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HYDROGRAPHY AND HYDRODYNAMICS

OF VIRGINIA ESTUARIES

IX. Mathematical Water Quality Study of Great Wicomico River and Cockrell Creek

by

P. V. Hyer
J. Jacobson

PREPARED UNDER
THE COOPERATIVE STATE AGENCIES PROGRAM
OF
THE VIRGINIA STATE WATER CONTROL BOARD AND
THE VIRGINIA INSTITUTE OF MARINE SCIENCE

Special Report No. 120
in Applied Marine Science and
Ocean Engineering

Virginia Institute of Marine Science
Gloucester Point, Virginia 23062

William J. Hargis, Jr.
Director

September 1976

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Project Officers

Dale Jones
Michael Bellanca

Virginia State Water Control Board

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ACKNOWLEDGMENTS

The comments and criticisms of Messrs. Dale Jones and R. A. Gregory and Dr. W. Kao from the Water Control Board are appreciated.

We thank Mrs. Shirley Crossley for her patient typing of this report and Ms. Marilyn Cavell for her data reduction.

The funding of this project is a long term joint program supported by the Virginia State Water Control Board and the Virginia Institute of Marine Science through the Cooperative State Agencies Program.

ABSTRACT

A water quality model was developed, calibrated and verified for the Great Wicomico River and Cockrell Creek. These tidal estuaries are characterized by a significant difference in dissolved oxygen between surface and bottom during critical periods, and so the model used was a two-layer model.

The model includes the effects of mean flow, tidal advection and density-induced circulation. The user has freedom to specify both point and nonpoint sources in geographical detail.

I. Summary and Conclusions

1. The Great Wicomico drainage area is rural and heavily wooded. Farming, commercial fishing and fish processing and recreational boating form the economic base of the area. The region is characterized by hot summers and mild winters.

2. A hydrographic survey was carried out in July, 1974. Five anchor stations were occupied in Cockrell Creek and four in the Great Wicomico. Time series data on salinity, temperature and dissolved oxygen concentration were produced for each of these stations. Slack water runs were conducted at the same time to collect data on salinity, temperature, dissolved oxygen and biochemical oxygen demand.

3. During the same period, a dye release was made in the Great Wicomico and another in Cockrell Creek. Dye concentration was monitored by both the slack water runs and the anchor station sampling.

4. In December, 1974, bottom oxygen demand was determined for three locations in Cockrell Creek. In March, 1975 bottom oxygen demand was determined for three locations in the Great Wicomico.

5. Survey data show that salinity is greater than ten parts per thousand as far upstream as the surveys extended. Salinity variation with tide stage normally were less than 0.5 parts

per thousand.

6. Vertical stratification sometimes occurs with respect to dissolved oxygen levels with bottom concentrations being quite low (less than 2 mg/ℓ) while surface concentrations are within acceptable limits, (i.e., greater than 5 mg/ℓ). This situation is more frequent and more pronounced in Cockrell Creek when dissolved oxygen concentrations near the bottom occasionally fall below one milligram per liter.

7. Stratified dissolved oxygen conditions seem to be associated with summer conditions of high temperature and extremely small freshwater inflow.

8. Another factor apparently contributing to this stratification condition is the weak tidal circulation typical of these estuaries. Tidal currents are normally less than 0.5 feet per second (15 cm/sec.).

9. A model has been completed and verified for those estuaries (Great Wicomico and Cockrell Creek). This model is two layer, real time including tidal action. The model uses an implicit integration scheme and predicts the concentration of dissolved oxygen, biochemical oxygen demand (nitrogenous and carbonaceous separately) and salinity.

10. The model includes gravitational circulation driven by the longitudinal salinity gradient. This circulation is weak in the Great Wicomico River and Cockrell Creek. However, the

model is suitable for estuaries where this type of circulation is much stronger.

11. The execution time of the model (CPU time) is approximately 0.002 seconds per reach per time step for four components, under the present operating system in use at the College of William and Mary.

II. Introduction

Field and modelling studies conducted for the Cooperative State Agencies (CSA) project were concentrated initially on the major Virginia estuaries, i.e. the James, York and Rappahannock. Once these studies were completed, attention was focused on certain smaller estuaries such as the Great Wicomico River which have specific problems (see figure 1).

The Great Wicomico River has been a consistently high producer of oysters (see figure 2). In recent years, however, the rate of setting of oyster spat has decreased drastically. If this trend continues, depletion of stocks will occur and production will decline. While the exact cause of this decline in set is unknown, there does appear to be a stratification in water quality, which could lead to suffocation of bottom-dwelling oyster spat. Specifically, dissolved oxygen concentrations vary with depth, the concentration near the bottom frequently falling below 4 mg/ℓ, and on occasion falling below 2 mg/ℓ.

Cockrell Creek has been a center for menhaden processing for a long time. Although only two active processing plants remain (see figure 3) from a peak number of ten, the legacy of bygone plants remains in the form of bottom sludge deposits built up over the years. These bottom sludge deposits exert an oxygen demand on the bottom water and cause deoxygenation of the deeper waters. Dissolved oxygen concentration near the bottom is frequently below 3 mg/ℓ and sometimes below one mg/ℓ.

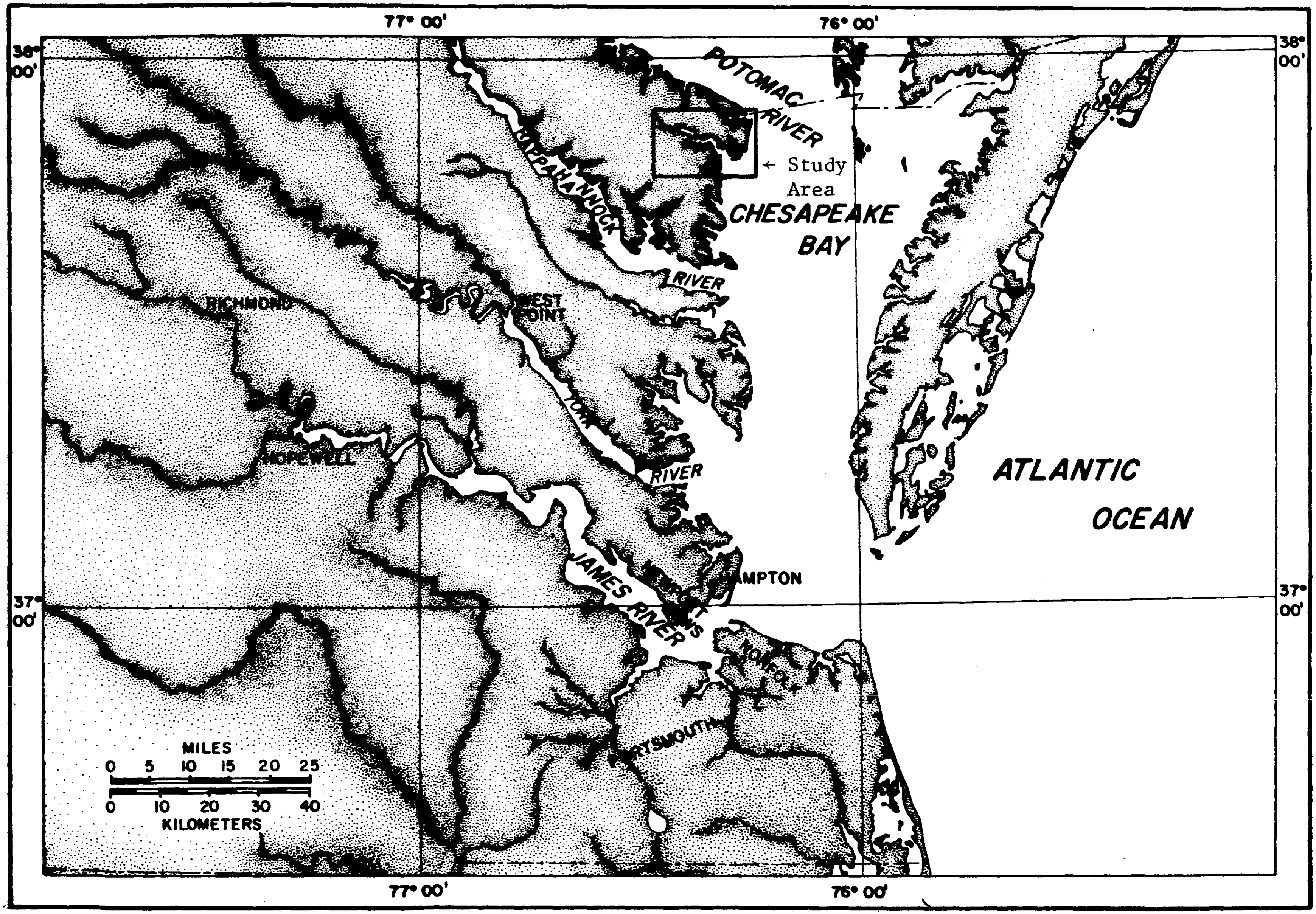


Figure 1. Study Area Site

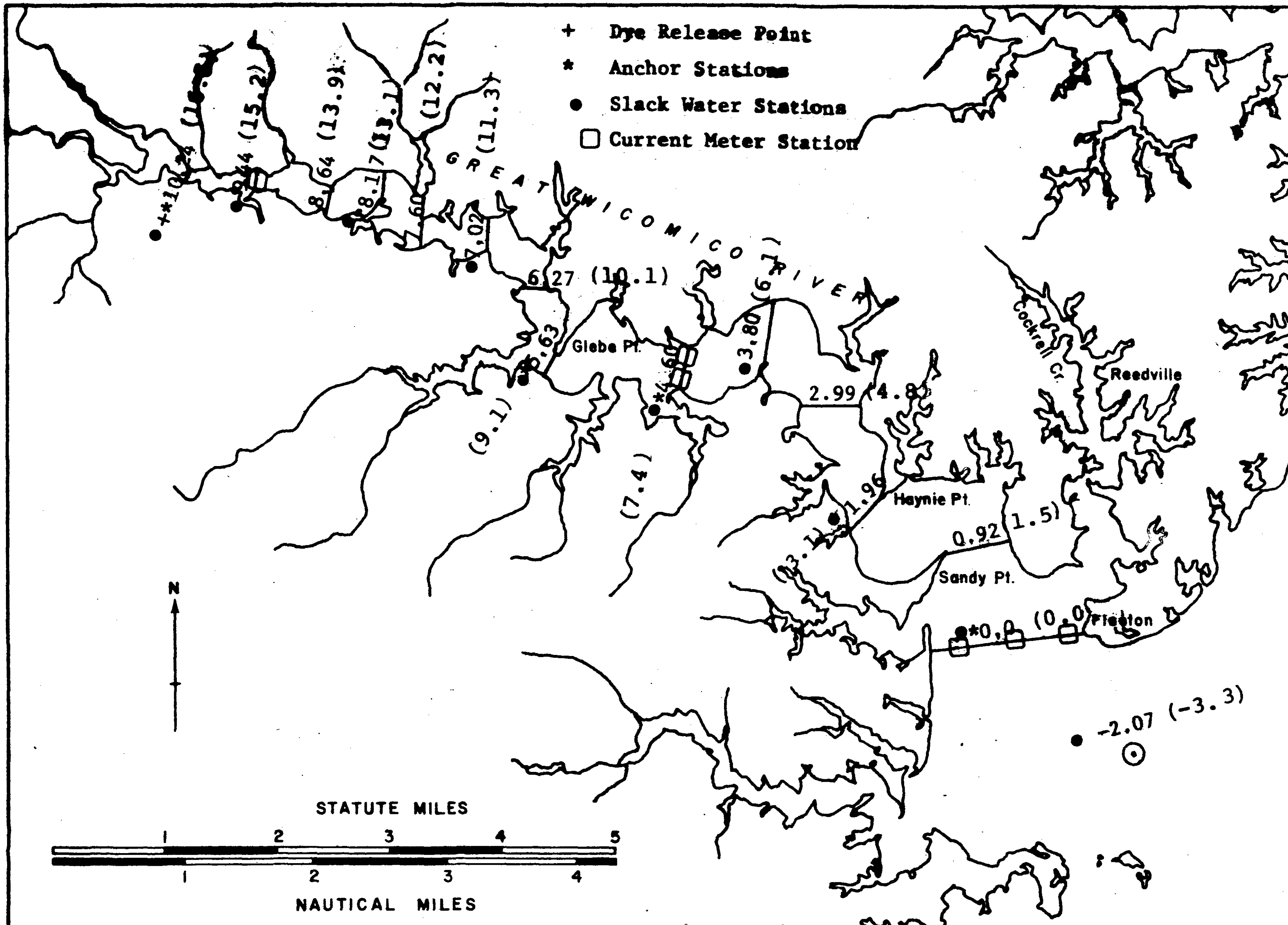


Figure 2. Survey Transects in Great Wicomico River Distance Upstream in Statute Miles (Kilometers).

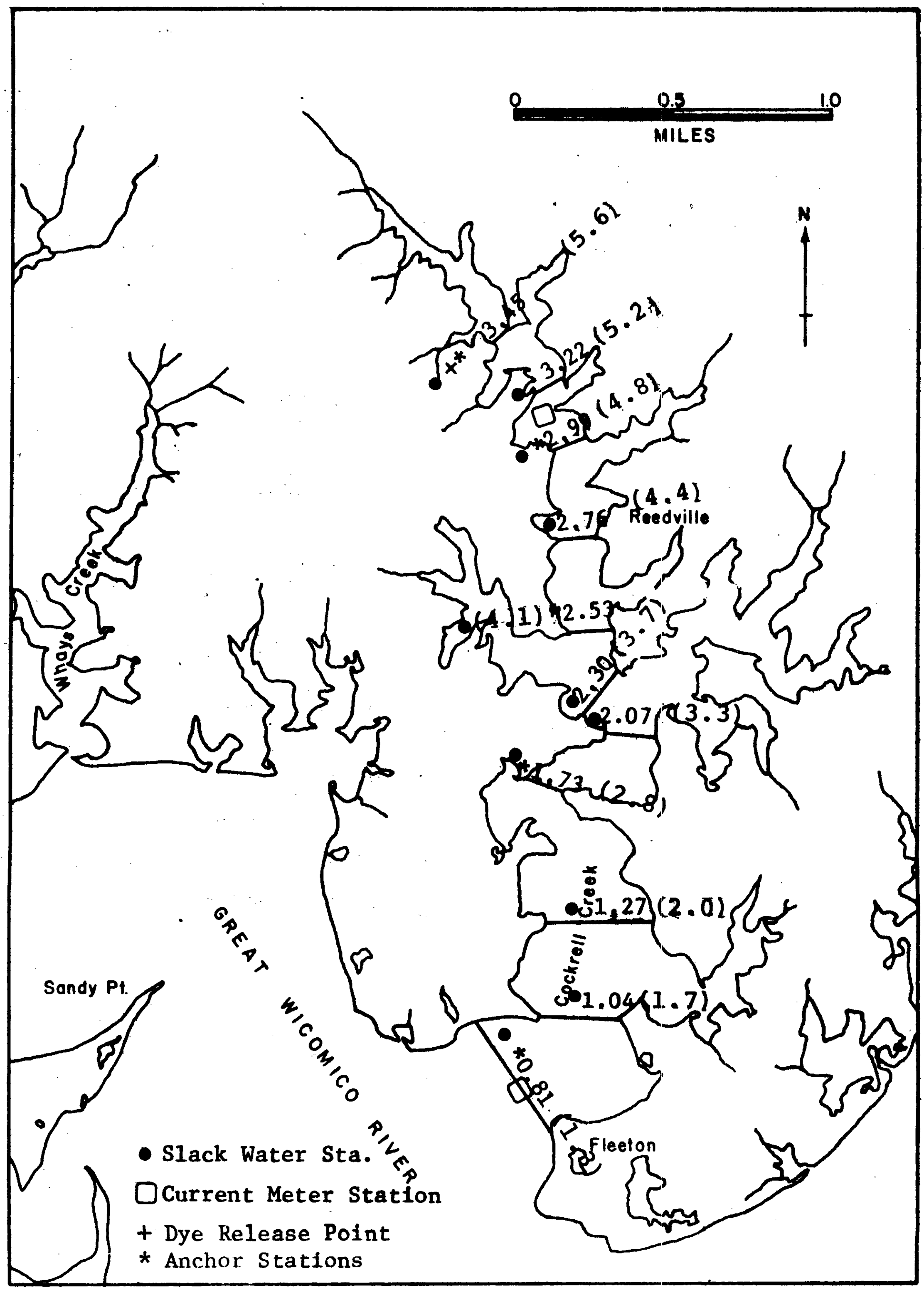


Figure 3. Survey Transects in Cockrell Creek
Distance Upstream in Statute Miles (Kilometers)

Measurements of bottom oxygen demand indicate, however, that bottom demand is greater in the Great Wicomico than in Cockrell Creek. This is not to say that the "natural" condition is worse than the man-made one, since the effect of bottom demand in Cockrell Creek is superimposed on the effect of point sources. When operating, the existing processing plants load the Creek with several thousand pounds per day of carbonaceous BOD, plus organic nitrogen and ammonia. Sometime in 1978 a sewage treatment plant will come on line to process domestic sewage from Reedville. This plant is designed to process 200 thousand gallons per day, discharging a maximum BOD concentration of 24 parts per million. It is expected that the addition of this point source will be more than offset by elimination of nonpoint effluent from faulty septic systems, etc.

