2 Geometric Data and Drainage Areas of 15 Reaches

	Reach No.	Length ft	Volume ft^3	Average Depth ft	Drainage Area mi^2
15	(T15-T16)	7089	0.285E9	13.86	13.34
14	(T14-T15)	7761	0.239E9	12.37	14.60
13	(T13-T14)	5067	0.136E9	11.95	9.52
12	(T12-T13)	7425	0.182E9	11.70	14.05
11	(T11-T12)	5736	0.113E9	13.18	10.79
10	(T10-T11)	5742	0.999E8	19.01	10.79
9	(T9 -T10)	5401	0.736E8	22.43	5.22
8	(T8 -T9)	8099	0.875E8	12.35	7.82
7	(T7 -T8)	10129	0.264E9	29.79	9.78
6	(T6 -T7)	8438	0.131E9	12.75	20.76
5	(T5 -T6)	7086	0.912E8	10.75	17.42
4	(T4 -T5)	10129	0.762E8	15.67	24.90
3	(T3 -T4)	9454	0.662E8	15.31	6.54
2	(T2 -T3)	7425	0.723E8	11.70	5.13
1	(T1 -T2)	8774	0.895E8	11.18	6.06

1 ft = 0.3048 m

1 ft^3 = 0.0283 m^3

1 mi^2 = 2.589 km^2

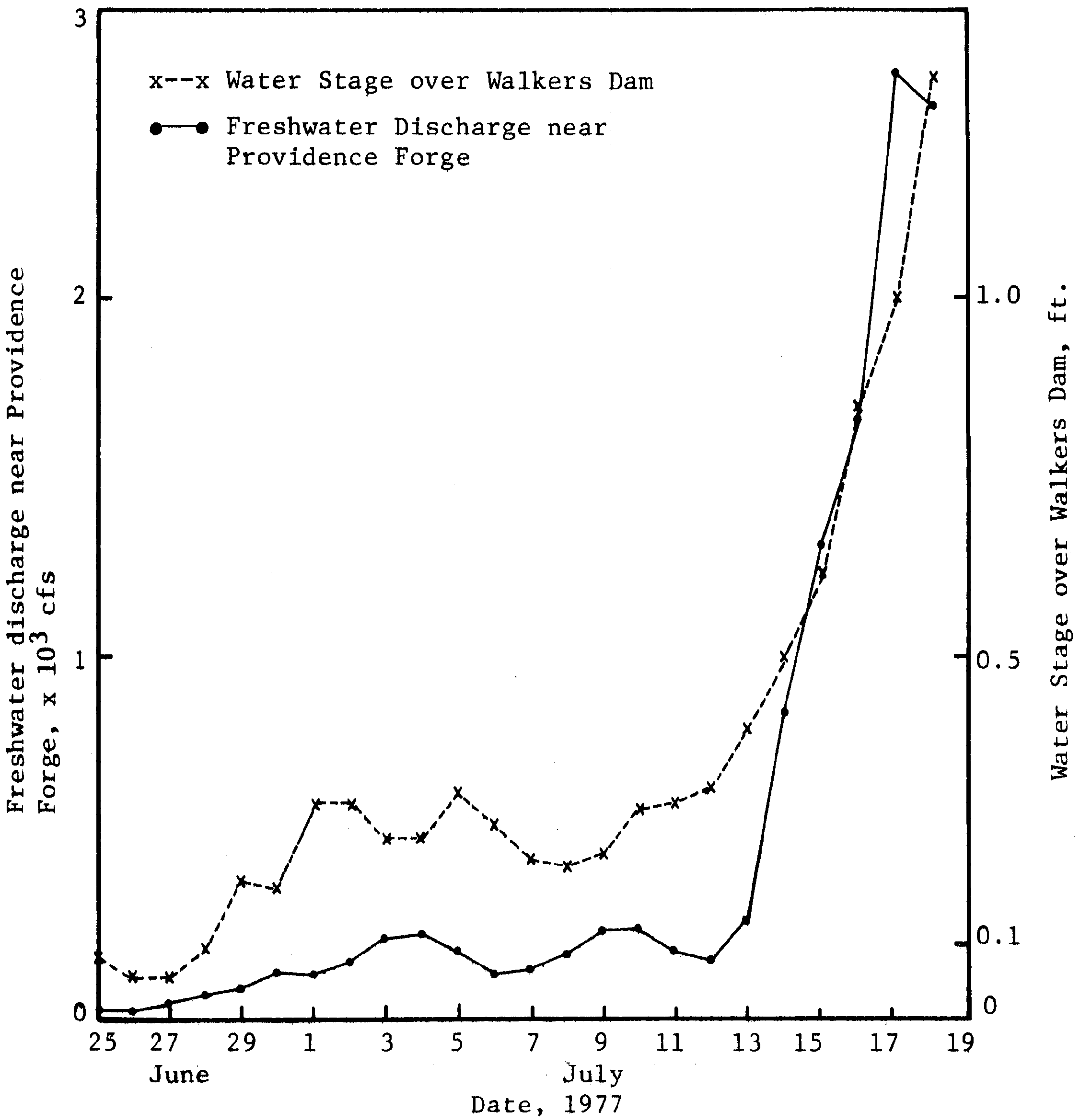

Figure 4.1. Freshwater discharge near Providence Forge and water stage at the Walkers Dam during the intensive field survey. 1 ft = .3048 m
1 cfs = .028 m^3/s

Table 4.3 Freshwater Discharge Near Providence Forge And Water Stage At Walkers Dam. 1 ft = 0.3048 m, 1 cfs = 0.0282 m^3/s

Date	Near Providence Forge		Average Discharge at Walkers Dam for the Model	At Walkers Dam	
	Discharge	Average Discharge (from 6/25 to the date)		Water Stage	Net Water Stage Over Dam
June-July 1975	cfs	cfs	cfs	ft	ft
June 25	30			3.09	0.09
26	27			3.06	0.06
27	44	34	40	3.06	0.06
28	70			3.10	0.10
29	83			3.19	0.19
30	133	64	76	3.17	0.17
July 1	128			3.30	0.30
2	159	84	100	3.30	0.30
3	222			3.25	0.25
4	237			3.25	0.25
5	188			3.31	0.31
6	124			3.27	0.27
7	140	122	145	3.22	0.22
8	179			3.21	0.21
9	248			3.23	0.23
10	254			3.29	0.29
11	195			3.30	0.30
12	163			3.32	0.32
13	277			3.40	0.40
14	844			3.50	0.50
15	1310			3.62	0.62
16	1660			3.85	0.85
17	2620	406	483	4.00	1.00

Notice that Drainage area upstream from Providence Forge = 248 mi^2, and drainage area upstream from Walkers Dam = 295 mi^2. Therefore,

$$\text{Colm.}(3)\times(\frac{295}{248}) = \text{Colm.}(4) .$$

Also Notice that Information about Walkers Dam and water stage was obtained from private communication with Mr. McGhee, Water Works, Newport News in January 1977. Walkers Dam is a broad-crested dam with fish ladder, hight = 3 ft and width = 750 ft.

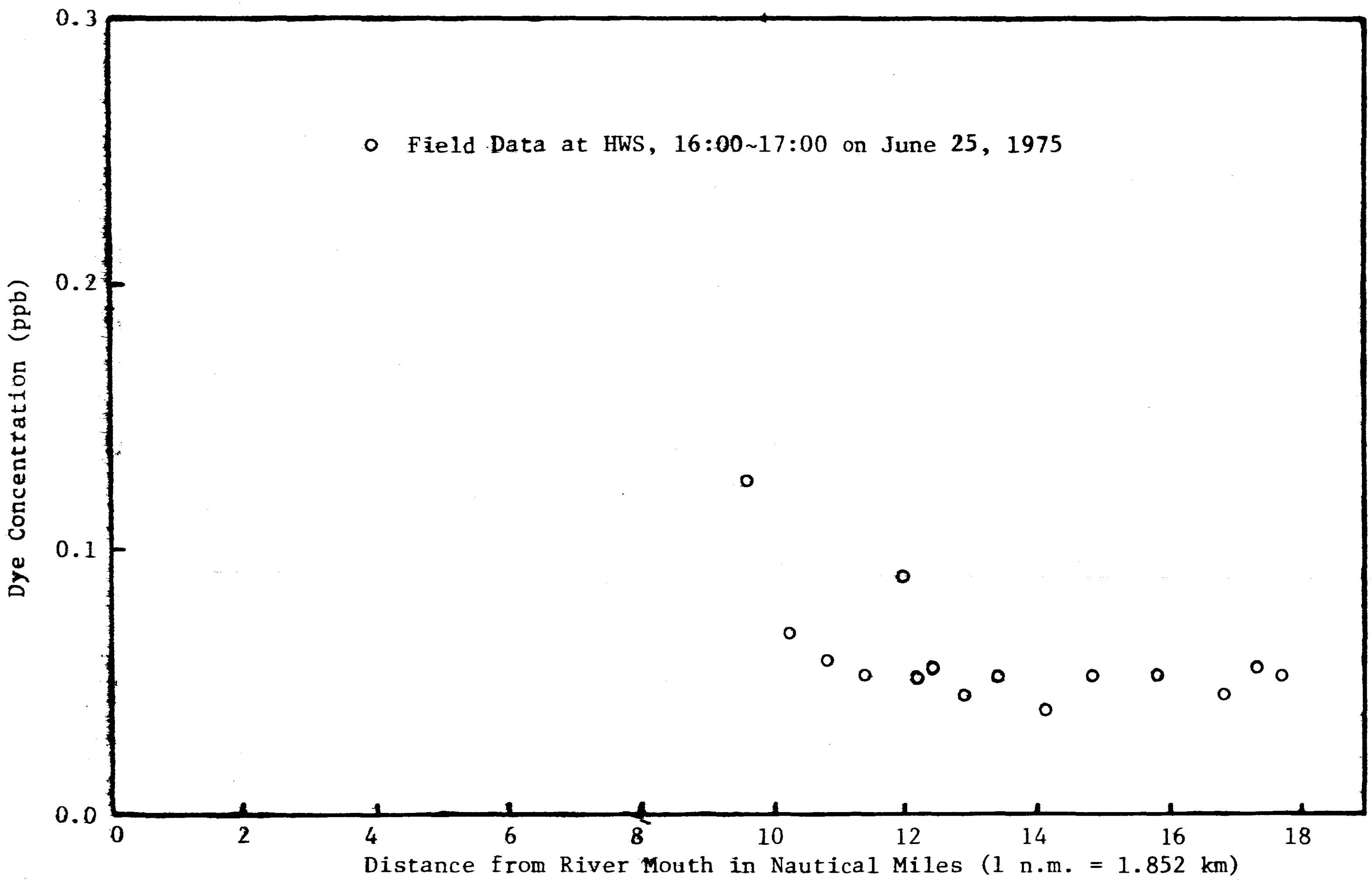

Figure 4.2. Background dye concentration of the estuary.

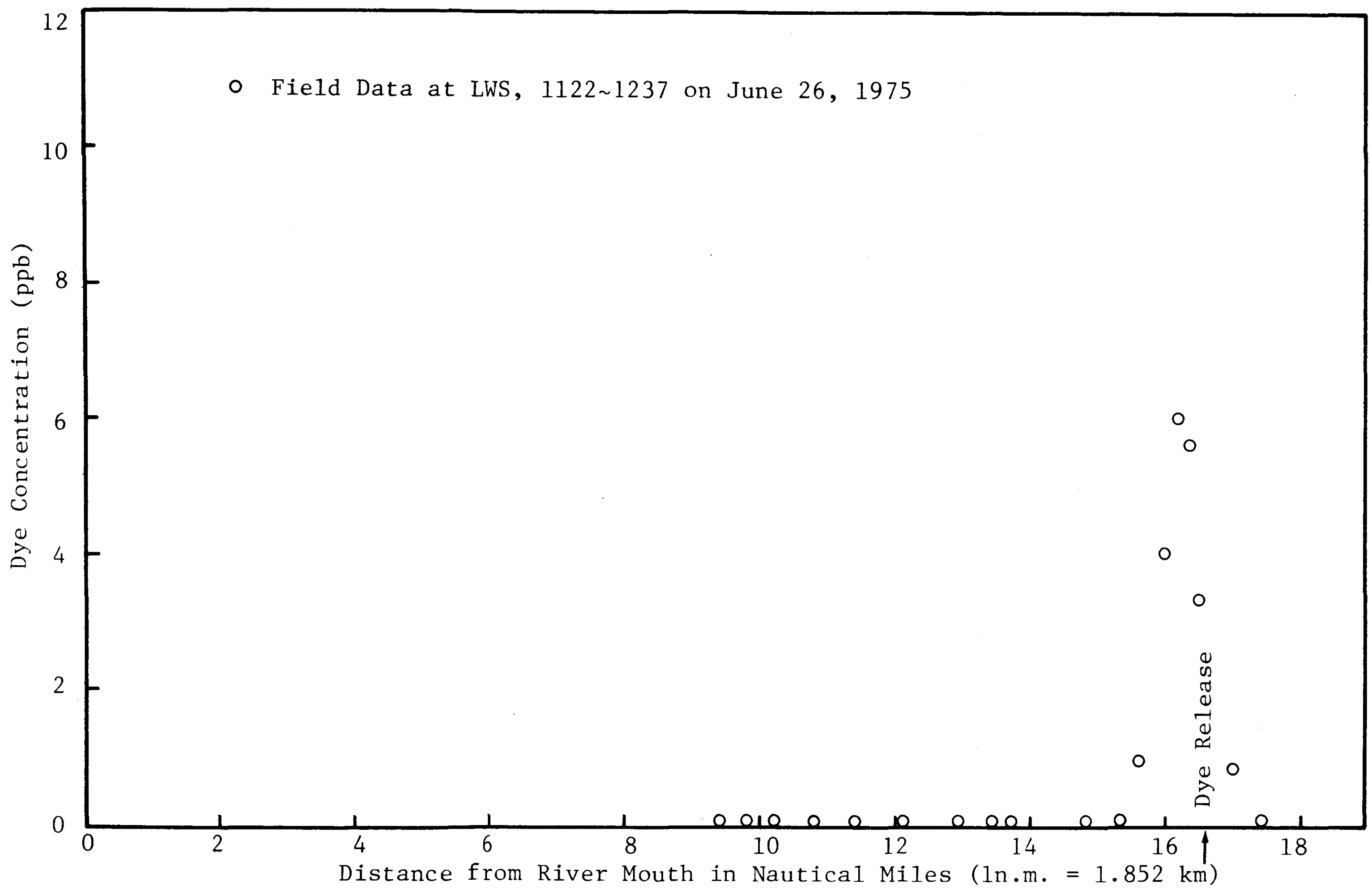

Figure 4.3a. The dye concentration of the estuary.

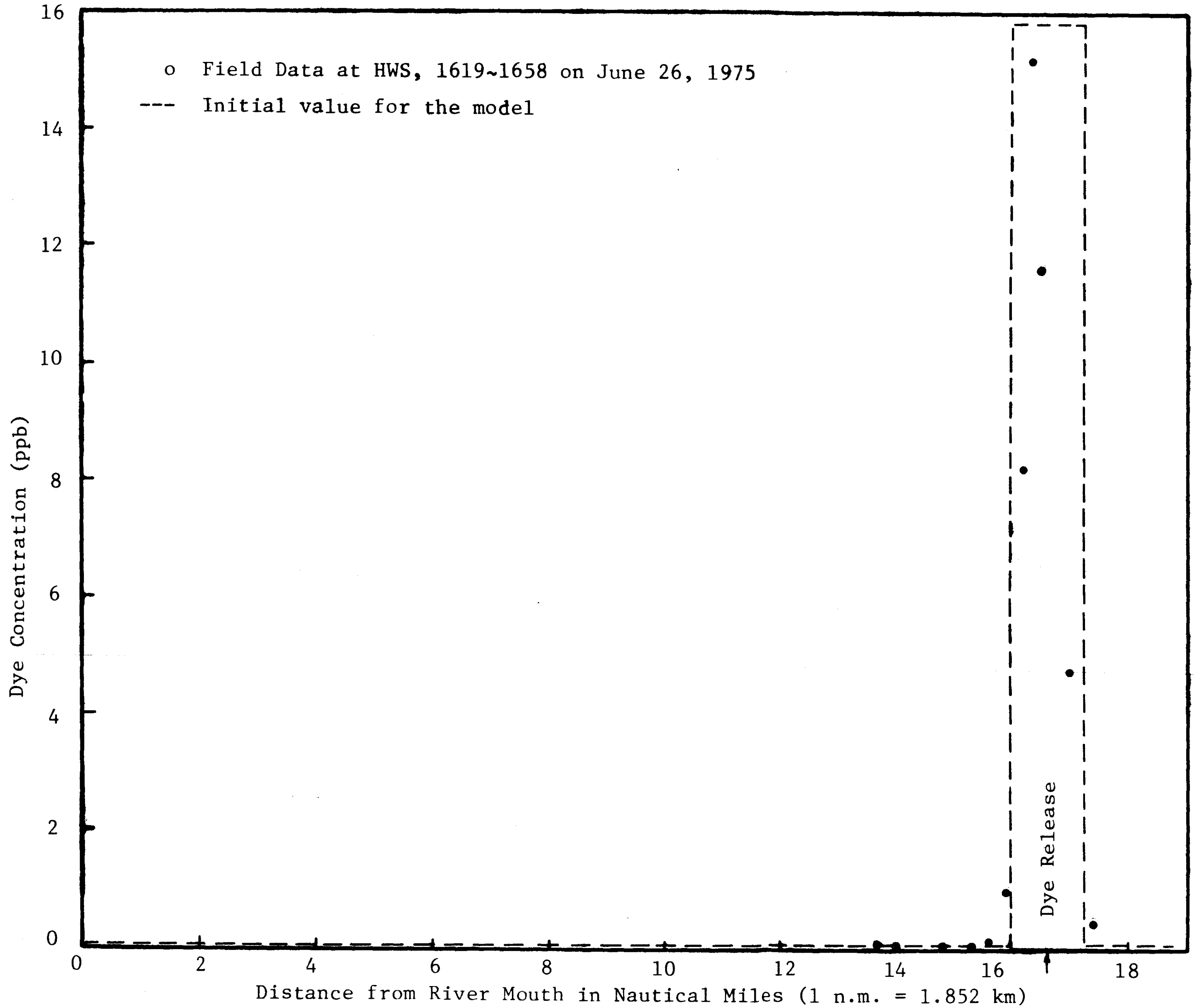

Figure 4.3b. The dye concentration of the estuary.

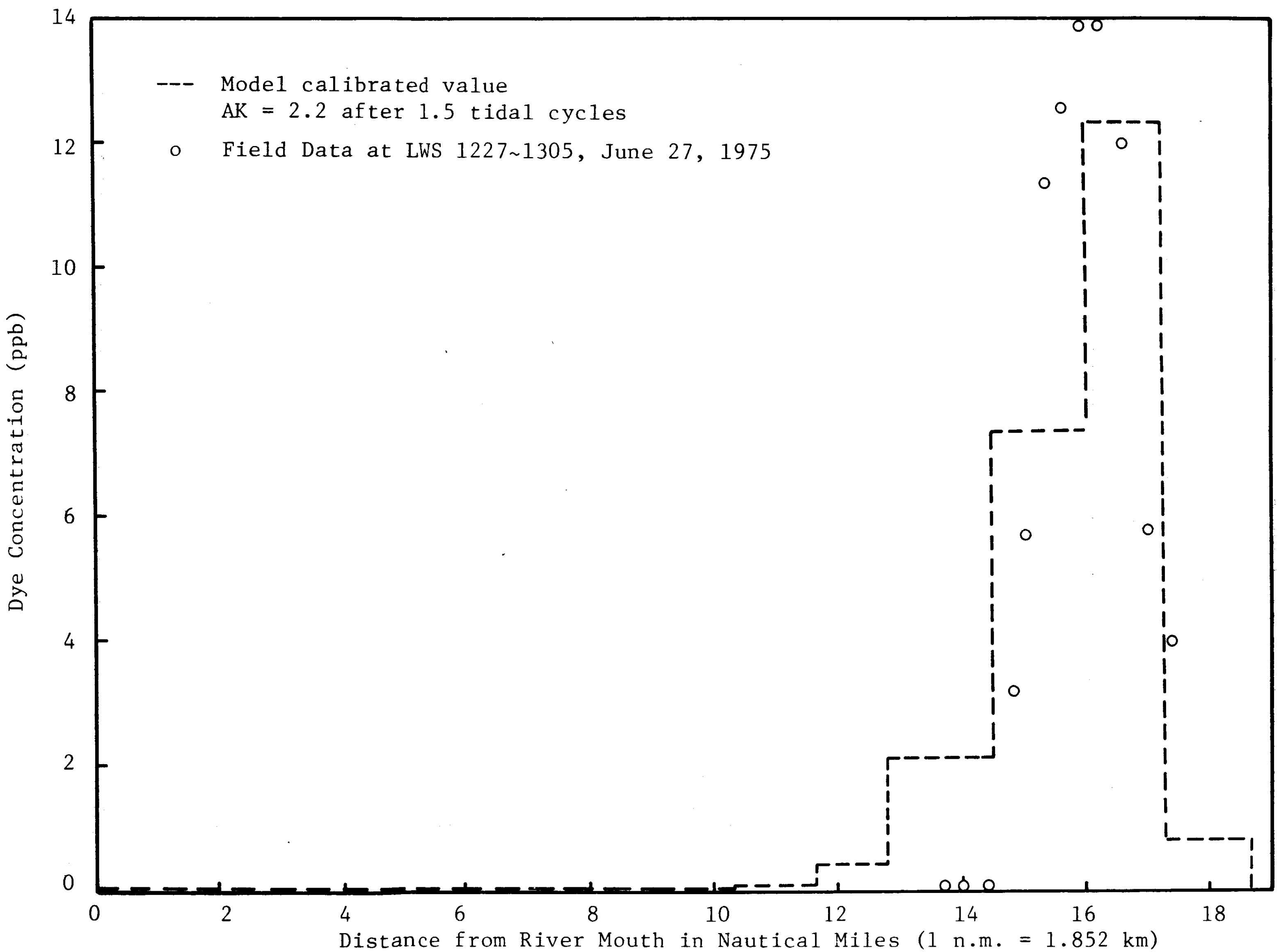

Figure 4.3c. The dye concentration of the estuary.

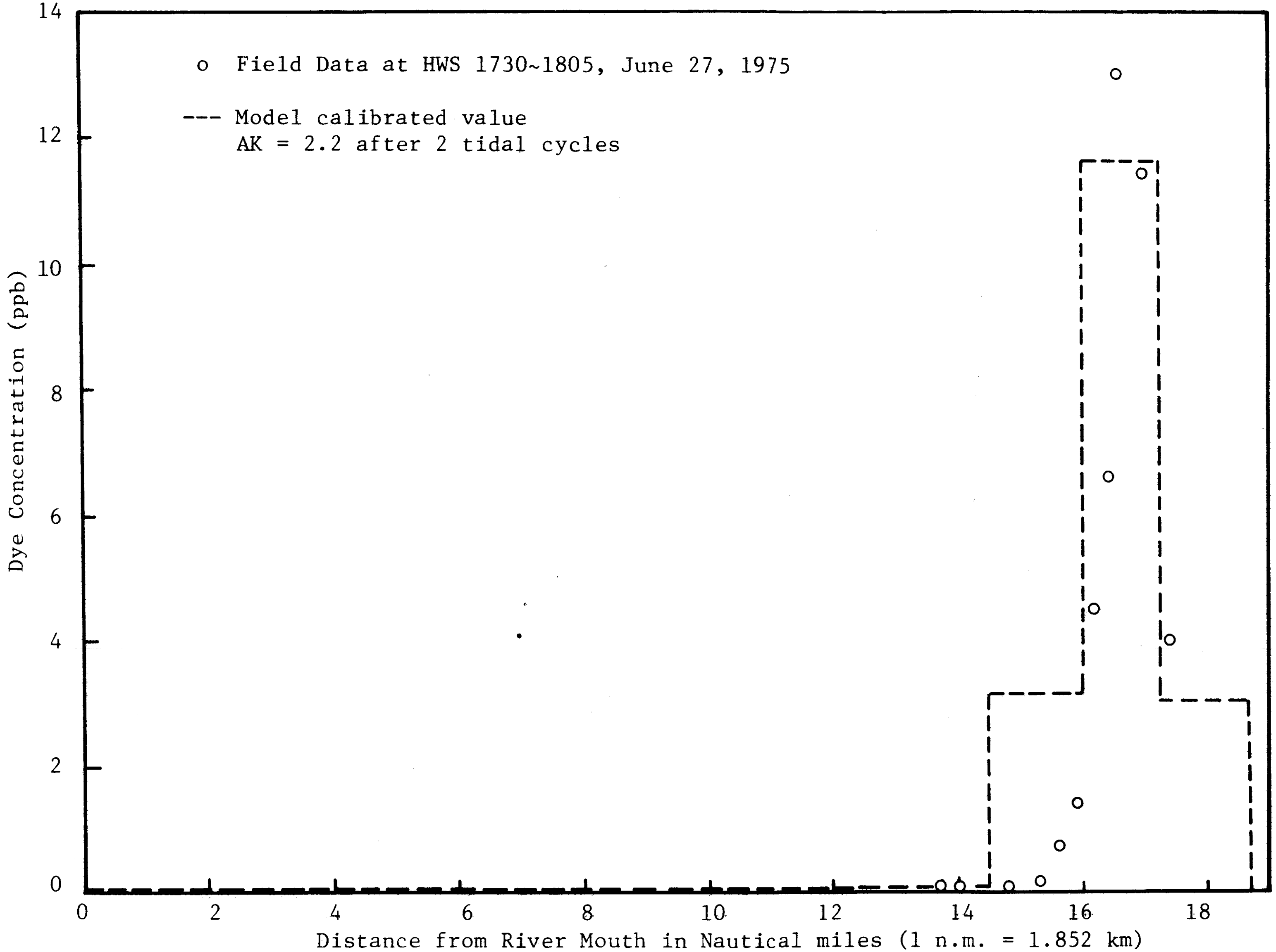

Figure 4.3d. The dye concentration of the estuary.

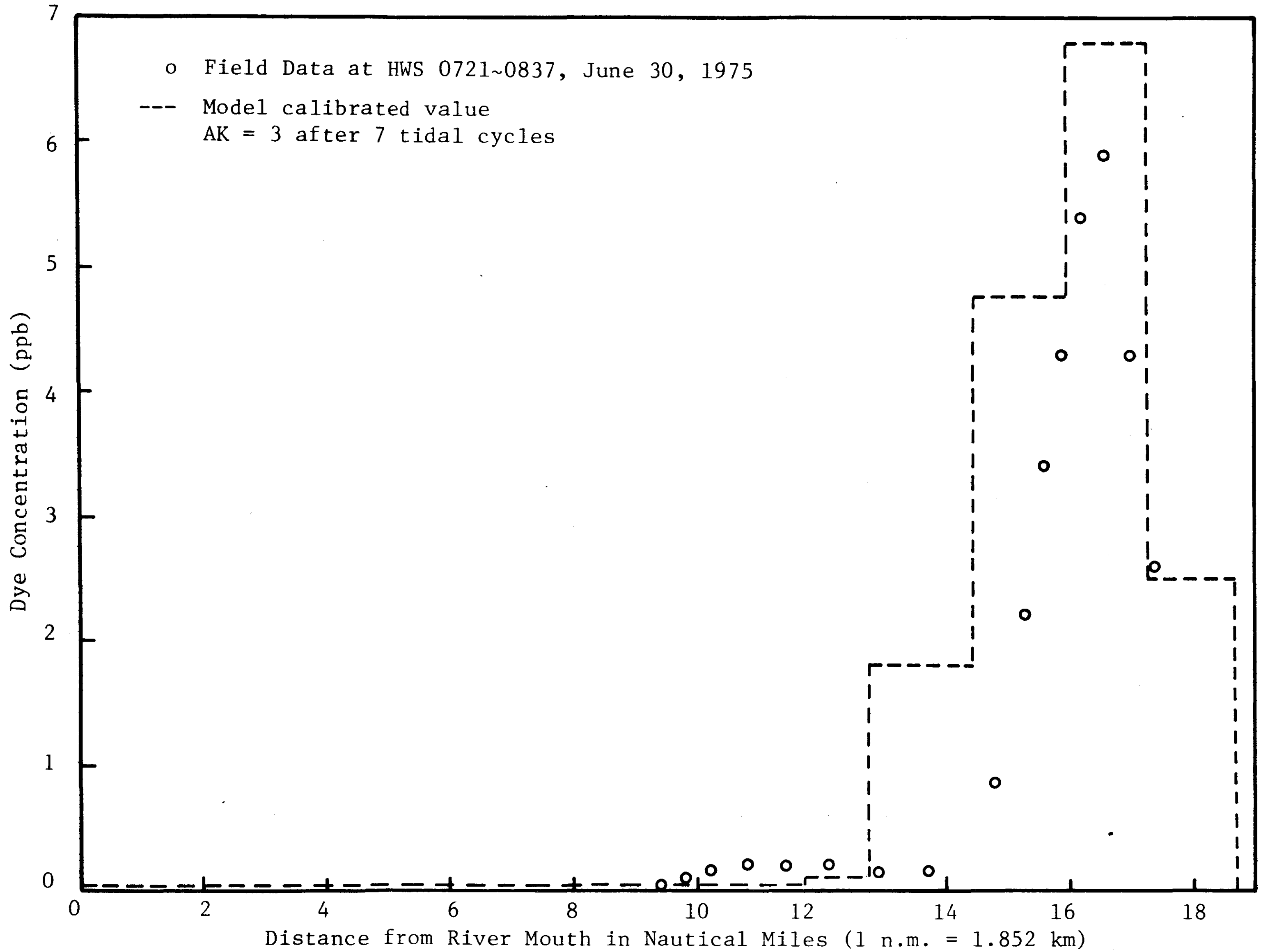

Figure 4.3e. The dye concentration of the estuary.