Both the Great Wicomico River and Cockrell Creek have stratified water quality conditions, with a significant difference between dissolved oxygen levels in the surface and bottom layers. A special model has been developed to deal with this situation. This model has two layers, with point and nonpoint sources of carbonaceous and nitrogenous BOD introduced into the upper layer and bottom oxygen demand exerted on the lower layer. The model is quite flexible, allowing the planner to specify point and non-point discharge at any location in the estuary. He also has wide control over the choice of water temperature and freshwater inflow. Tidal current strength and basin geometry may be specified with as much detail as observations allow. The model is compact and rapid, enabling economical evaluation of a variety of waste allocations in conjunction with any realistic natural condition.

This report describes the two-layer model and the calibration and verification results for the Great Wicomico River and Cockrell Creek. A sensitivity analysis illustrating the flexibility and wide range of usefulness of the model also is included.

III. Description of Study Area

The drainage area of the Great Wicomico River takes in a portion of Northumberland County (see figure 1). This region is rural, with about half the land area covered by forest. Farming, commercial fishing and fish processing are the financial mainstays for the area.

Mean daily minimum temperatures are approximately thirty degrees and sixty-nine degrees Fahrenheit (minus one and twenty-one degrees Celsius) for January and July, respectively. The corresponding mean daily maximum temperatures are forty-eight degrees and eighty-eight degrees Fahrenheit respectively (nine and thirty-one degrees Celsius). Precipitation in the drainage basin exceeds forty-six inches (117 cm) per year. Autumn is drier than the rest of the year. Precipitation in the summer tends to occur as brief, heavy thundershowers, rather than as the more prolonged storms that occur throughout the rest of the year.

The Great Wicomico River empties directly into Chesapeake Bay. The land area of the drainage basin is only 70.6 square miles (182.8 km^2), resulting in relatively little freshwater inflow to the river. Tidal action is also weak, with the tidal current amplitude being on the order of 0.5 ft/sec (15 cm/sec) or less. Since the stream is short, there is very little time lag in the upstream propagation of the tidal wave.

Cockrell Creek is a tributary to the Great Wicomico. The creek empties into the river close to the river mouth. The creek has characteristics similar to the river; small drainage area (4.6 square miles, or 11.9 km^2) weak tidal action and low freshwater input. Two fish processing plants as well as the town of Reedville are located on Cockrell Creek. During the summer, the two plants introduce a total of about 5000 lb/day (2300 kg/day) of five-day carbonaceous BOD and about 900 lb/day (410 kg/day) of organic mitrogen and ammonia (as N).

IV. Hydrographic Survey

1. Field Study

To provide data for model verification, an intensive field survey was conducted in July, 1974. This survey included both anchor stations, slack water runs and a dye release. Their locations are shown in figures 2 and 3. Schematic diagrams indicating river mile are shown in figures 4 and 5.

The anchor stations were monitored for daylight periods of thirteen hours each on two successive days. Five stations were occupied in Cockrell Creek and four in the Great Wicomico. At these stations, temperature and conductivity were measured and samples taken for dissolved oxygen and dye. Measurements and samples were taken hourly and at two-meter vertical intervals.

Four slack water runs were made during the survey period. There were ten stations each on Cockrell Creek and the Great Wicomico River. At these stations, dissolved oxygen and dye were sampled and temperature and conductivity measured at surface and bottom, and, in some cases, mid-depth.

Separate batch releases of dye were made in Cockrell Creek at mile 3.4 (5.5 km) and far upstream in the Great Wicomico at mile 10.3 (16.6 km) on the day preceding the intensive survey, in order to determine the flushing characteristics of the two systems. One barrel of Rhodamine WT dye (20%

Great Wicomico River

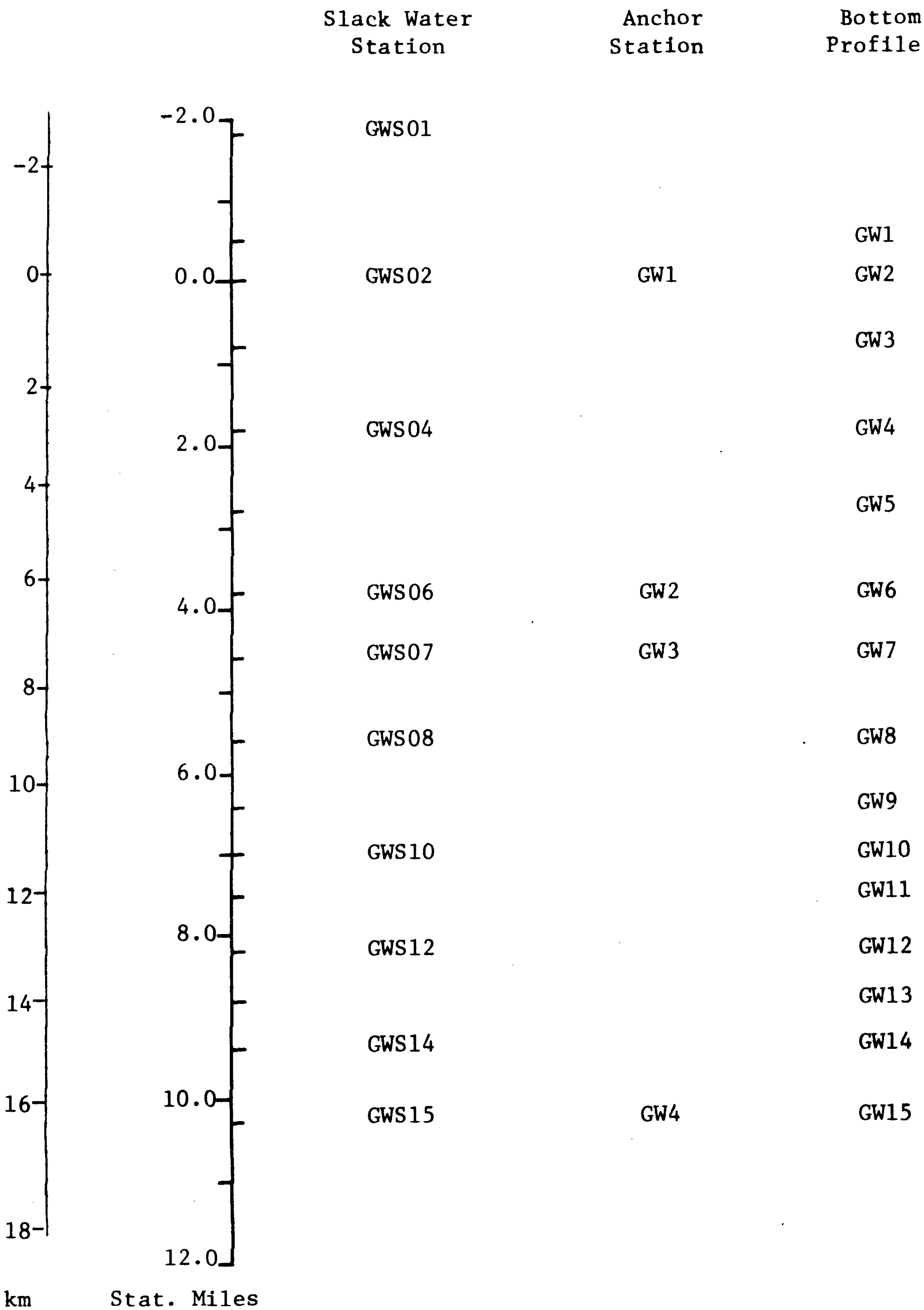


Figure 4. Schematic of Great Wicomico Survey Transects

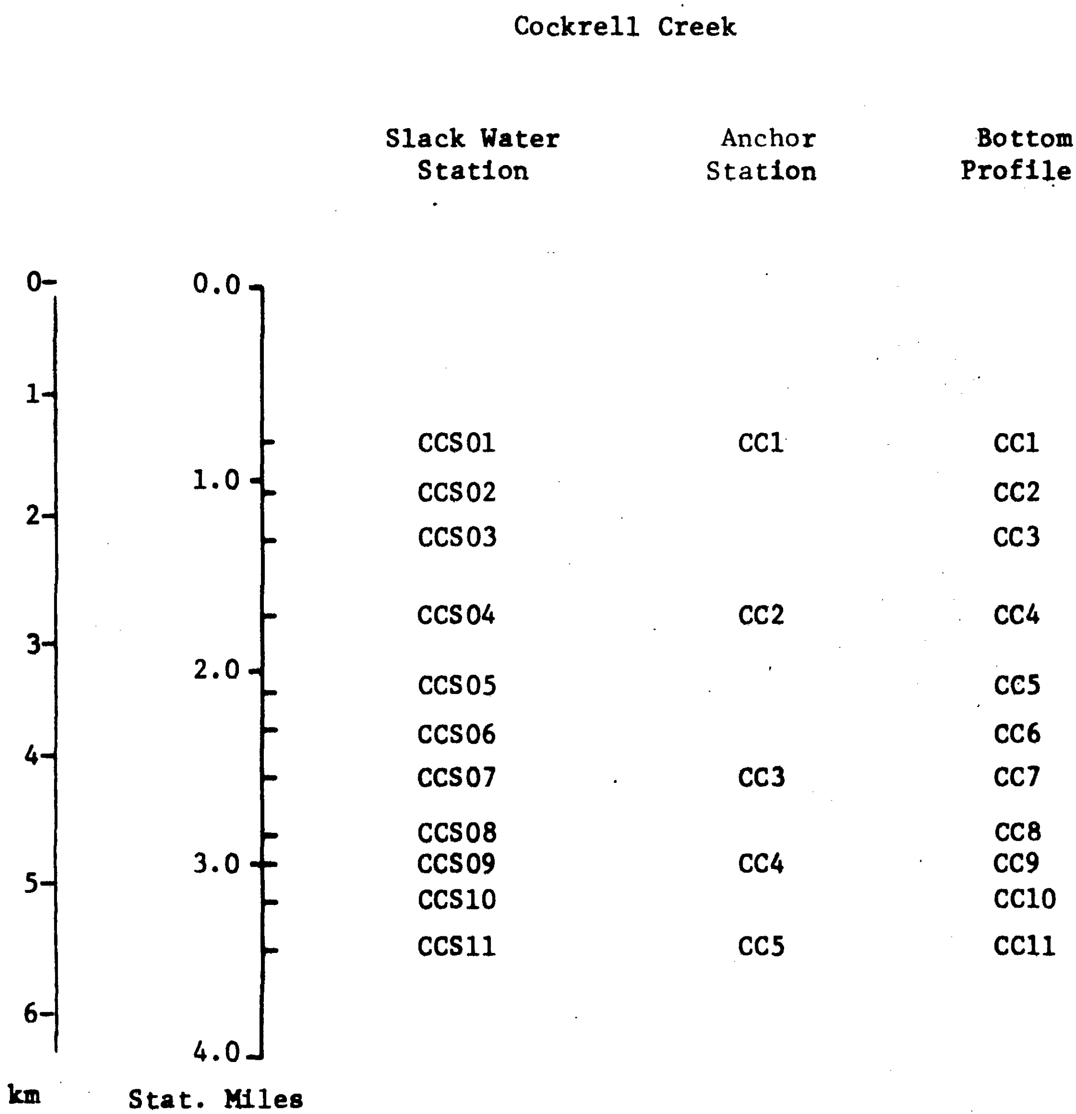


Figure 5. Schematic of Cockrell Creek Survey Transects

solution)was released at high water slack and subsequently sampled during the survey. Two-thirds of the dye was released to the Great Wicomico and the remainder in Cockrell Creek.

Six current meter strings were anchored on three transects of the Great Wicomico (see figure 2). Two meter strings were placed in Cockrell Creek. These meters were Braincon film-recording savonius rotor types giving twenty minute averages of current speed and direction and were kept in place for a period of three days encompassing the time that the intensive survey stations were occupied.

To provide geometrical data for the model, fifteen bathymetric profiles were taken on the Great Wicomico and eleven on Cockrell Creek. Their locations are shown in figures 4 and 5.

2. Instruments and Analyses

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 $0.1^{o}C$; salinity is accurate to 0.1 ppt. Dye concentration was measured in the laboratory using a Turner Associates model 10-000 fluorometer. Dye concentration is accurate to one percent of full scale or 0.02 parts per billion, 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 (ppm).

A Raytheon Model DE719 fathometer was used for bottom profiling. The accuracy of the depth soundings is 0.5 feet (15 cm).

3. Results

The water quality survey data were compiled, edited, keypunched and stored in the VIMS data file on a magnetic disk. The results of the survey are summarized in Appendix A. Appendix B contains a graphical summary of the dye study data.

The bottom cross-section profiles, corrected to mean tide level according to the tide tables, are shown in Appendix C. Longitudinal distance between transects was determined from C&GS navigation charts. The location of a water quality interface, i.e., a depth at which dissolved oxygen concentration changed sharply was determined for each transect using VIMS and Water Control Board data. These results were used to calculate areas for the upper and lower layers. Volumes between transects were calculated by multiplying the average of the transect areas by the distance between. For the reach covering the mouth of Cockrell Creek, however, the volume was augmented to include Cockrell Creek up to one tidal excursion from its mouth. The highly indented nature of Cockrell Creek required the addition of the volumes of the numerous arms on the creek. These volumes were obtained by surface area planimetry multiplied by mean depth obtained from navigation charts. Geometrical data are summarized in Tables 1 & 2.

Accumulated drainage area for the Great Wicomico was plotted from data tabulated by the Division of Water Resources (1972). These data are shown in figure 6. For Cockrell Creek, however, only figures for total drainage area and length of drainage basin were available. Model inputs for lateral inflow were calculated by linear interpolation.

Table 1

Geometric Data for Great Wicomico River

Distance Upstream (Statute mi)	(km)	Upper Layer Cross-section Area (ft^2)	(m^2)	Lower Layer Cross-section Area (ft^2)	(m^2)	Accumulated Drainage Area (mi^2)	(km^2)
10.2	16.5	2350	218	1300	121	43.7	113.1
9.4	15.2	3760	349	650	60	44.5	115.2
8.6	13.9	5520	513	3780	351	45.5	117.8
8.2	13.1	5810	540	3840	357	48.1	124.5
7.6	12.2	7760	721	4140	385	48.7	126.1
7.0	11.3	10510	976	4770	443	49.3	127.6
6.3	10.1	7690	714	6210	577	52.2	135.1
5.6	9.1	8210	763	9280	862	52.8	136.7
4.6	7.4	14620	1358	12030	1118	57.6	149.1
3.8	6.1	19700	1830	13540	1258	58.4	151.2
3.0	4.8	27700	2573	14600	1356	61.2	158.4
2.0	3.1	14700	1366	10300	957	62.2	161.0
0.9	1.5	34600	3214	16100	1496	66.3	171.6
0.0	0.0	67580	6278	21120	1962	70.6	182.8

Table 2

Geometric Data for Cockrell Creek

Distance Upstream statute miles	km	Upper Layer Cross-section Area ft²	m²	Lower Layer Cross-section Area ft²	m²	Accumulated Drainage Area mi²	km²
3.4	5.6	1370	127	790	734	1.2	3.1
3.2	5.2	2440	227	1420	132	1.4	3.6
3.0	4.8	2920	271	1690	157	1.6	4.1
2.8	4.4	3670	341	2120	197	1.8	4.7
2.5	4.1	4540	422	2630	244	2.0	5.2
2.3	3.7	6270	582	3630	337	2.2	5.7
2.1	3.3	5410	503	3140	292	2.4	6.2
1.7	2.8	7610	707	4410	410	2.7	7.0
1.3	1.7	8620	801	5000	464	3.2	8.3
1.0	1.7	10130	941	5870	545	3.4	8.8
0.8	1.3	9100	845	5270	490	3.6	9.3

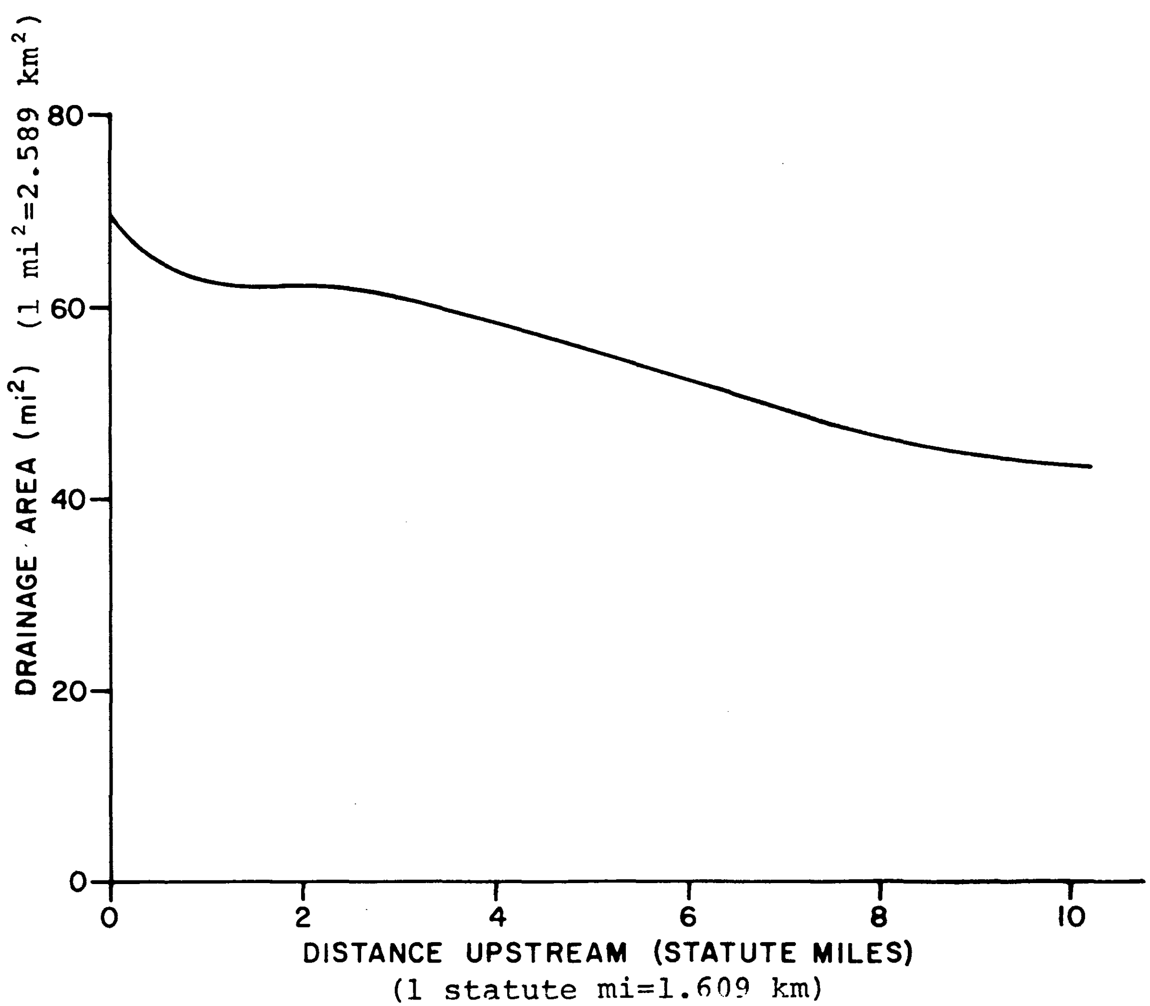


Figure 6. Accumulated drainage area for the Great Wicomico River.

V. Two-Layer Tidal Estuary Model

1. Basic Principles of the Model

In certain estuaries, a combination of factors such as low natural freshwater flow, weak tidal action and organic deposits on the bottom produces great difference in water quality between the surface waters and those near the bottom. A two-layer mathematical model is necessary for study of these systems. Such a model has been developed at VIMS.

The mass balance equation for the mathematical model includes the following terms:

i) horizontal tidal and mean advection;

ii) vertical turbulent diffusion;

iii) vertical mean advection;

iv) source and sink terms for each water quality constituent,

a. salinity: none

b. dissolved oxygen: reaeration in surface layer; bottom oxygen demand in bottom layer, carbonaceous BOD decay, nitrogenous BOD decay.

c. carbonaceous BOD: loadings; decay

d. nitrogenous BOD: loadings; decay

Mathematically:

$$\frac{\partial C}{\partial t} + (u + U_t)\frac{\partial C}{\partial x} + w\frac{\partial C}{\partial z} = \frac{\partial}{\partial z}\left(K_z \frac{\partial C}{\partial z}\right) + \text{source} - \text{sink}$$

where

u = mean horizontal velocity

U_t = horizontal tidal velocity

w = mean vertical velocity

K_z = vertical eddy dispersion coefficient

C = any one of the constituents being modeled

The estuary is divided into finite volume elements:

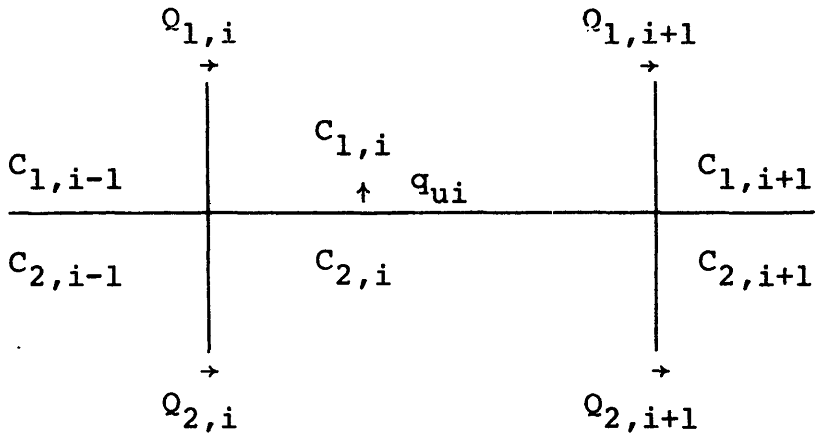
1, i-1	1, i	1, i+1
2, i-1	2, i	2, i+1

← up river   down river →

With this finite differencing, the forms of the transport terms are as follows:

$$\frac{\partial}{\partial t}(V_{\ell,i}C_{\ell,i}) = Q_{\ell,i}\left((1-\alpha)C_{\ell,i-1} + \alpha C_{\ell,i}\right)$$
$$- Q_{\ell,i+1}\left((1-\beta)C_{\ell,i} + \beta C_{\ell,i+1}\right)$$
$$\pm 0.5\, q_{ui}\left(C_{1,i} + C_{2,i}\right) \pm \left(C_{2,i} - C_{1,i}\right)$$

where the subscript ℓ refers to the layer (ℓ=1 for the surface layer, ℓ=2 for the bottom). The horizontal advection factor, $Q_{\ell,i}$ includes both mean advection and an alternating tidal flow. The interpolation factors α and β change value according to the direction of tidal flow. The following figure shows the nomenclature used in the model:



The horizontal flows have an alternating tidal component and a mean component. The vertical flow, q_u, is calculated from the convergence of the mean flow in the lower layer.

The advective flows and the time dependence of the reach volume are related:

$$\frac{\partial V_{\ell,i}}{\partial t} = Q_{\ell,i} - Q_{\ell,i+1} \pm q_{u,i}$$

since $\frac{\partial}{\partial t}(V_{\ell,i}C_{\ell,i}) = \frac{\partial V_{\ell,i}}{\partial t} C_{\ell,i} + V_{\ell,i} \frac{\partial C_{\ell,i}}{\partial t}$, it follows

$$\begin{aligned} \text{that } V_{\ell,i} \frac{\partial C_{\ell,i}}{\partial t} &= Q_{\ell,i}\, \alpha\, (C_{\ell,i-1} - C_{\ell,i}) \\ &+ Q_{\ell,i+1}(1 - \beta)(C_{\ell,i} - C_{\ell,i+1}) \\ &\pm 0.5\, q_{ui}\, (C_{2,i} - C_{1,i}) \pm E_i(C_{2,i} - C_{1,i}) \end{aligned}$$

where $V_{\ell,i}$ is the volume of the ℓth layer of the ith reach and E_i is the vertical turbulent mixing coefficient.

The vertical exchange terms take the positive sign for $\ell=1$ and negative for $\ell=2$. The interpolation factors α and β change according to direction of flow. There is a model input ϕ such that $0.5 \leq \phi \leq 1$. For ebbing current, i.e., positive flow:

$$Q_{\ell,i} \geq 0 \quad \rightarrow \alpha = \phi$$

$$Q_{\ell,i+1} \geq 0 \quad \rightarrow \beta = \phi$$

In the case of flooding tide

$$Q_{\ell,i} < 0 \quad \rightarrow \alpha = 1 - \phi$$

$$Q_{\ell,i+1} < 0 \quad \rightarrow \beta = 1 - \phi$$

Calculation of Mean Horizontal Flow

The following procedure has been developed for computing the mean flow in each layer as a function of distance and freshwater inflow.

Hansen and Rattray (1965) have derived the longitudinal transport in a stratified estuary as a function of depth. In the absence of wind stress, this transport is

$$\phi(\eta) = \frac{1}{2}(2 - 3\eta + \eta^3) - \frac{\nu Ra}{48}(\eta - 3\eta^3 + 2\eta^4)$$

The horizontal velocity profile associated with this transport function is

$$u(\eta) = \frac{3}{2}(1 - \eta^2) + \frac{\nu Ra}{48}(1 - 9\eta^2 + 8\eta^3)$$

where η is the dimensionless depth and νRa is a dimensionless parameter describing the intensity of estuarine gravitational circulation. Inspection of the velocity profile curves reveals that the dimensionless level of no motion is very nearly 0.5.

Using this approximation, the transport in the upper layer is:

$$Q_u = Q\left(\frac{11}{16} + \frac{\nu Ra}{192}\right)$$

where Q is the freshwater inflow. This is the difference between the transport function at the surface and at the mid-depth. The transport in the lower layer is then:

$$Q_L = Q - Q_u$$

The quantity νRa can be calculated from field data. Hansen and Rattray (1966) give the following relation

$$\nu Ra = 16F_m^{-3/4} \qquad \text{, where}$$

$$F_m = U_v / \sqrt{gh\Delta\rho/\rho} \qquad \text{, a densimetric Froude number.}$$

The parameter F_m is calculated empirically for conditions at the mouth of the river. To allow for the streamwise variation of mean flow, the following equation is used

$$Q_u = \begin{cases} Q\left(\frac{11}{16} + \frac{\nu Ra}{192} f\left(\frac{x}{L}\right)\right) & \text{for } x < L \\ \frac{11}{16} Q & \text{for } x \geq L \end{cases}$$

where $f(\frac{x}{L})$ is derived empirically and L is the intrusion length. Gravitational circulation is assumed to increase monotonically going downstream.

$f(0) = 1$, and

$f(1) = 0$.

To extrapolate intrusion length from one condition to the general case, a scaling argument is used. According to Hansen and Rattray (1966):

$$L = \frac{M\ Q\ D}{\nu K_v B}$$

where M is a tidal mixing parameter, Q is freshwater flow, D is depth and B is width and K_v is the vertical turbulent mixing coefficient. From Hansen and Rattray (1966):

$$\frac{M}{\nu} \sim Q^{-7/5}, \text{ so that}$$

$$L \sim Q^{-2/5}.$$

The functional form of f $(\frac{x}{L})$ was chosen in the process of model calibration to be:

$$f(\frac{x}{L}) = \sqrt{1 - \frac{x}{L}};\ x<L$$

Vertical Mixing

The vertical mixing coefficient E_i is determined in the model by successive trial. In practice, useful values tend to be in the range 0.2 - 0.3 cm^2/sec.

Vertical Advection

Vertical volume transport from the lower layer into the upper is calculated directly from the convergence of the mean flow in the lower layer.

Tidal Advection

Tidal current is imposed as a sinusoidal function of time:

$$Q_{\ell,i} = A_{\ell,i} U_{t\ \ell,i} \sin\left(\frac{2\pi t}{T} + \lambda_{\ell,i}\right)$$

, where $A_{\ell,i}$ is the cross-sectional area of the ℓ layer of the ith cross-section, $U_{t\ \ell,i}$ is the tidal current amplitude, T is the tidal period, t is time and $\lambda_{\ell,i}$ is the tidal phase.