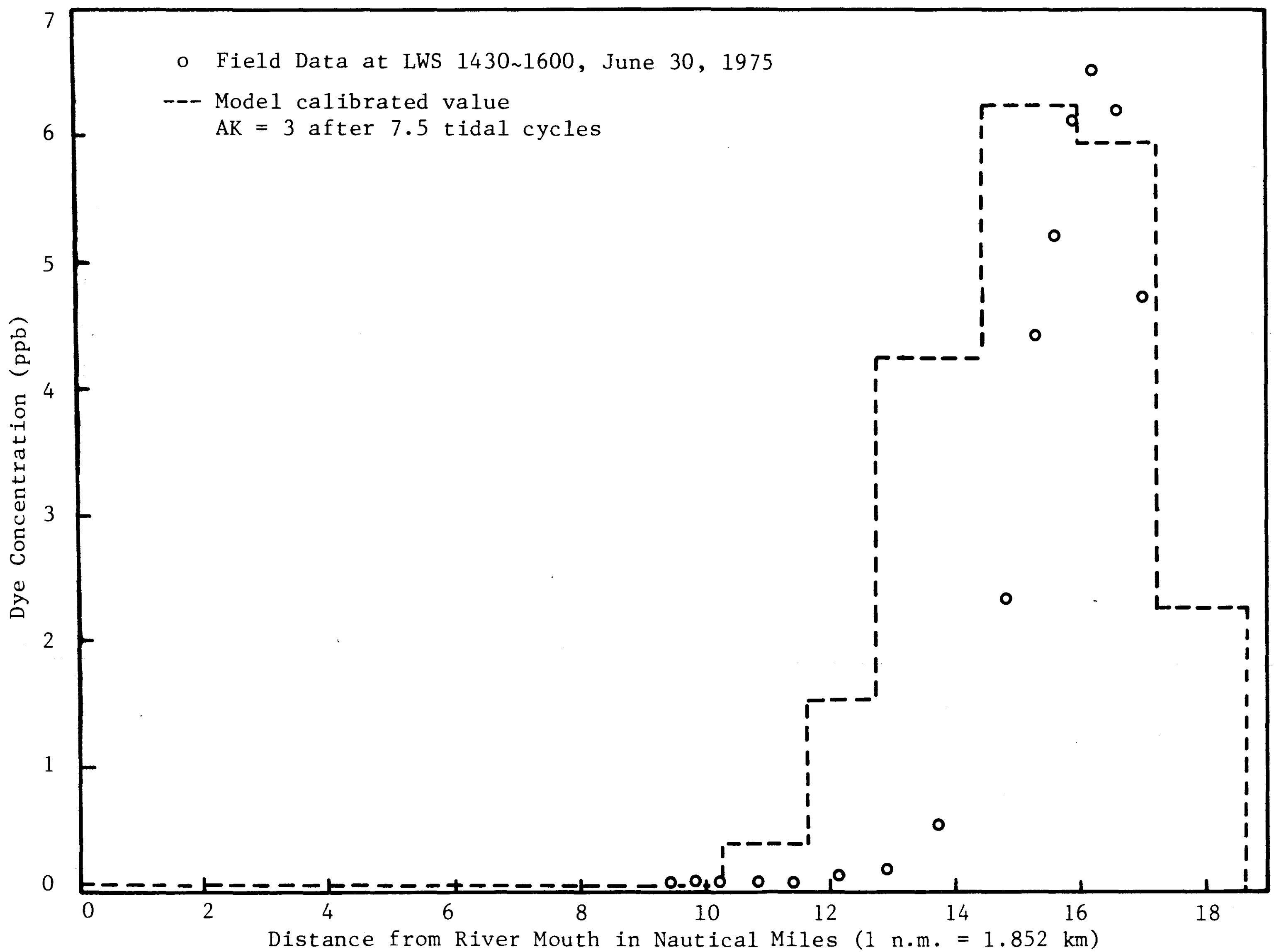

Figure 4.3f. The dye concentration of the estuary.

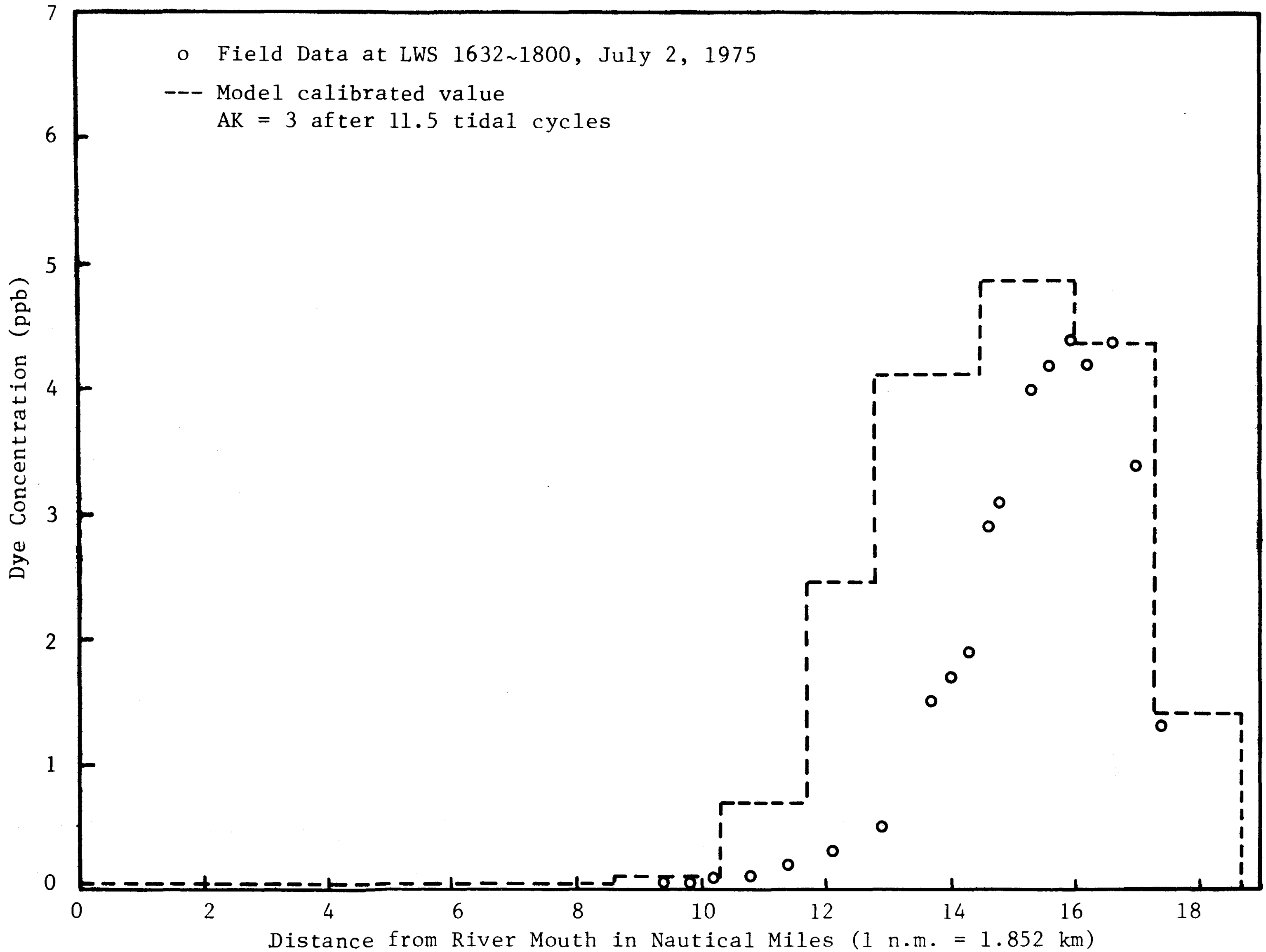

Figure 4.3g. The dye concentration of the estuary.

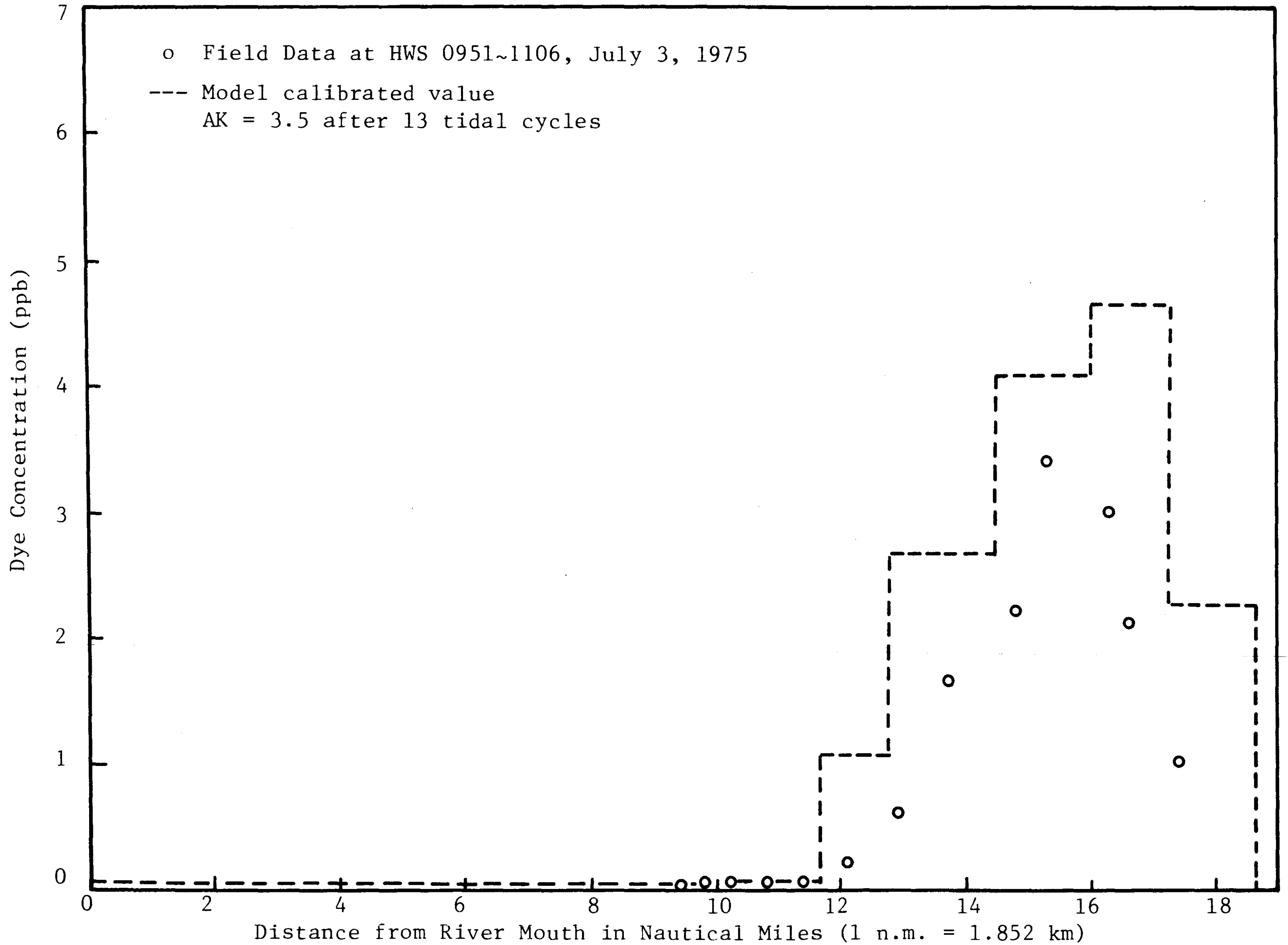

Figure 4.3h. The dye concentration of the estuary.

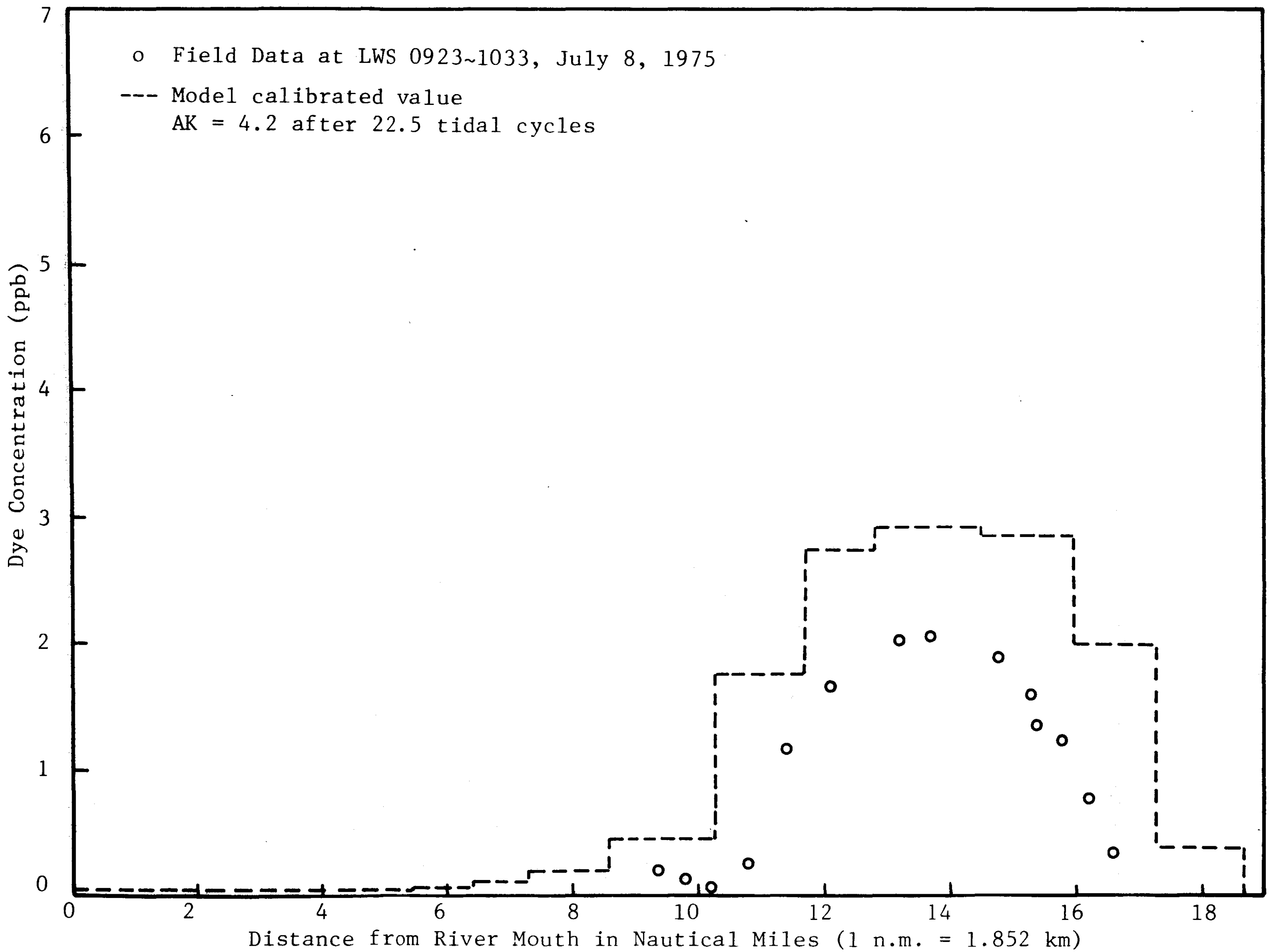

Figure 4.3i. The dye concentration of the estuary.

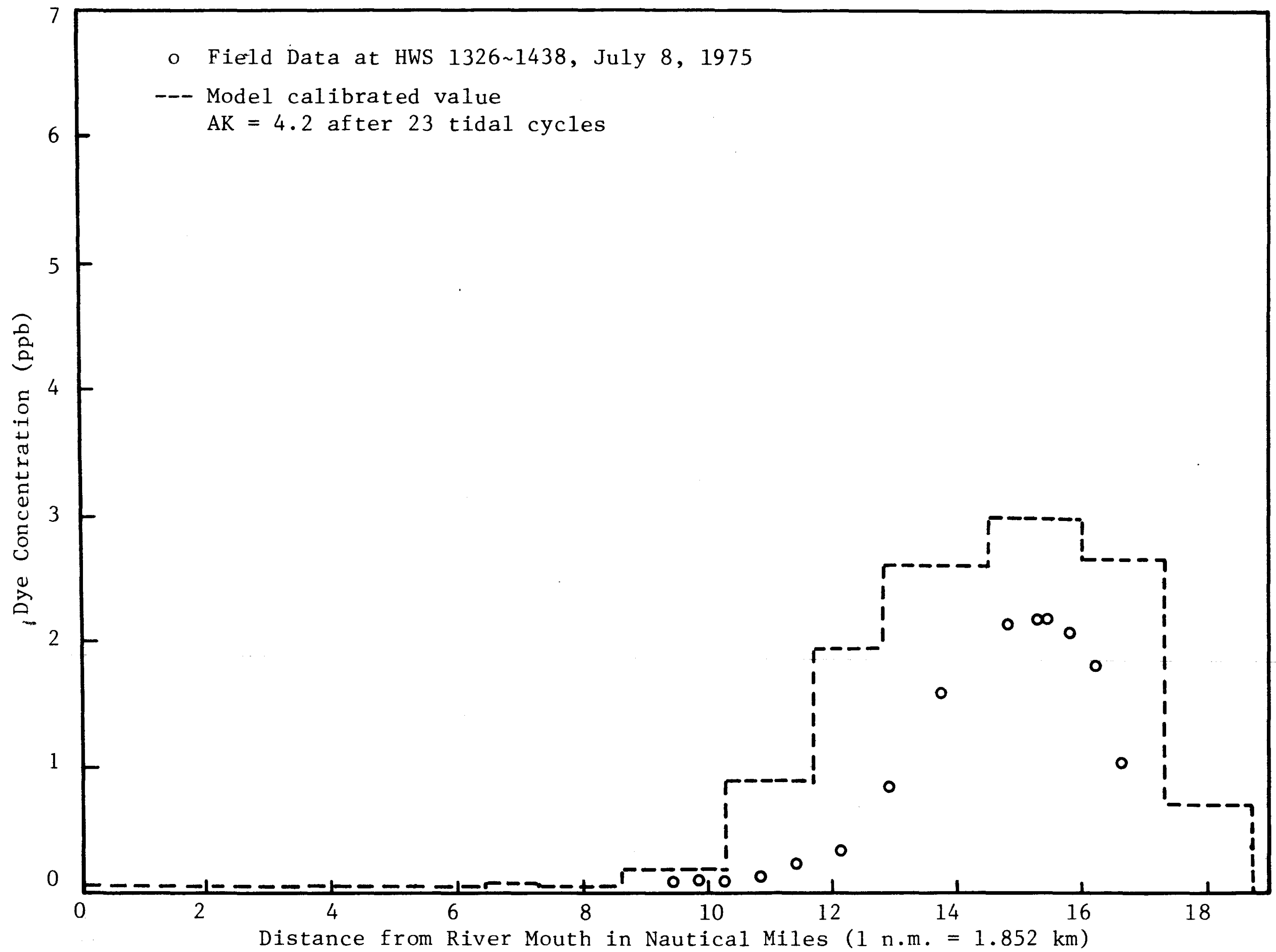

Figure 4.3j. The dye concentration of the estuary.

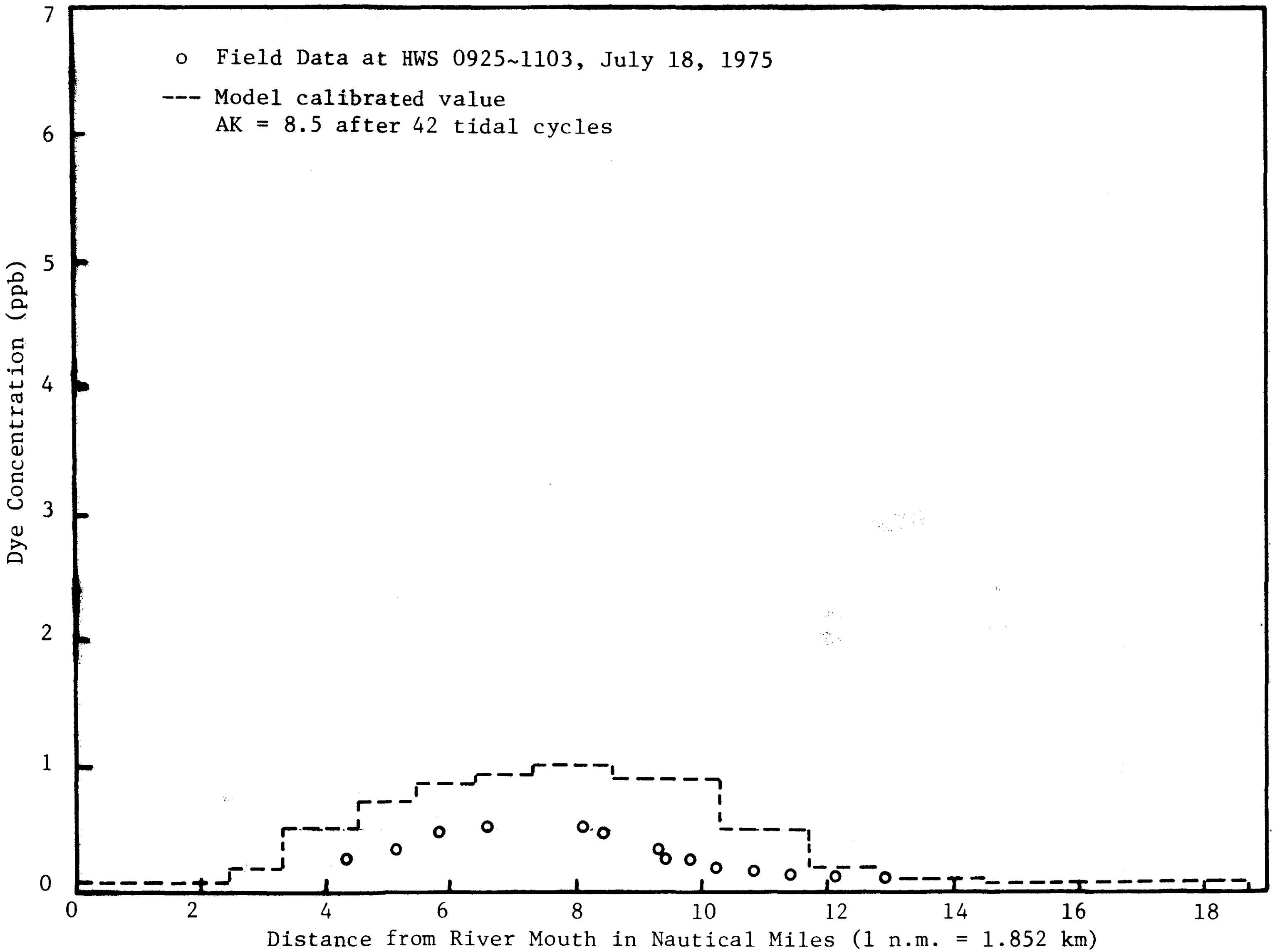

Figure 4.3k. The dye concentration of the estuary.

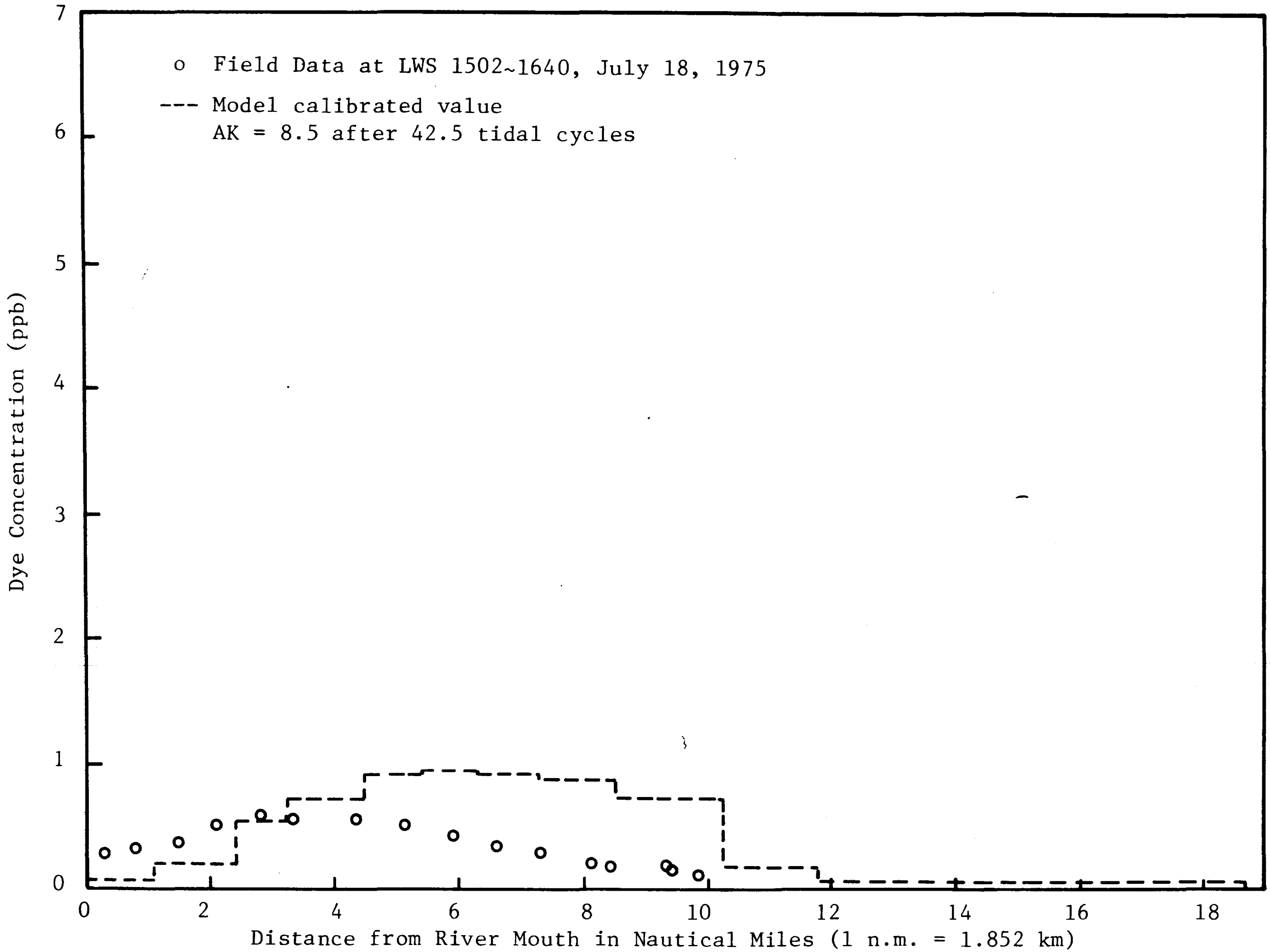

Figure 4.3L. The dye concentration of the estuary.

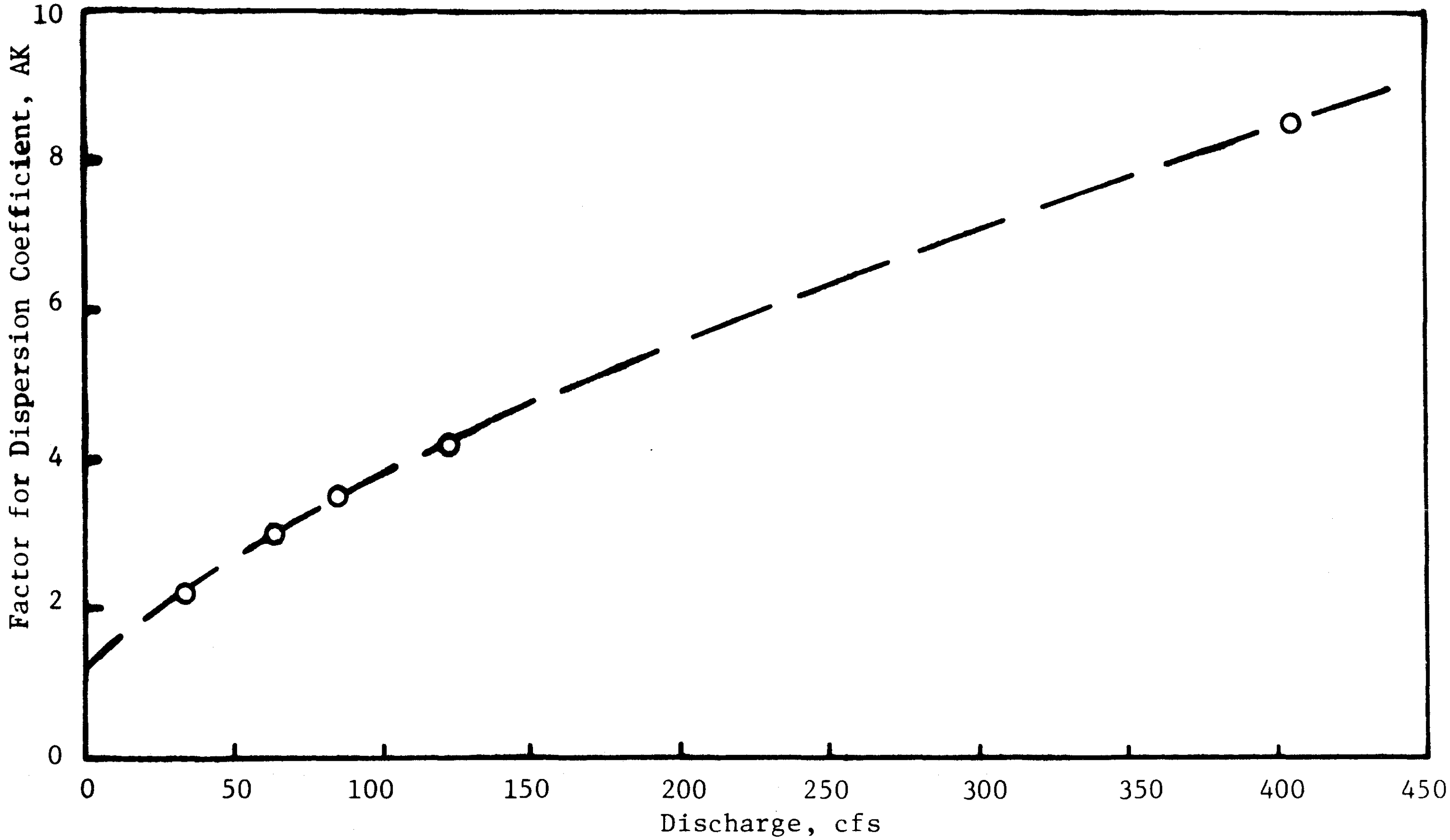

Figure 4.4. Dispersion coefficient vs. freshwater discharge at station near Providence Forge, 1 cfs = .028 m^3/s.