Integration Procedure

The concentration in the ℓ layer of the i reach depends on the other layer in the i reach and on the two adjacent reaches, as well as explicit time-dependent terms,

$$\frac{\partial C_{\ell,i}}{\partial t} = F_i(C_{\ell,i-1}, C_{\ell,i}, C_{\ell,i+1}) + G_i(C_{3-\ell,i}) + H_i(t)$$

where ℓ=1 denotes the upper layer and ℓ=2 the lower layer and F, G & H are functions of the variables indicated. When ℓ=2, 3-ℓ=1 and vice-versa. If the concentration C is known at time $j\Delta t$, where Δt is the time step and j is an integer, then the implicit scheme means that the unknown concentrations at time $(j+1)\Delta t$ depend on one another:

$$\frac{\partial C_i}{\partial t}\left((j+\tfrac{1}{2})\Delta t\right) = \frac{C_i^{j+1} - C_i^j}{\Delta t} = \frac{1}{2} F_i(C^j_{\ell,i-1}, C^j_{\ell,i}, C^j_{\ell,i+1})$$

$$+ \frac{1}{2} F_i(C^{j+1}_{\ell,i-1}, C^{j+1}_{\ell,i}, C^{j+1}_{\ell,i+1})$$

$$+ \frac{1}{2}\left(G_i(C^j_{3-\ell,i}) + G_i(C^{j+1}_{3-\ell,i})\right)$$

$$+ \frac{1}{2}\left(H_i(j\Delta t) + H_i\left((j+1)\Delta t\right)\right)$$

Since the equations are linear, the forward time step terms can be isolated and the others lumped together as a known input. One further assumption is to treat the vertical exchange term at the back time step only, i.e.

$$\frac{1}{2}\left(G_i(C^j_{3-\ell,i}) + G_i(C^{j+1}_{3-\ell,i})\right) \rightarrow G_i(C^j_{3-\ell,i})$$

In this way the equations are "tridiagonalized":

$$-\frac{\alpha_i \Delta t}{2} C^{j+1}_{\ell,i-1} - \frac{\beta_i \Delta t}{2} C^{j+1}_{\ell,i+1} + \left(1 - \frac{\Gamma_i \Delta t}{2}\right) C^{j+1}_{\ell,i} = M^j_i$$

where the terms α_i, β_i, Γ_i, and M^j_i are known. The method for solving such a system of equations is explained in an earlier report (Fang, et al., 1973).

VI. Application of Two-Layer Model to Great River and Cockrell Creek

1. Evaluation of Parameters

(i) Physical Parameters

a. Freshwater inflow. Neither Cockrell Creek nor the Great Wicomico River has a gauging station. It was necessary to estimate this input to the model. Based on an annual precipitation (Va. Division of Water Resources, 1972, p. 1-9) of 46 inches (117 cm) and a runoff rate of 19% (ibid, p. 2-2), freshwater inflow at the upstream transect was set at one CFS per square mile of headwater drainage area (i.e., 0.011 micron/sec).

b. Tidal current. An array of current meters was placed at the mouth of the Great Wicomico. A total tidal prism was calculated using the cross-sectional average of the tidal current measured by these meters. The accumulated tidal prism was calculated for each reach by assuming a uniform tide range up to mile 5 (8 km) (U.S. Dept. of Commerce, 1974) and linearly increasing tide range from mile 5 (8 km) to mile 10 (16 km). Tide current amplitude was calculated from the accumulated tidal prism. An essential assumption in such calculations is that there is very little time delay in the propagation of the tidal wave. This assumption is borne out by the Tide Tables (U.S. Dept. of Commerce, 1974). A similar procedure was followed for Cockrell Creek, with the downstream boundary condition derived from the deduced tidal height at this reach of the Great Wicomico.

c. Circulation intensity parameter. The model parameter νRa determines the intensity of two-layer circulation compared to freshwater discharge. Based on findings from other watersheds (Hansen & Rattray, 1965) this parameter was set at 2000 for both streams.

d. Salinity intrusion length. The normal freshwater flow (QNORM) and normal intrusion distance (FLNORM) must be determined simultaneously. Ideally, two sets of data representing highly differing flow conditions are needed to determine these parameters. For the present study, however, QNORM was set equal to the existing flow and FLNORM was adjusted to reproduce the salinity distribution.

(ii) Biochemical Inputs

a. Reaeration Coefficient k_2: O'Connor and Dobbins (1956) presented a theoretical derivation of the reaeration coefficient, in which fundamental turbulence parameters were taken into account. They derived the following formula:

$$(k_2)_{20} = \frac{(D_c U)^{1/2}}{H^{3/2}}$$

where D_c is the molecular diffusivity of oxygen in water, U and H are the cross-sectional mean velocity and depth respectively, and $(k_2)_{20}$ is the reaeration coefficient at 20°C. This formula has been shown to give a satisfactory estimate of k_2 for a river reach with cross-sectional mean depth and velocity more or less uniform throughout the reach.

However, this formula must be modified when dealing with two layered systems. The factor $H^{3/2}$ appearing in the denominator must be broken into two factors.

$$H^{3/2} = H_s^{\ 1/2} \ H_v, \text{ where}$$

H_v is the mean depth of the volume to which oxygen is being replenished. In the two layered model $H_v=H_1$, i.e., the mean depth of the upper layer. The other depth, H_s is the characteristic depth of the vertical shear of the horizontal flow. This depth will have an intermediate value between the depth of the upper layer and the total depth. Hence,

$$H_s = H_1 + 0.5 \ H_2,$$

i.e., the depth of the upper layer plus half the depth of the lower layer, will be approximately correct.

To adjust k_2 for temperatures other than 20^{oC} Elmore and West's (1961) formula is used

$$k_2 = (k_2)_{20} \cdot 1.024^{(\theta-20)}$$

where θ is the water temperature in centigrade degrees.

b. BOD Decay Rates: k_c and k_n

The decay rates of CBOD (carbonaceous biochemical oxygen demand) and NBOD (nitrogenous biochemical oxygen demand) were determined by the model calibration, i.e., adjustment of decay rates until the model results agree satisfactorily with the CBOD and NBOD distribution measured in the field. The decay rates also depend on water temperature; the following formulas are used for this temperature dependence,

$$k_c = (k_c)_{20} \cdot 1.047^{(\theta-20)}$$

$$k_n = (k_n)_{20} \cdot 1.017^{(\theta-20)}$$

c. Saturated Oxygen Content, DOS,

The saturation concentration of dissolved oxygen depends on temperature and salinity. From tables of saturation concentration (Carrett and Green, 1967) a polynomial equation was determined by a least-squares method.

$$\begin{aligned} DOS = {} & 14.6244 - 0.367134\theta + 0.0044972\theta^2 \\ & - 0.0966S + 0.00205\theta S + 0.0002739S^2 \end{aligned}$$

where S is salinity in parts per thousand and DOS is in mg/liter.

d. Benthic Oxygen Demand, BEN

The bottom sediment of an estuary may vary from deep deposits of sewage or industrial waste origin to relatively shallow deposits of natural material of plant origin and finally to clean rock and sand. The oxygen consumption rate of the bottom deposits must be determined with field measurements. Field data were used wherever they are available. A value of 1.0 $gm/m^2/day$ at 20^oC is typical average for most estuaries. The temperature effect was simulated by (Thomann, 1972).

$$BEN = (BEN)_{20} \cdot 1.065^{(\theta-20)}$$

where $(BEN)_{20}$ is the benthic demand at 20^oC.

2. Calibration and Verification

The model was calibrated using data from the intensive survey of July 1974. The point source loadings for carbonaceous and nitrogenous BOD were calculated from the results of an effluent survey conducted in June 1974 by the Water Control Board. The survey results are shown in Table 3. Bottom oxygen demand values were determined from VIMS observations. Cockrell Creek was surveyed in Dec., 1974 and the Great Wicomico River in March, 1975. The results are shown in Table 4 (for locations, see figures 2 & 3).

Figure 7 shows the observed salinities and model results for the Great Wicomico for July 17, 1974. Salinity is high (greater than 10 ppt) over the entire reach being modeled. These particular estuaries are probably saline upstream to the limit of tidal action. Salinity stratification is slight, usually about 0.5 ppt difference, whereas dissolved oxygen stratification is great. Figure 8 shows the comparison of Cockrell Creek observed salinity and model result. In this case the salinity falloff is even more gradual and the salinity stratification is even more weak. Given appropriate boundary conditions and flow parameters, the model presumably will be valid in the opposite extreme, namely the fjord-type estuary.

Figures 9 & 10 show the comparison of observed and modeled dissolved oxygen for the Great Wicomico for July 16 & 17 respectively. The basic calibration was performed using the data for July 17, since these data were better from the standpoint of scatter and internal consistency. The model results for July 16 differ from those for July 17 by virtue of different boundary conditions for dissolved

Table 3

Reported Effluents to Cockrell Creek June 25-26, 1974

	Five-day Carbonaceous BOD		Organic Nitrogen		Ammonia	
	(lb/day)	(kg/day)	(lb/day)	(kg/day)	(lb/day	(kg/day)
Standard Products	3339	1514	270	122	121	55
Zapata-Haynie	1490	676	348	158	201	91

Table 4

Bottom Oxygen Demand

Great Wicomico River and Cockrell Creek

Stream	Location (stat. mi.)	Bottom Oxygen Demand ($gm/m^2/da$)
Cockrell Creek	1.04	1.8
"	2.30	1.0
Great Wicomico	0.0	2.4
"	3.80	2.3
"	4.60	2.5

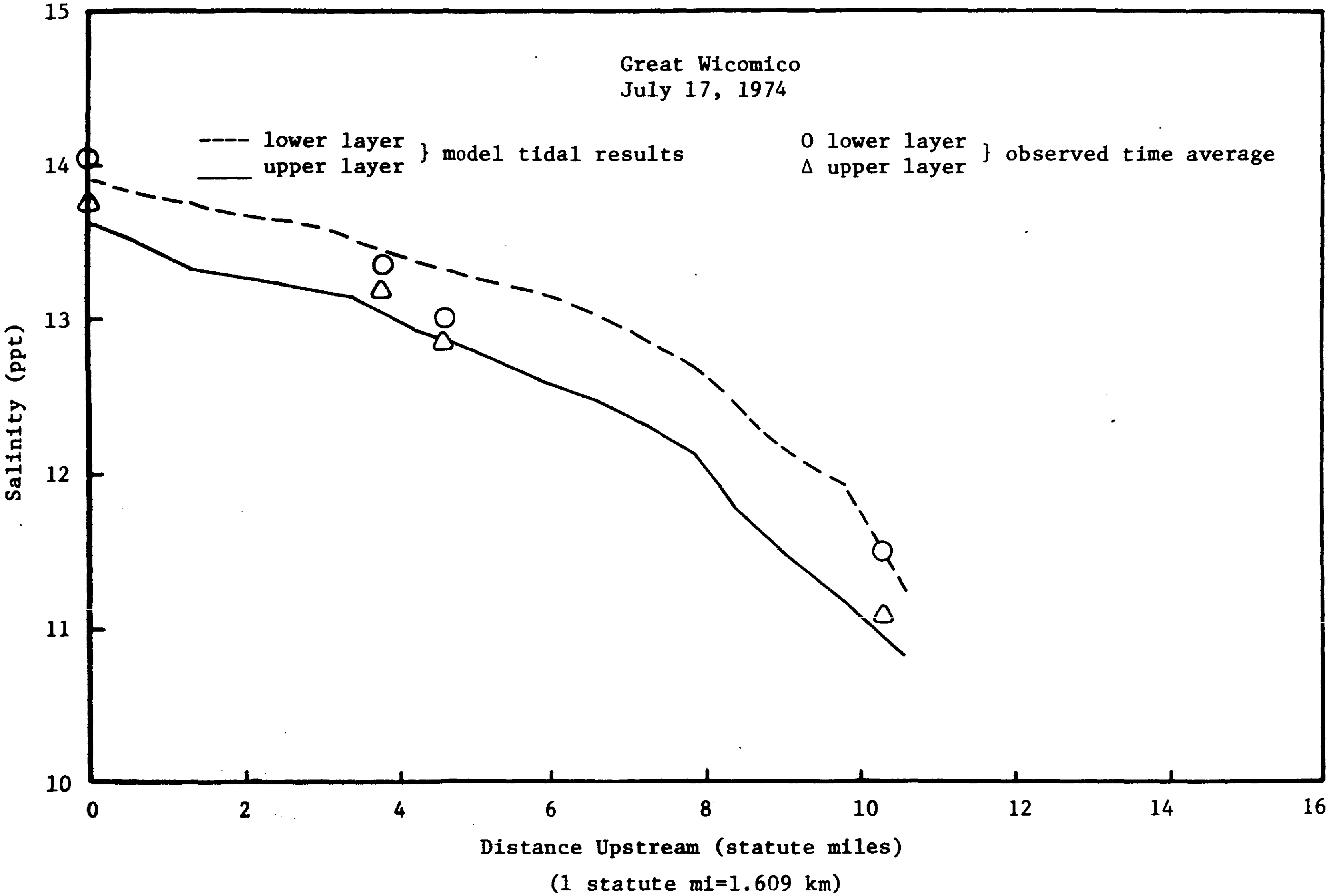


Figure 7. Observed salinity and model results for the Great Wicomico River for July 17, 1974.

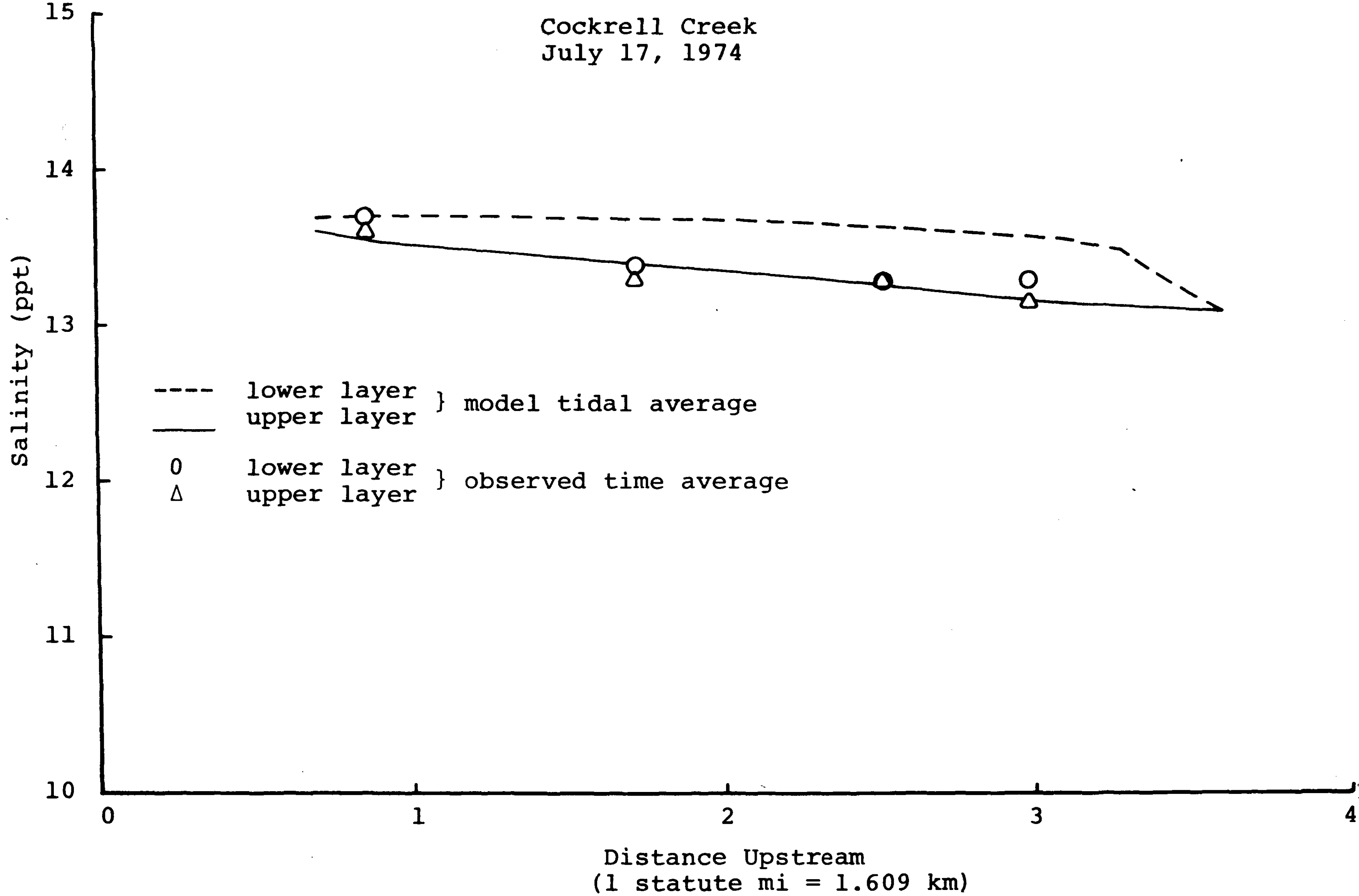


Figure 8. Observed salinity and model results for Cockrell Creek for July 17, 1974.

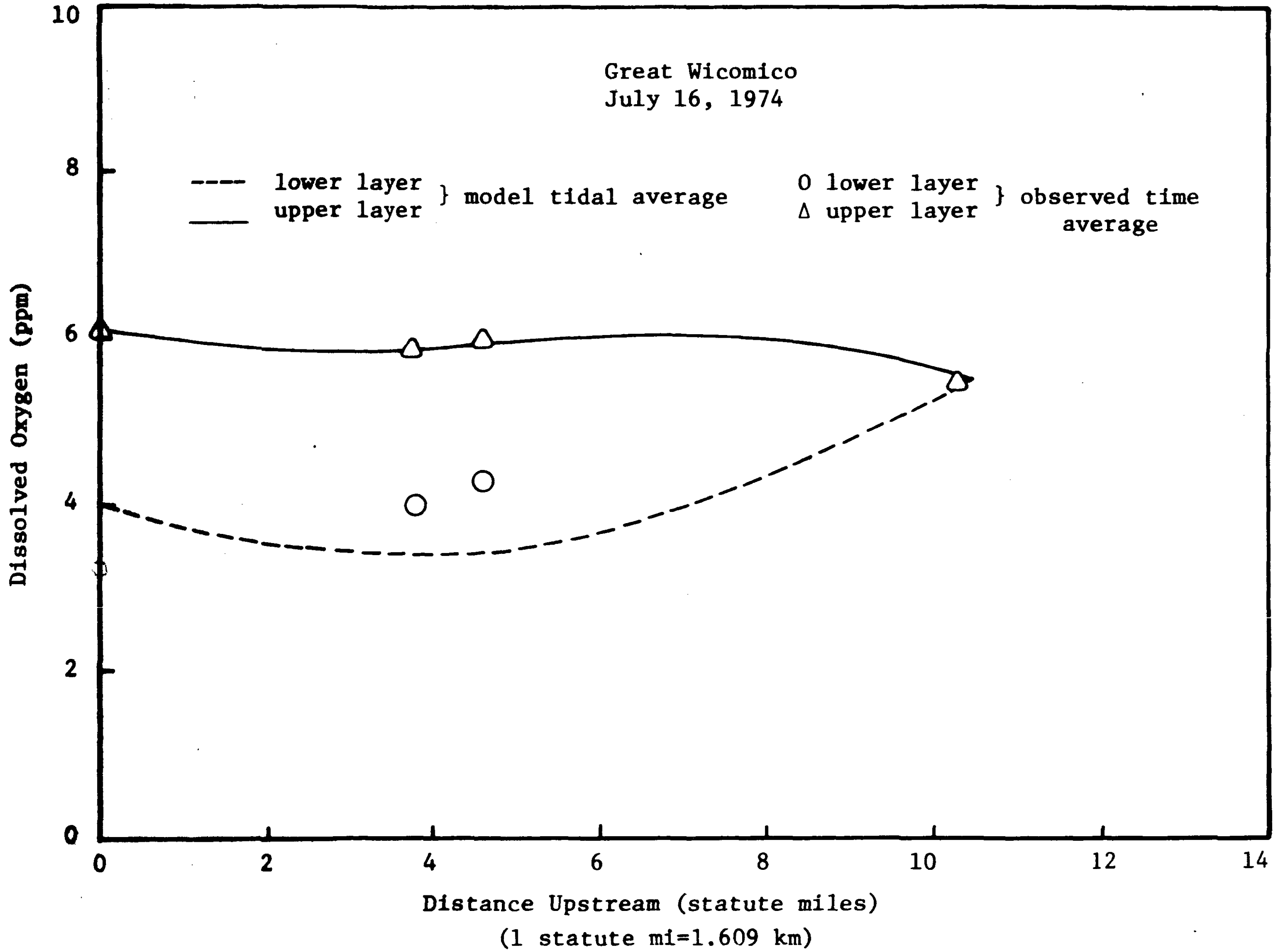


Figure 9. Observed dissolved oxygen and model results for the Great Wicomico River, July 16, 1974.

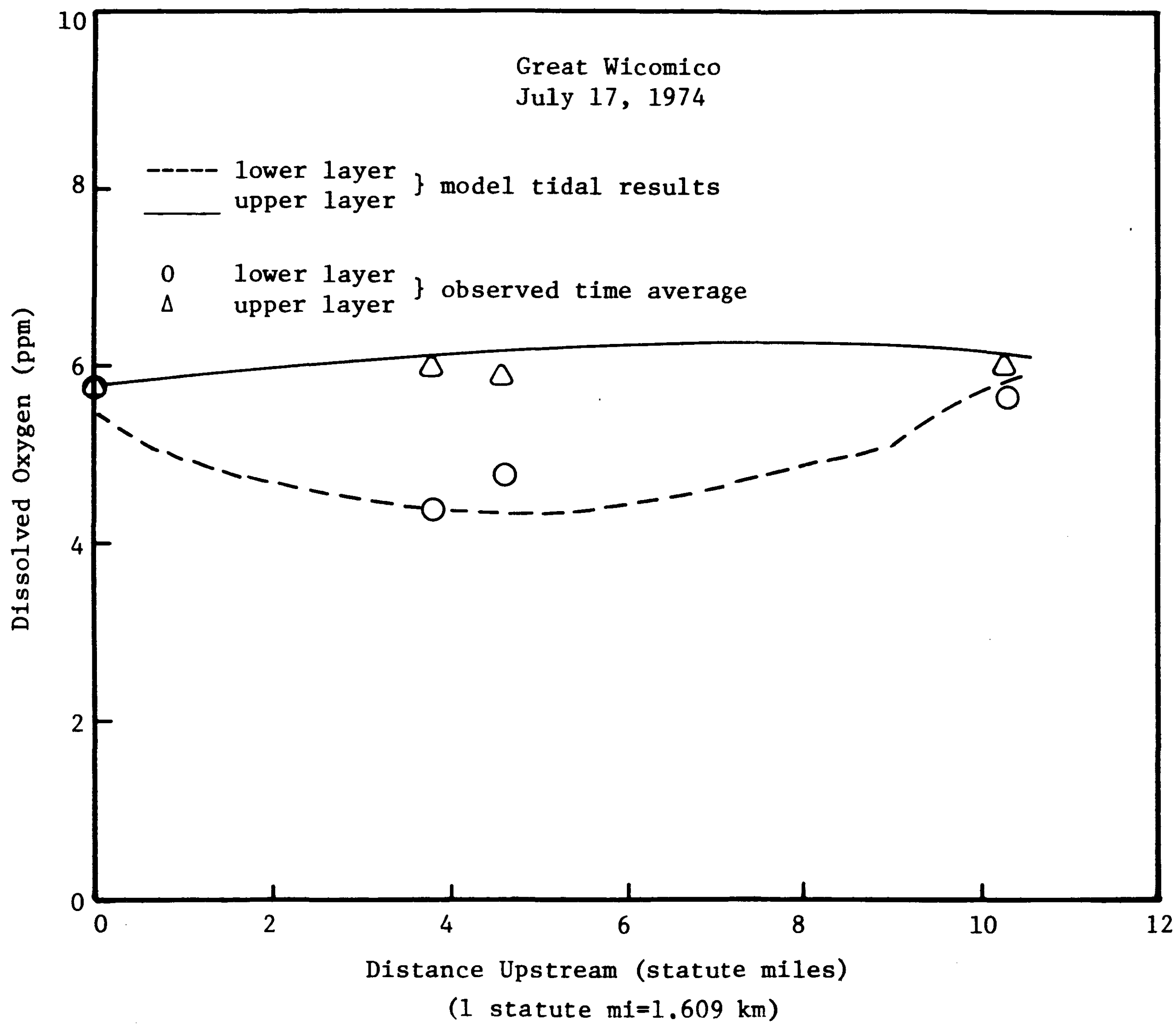


Figure 10. Observed dissolved oxygen and model results for the Great Wicomico River, July 17, 1974.

oxygen and in no other way. It is not readily apparent why the dissolved oxygen should have been so much lower at the mouth of the Great Wicomico on the 17th compared to the 16. The hourly data (see Appendix A) show that the difference was consistent, especially in the lower layer. There is no known point source in the Great Wicomico. The observed oxygen sag results basically from the combination of bottom oxygen demand and weak tidal action.

Figures 11 & 12 show the comparison of observed and modeled DO for Cockrell Creek for July 16 & 17, respectively. As with the Great Wicomico, July 17 data provided the basic calibration; the July 16 model results were obtained by changing the DO boundary conditions. Cockrell Creek contains both point source loadings and bottom oxygen demand; hence both upper and lower layers exhibit sags. In the model, point source loadings enter the upper layer. This approximation is physically reasonable and appears to produce satisfactory results.

Both streams were sampled on June 27, 1975, at slack before flood. These data were used for verification of dissolved oxygen and salinity. Average point source loading for the month of June for Cockrell Creek was provided by the Water Control Board. Figures 13 & 14 show the observed salinity and model results for the Great Wicomico and Cockrell Creek, respectively. Lacking flow data, the assumed fresh water inflows were the same as for the

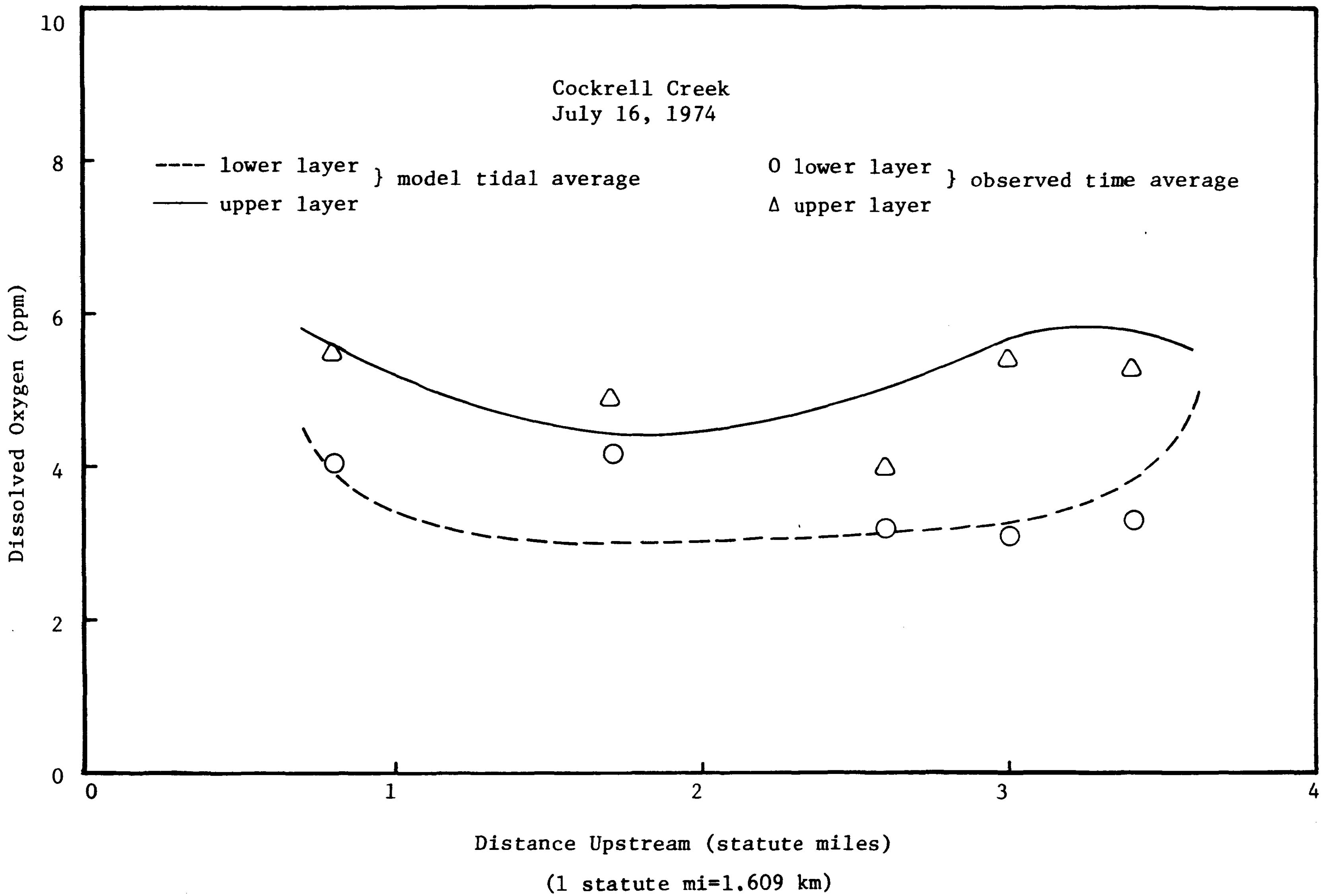


Figure 11. Observed dissolved oxygen and model results for Cockrell Creek, July 16, 1974.