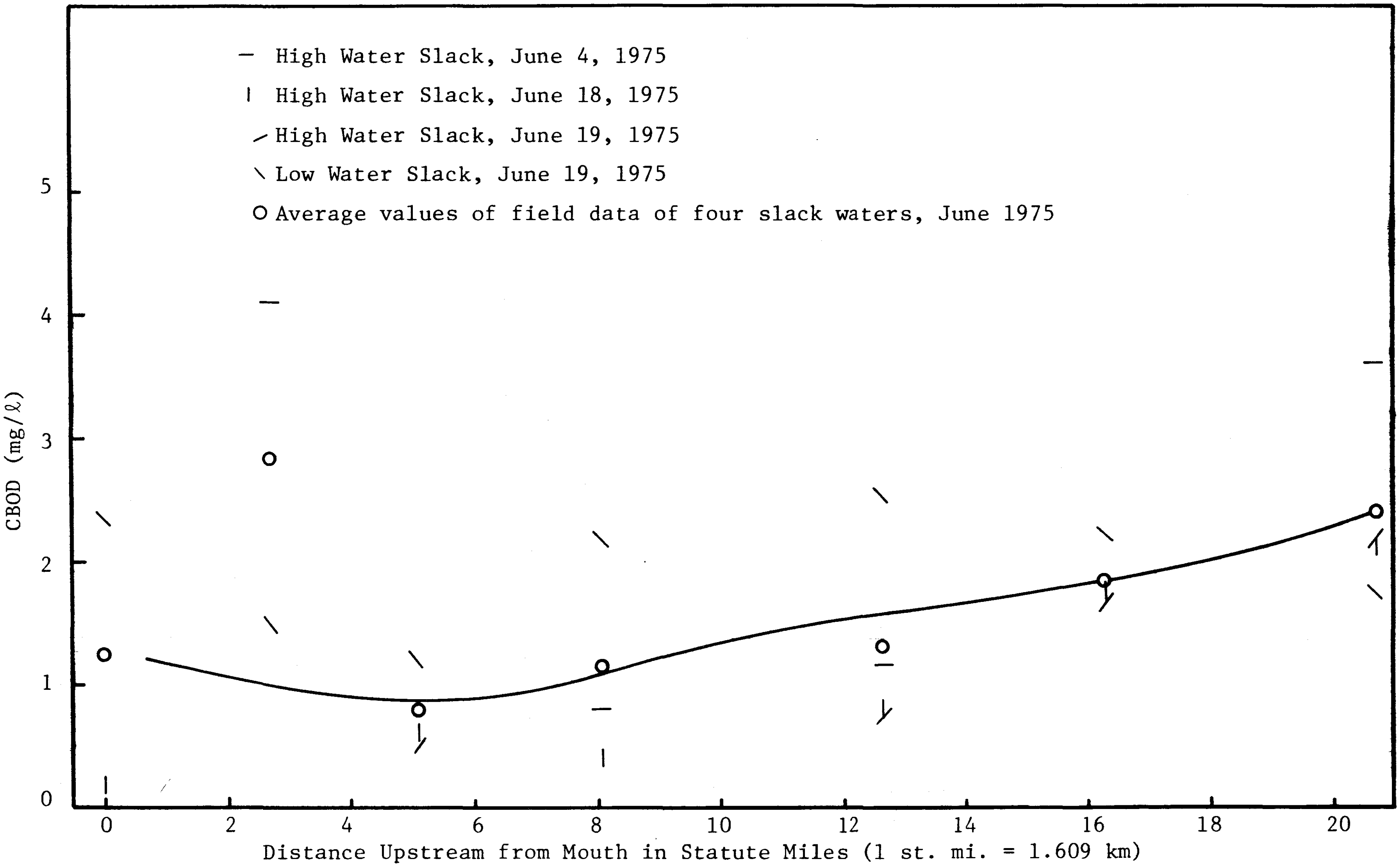

Figure 4.5. Longitudinal distribution of CBOD.

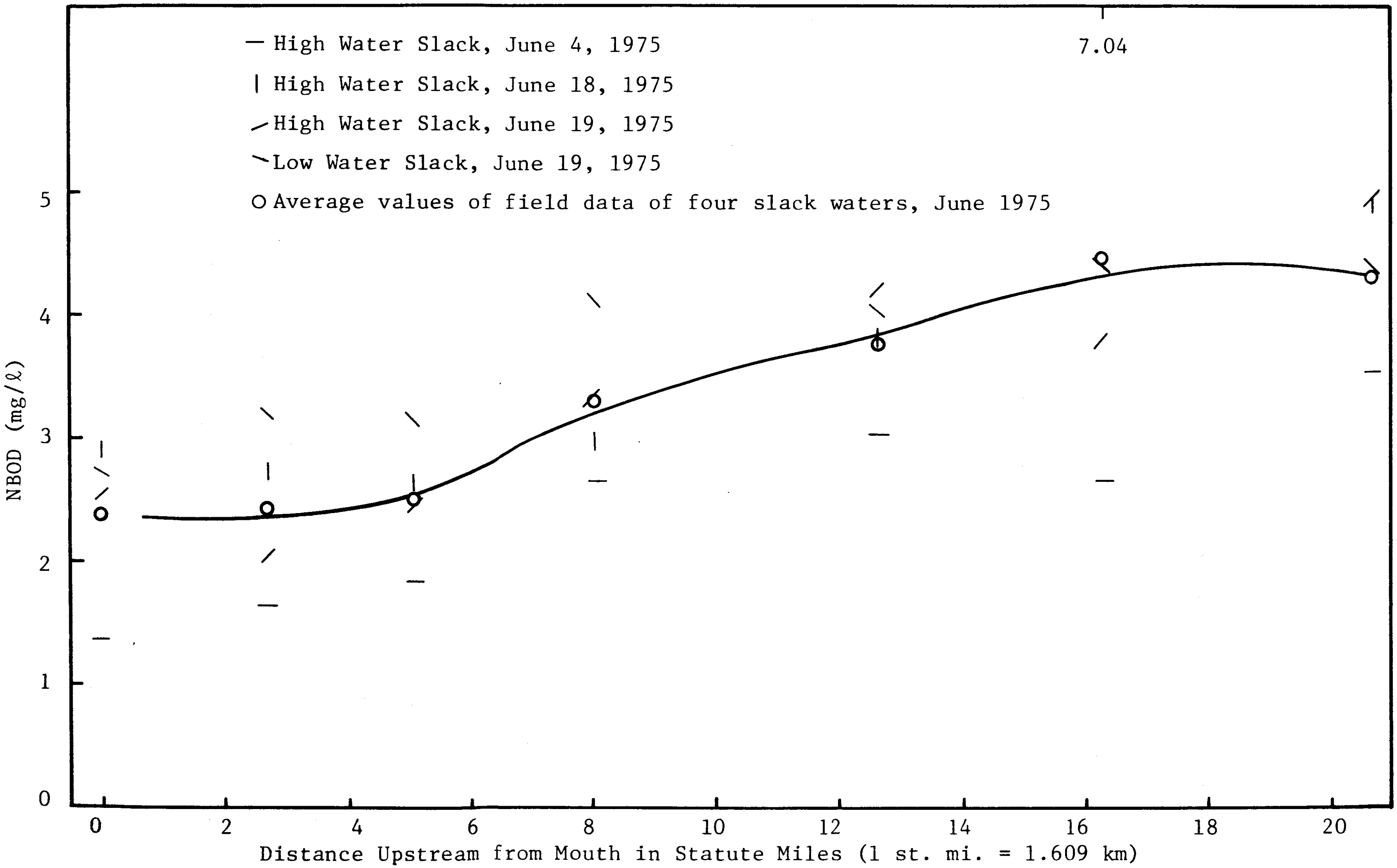

Figure 4.6. Longitudinal distribution of NBOD.

Table 4.4 The Contributions Of CBOD And NBOD Non-Point Sources, Photosynthesis-Respiration Of DO, And Benthic DO Demand

Reach Number	CBOD lbs/day	or mg/l	NBOD lbs/day	or mg/l	Photosynthesis-Respiration of DO $gm/m^2/day$	Benthic DO Demand $gm/m^2/day$
1	1400	1.8	4000	5.0	4.0	1.0
2	1200	1.8	3200	5.0	4.0	1.0
3	1100	1.8	3000	5.0	4.0	1.0
4	1100	1.8	3400	5.0	4.0	1.0
5	1300	1.8	4000	5.0	4.0	1.0
6	2000	1.8	4500	4.0	4.0	1.1
7	4100	1.8	9000	4.0	4.0	1.1
8	1400	1.8	3100	4.0	2.0	1.1
9	50	0.0	2600	4.0	2.0	1.1
10	50	0.0	3600	4.0	2.0	1.1
11	50	0.0	2000	2.0	2.0	1.6
12	50	0.0	3100	2.0	2.0	1.6
13	50	0.0	2300	2.0	2.0	1.6
14	50	0.0	4200	2.0	2.0	1.6
15	50	0.0	5000	2.0	2.0	1.6

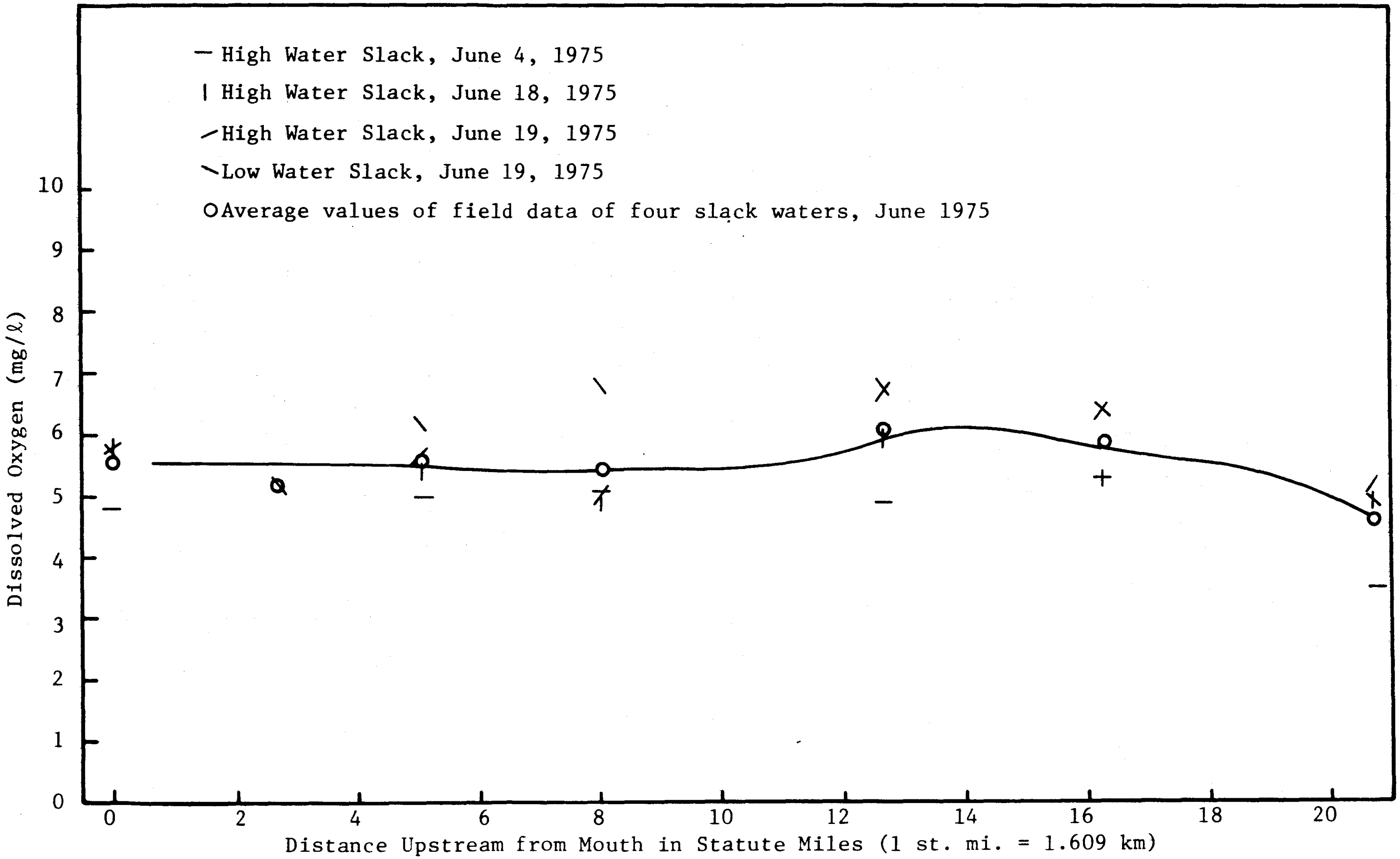

Figure 4.7. Longitudinal distribution of D.O.

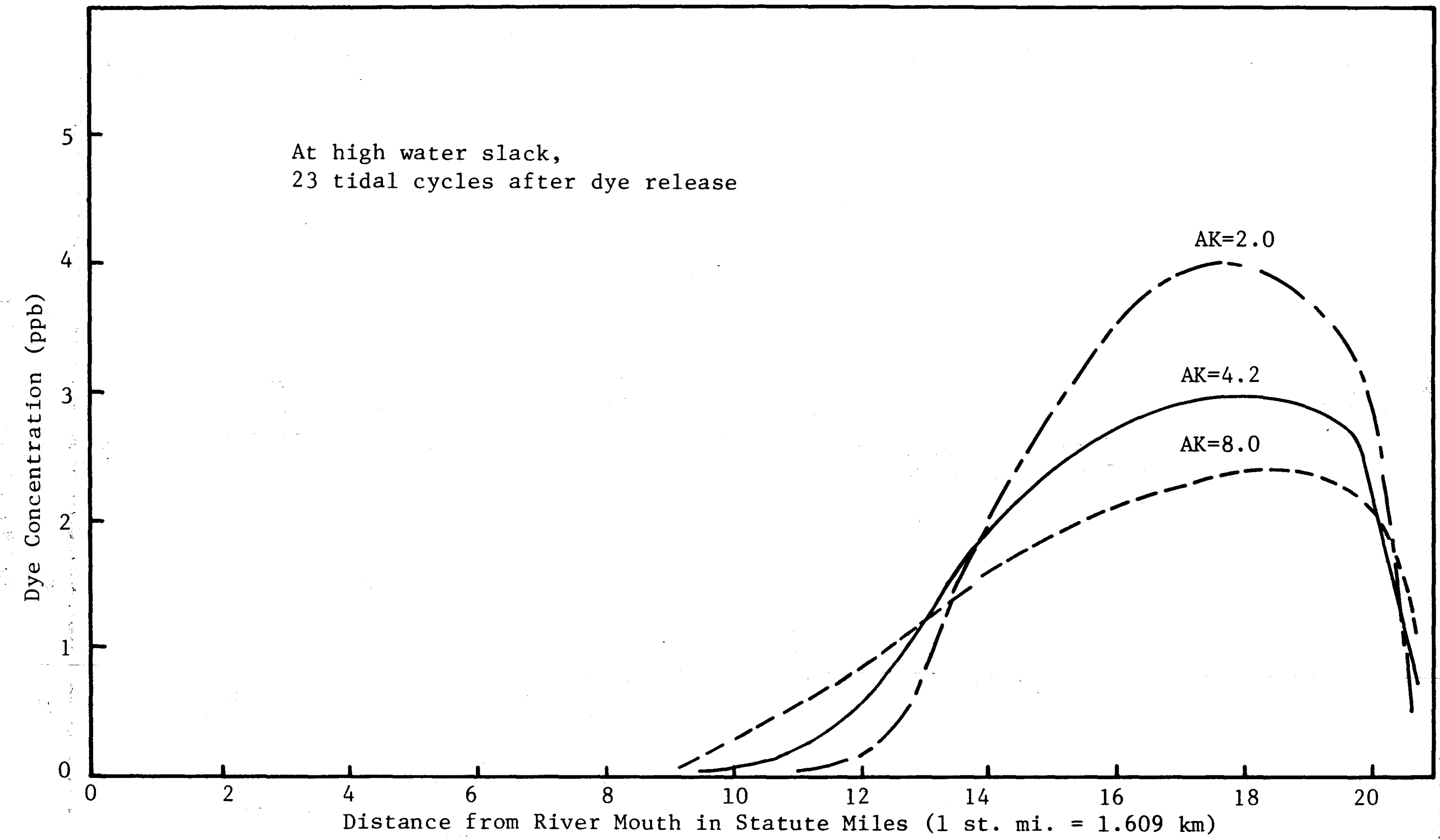

Figure 4.8a. Effects of dispersion coefficient on dye concentration distribution.

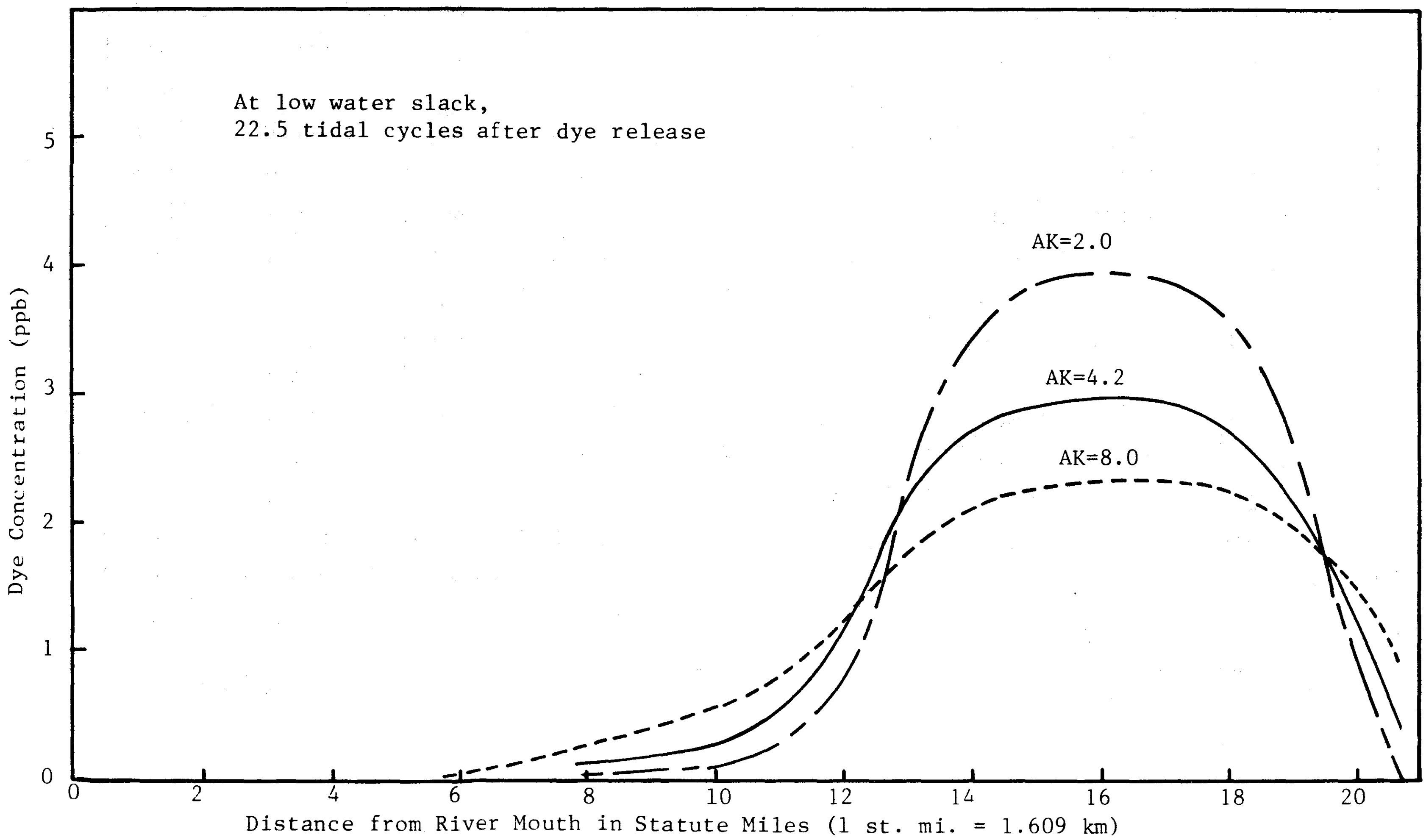

Figure 4.8b. Effects of dispersion coefficient on dye concentration distribution.

Table 4.5 Spatial Distribution Of CBOD, NBOD And DO With Respect To Various Dispersion Coefficient, AK.

River Reach	CBOD (mg/l)			NBOD (mg/l)			DO (mg/l)		
	AK=1.0	AK=4.8 (calibrated)	AK=8.0	AK=1.0	AK=4.8 (calibrated)	AK=8.0	AK=1.0	AK=4.8 (calibrated)	AK=8.0
1	2.400	2.400	2.400	4.296	4.296	4.296	4.620	4.620	4.620
2	2.152	2.152	2.152	4.415	4.414	4.413	5.317	5.317	5.317
3	1.962	1.961	1.961	4.394	4.392	4.391	5.609	5.610	5.610
4	1.786	1.786	1.785	4.259	4.257	4.256	5.876	5.876	5.876
5	1.659	1.659	1.658	4.085	4.083	4.082	6.115	6.114	6.113
6	1.557	1.556	1.556	3.835	3.833	3.831	5.948	5.947	5.946
7	1.427	1.427	1.426	3.614	3.612	3.611	5.489	5.490	5.492
8	1.236	1.236	1.236	3.373	3.371	3.370	5.480	5.481	5.482
9	1.064	1.065	1.066	3.165	3.164	3.162	5.403	5.404	5.405
10	0.944	0.946	0.947	2.939	2.939	2.939	5.411	5.412	5.412
11	0.881	0.883	0.885	2.663	2.664	2.665	5.462	5.462	5.462
12	0.900	0.902	0.904	2.475	2.476	2.477	5.530	5.530	5.529
13	0.978	0.979	0.980	2.394	2.395	2.396	5.552	5.552	5.551
14	1.075	1.075	1.076	2.364	2.365	2.365	5.544	5.543	5.543
15	1.198	1.198	1.198	2.370	2.370	2.370	5.527	5.527	5.527

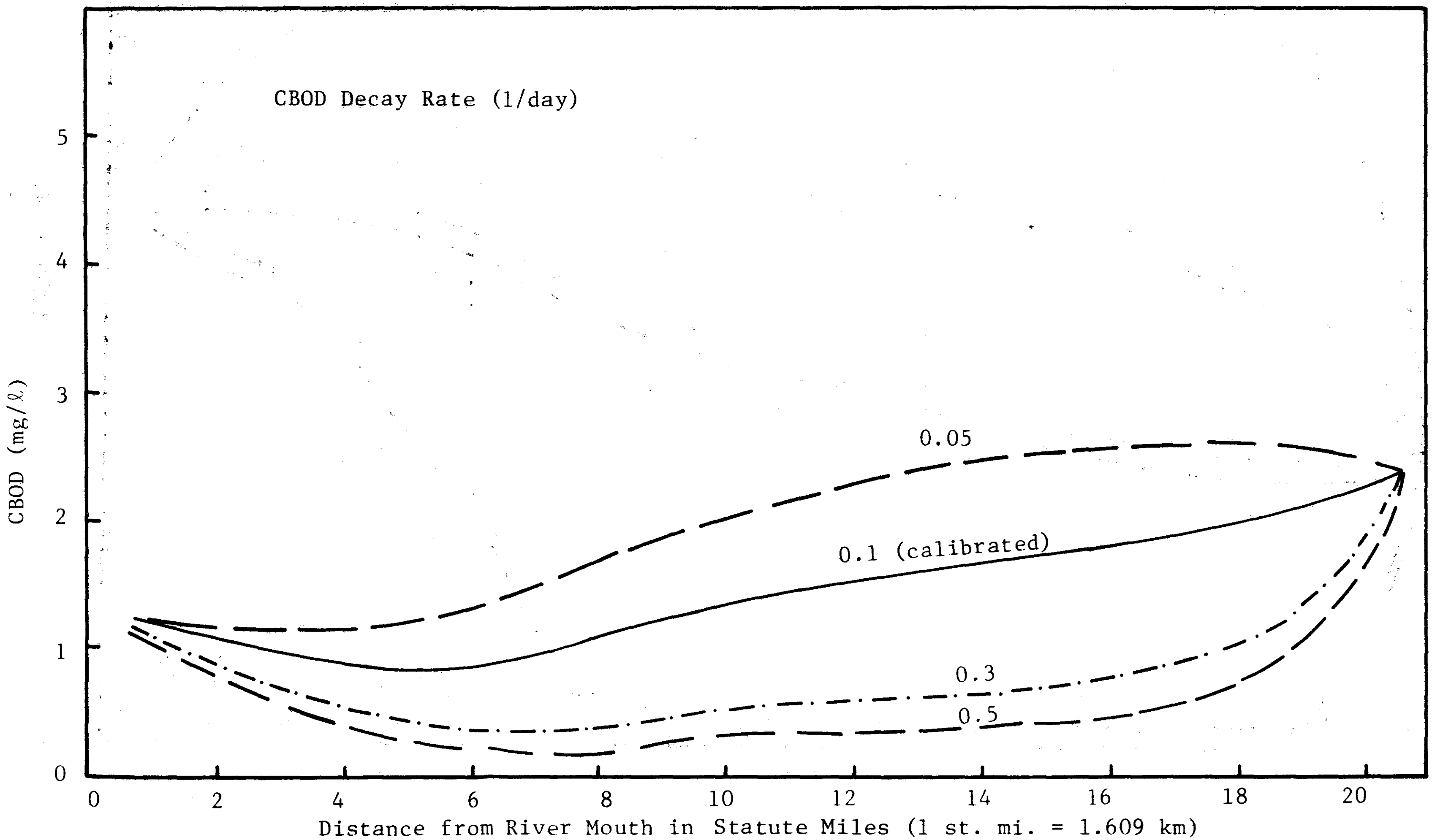

Figure 4.9. Effects of decay rate on CBOD distribution.

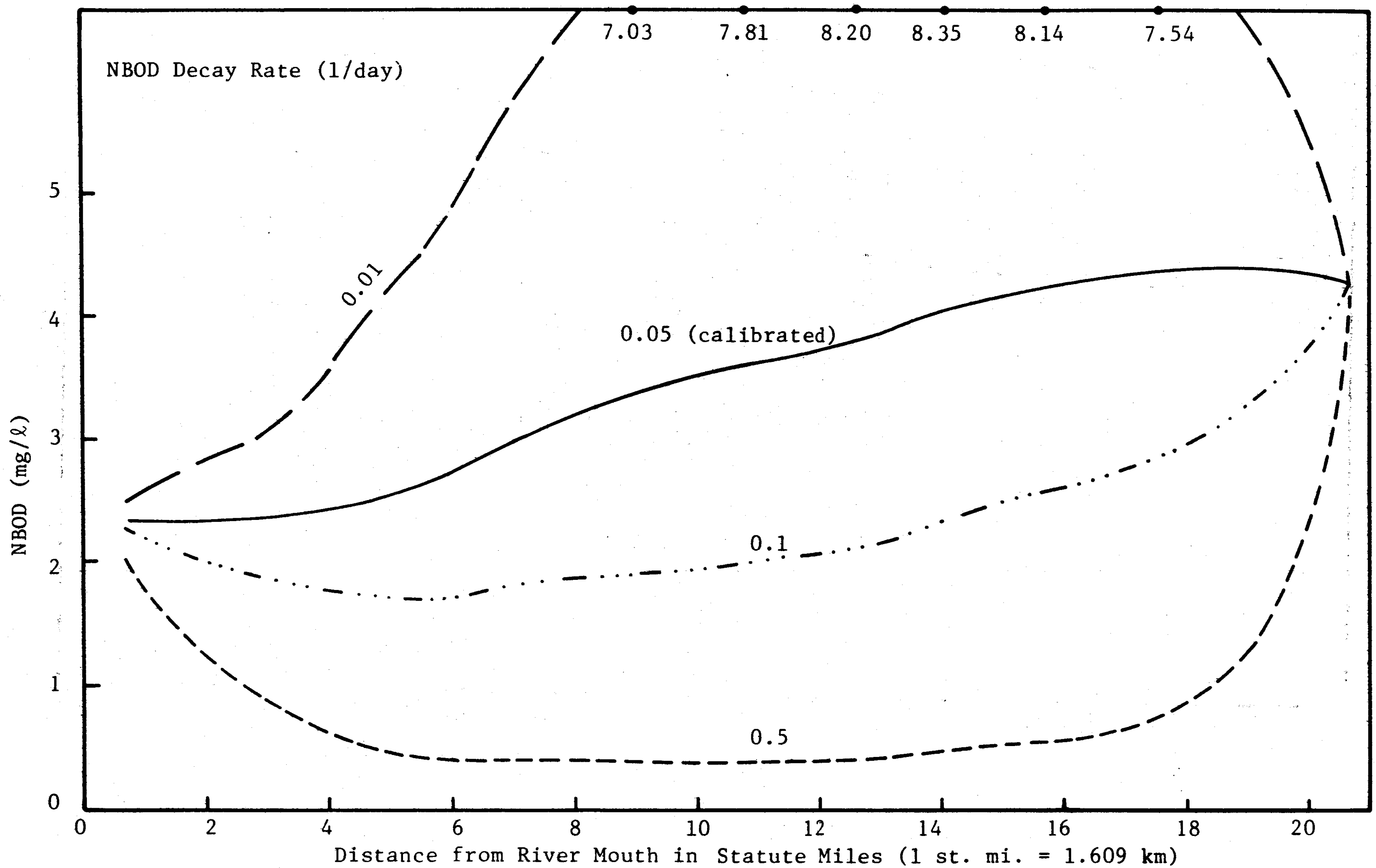

Figure 4.10. Effects of decay rate on NBOD distribution.

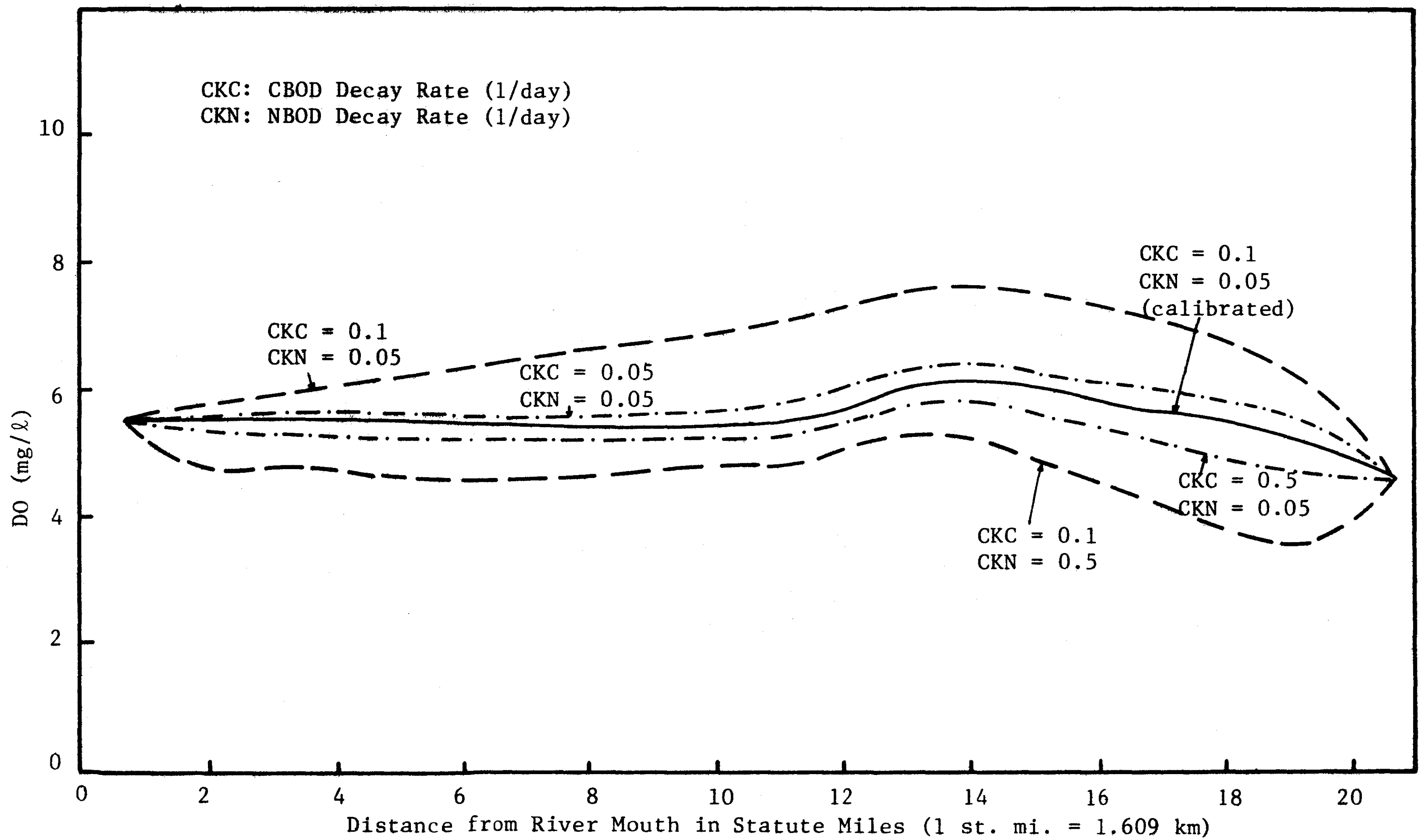

Figure 4.11. Effects of CBOD and NBOD decay rate on DO distribution.

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APPENDIX A. GRAPHIC SUMMARY OF TIDE STAGE AND CURRENT

Tide stages at Chickahominy Bridge and near Walkers Dam are graphically summarized. Current speed and direction near surface and bottom at 6 anchor stations are also graphically summarized here. For current at the other different depths, the reader is referred to the original set of field data.

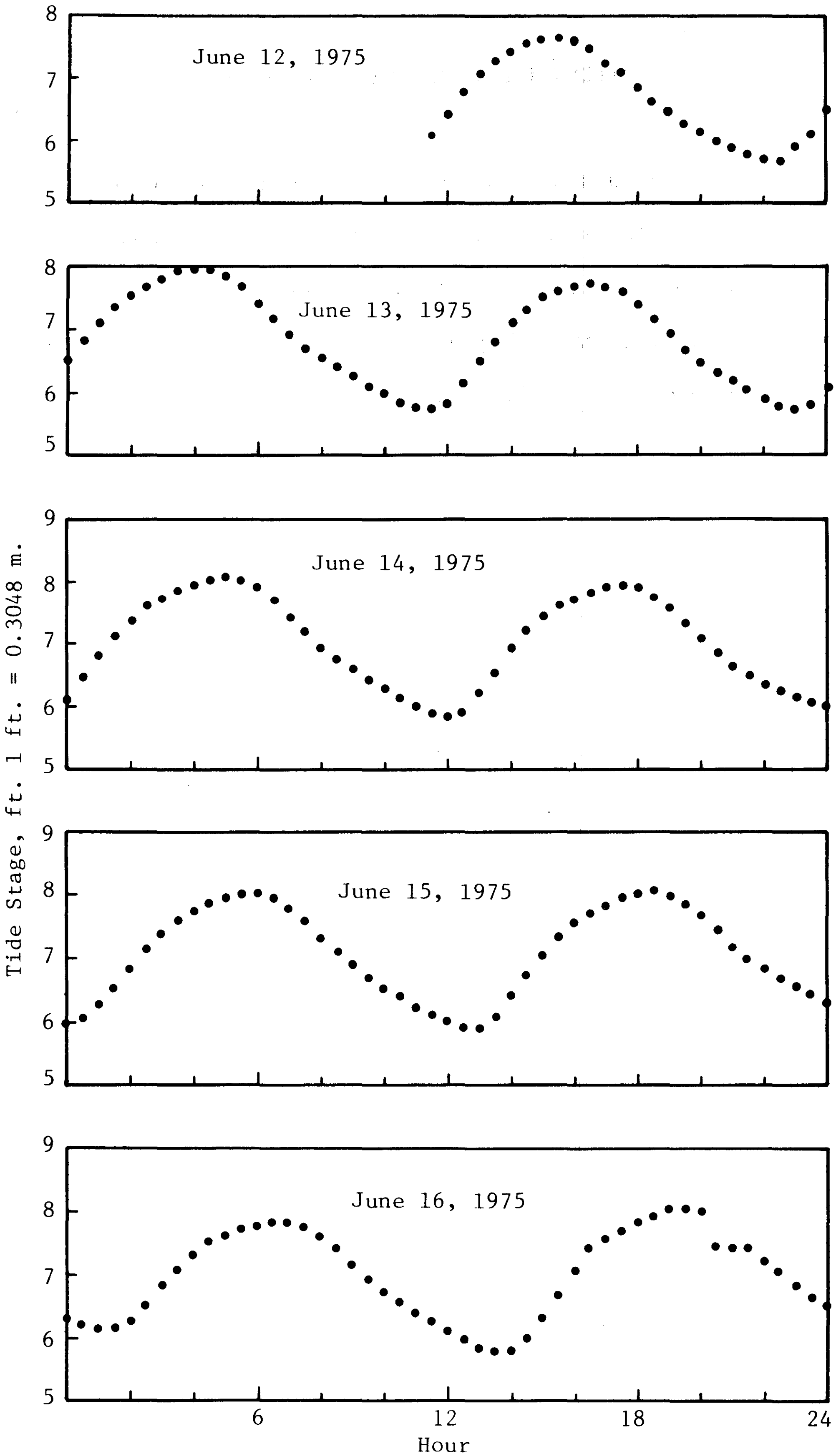

Figure A.1a. Tide stage at Chickahominy Bridge.

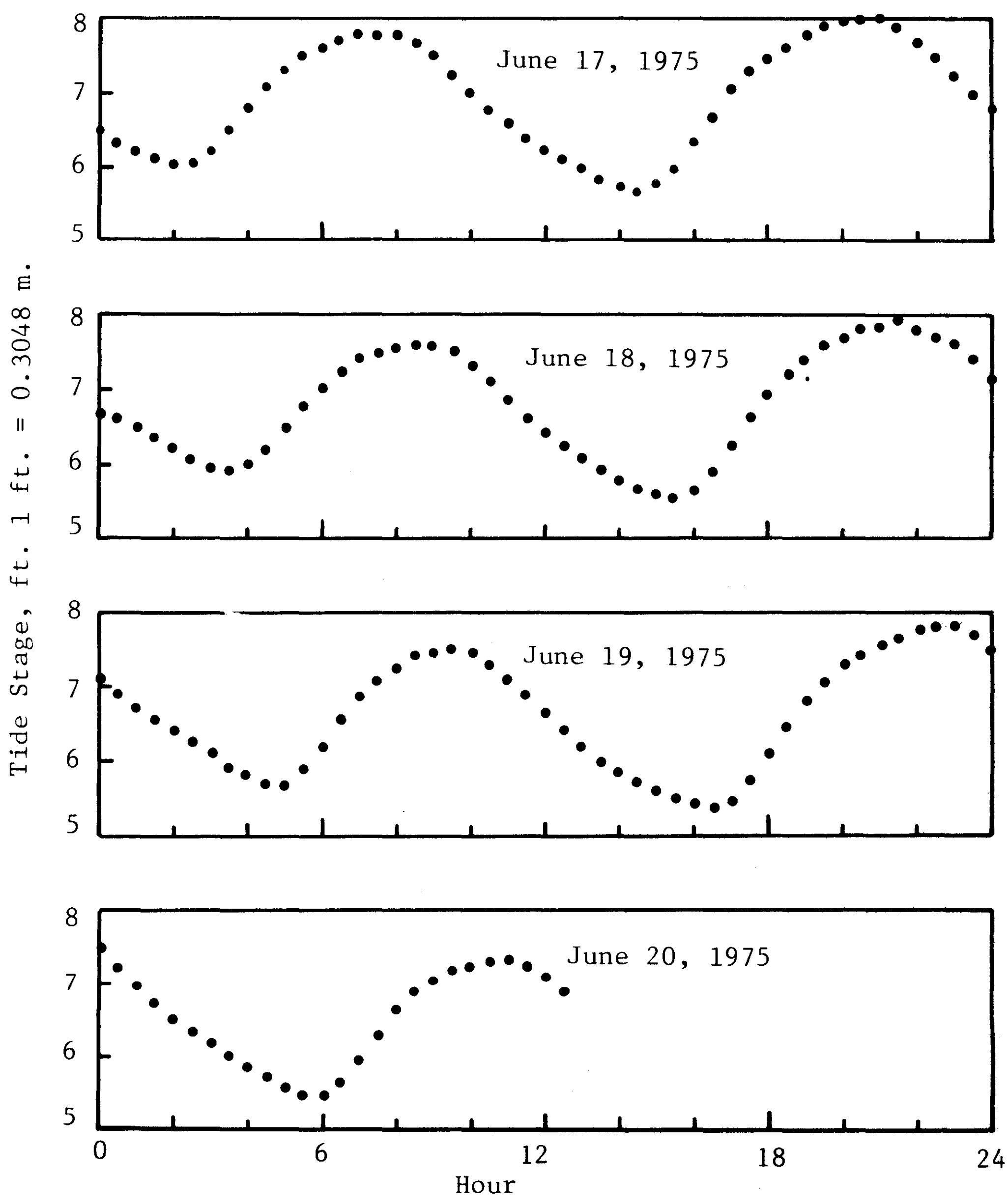

Figure A.1b. Tide stage at Chickahominy Bridge.

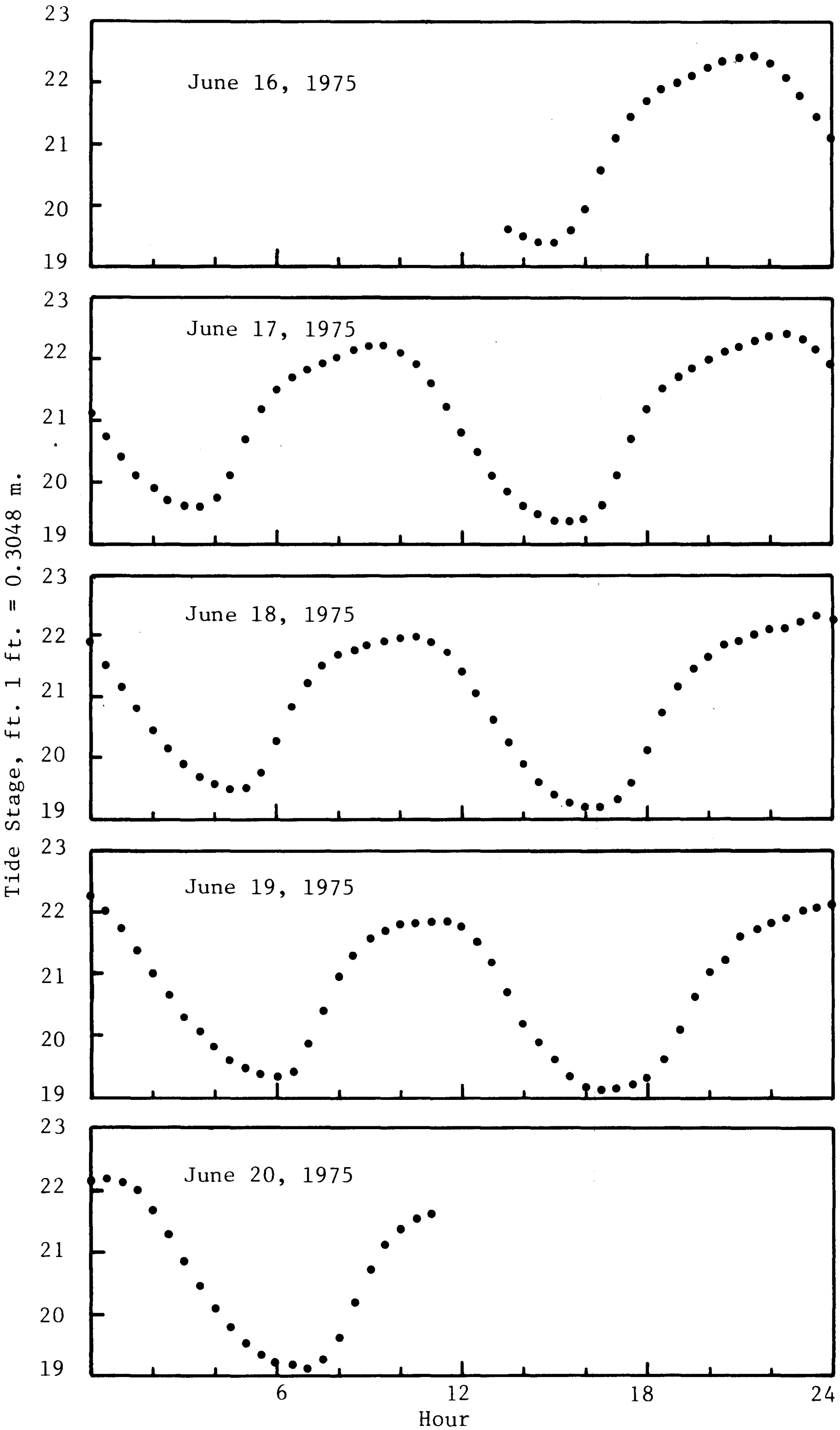

Figure A.2. Tide stage near Walkers Dam.

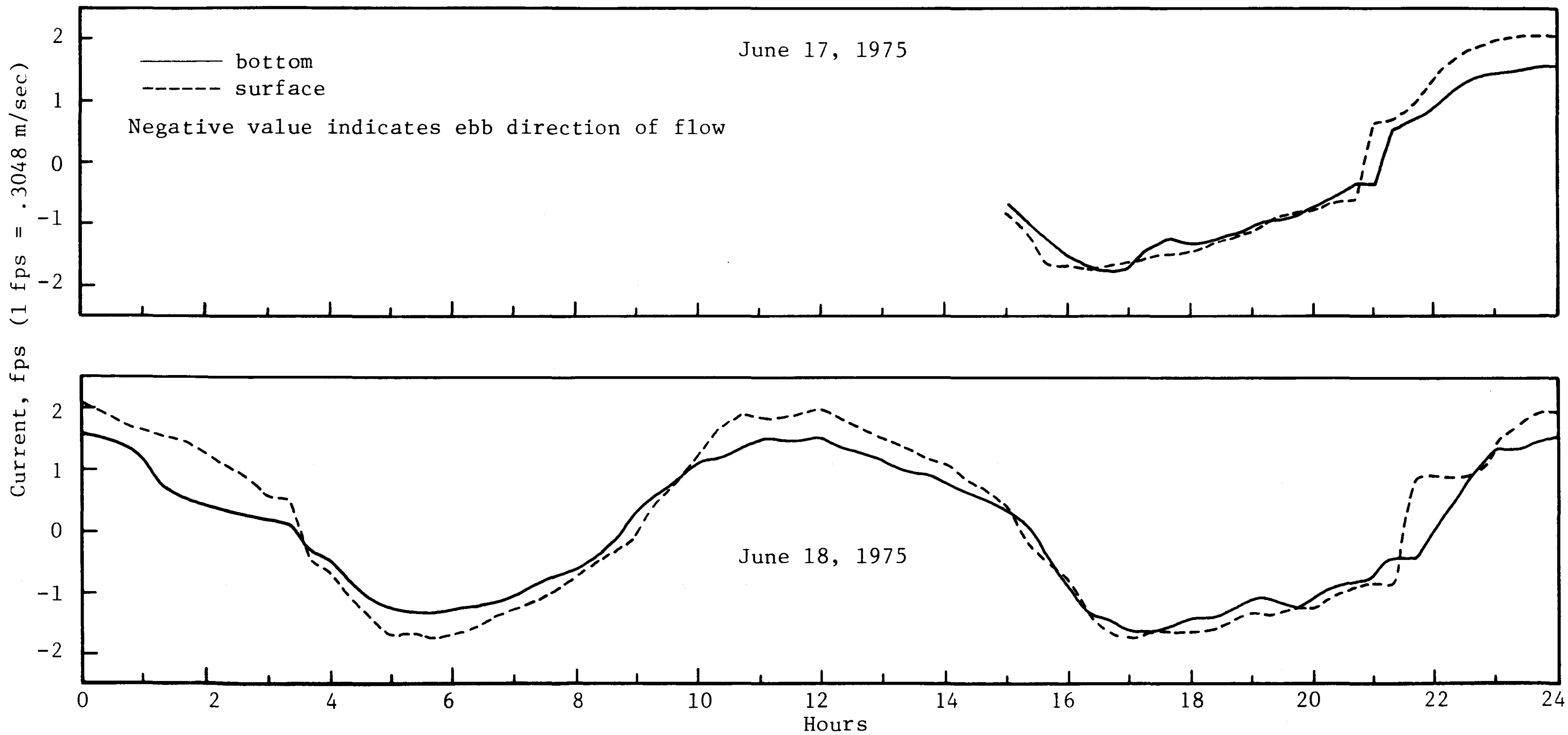

Figure A.3a. Tidal current at station JC1 (see Fig. 3.1 and Table 3.1).

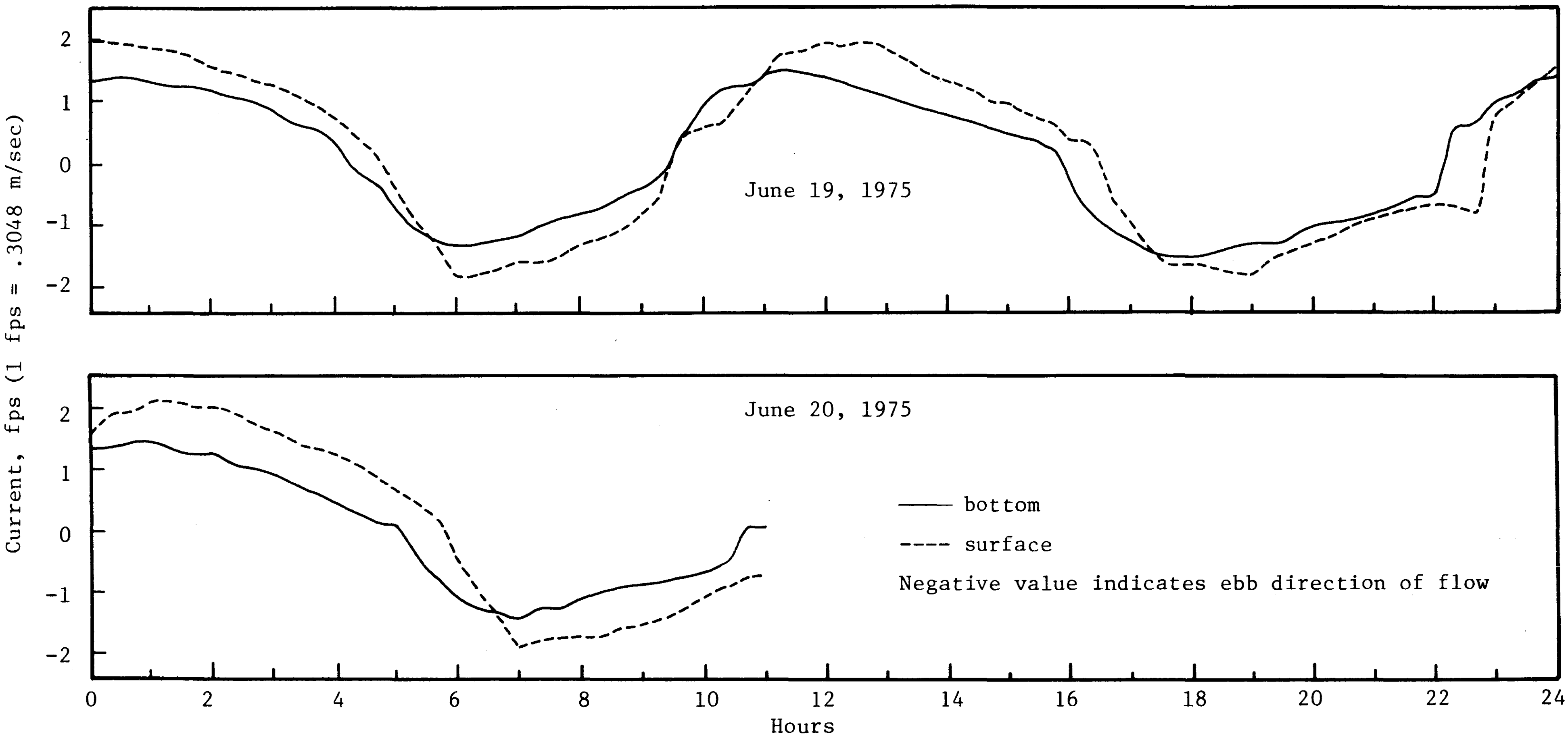

Figure A.3b. Tidal current at station JC 1 (see Fig. 3.1 and Table 3.1).

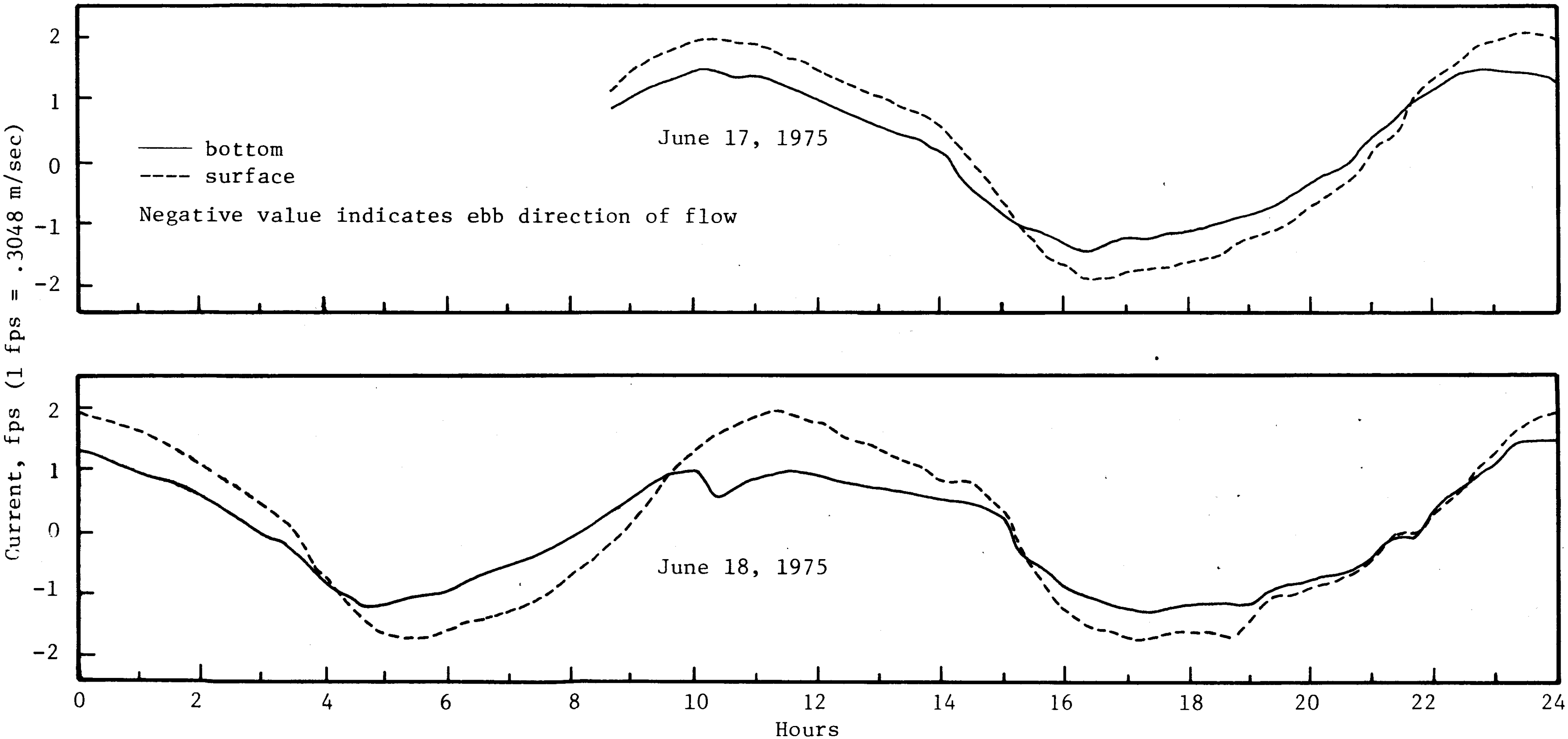

Figure A.4a. Tidal current at station JC2 (see Fig. 3.1 and Table 3.1).

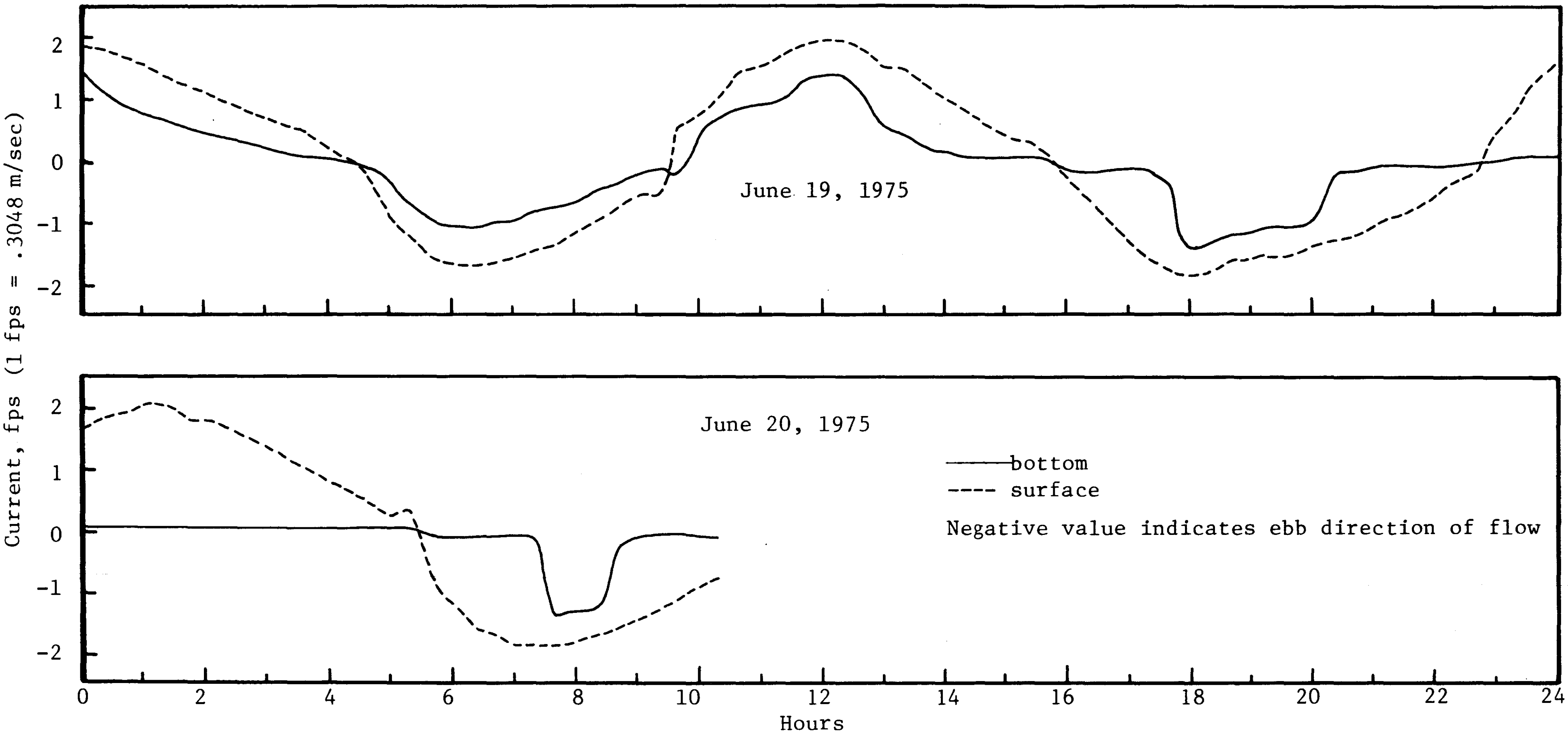

Figure A.4b. Tidal current at station JC2 (see Fig. 3.1 and Table 3.1).