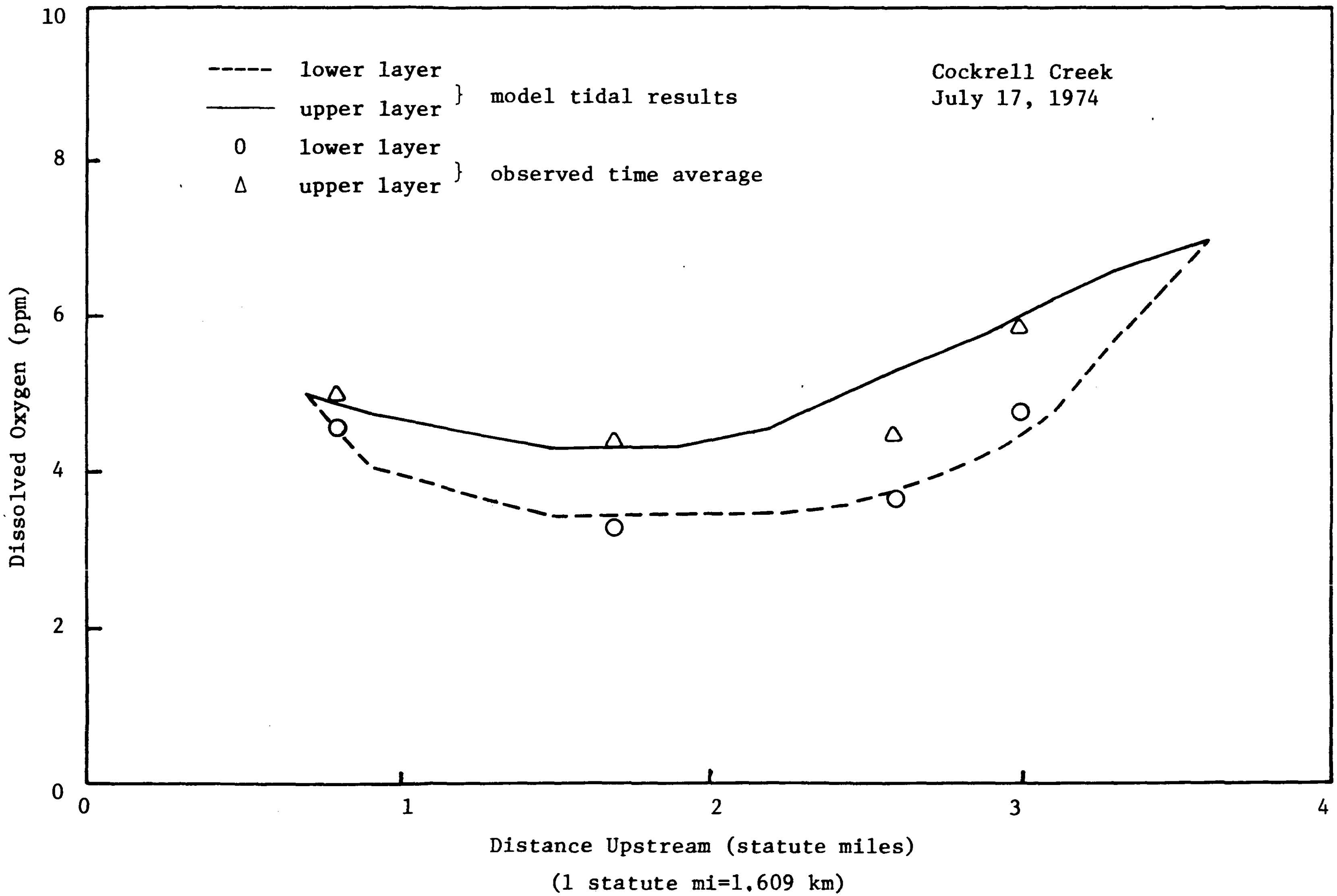


Figure 12. Observed dissolved oxygen and model results for Cockrell Creek, July 17, 1974.

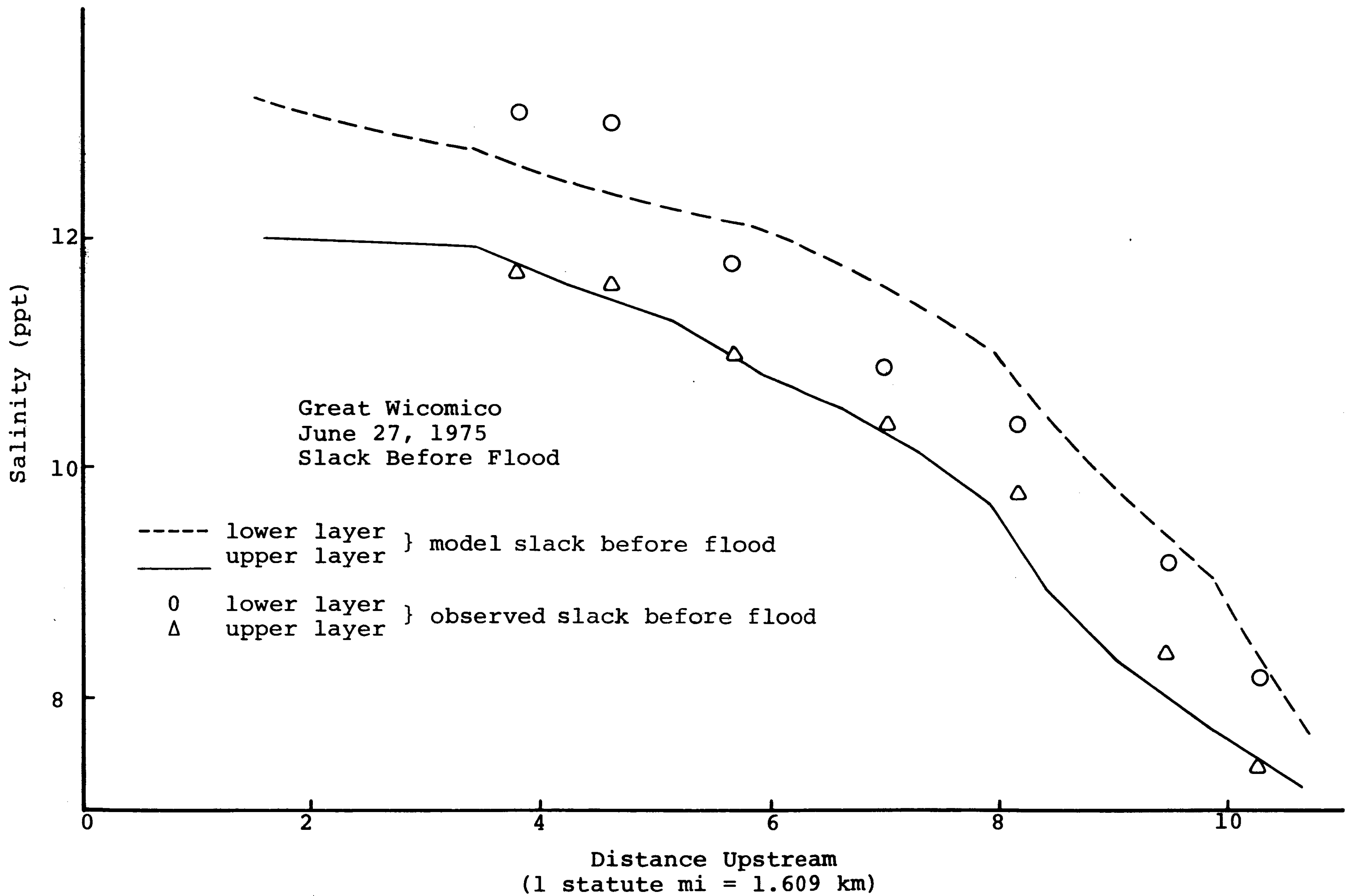


Figure 13. Observed salinity and model results for the Great Wicomico River, June 27, 1975.

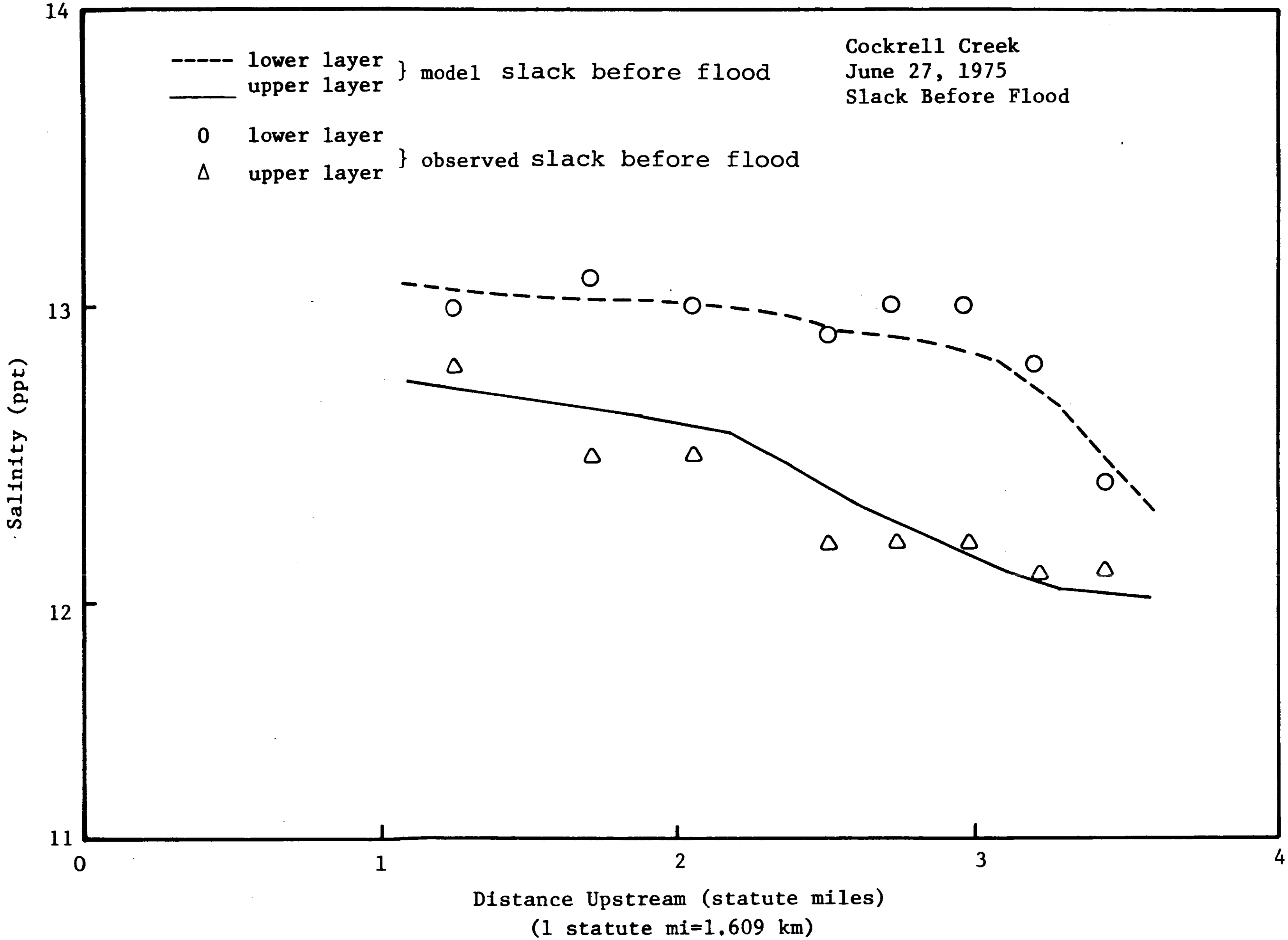


Figure 14. Observed salinity and model results for Cockrell Creek, June 27, 1975.

calibration. In the situation when finite boundary conditions for salinity are applied at both ends of the estuary, these boundary conditions appear to dominate the salinity distribution.

Figures 15 & 16 show the observed dissolved oxygen distribution and model verification results for the Great Wicomico and Cockrell Creek, respectively. The observations unfortunately contain considerable scatter, particularly in the Great Wicomico. However, the model results reproduce the general trend of the observations.

For these streams, gravitational circulation was not an important factor as can be seen by the lack of vertical stratification in the salinity distribution. In the model, the actual ratio of gravitational circulation to tidal flux was about 0.01. The model, however is valid in this limiting case as well as for situations where gravitational circulation is very important.

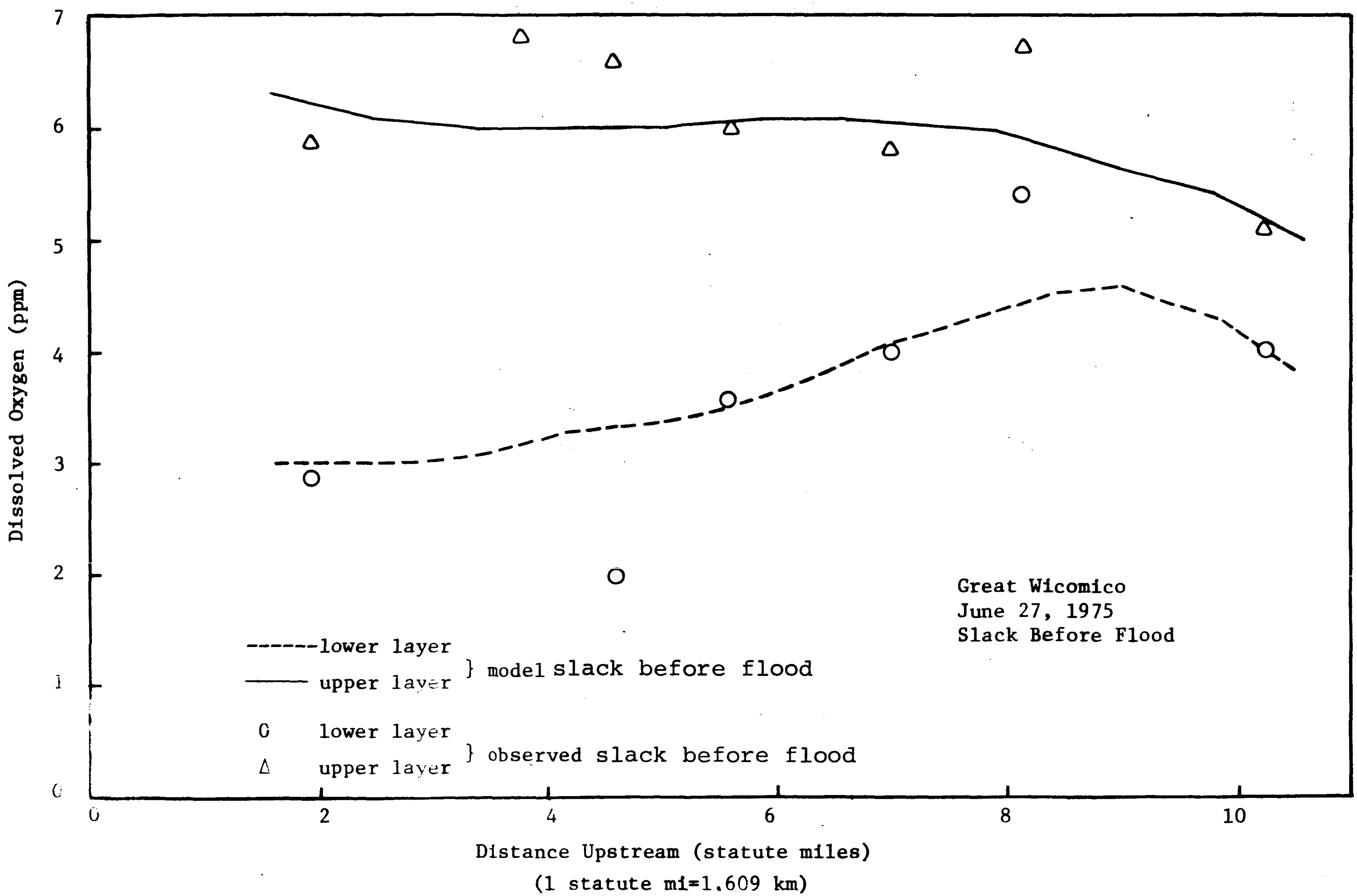


Figure 15. Observed dissolved oxygen and model results for the Great Wicomico River, June 27, 1975.

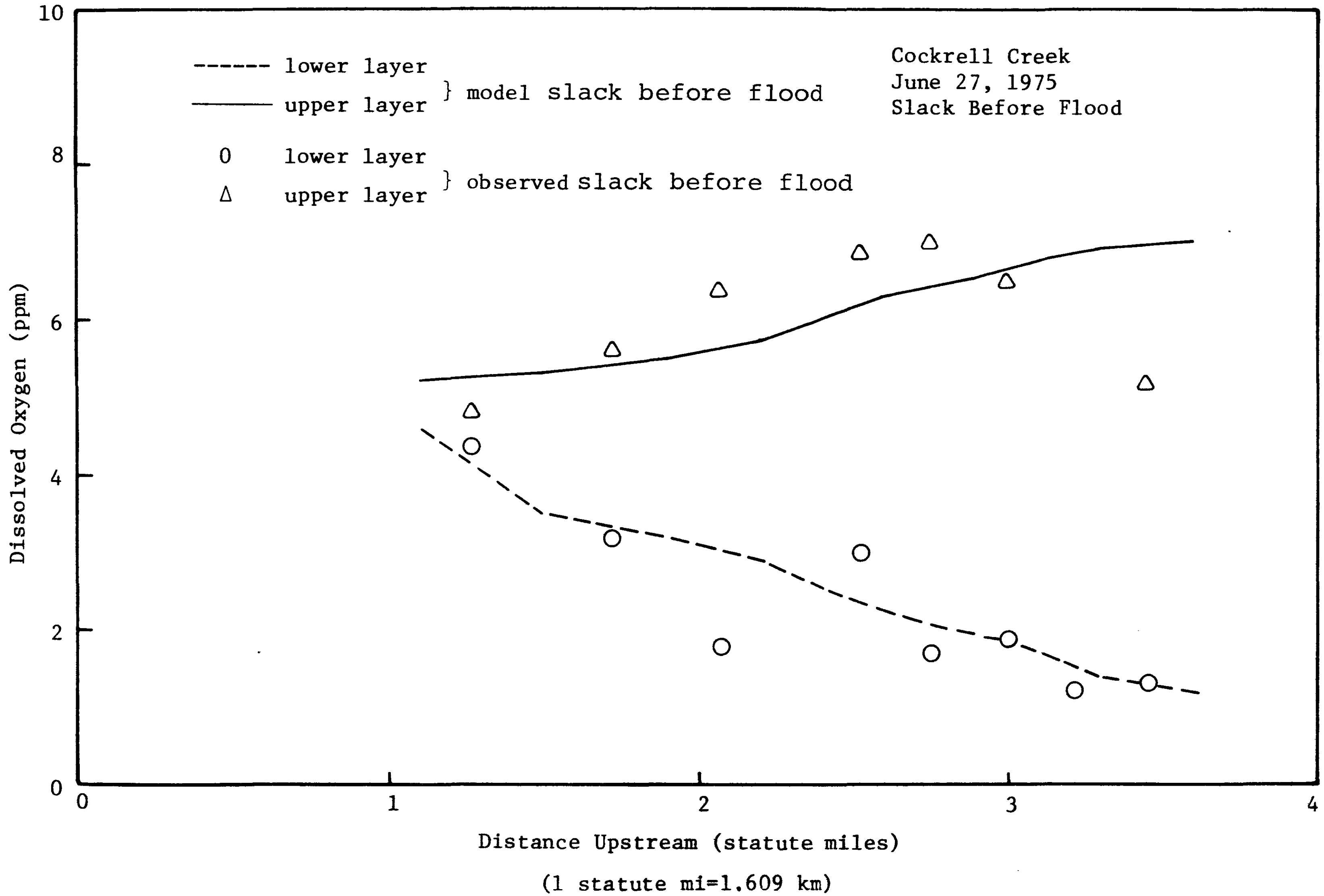


Figure 16. Observed dissolved oxygen and model results for Cockrell Creek, June 27, 1975.

VII. Sensitivity Analysis

To be most useful and flexible, a model must be sensitive to changes in the various input parameters. There is little point to providing for variable input of a parameter which has no impact on the results even when changed substantially. Several computer runs were made to demonstrate the sensitivity and flexibility of the model.

A. Point Sources

The Cockrell Creek model was run with the point-source carbonaceous BOD reduced by 33% (see figure 17). A measurable change in the DO sag was produced, but oxygen in the lower layer remained unaffected. In another run, both carbonaceous and nitrogenous BOD were reduced 90%. In this case the sag disappeared and the minimum DO occurred at the boundary (see figure 17). Again there was no appreciable effect in the lower layer. To get a somewhat truer picture of this situation, a run was made with 90% removal and the downstream boundary condition increased to 7.5. These conditions produced a sag with a minimum value of DO of nearly seven parts per million (see figure 18) with no effect in the lower layer. The lower layer appears to be controlled by the bottom demand and not affected by point source loadings.

B. Temperature

Although the atmospheric reaeration rate increases with temperature, saturation concentration of dissolved oxygen

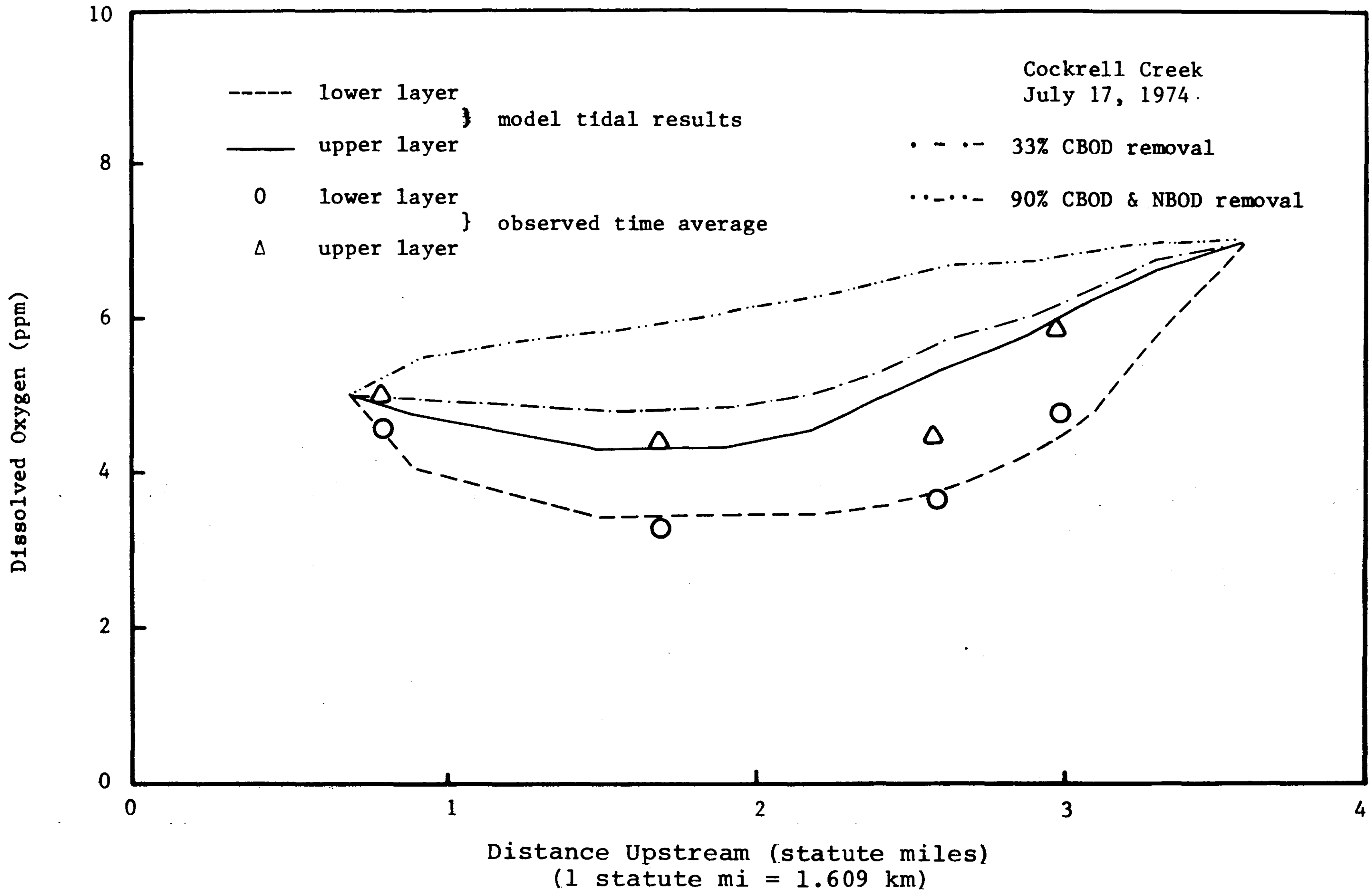


Figure 17. Model runs with 33% carbonaceous BOD removal and with 90% BOD removal.

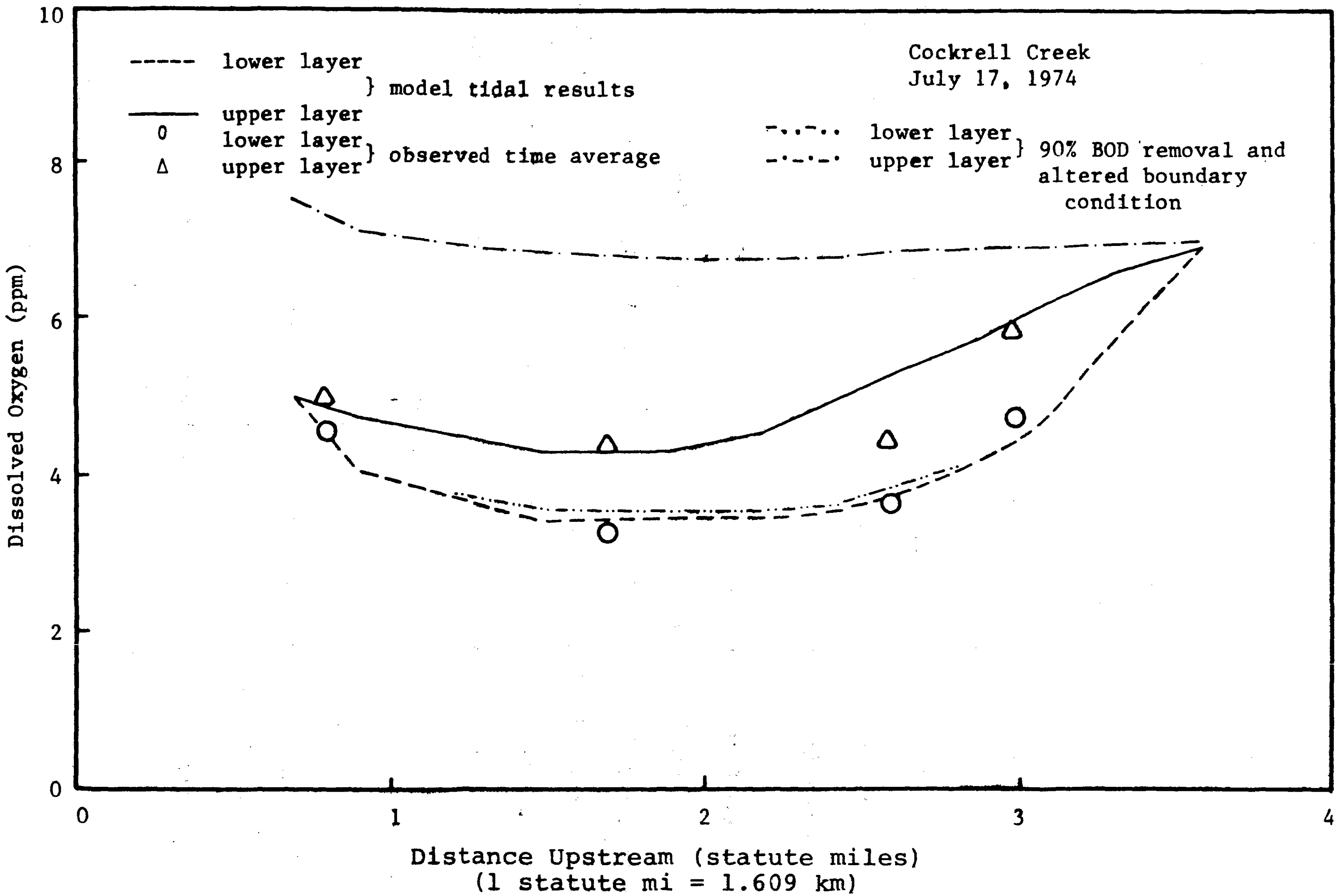


Figure 18. Model run with 90% BOD removal and adjusted boundary condition.

decreases with temperature. The exertion rates of BOD and bottom oxygen demand also increase with temperature, so that dissolved oxygen levels tend to fall as temperature increases. Figure 19 shows the results of model runs with temperatures $2^{\circ}C$ higher and lower than natural. The effect of varying temperature is perceptible.

C. BOD Decay Rate

A comparison run was made with carbonaceous BOD decay rate increased by 30%. The effect tends to be greatest in the surface layer, in the vicinity of the point source, as can be seen in figure 20.

D. Bottom Oxygen Demand

While point source loadings in the surface layer tend to have little influence on the lower layer, bottom oxygen demand influences both layers. The result of reducing bottom oxygen demand by 50% is greatest for the lower layer (see figure 21). The upper layer is relatively unaffected.