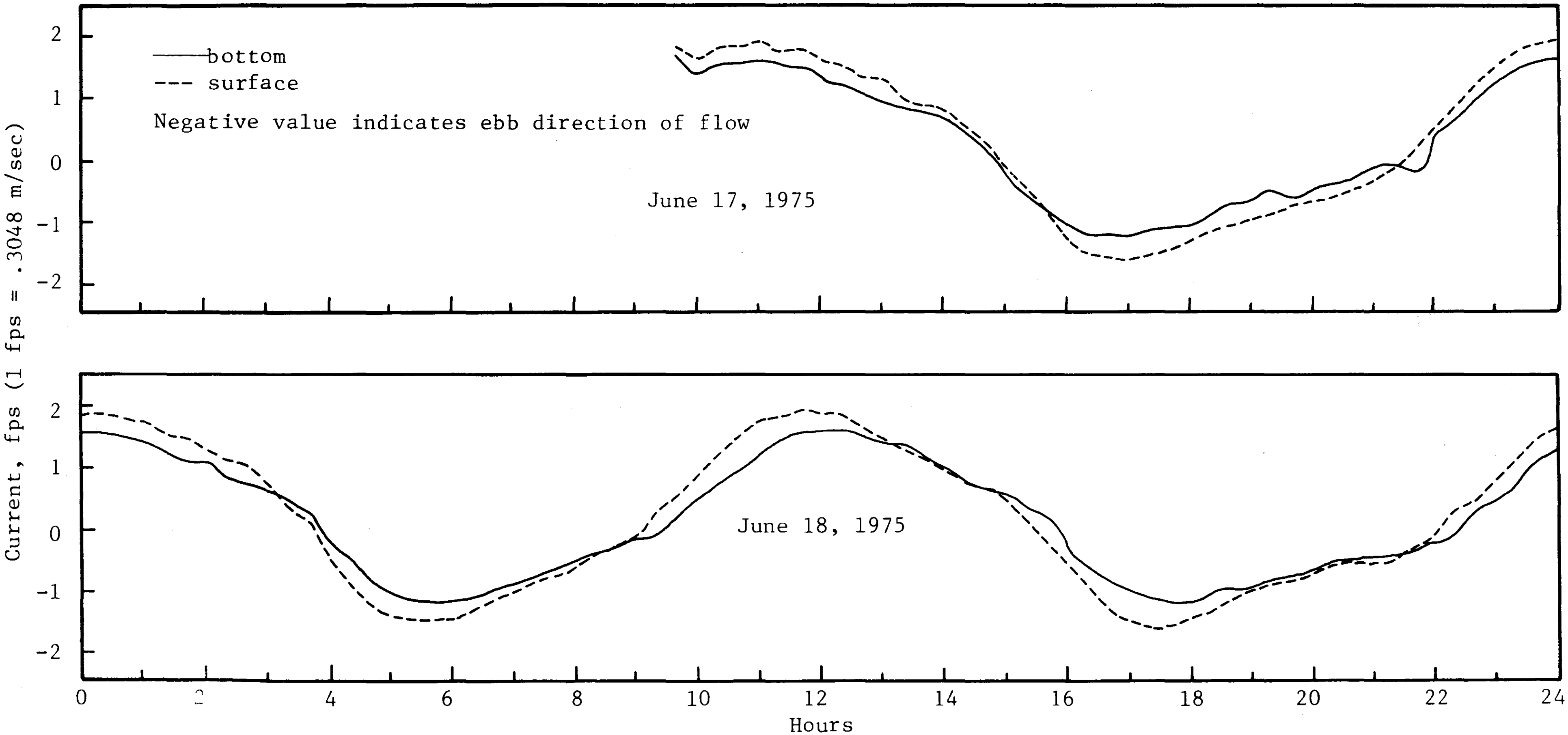

Figure A.5a. Tidal current at station JC3 (see Fig. 3.1 and Table 3.1).

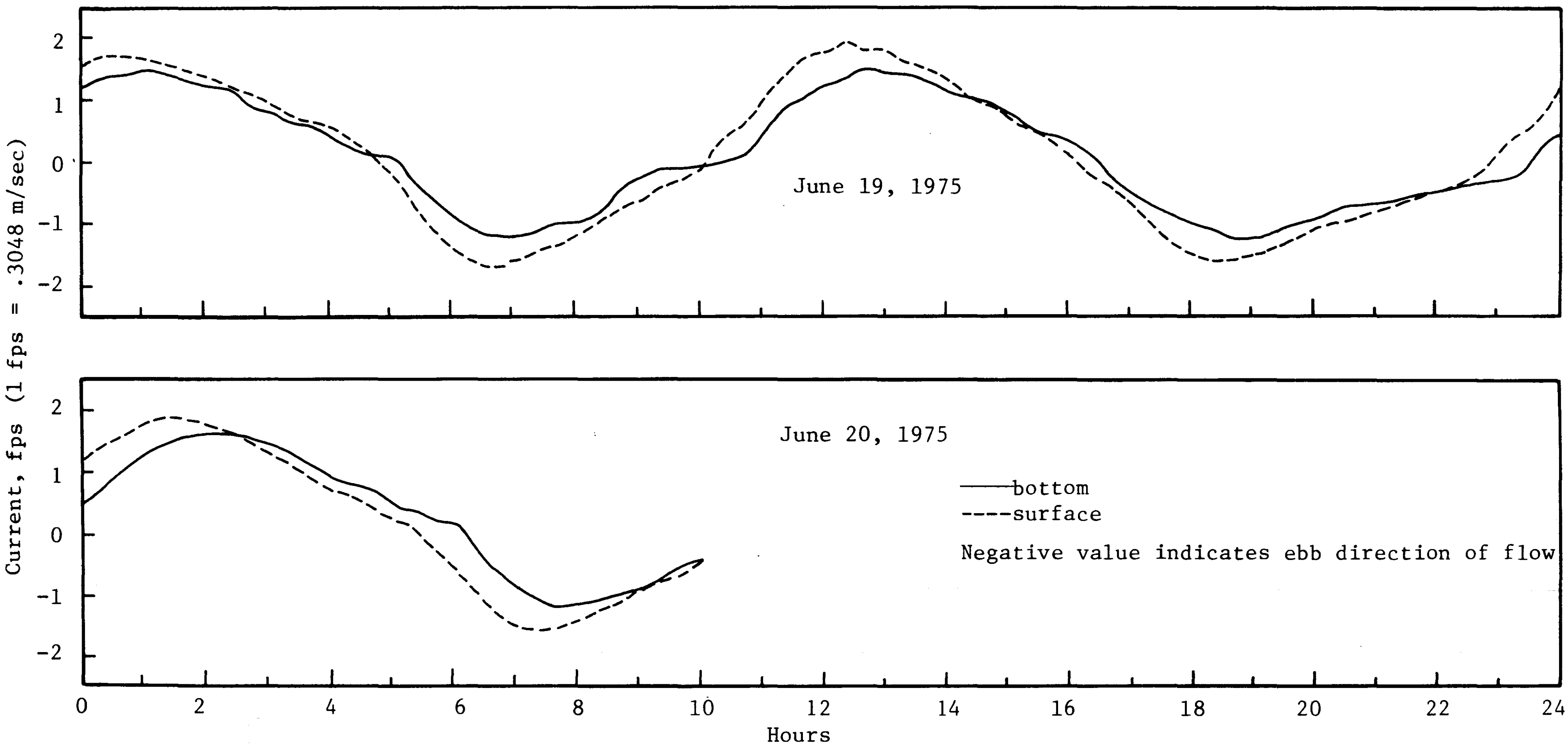

Figure A.5b. Tidal current at station JC3 (see Fig. 3.1 and Table 3.1).

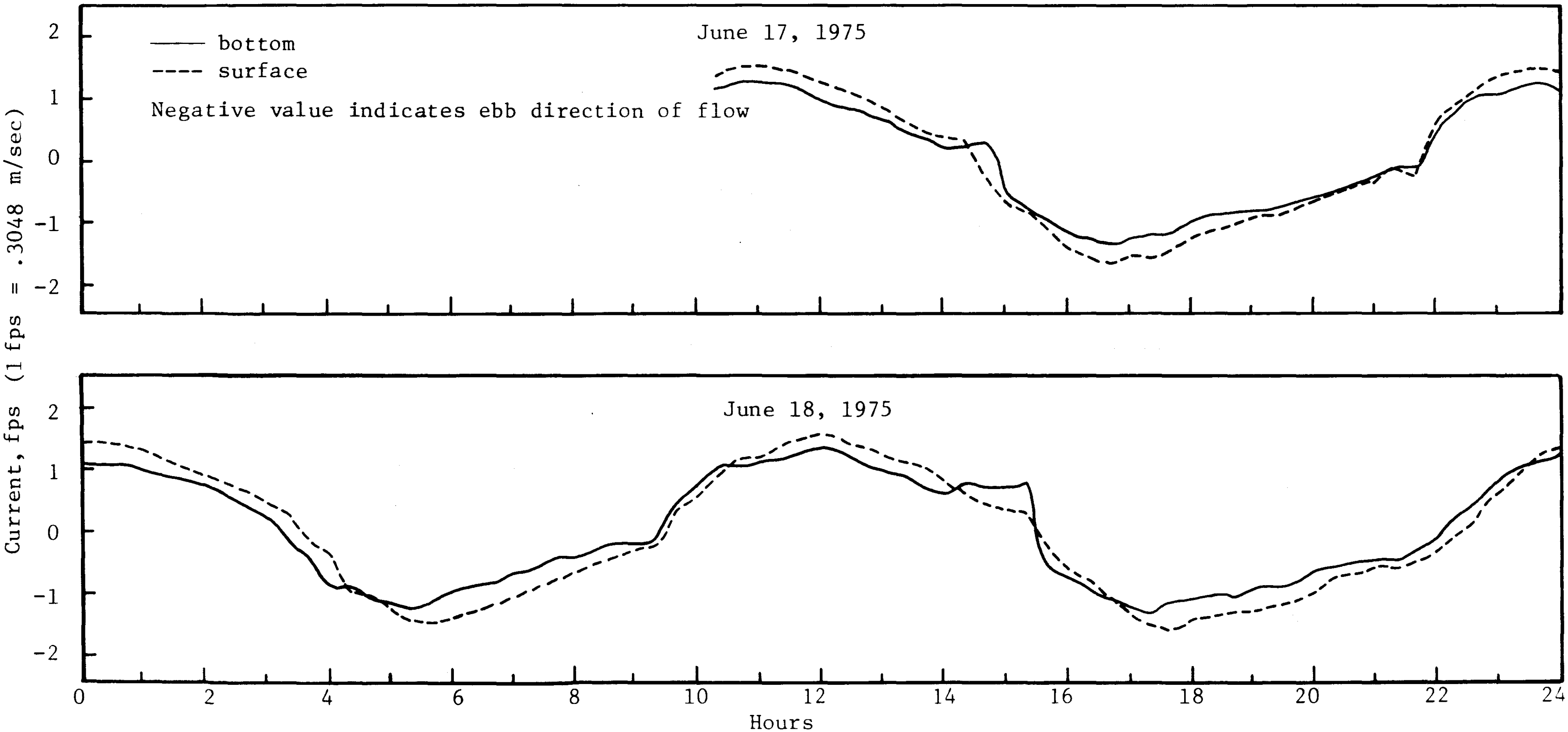

Figure A.6a. Tidal current at station JC 4 (see Fig. 3.1 and Table 3.1)

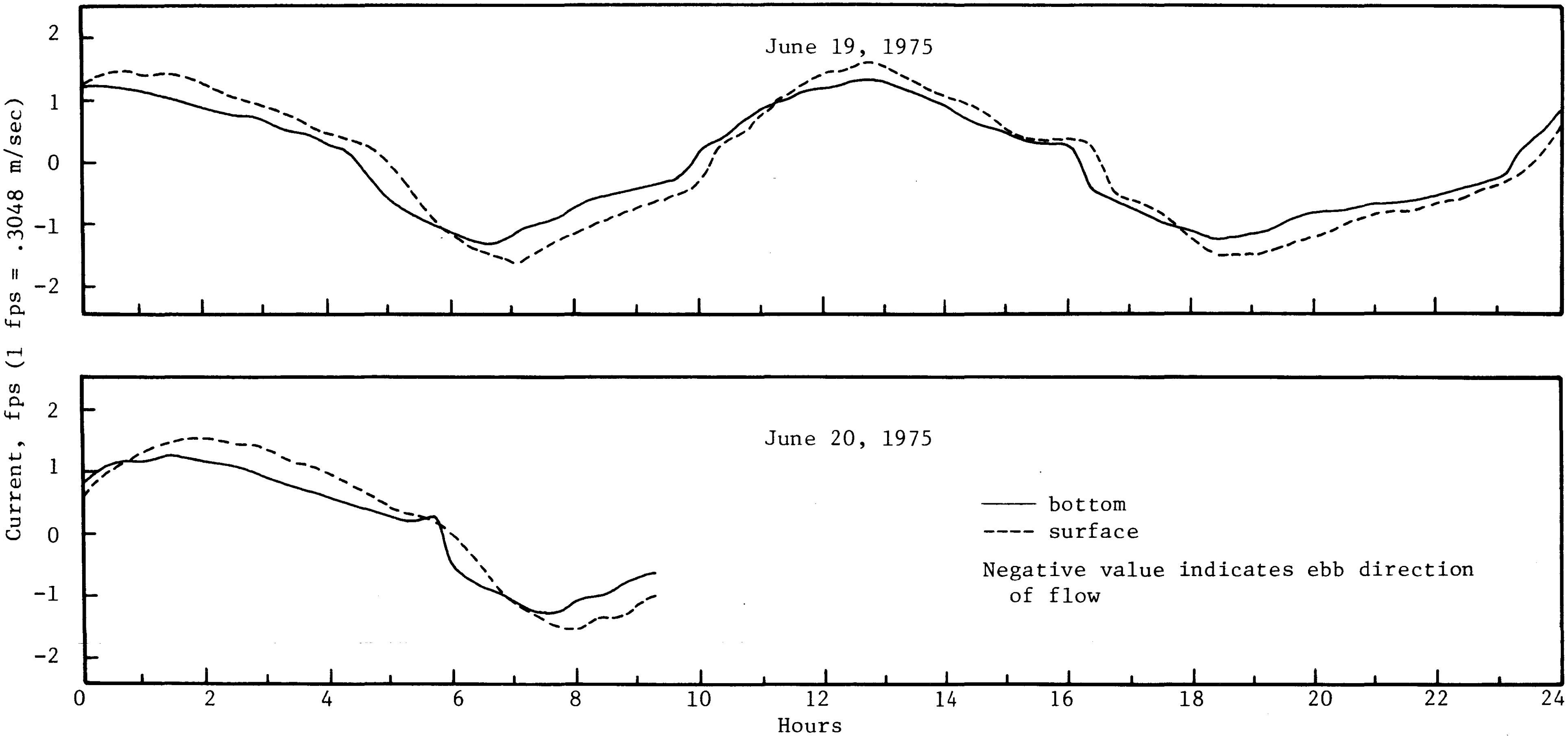

Figure A.6b. Tidal current at station JC4 (see Fig. 3.1 and Table 3.1).

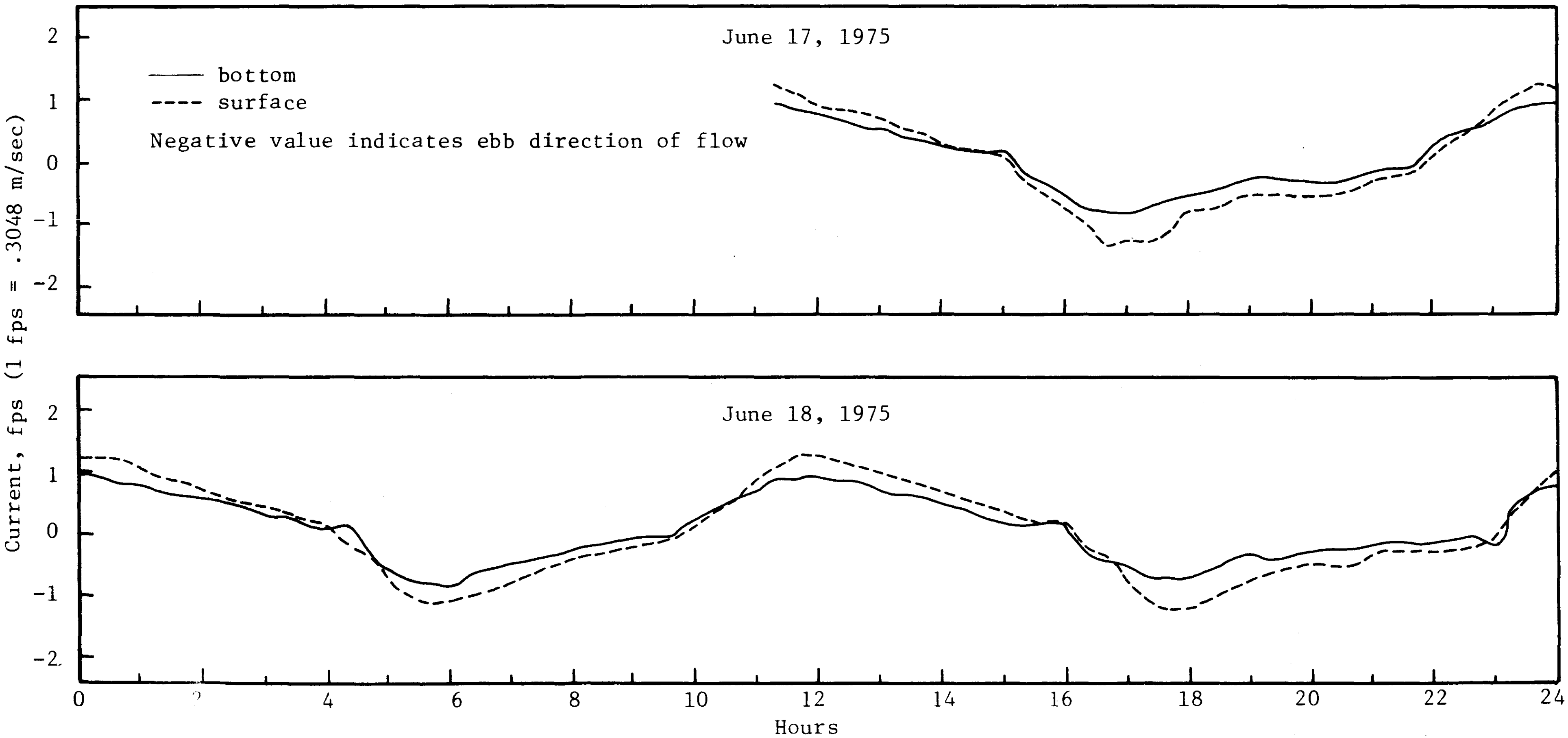

Figure A.7a. Tidal current at station JC5 (see Fig. 3.1 and Table 3.1).

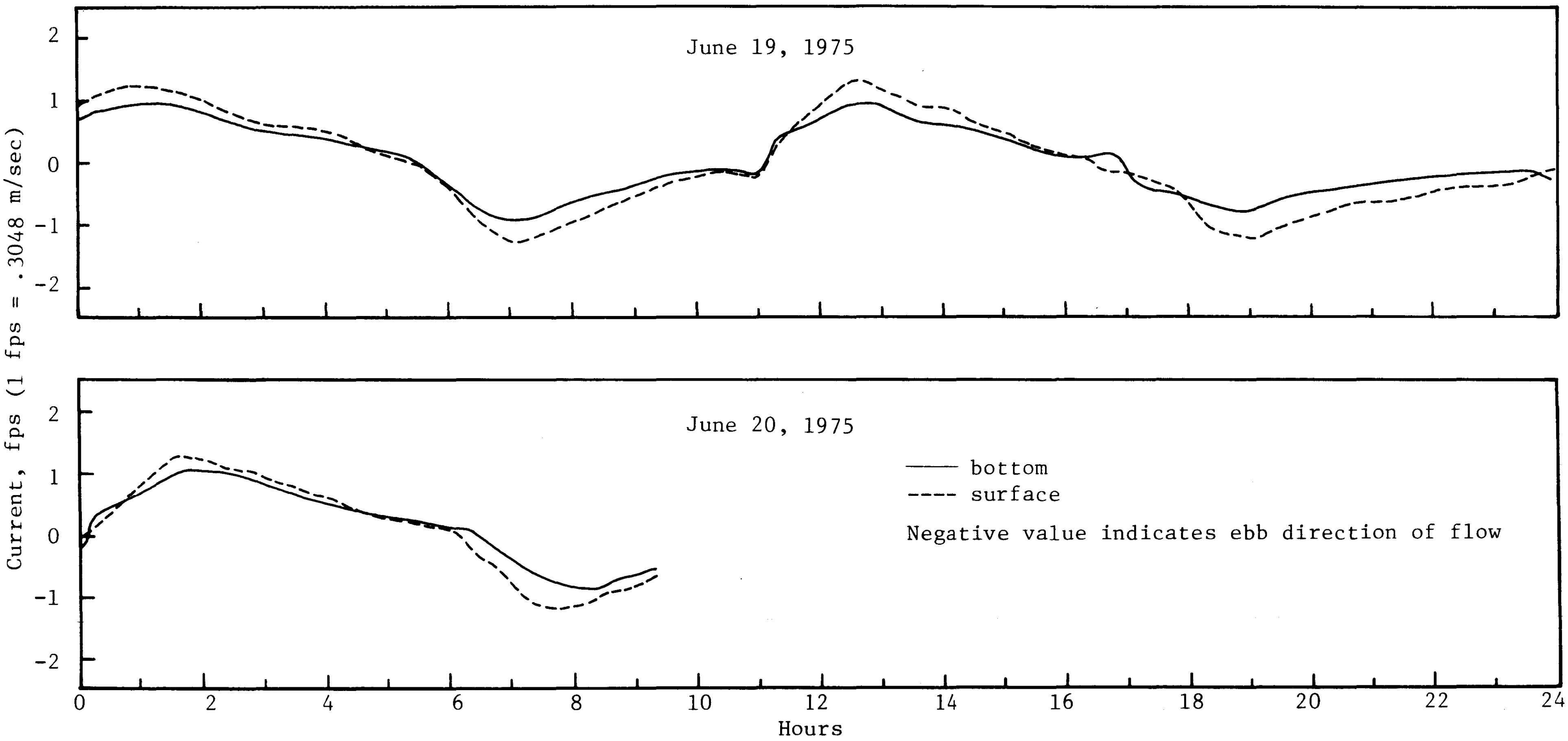

Figure A.7b. Tidal current at station JC5 (see Fig. 3.1 and Table 3.1).

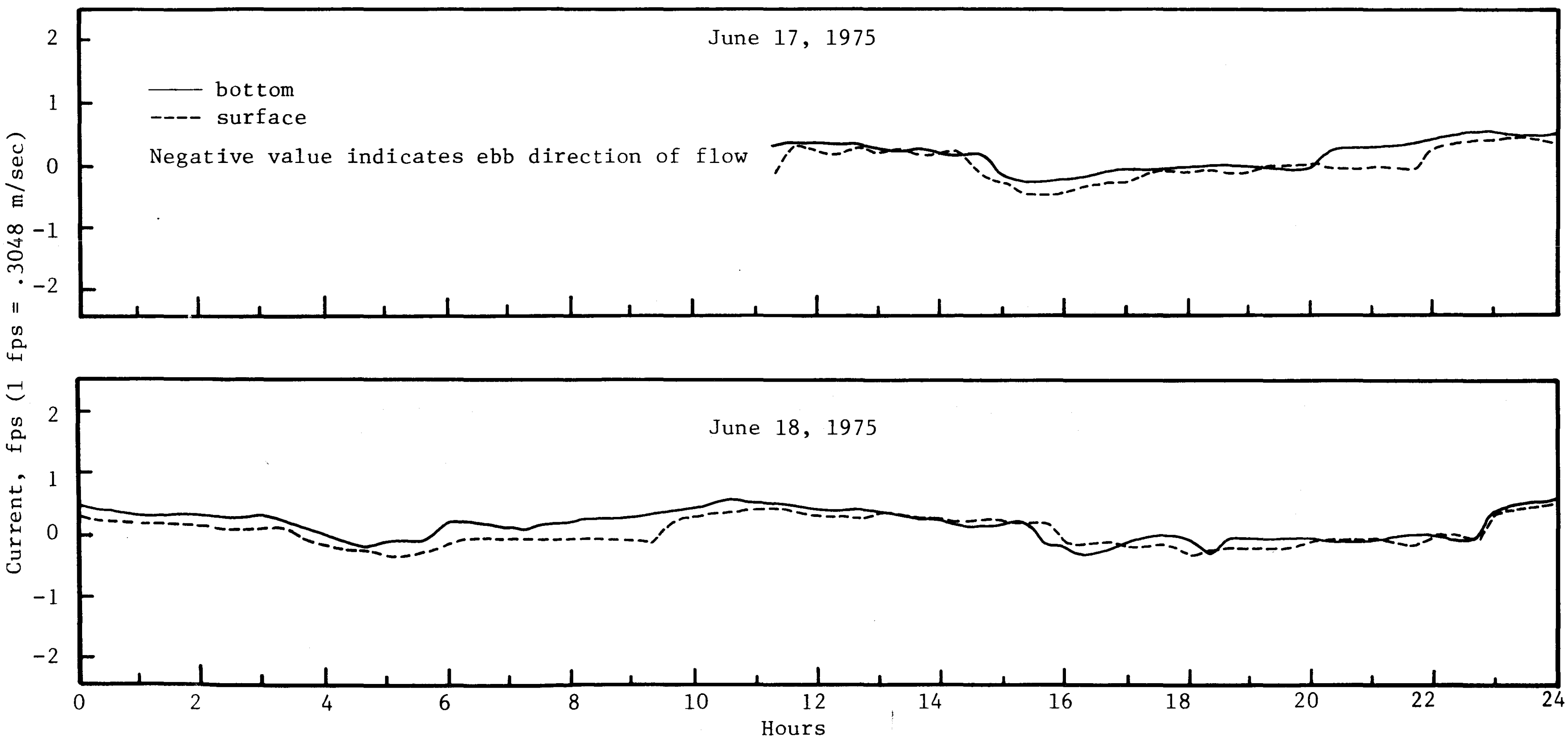

Figure A.8a. Tidal current at station JC6 (see Fig. 3.1 and Table 3.1).

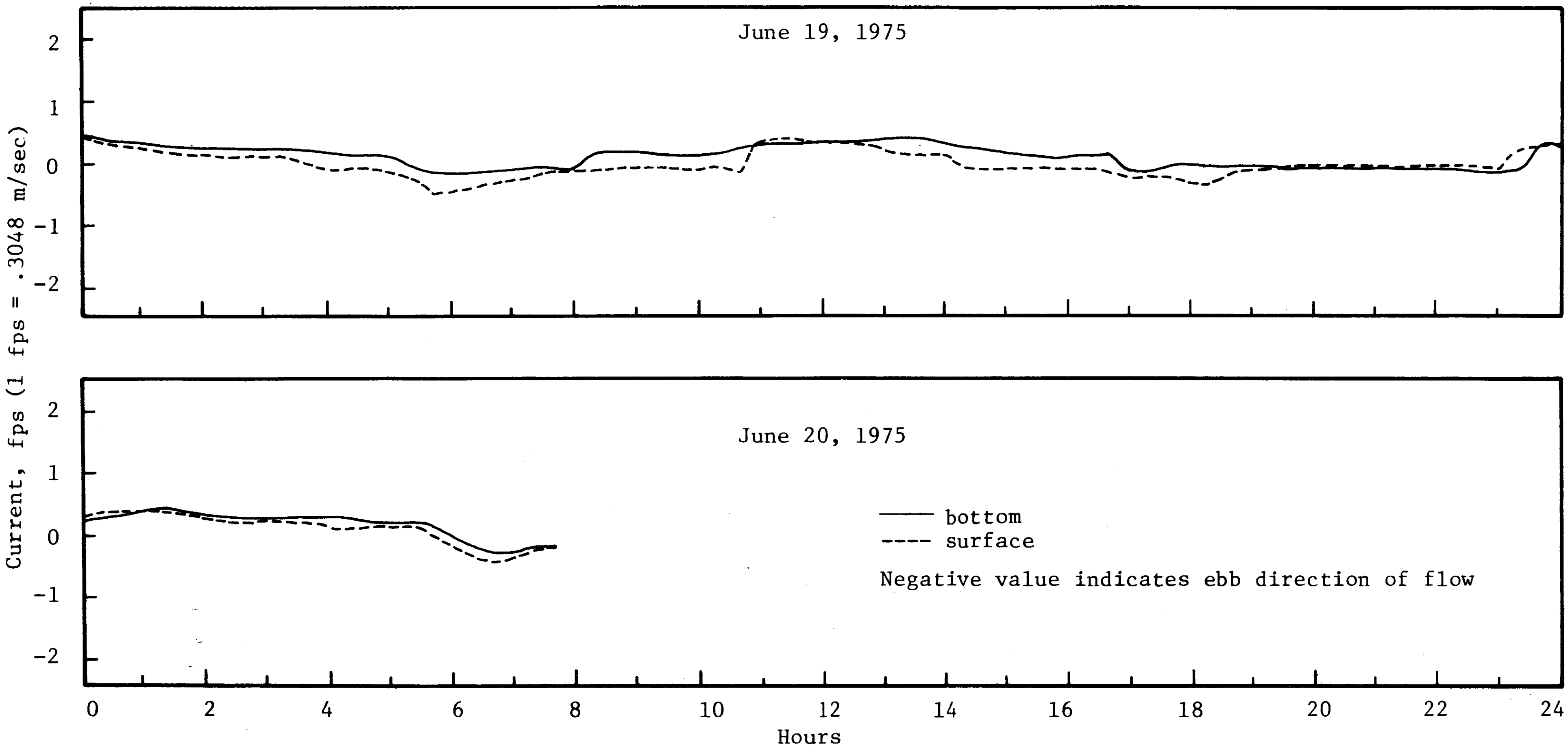

Figure A.8b. Tidal current at station JC6 (see Fig. 3.1 and Table 3.1).

APPENDIX B. SUMMARY OF WATER QUALITY DATA

The water quality data from 6 anchor stations and 4 slack water runs were sampled at several depths at each station. This appendix only presents the data near surface and bottom. In addition, Figures 4.5 thru 4.7 also show the graphic summary of CBOD, NBOD and DO for the four slack water runs. The reader is referred to the original set of field data for more information.

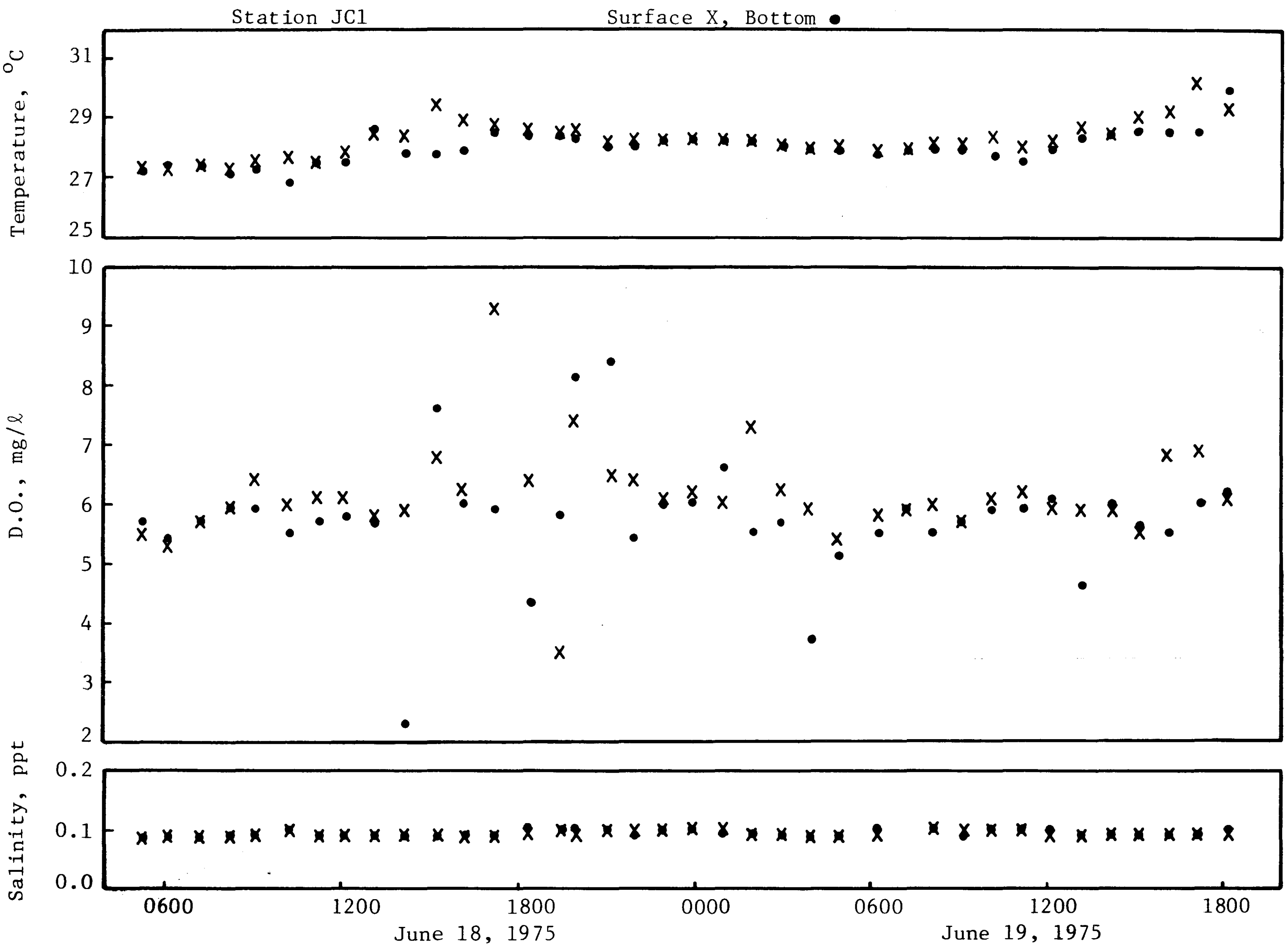

Figure B.1. Temporal and depth variations of temperature, DO, and salinity.

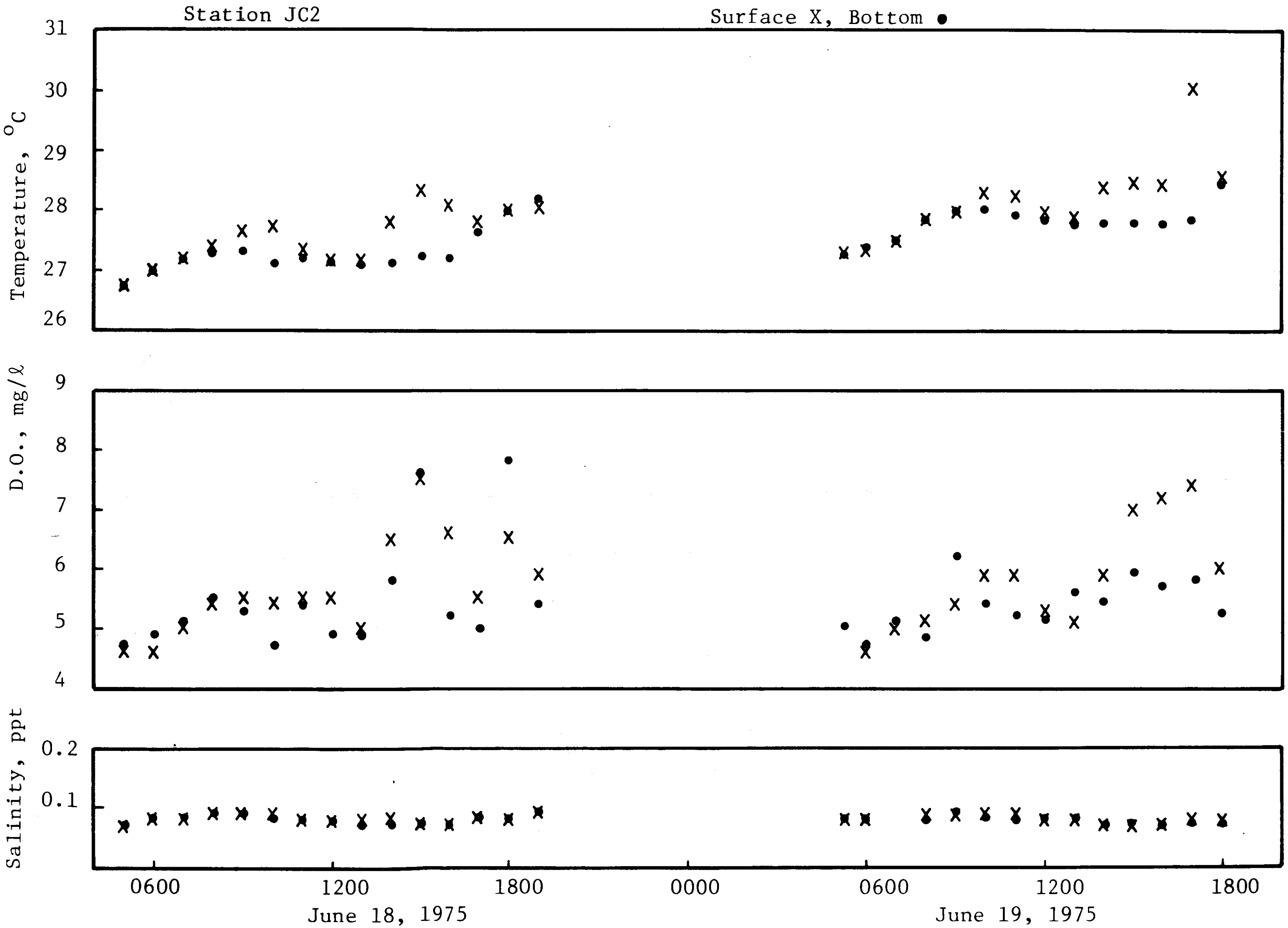

Figure B.2. Temporal and depth variation of temperature, DO, and salinity.

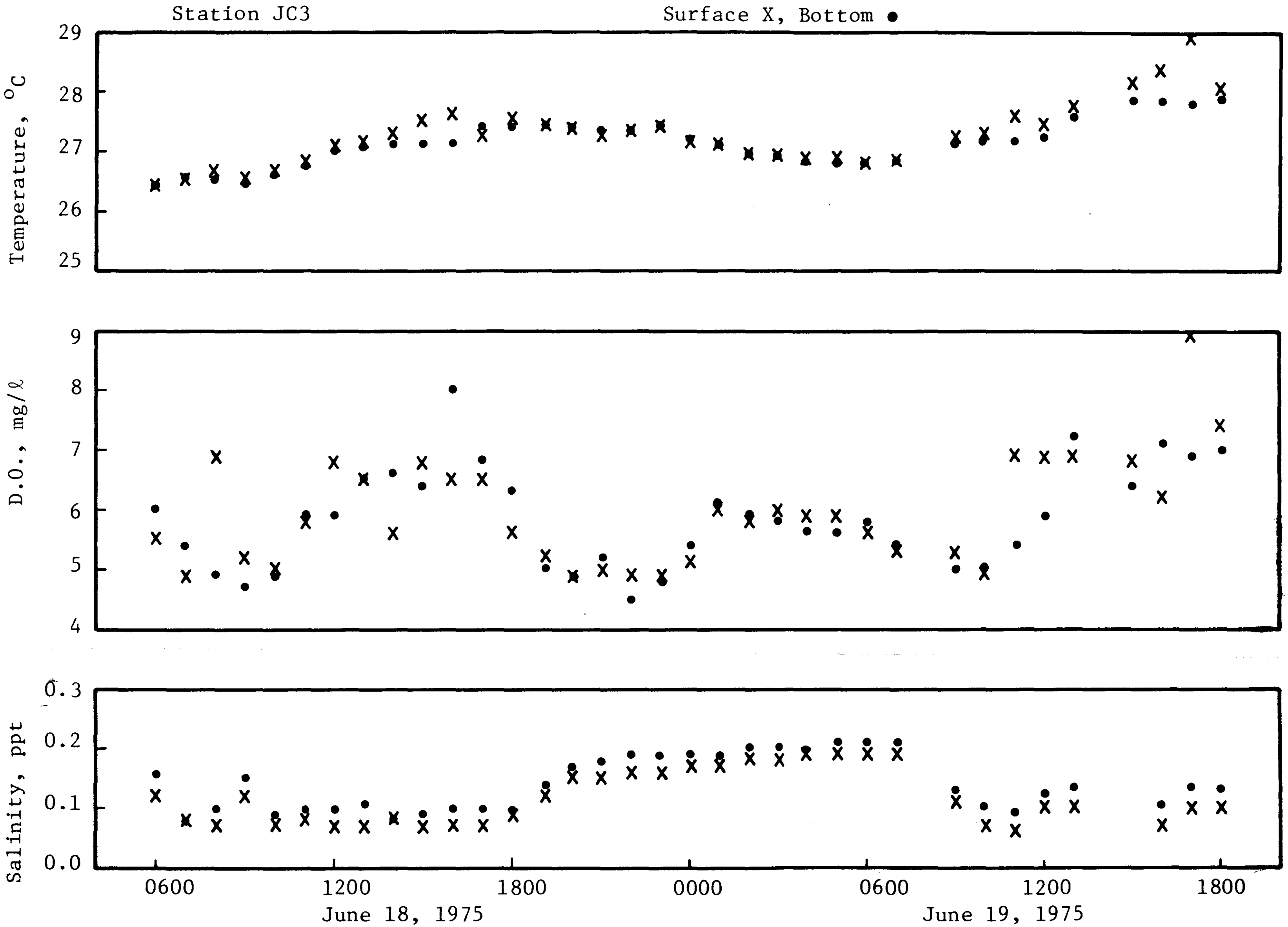

Figure B.3. Temporal and depth variation of temperature, DO, and salinity.

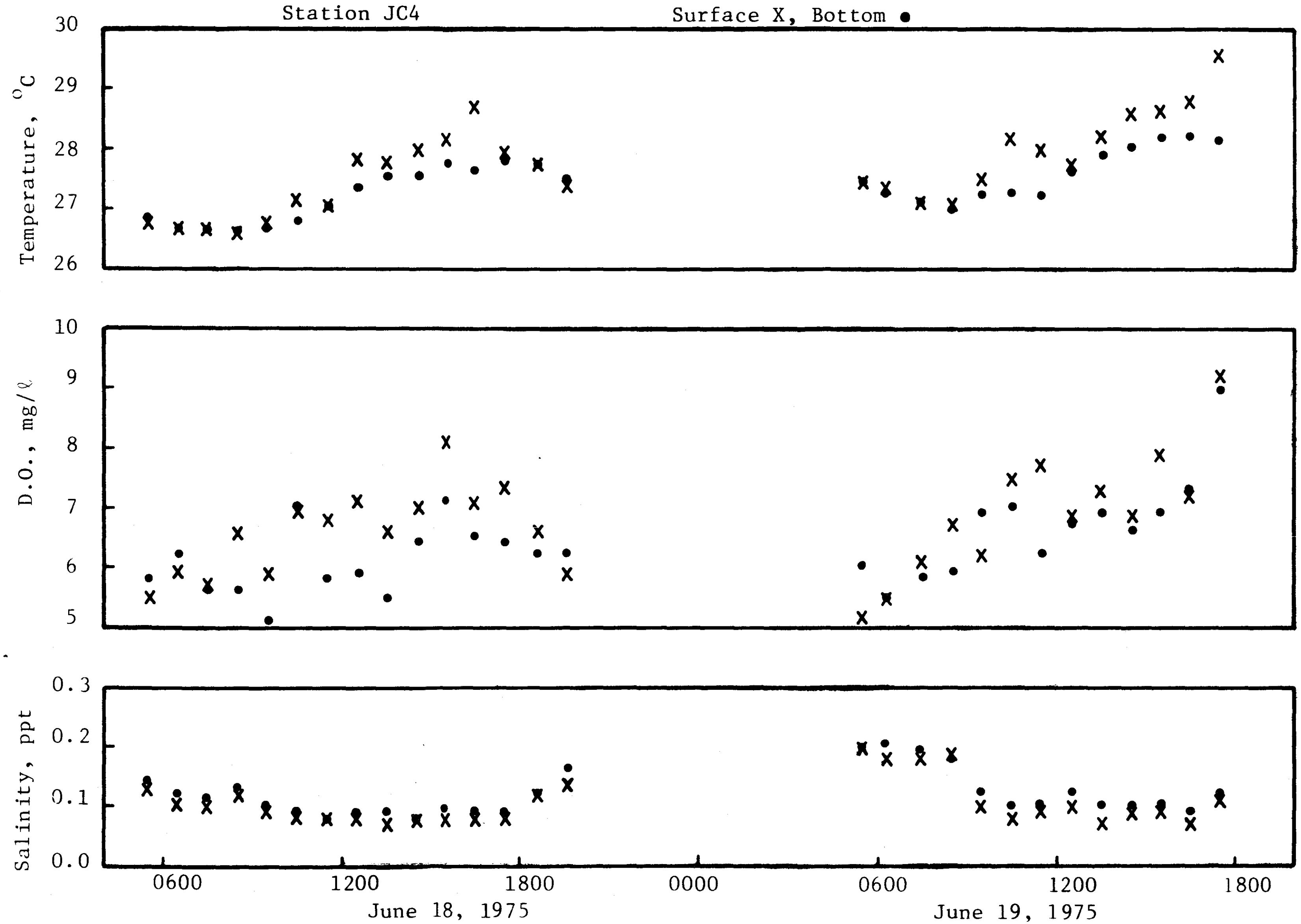

Figure B.4. Temporal and depth variation of temperature, DO, and salinity.

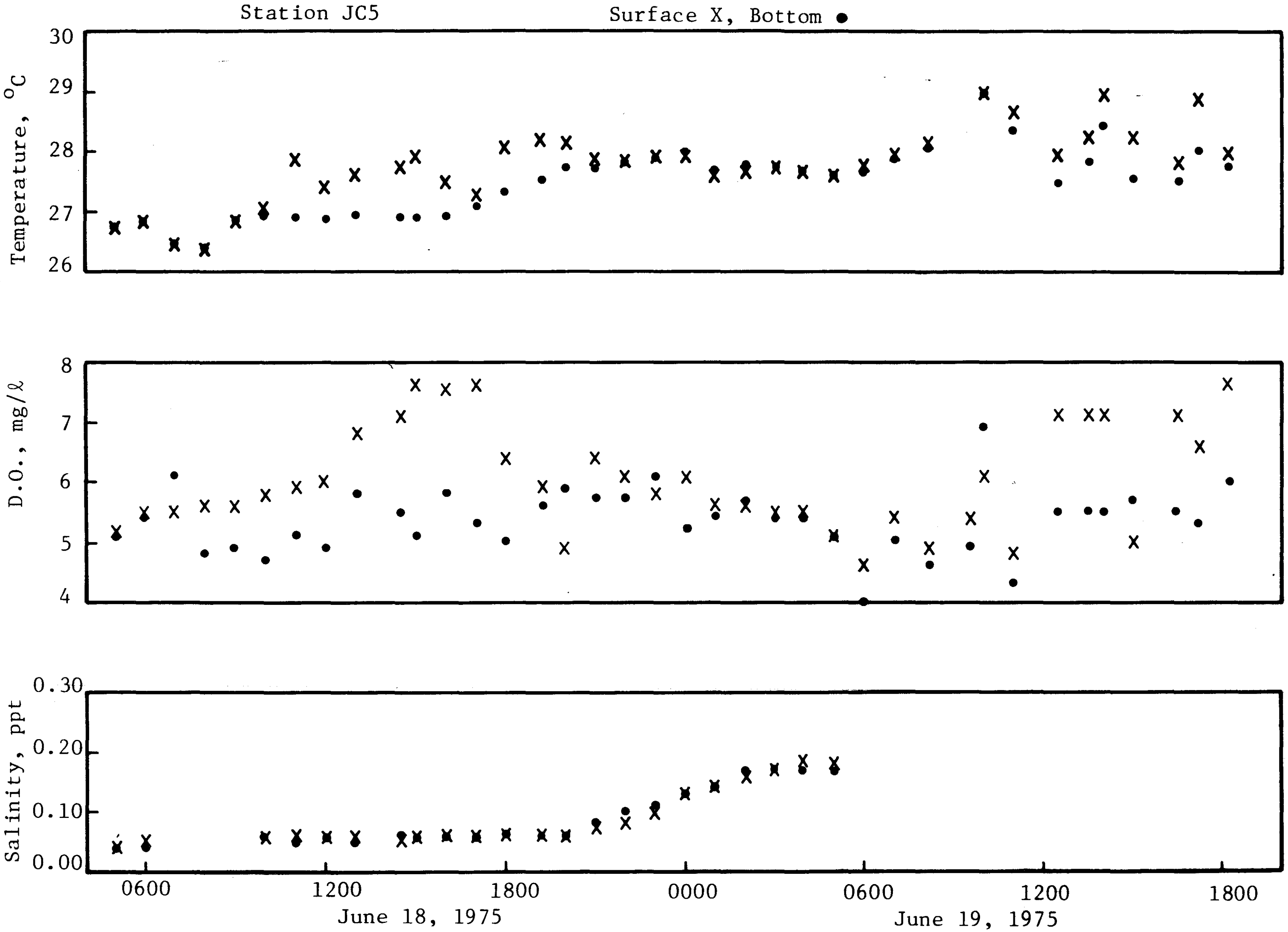

Figure B.5. Temporal and depth variation of temperature, DO, and salinity.

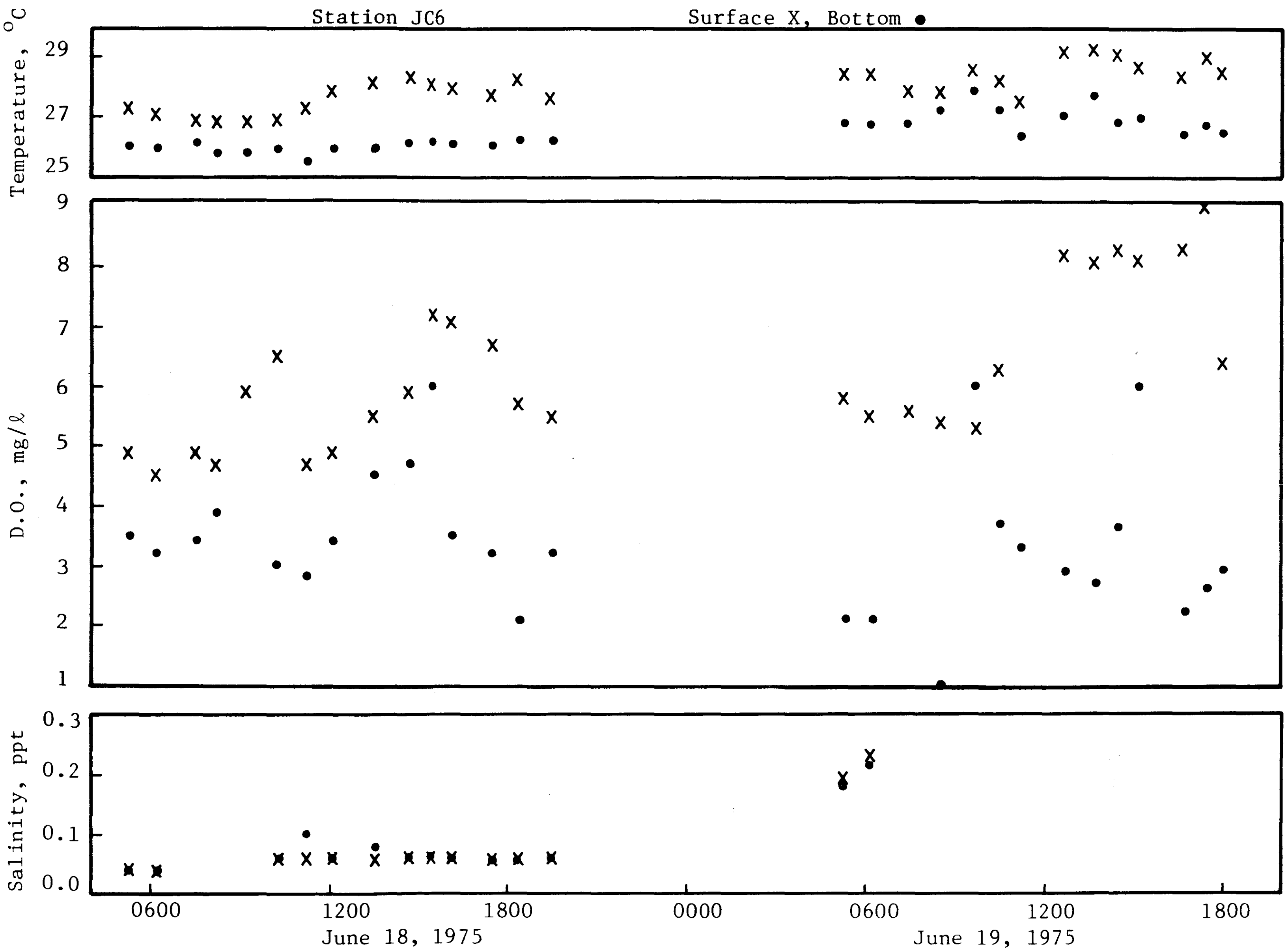

Figure B.6. Temporal and depth variation of temperature, DO, and salinity.

Table B.1. Water Quality Data of High Water Slack, 08:30~10:30, on June 4, 1975.

(In each space below, the first and the second row present respectively the values near the surface and the bottom of the river)

Distance from River Mouth mi (km)	Water Conductivity mmhos/cm^2	Water Temperature ^oC	Salinity ppt	DO mg/ℓ	BOD_5 mg/ℓ	TKN mg/ℓ
	0.13	25.48	0.08	5.3	-	0.30
0.0 (0.0)	0.13	25.28	0.08	4.6	-	0.31
	0.14	25.77	0.08	4.7	-	0.38
2.65 (4.26)	0.13	25.71	0.08	5.4	2.81	0.36
	0.13	25.76	0.08	5.2	-	0.44
4.72 (7.60)	0.13	25.71	0.08	4.9	-	0.36
	0.11	25.83	0.07	5.3	0.54	0.60
7.94 (12.78)	0.10	25.58	0.06	4.9	-	0.56
	0.09	26.03	0.06	6.1	0.77	0.66
11.51 (18.52)	0.09	25.84	0.06	4.2	-	0.66
	0.08	25.90	0.06	5.3	-	0.51
16.11 (25.93)	0.08	25.81	0.06	5.4	-	0.66
	0.08	25.95	0.06	8.0	2.40	0.80
20.71 (33.33)	0.08	24.75	0.06	1.6	-	0.74

Table B.2. Water Quality Data of High Water Slack, 08:00~09:30, on June 18, 1975.

(In each space below, the first and the second row present respectively the values near the surface and the bottom of the river)

Distance from River Mouth mi (km)	Water Conductivity mmhos/cm^2	Water Temperature ^oC	Salinity ppt	DO mg/ℓ	BOD_6 mg/ℓ	TKN mg/ℓ
	0.15	27.57	0.08	5.8	-	0.51
0.0 (0.0)	0.15	27.55	0.08	5.8	0.11	0.78
	0.15	27.44	0.08	-	-	0.53
2.65 (4.26)	0.15	27.44	0.08	-	-	0.67
	0.14	27.53	0.08	5.4	0.44	0.50
4.72 (7.60)	0.14	27.46	0.08	5.4	-	0.66
	0.11	26.94	0.07	5.4	0.30	0.64
7.94 (12.78)	0.10	26.87	0.06	4.7	-	0.66
	0.08	27.06	0.06	6.2	0.98	0.86
11.51 (18.52)	0.08	26.91	0.06	5.5	0.18	0.80
	0.07	27.10	0.05	5.7	1.34	1.16
16.11 (25.93)	0.07	27.08	0.05	4.8	1.20	1.93
	0.07	27.22	0.05	6.0	2.43	1.07
20.71 (33.33)	0.07	26.23	0.05	3.7	0.63	-

Table B.3. Water Quality Data of High Water Slack, 09:00~11:00, on June 19, 1975.

(In each space below, the first and the second row present respectively the values near the surface and the bottom of the river)

Distance from River Mouth mi (km)	Water Conductivity mmhos/cm^2	Water Temperature ^oC	Salinity ppt	DO mg/ℓ	BOD_5 mg/ℓ	TKN mg/ℓ
	-	28.10*	-	5.8	-	0.57
0.0 (0.0)	-	27.90*	-	5.7	-	0.55
	-	27.92*	-	-	-	0.47
2.65 (4.26)	-	27.87*	-	-	-	0.43
	-	28.00*	-	5.7	0.33	0.54
4.72 (7.60)	-	27.90*	-	5.8	-	0.55
	-	27.30*	-	5.0	-	0.78
7.94 (12.78)	-	27.15*	-	5.0	-	0.68
	-	27.40*	-	6.8	0.42	0.97
11.51 (18.52)	-	27.22*	-	6.9	0.41	0.88
	-	27.70*	-	5.9	0.43	0.67
16.11 (25.93)	-	27.42*	-	6.9	1.76	0.99
	-	29.00*	-	6.3	1.47	1.04
20.71 (33.33)	-	26.40*	-	3.7	-	0.93

* Measured on an ARA unit in the field.

Table B.4. Water Quality Data of Low Water Slack, 16:00~17:30, on June 19, 1975.

(In each space below, the first and the second row present respectively the values near the surface and the bottom of the river)

Distance from River Mouth mi (km)	Water Conductivity mmhos/cm^2	Water Temperature °C	Salinity ppt	DO mg/ℓ	BOD_5 mg/ℓ	TKN mg/ℓ
	-	30.10*	-	6.1	0.57	0.67
0.0 (0.0)	-	28.50*	-	5.6	2.56	0.48
	-	29.05*	-	5.8	1.01	0.71
2.65 (4.26)	-	28.00*	-	4.8	0.95	0.70
	-	29.37*	-	6.4	0.97	0.80
4.72 (7.60)	-	27.70*	-	5.6	0.62	0.58
	-	28.90*	-	7.5	1.66	0.89
7.94 (12.78)	-	27.82*	-	6.4	1.24	0.90
	-	29.25*	-	7.6	-	0.85
11.51 (18.52)	-	26.28*	-	6.1	1.70	0.92
	-	30.00*	-	7.6	1.71	0.97
16.11 (25.93)	-	27.52*	-	5.2	1.26	0.94
	-	31.20*	-	7.2	2.14	1.01
20.71 (33.33)	-	26.70*	-	2.6	0.17	0.92

* Measured on an ARA unit in the field.

APPENDIX C BENTHIC OXYGEN DEMAND

The benthic oxygen demand from field observation on June 25, 1975 is presented in the following table.

Table C.1 Benthic Oxygen Demand

Station (see fig.3.1 and table3.1)	Benthic Oxygen Demand $gm/m^2/day$
JC6	1.0
JC4	1.1
JC2	1.6

APPENDIX D. GEOMETRIC DATA OF 16 TRANSECTS

The cross-sectional profiles of 16 transects are presented. Two soundings from two boat runs at each transect are also shown in this appendix. The reader is referred to Table 4.1 for the average geometric data at each transect.

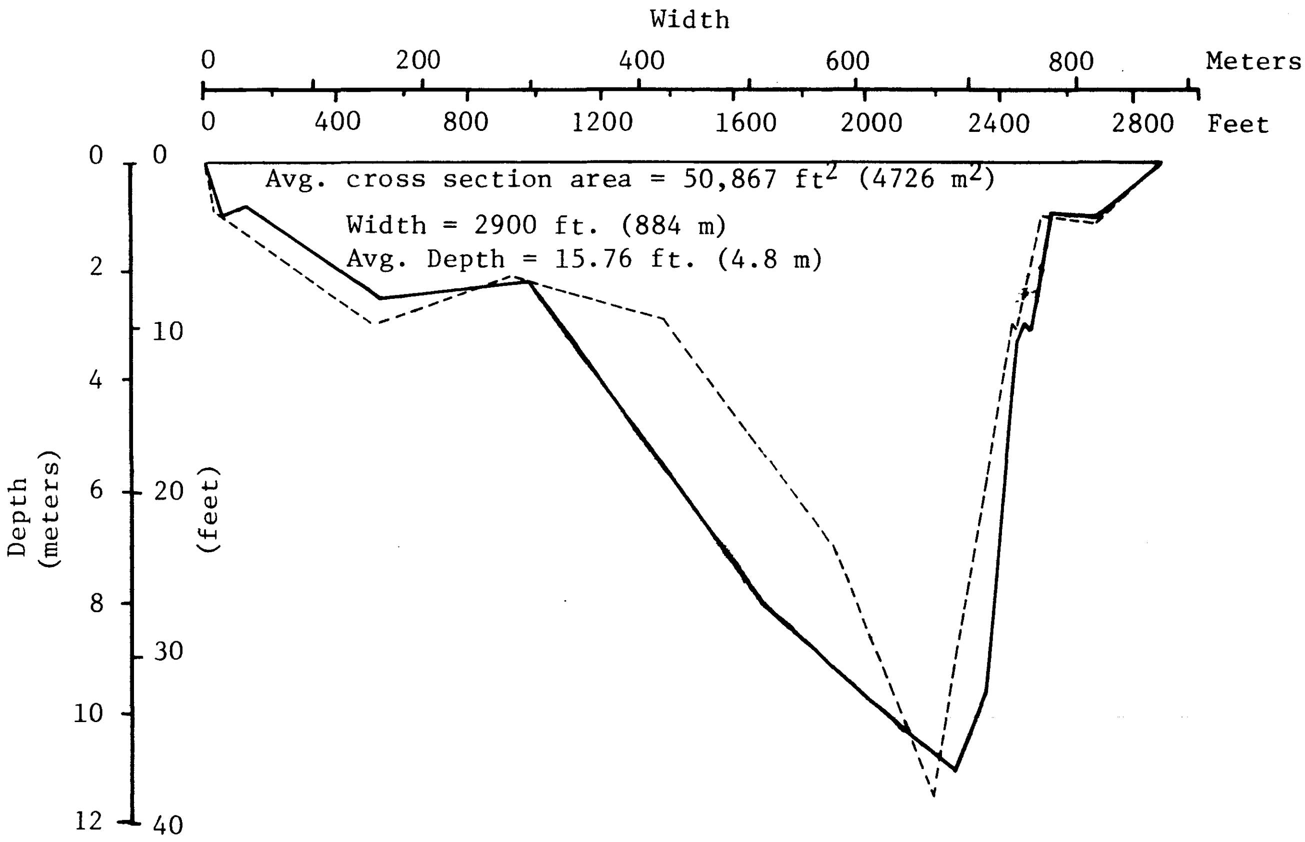

Figure D.1. Cross-sectional profile of transect T16, 0.0 statute miles (0.0 km) from river mouth, measured on June 26, 1975.

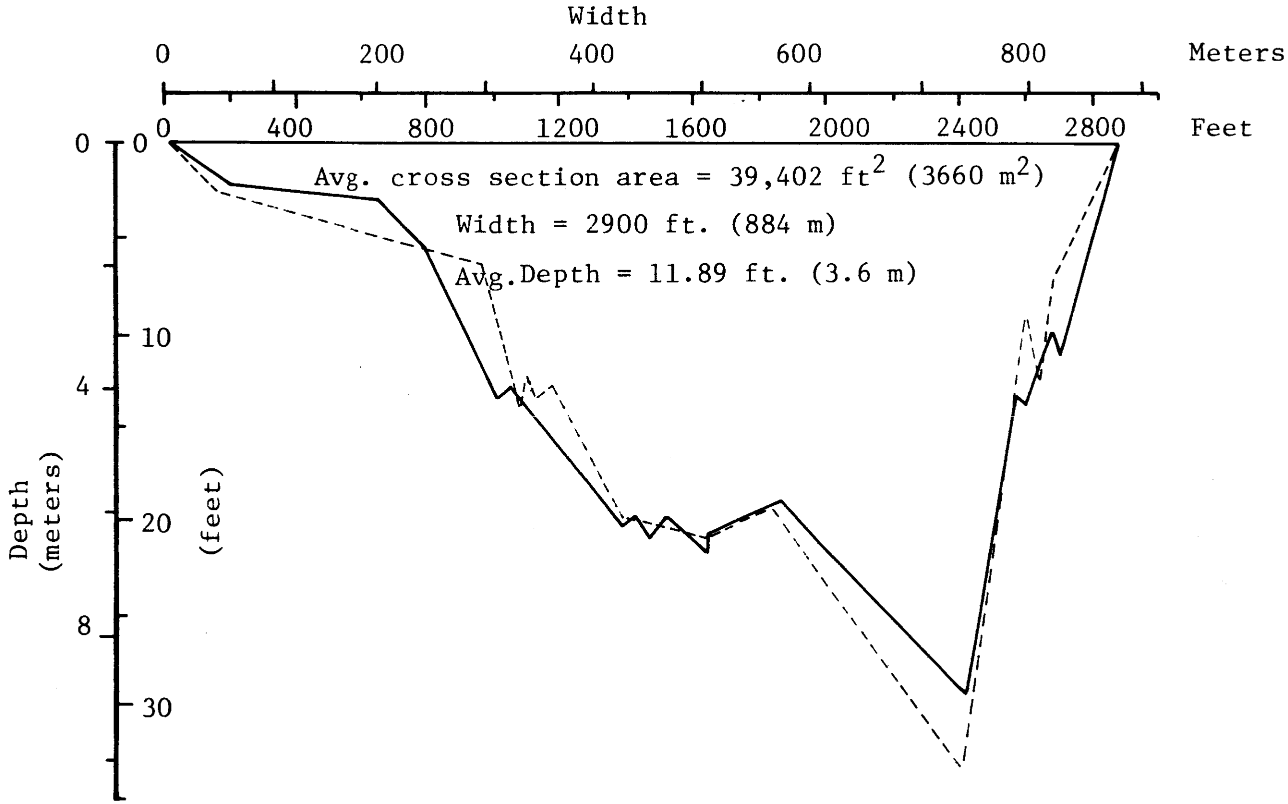

Figure D.2. Cross-sectional profile of transect T15, 1.3 statute miles (2.2 km) from river mouth, measured on June 26, 1975.

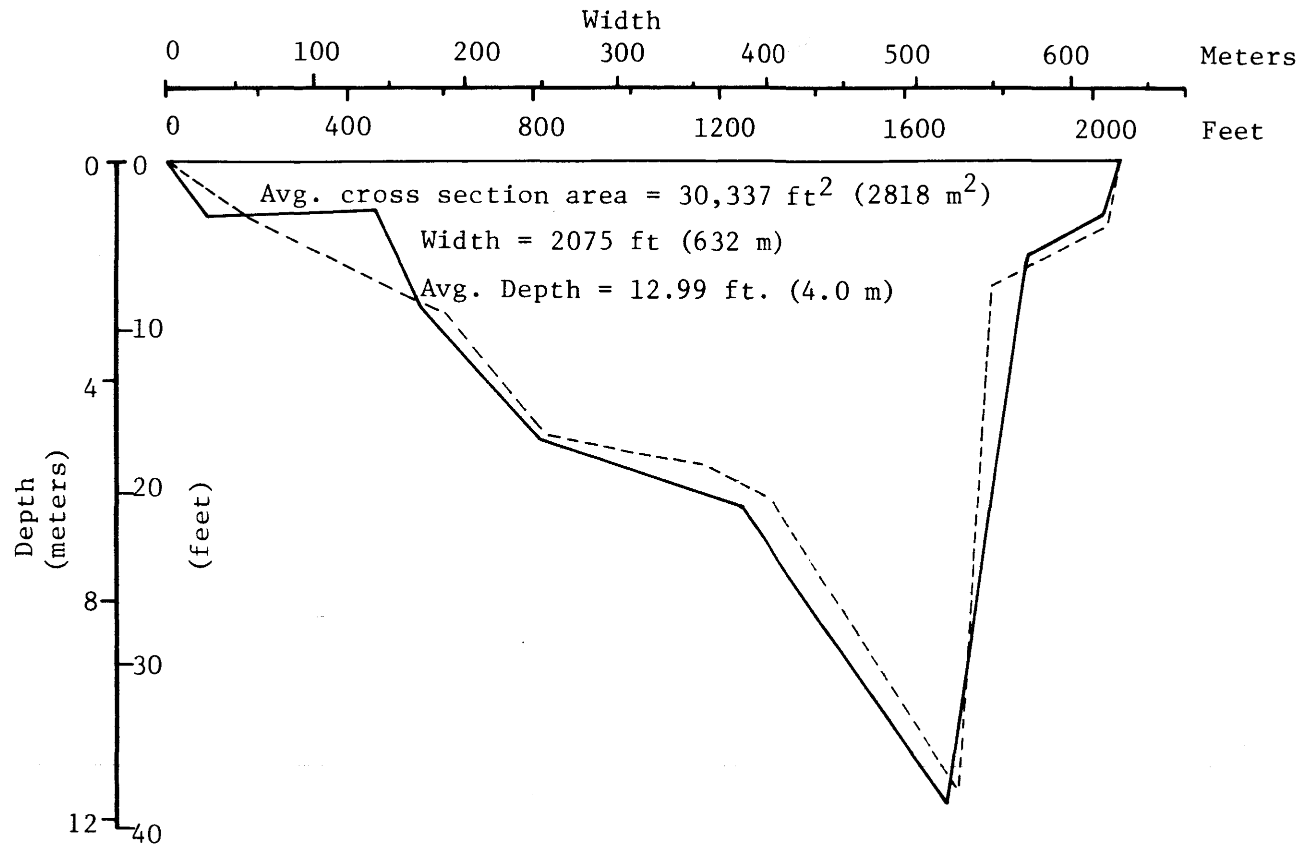

Figure D.3. Cross-sectional profile of transect T14, 2.8 statute miles (4.5 km) from river mouth measured on June 26, 1975.

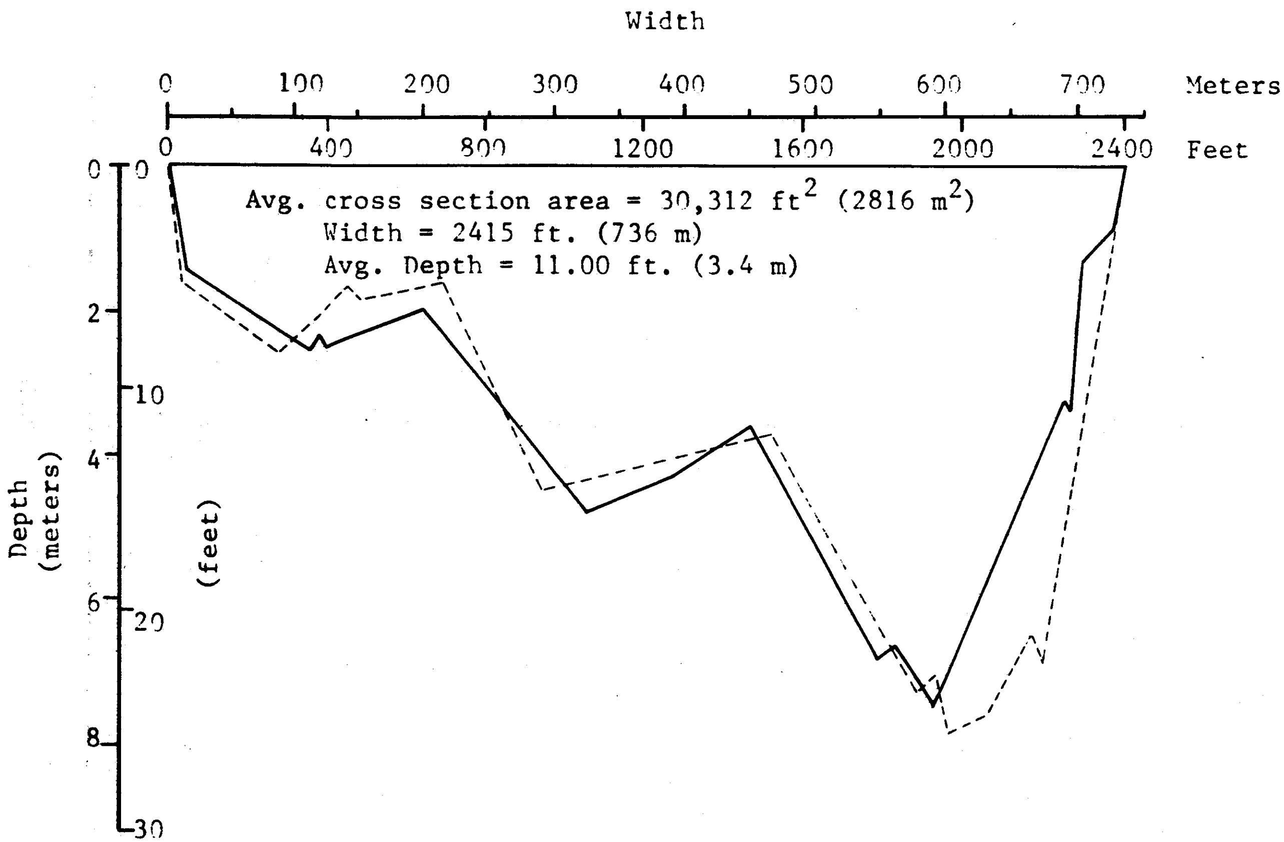

Figure D.4. Cross-sectional profile of transect T13, 6.1 statute miles (5.2 km) from river mouth, measured on June 26, 1975.

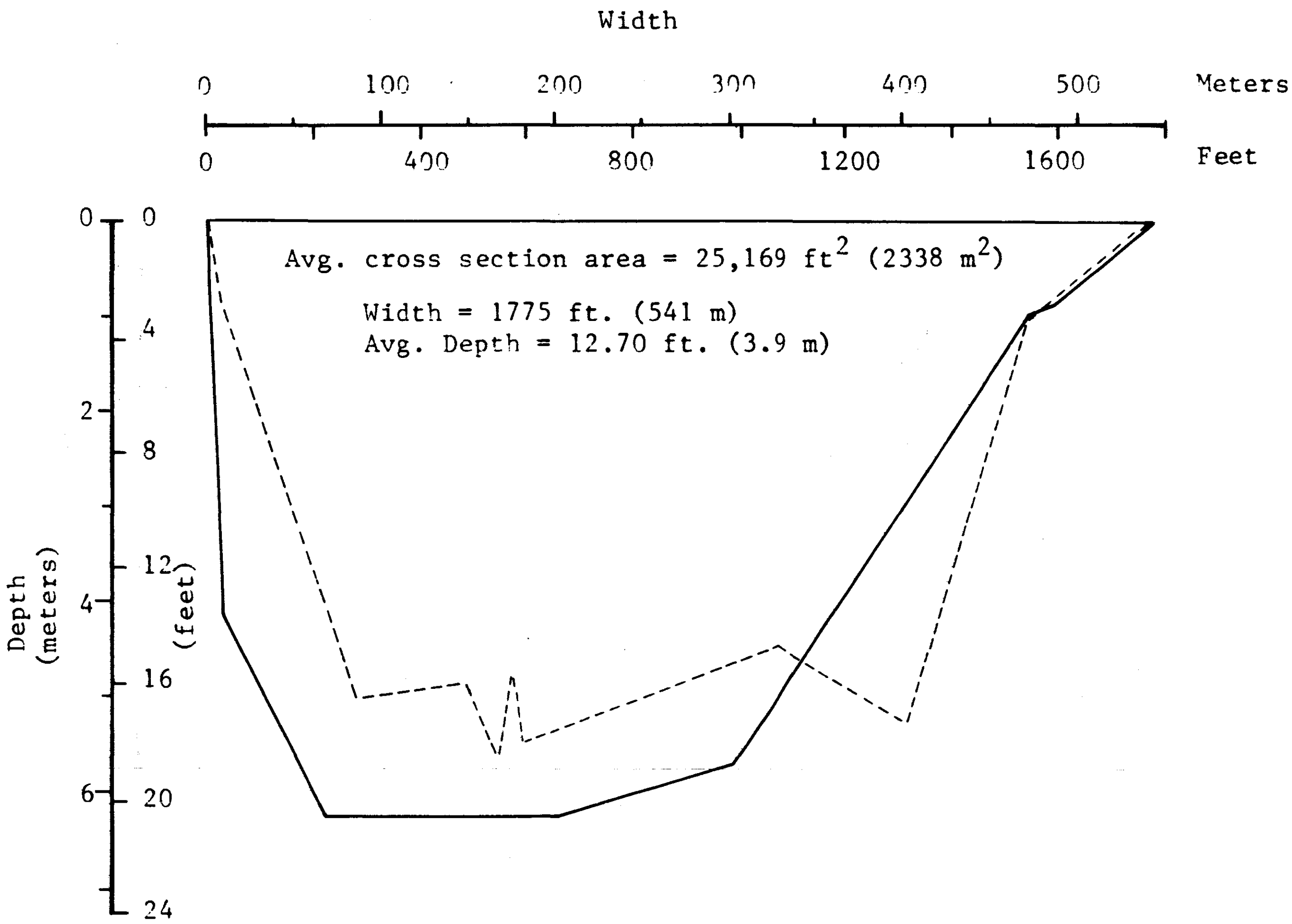

Figure D.5. Cross-sectional profile of transect T12, 8.3 statute miles (6.3 km) from river mouth, measured on June 26, 1975.

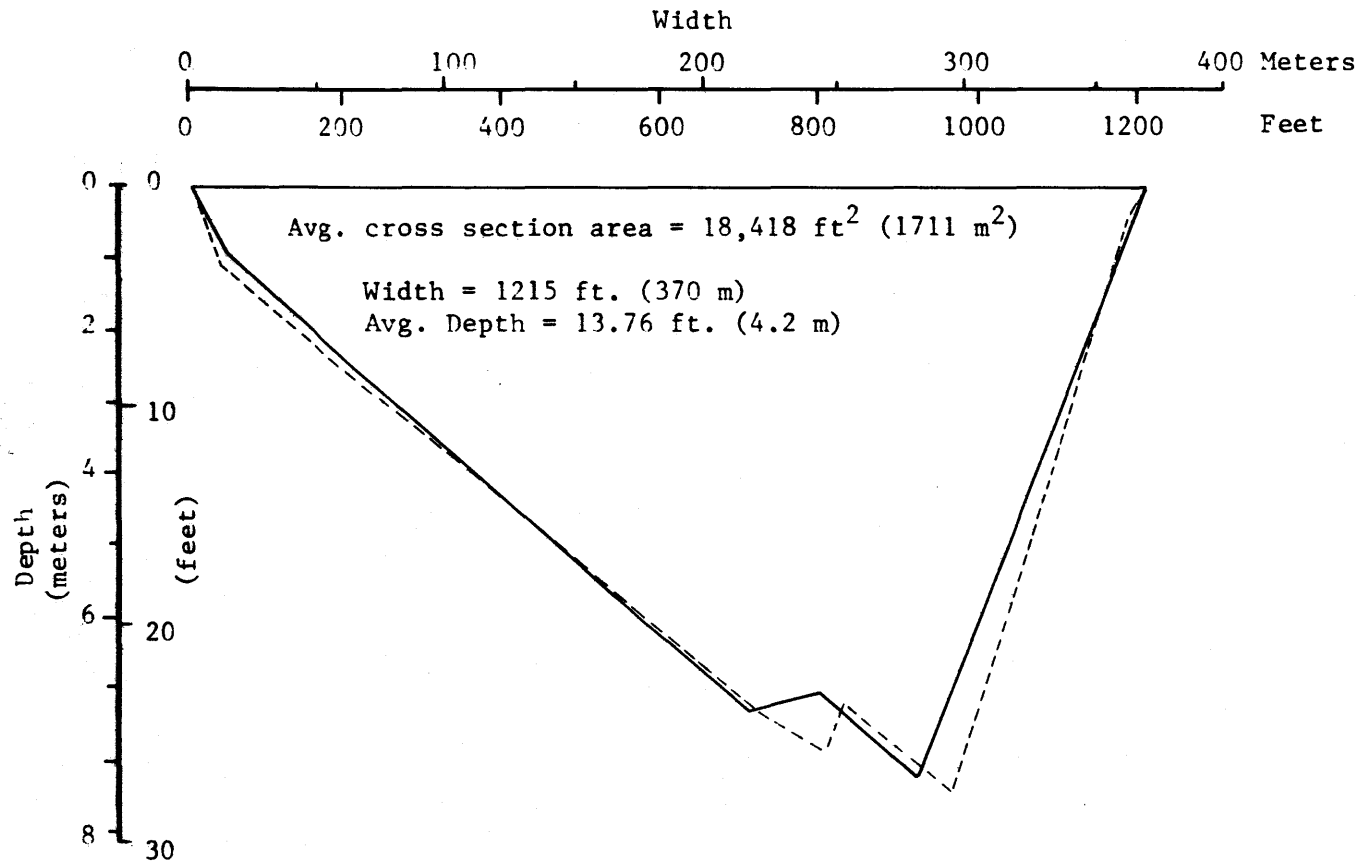

Figure D.6. Cross-sectional profile of transect T11, 6.3 statute miles (10.1 km) from river mouth, measured on June 26, 1975.

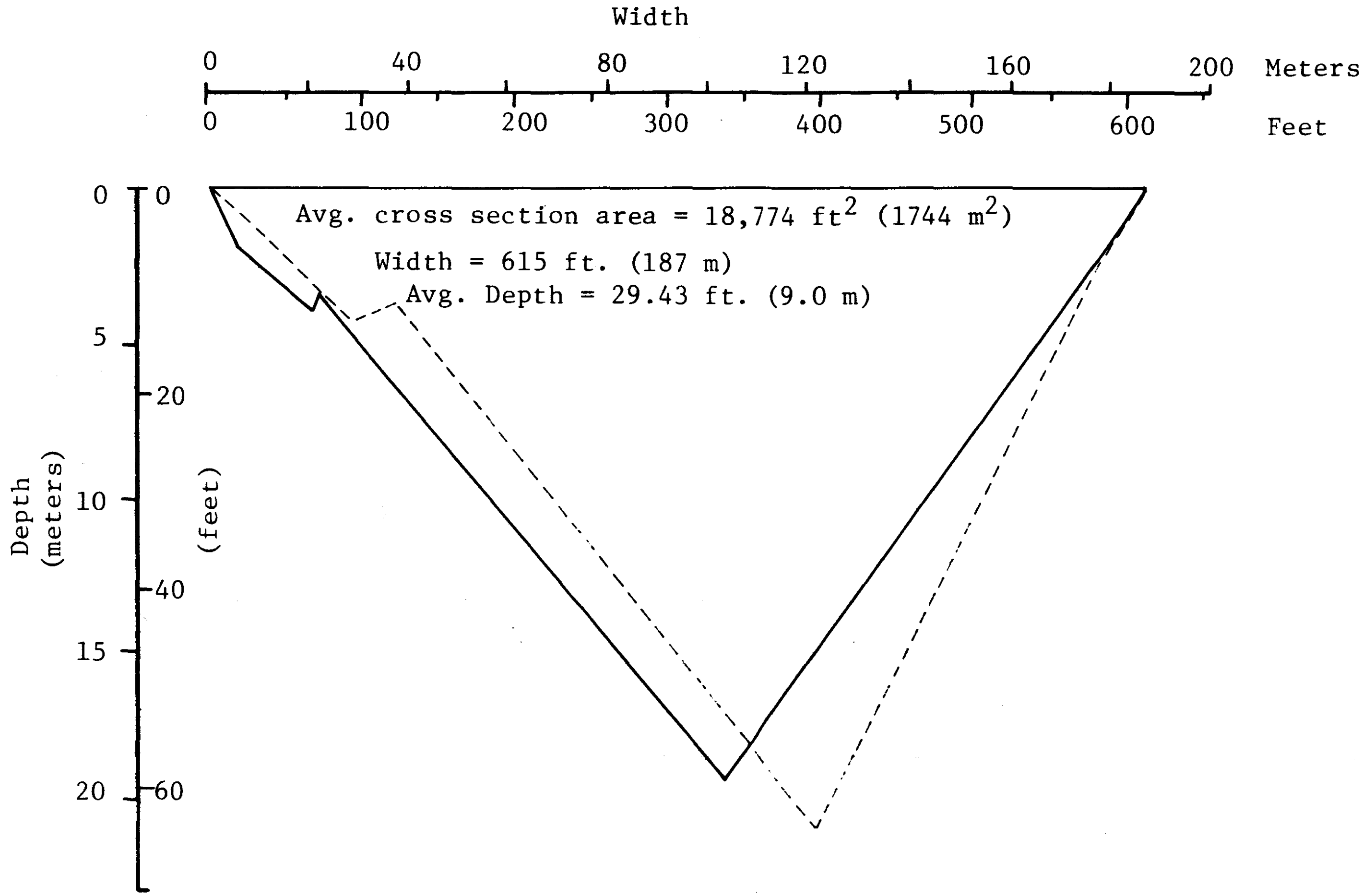

Figure D.7. Cross-sectional profile of transect T10, 7.4 statute miles (11.8 km) from river mouth, measured on June 26, 1975.

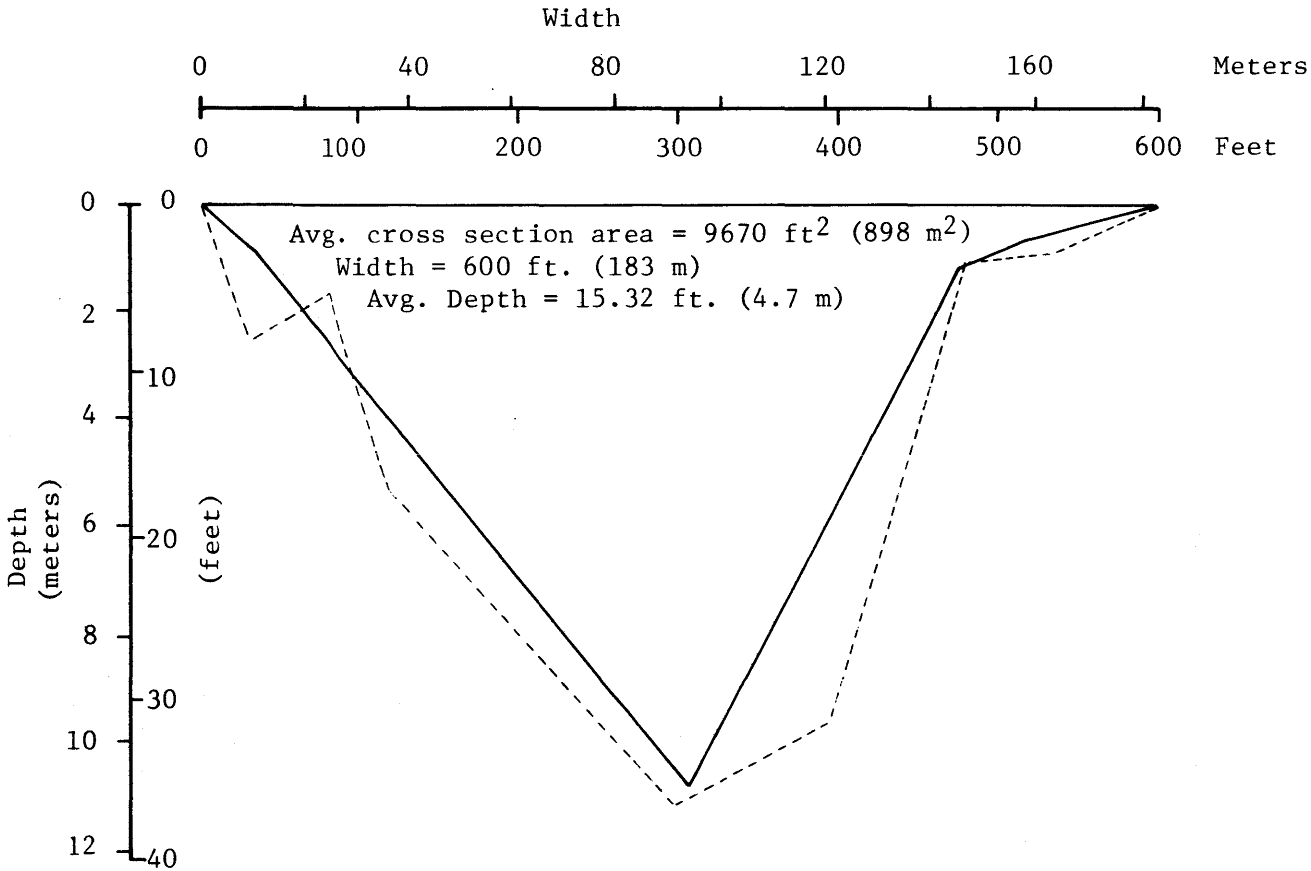

Figure D.8. Cross-sectional profile of transect T9, 8.4 statute miles (13.5 km) from river mouth, measured on June 26, 1975.

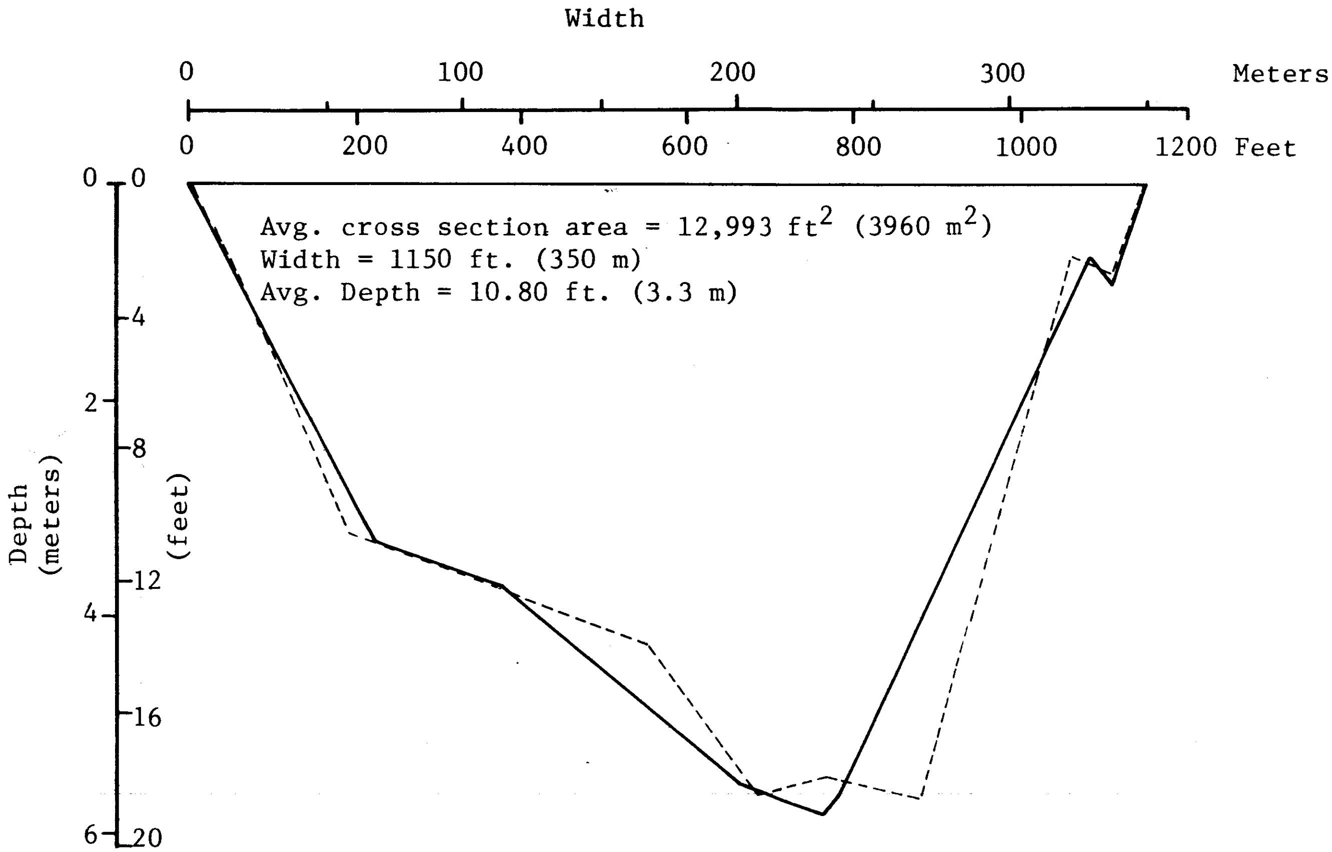

Figure D.9. Cross-sectional profile of transect T8, 9.9 statute miles (15.9 km) from river mouth, measured on June 26, 1975.

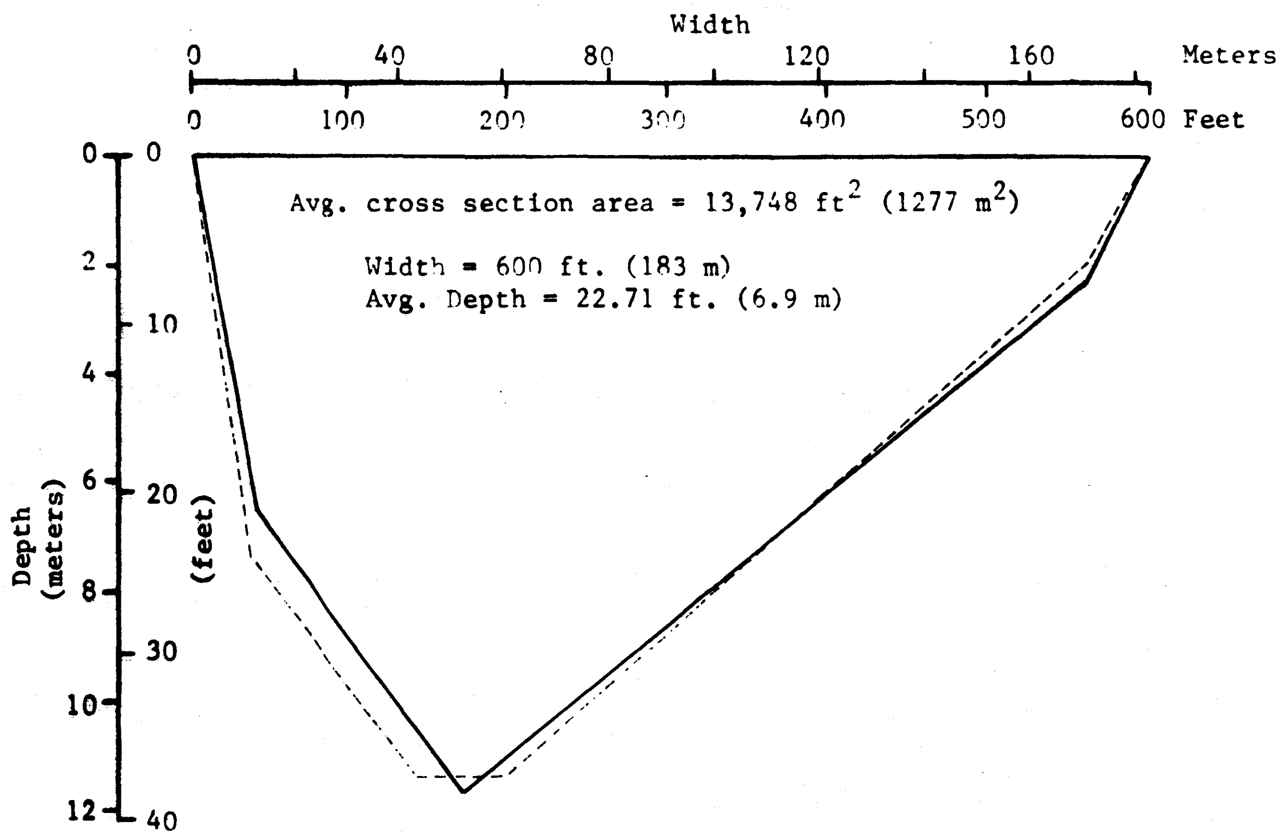

Figure D.10. Cross-sectional profile of transect T7, 11.8 statute miles (19.0 km) from river mouth, measured on June 26, 1975.

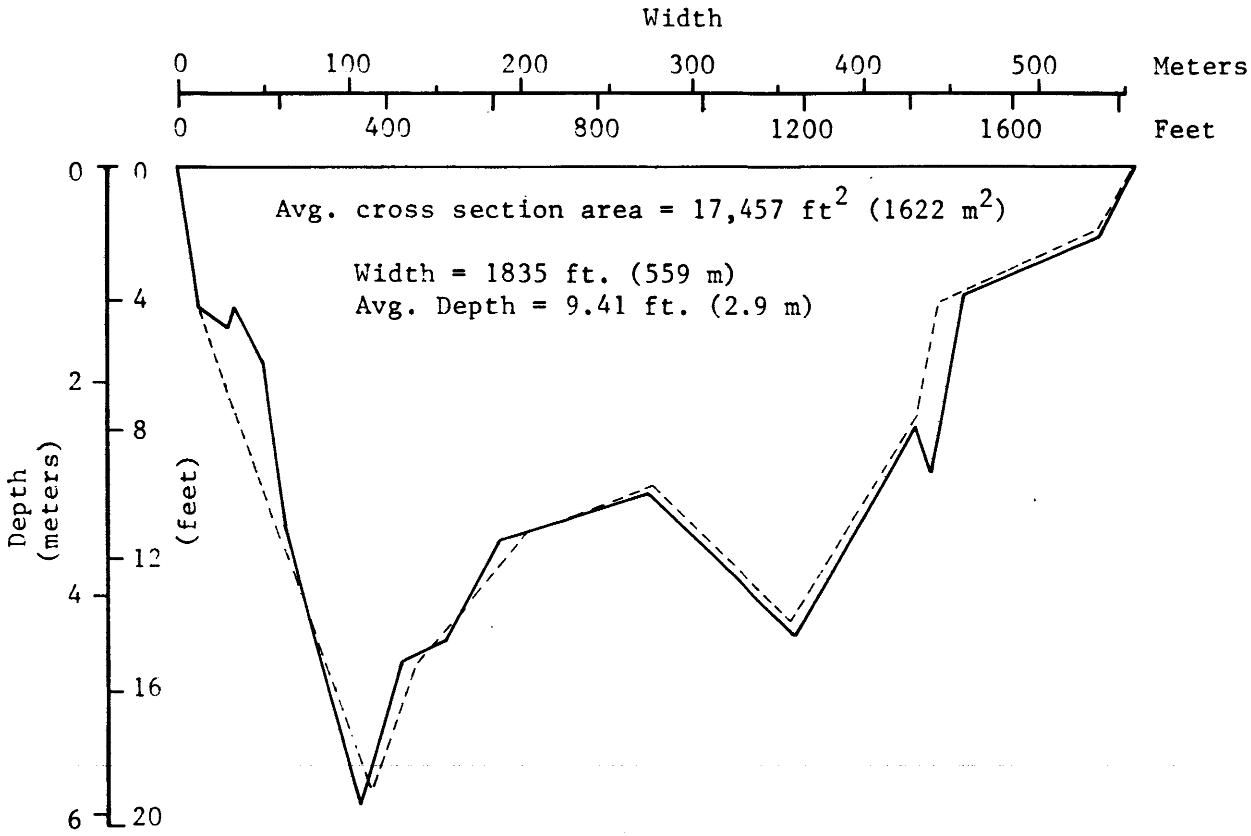

Figure D.11. Cross-sectional profile of transect T6, 13.4 statute miles (21.6 km) from river mouth, measured on June 26, 1975.

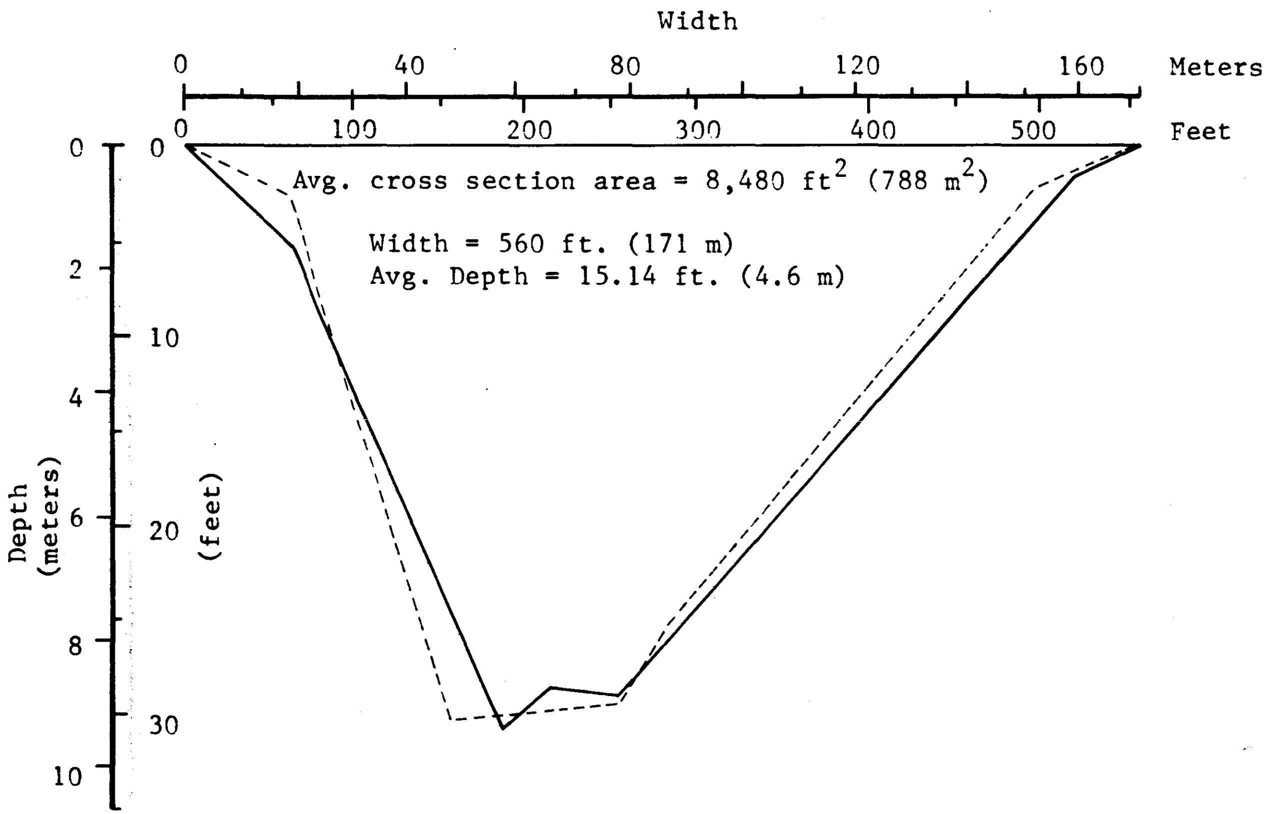

Figure D.12. Cross-sectional profile of transect T5, 14.8 statute miles (23.8 km) from river mouth, measured on June 26, 1975.

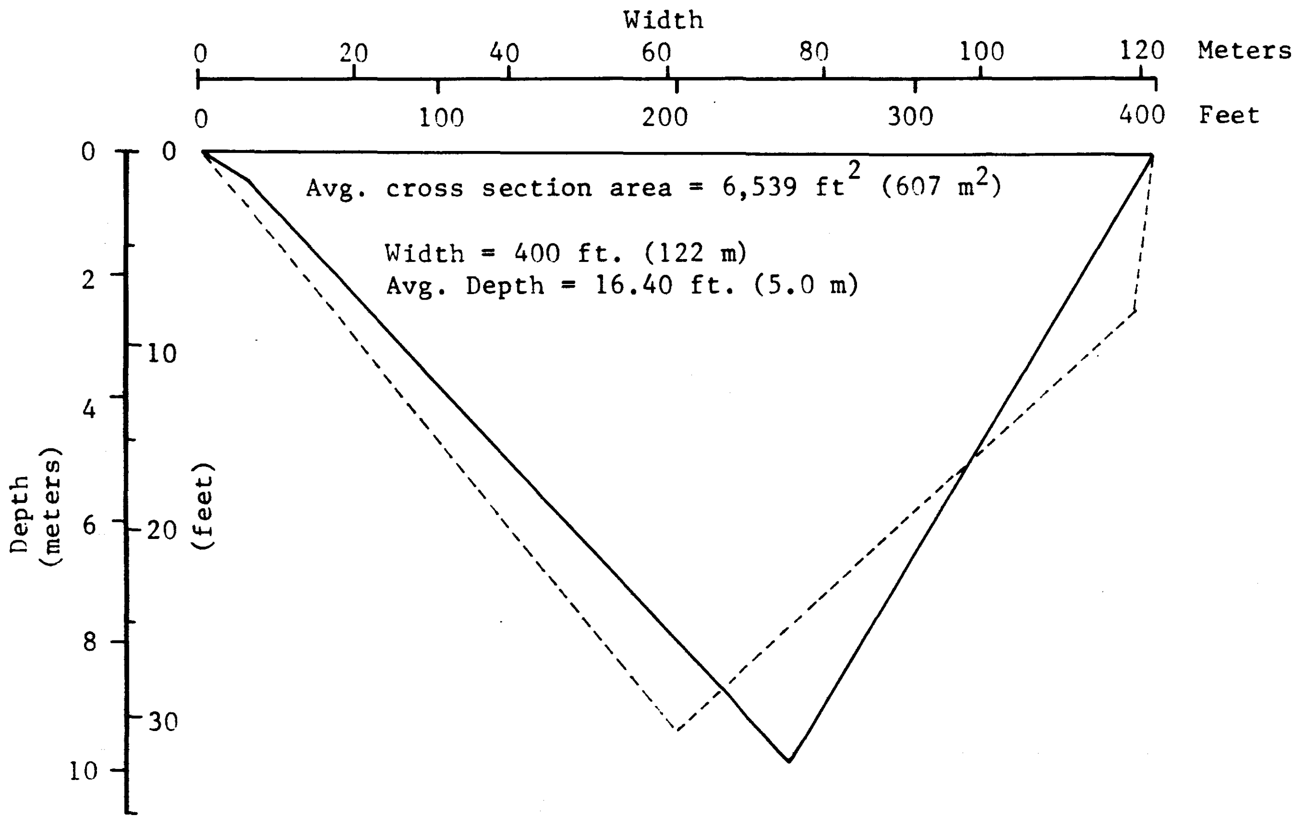

Figure D.13. Cross-sectional profile of transect T4, 16.7 statute miles (26.8 km) from river mouth, measured on June 26, 1975.

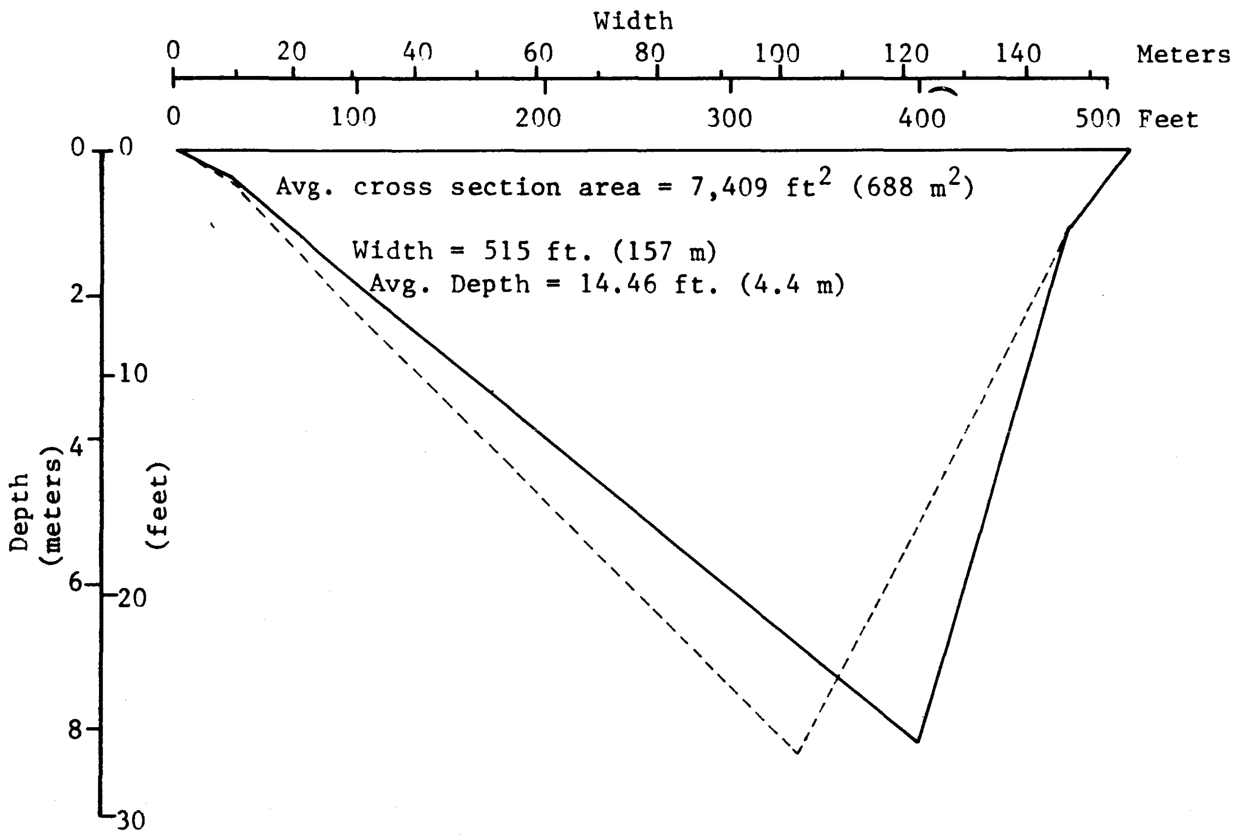

Figure D.14. Cross-sectional profile of transect T3, 29.7 statute miles (19.9 km) from river mouth, measured on June 26, 1975.

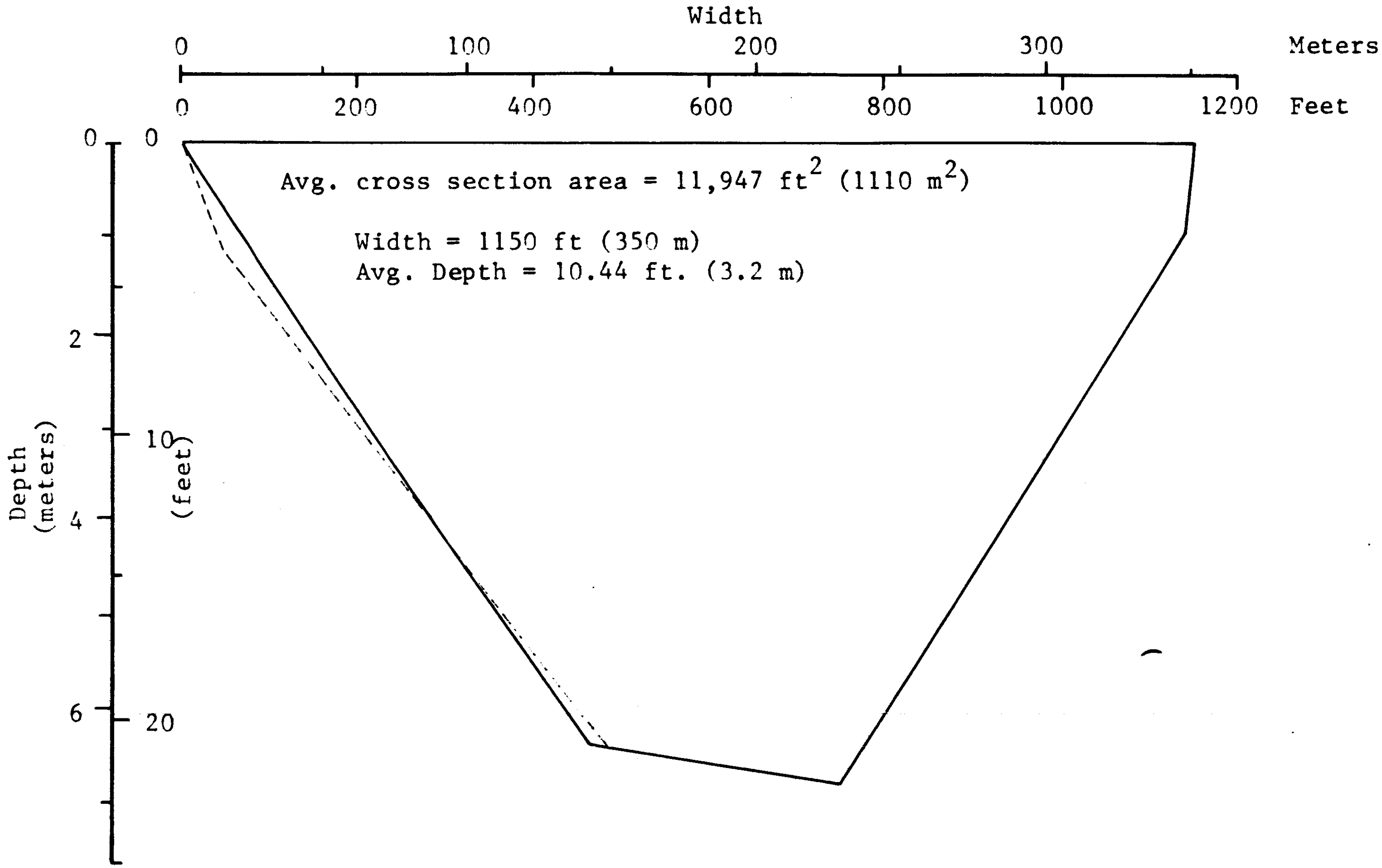

Figure D.15. Cross-sectional profile of transect T2, 19.9 statute miles (32.0 km) from river mouth, measured on June 26, 1975.

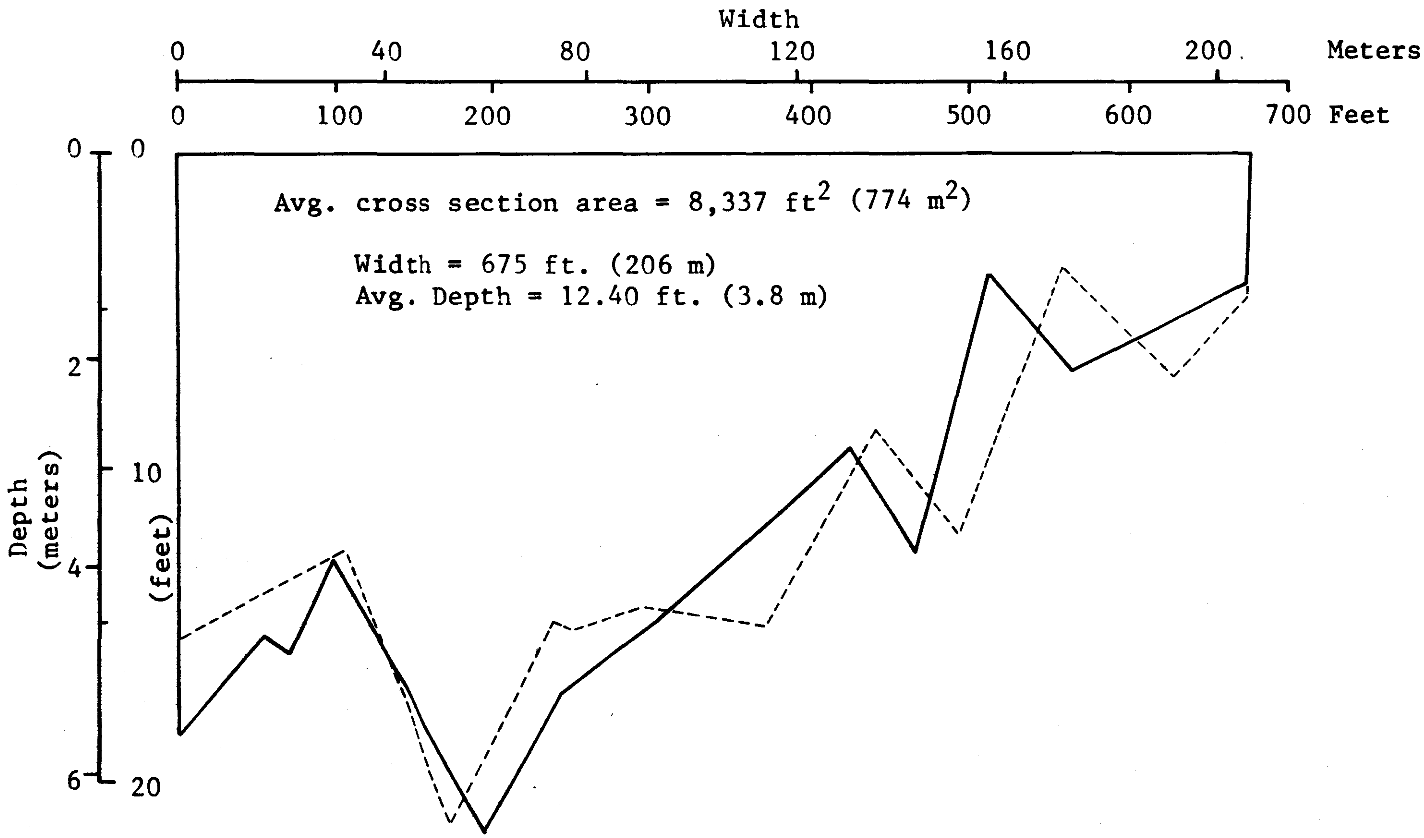

Figure D.16. Cross-sectional profile of transect T1, 21.5 statute miles (34.7 km) from river mouth, measured on June 26, 1975.