E. Freshwater Inflow

The Great Wicomico River model was run for the extreme cases of freshwater inflow of ten times the calibration flow and one tenth of the calibration flow (see figure 22). The high flow enhanced the two-directional flow and thus increased dramatically the dissolved oxygen levels in both layers. The low-flow situation results in weaker upstream flow in the bottom layer and hence in less replenishment of

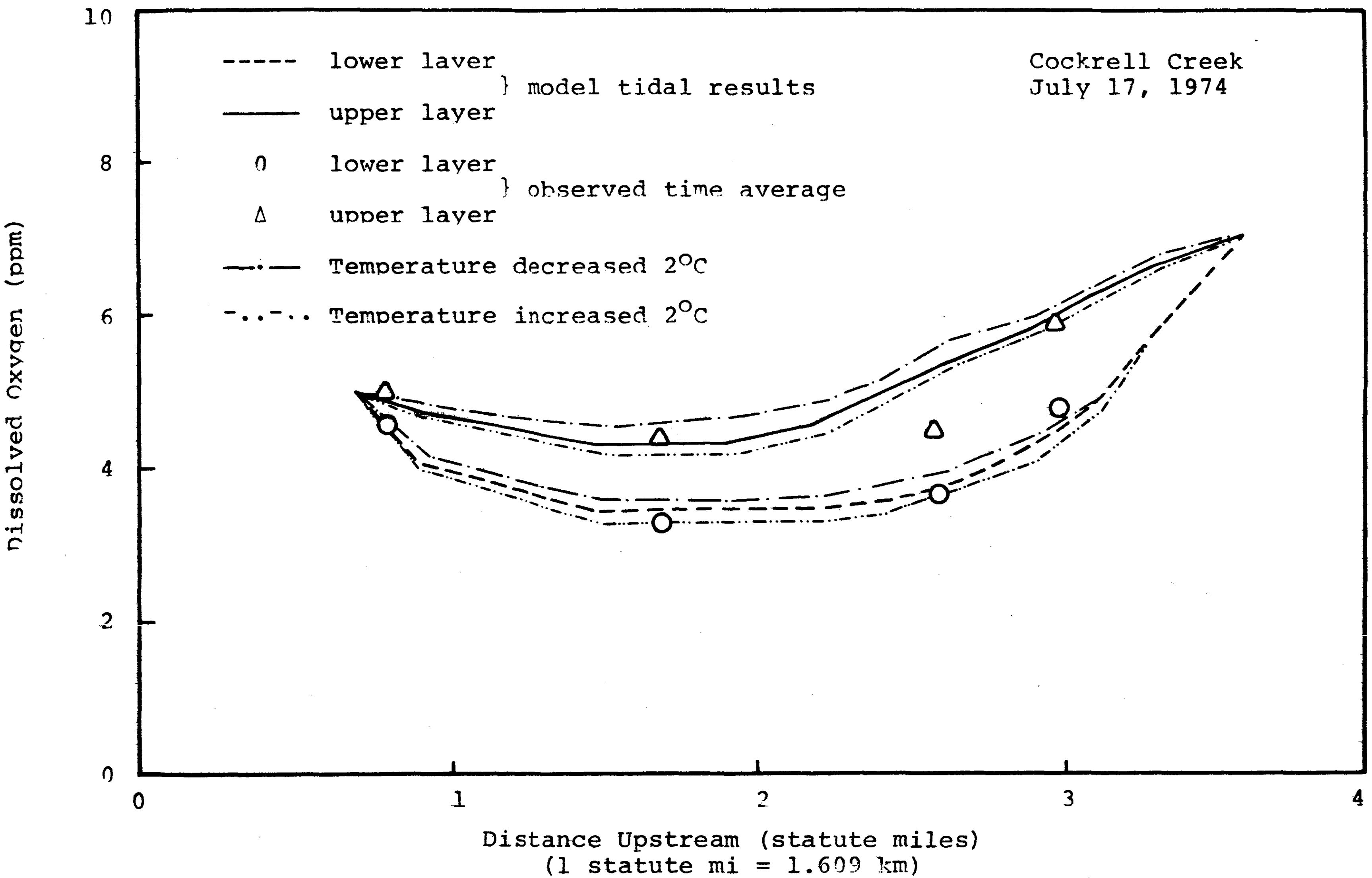


Figure 19. Model runs with water temperature 2°C higher and lower than observed.

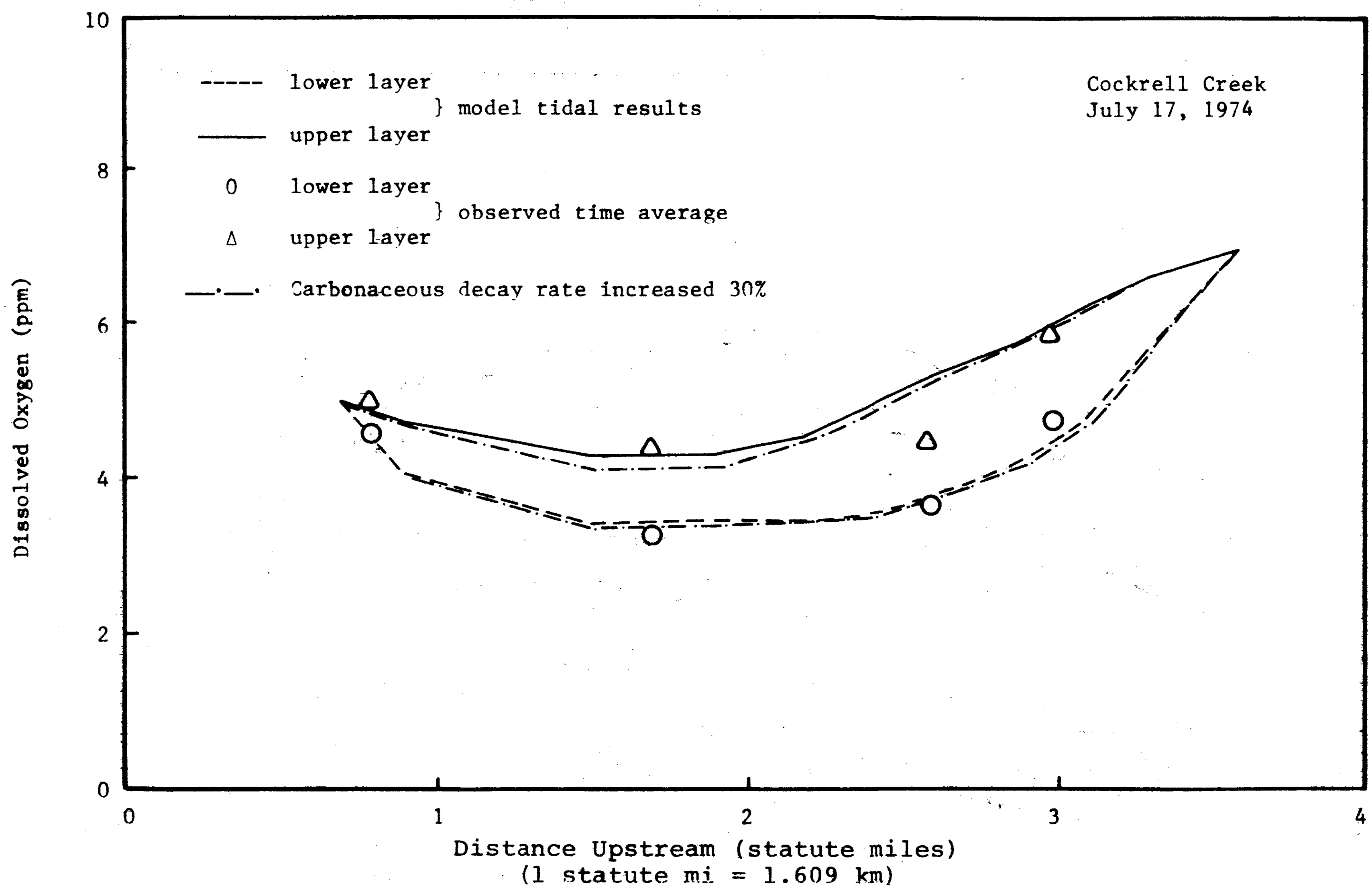


Figure 20. Model run with carbonaceous decay rate increased 30%.

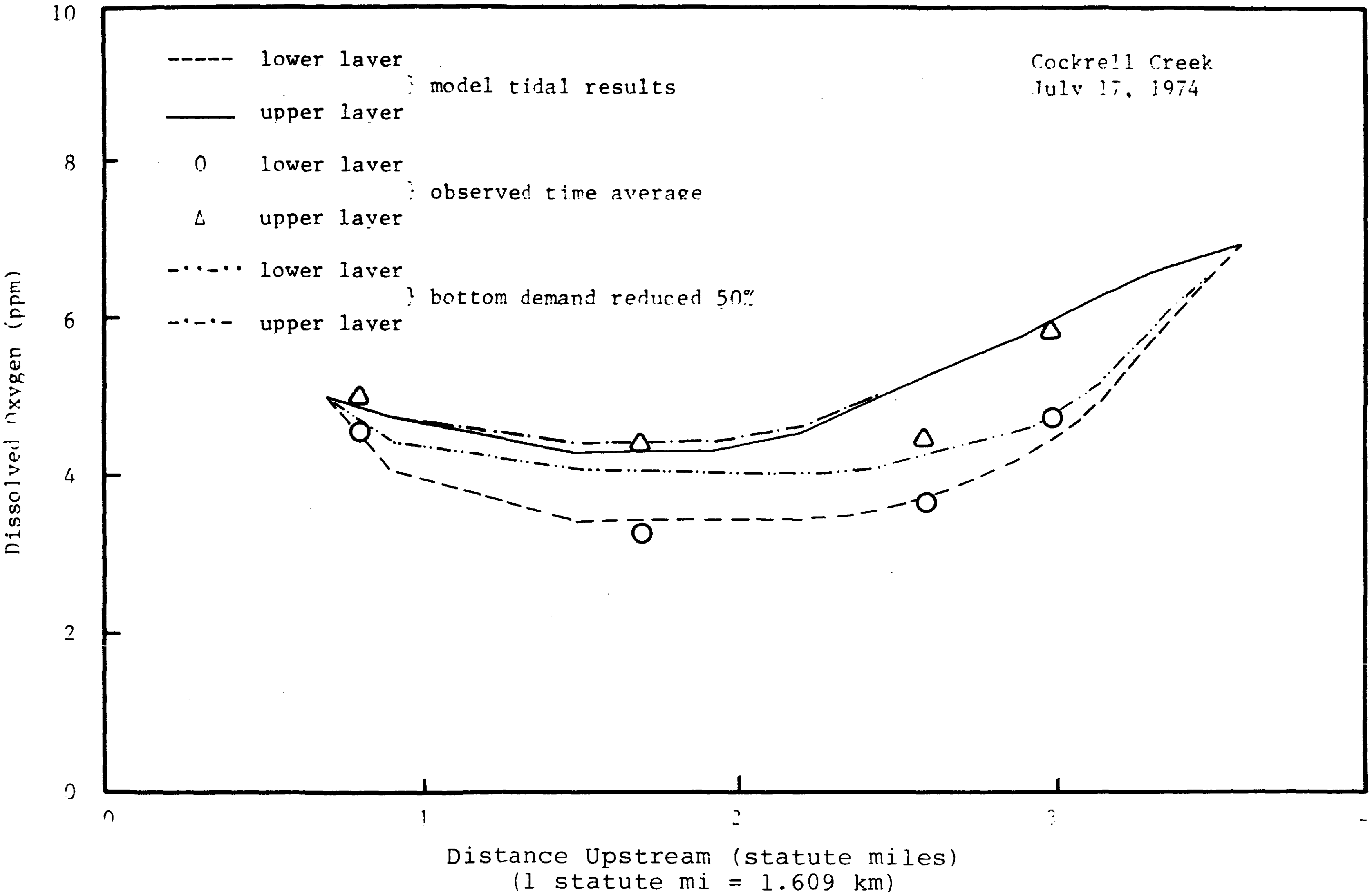


Figure 21. Model run with bottom oxygen demand reduced 50%.

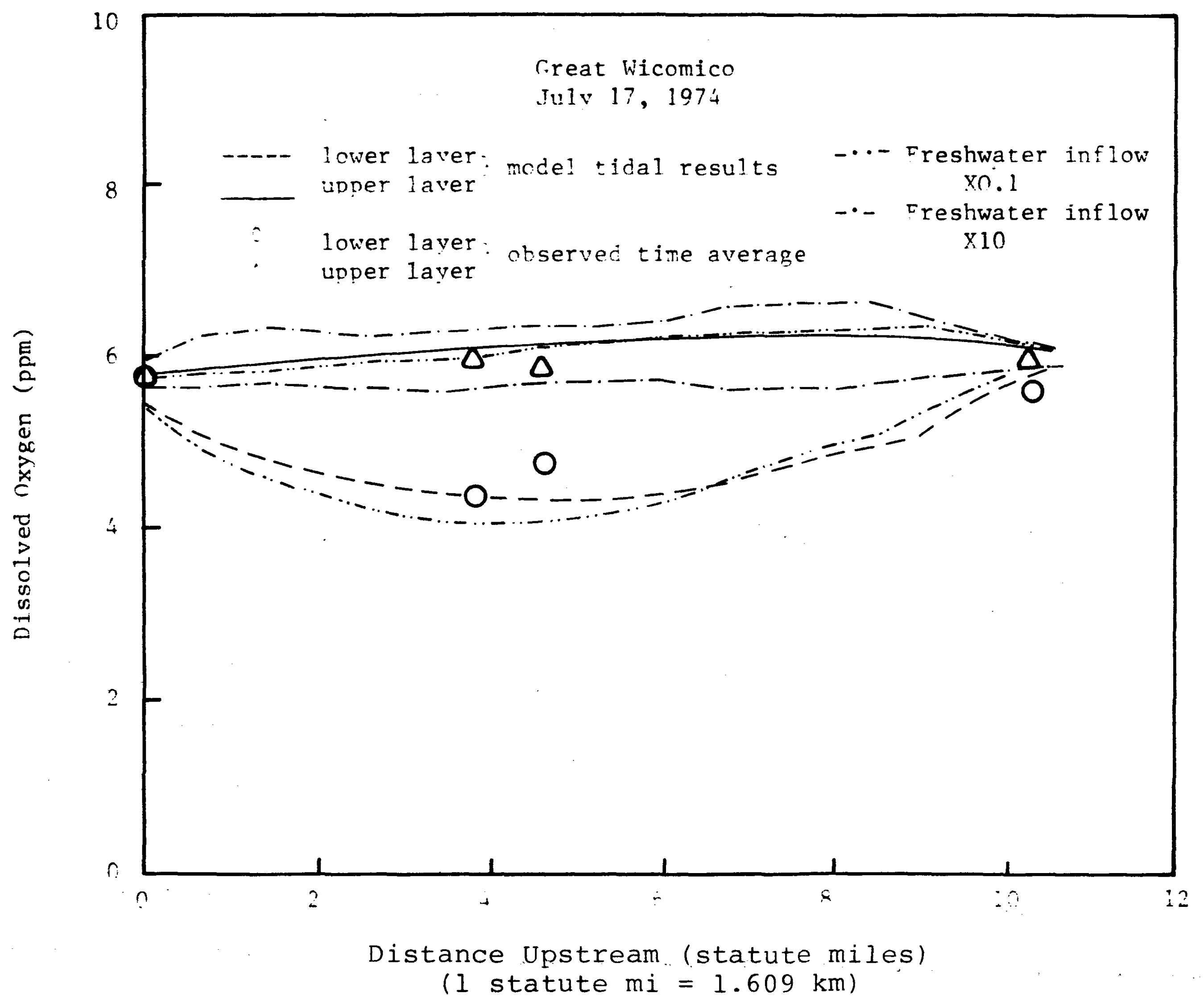


Figure 22. Model runs with freshwater inflows ten times those observed and one-tenth of observed.

dissolved oxygen by net advection from the downstream boundary.

F. Tidal Current

Increasing tidal current increases the rate of tidal mixing and also increases the atmospheric reaeration rate. Both of these effects can be seen in figure 23. Reaeration is responsible for the increase of dissolved oxygen in the surface layer; in the lower layer it is the influence of the boundary conditions that raises the DO level. Reducing the tidal current has the opposite effect as can also be seen in figure 23.

The natural factors which the user can vary in the model are chiefly temperature, tidal current and fresh-water inflow. The degree of artificial variation of tidal current amplitude was greater than what is possible in nature. Nevertheless the effect on model predictions is ten percent or less. Temperature shifts of 2^{o}C produce a somewhat smaller effect. However, the yearly range of water temperature in this type of estuary exceeds 25^{o}C, so that on a seasonal basis water temperature is quite important. The high flow case, with its dramatic effect, was within the realm of possibility. Based on statistics for Piscataway Creek (Division of Water Resources, 1972, p. 5-15), a runoff of 10 cfs per square mile of drainage area (0.11 microns per second) lasting one day can be expected to occur more often than once in two years.

The sensitivity analysis runs give some insights into the workings of the estuary. It can be seen, for example,

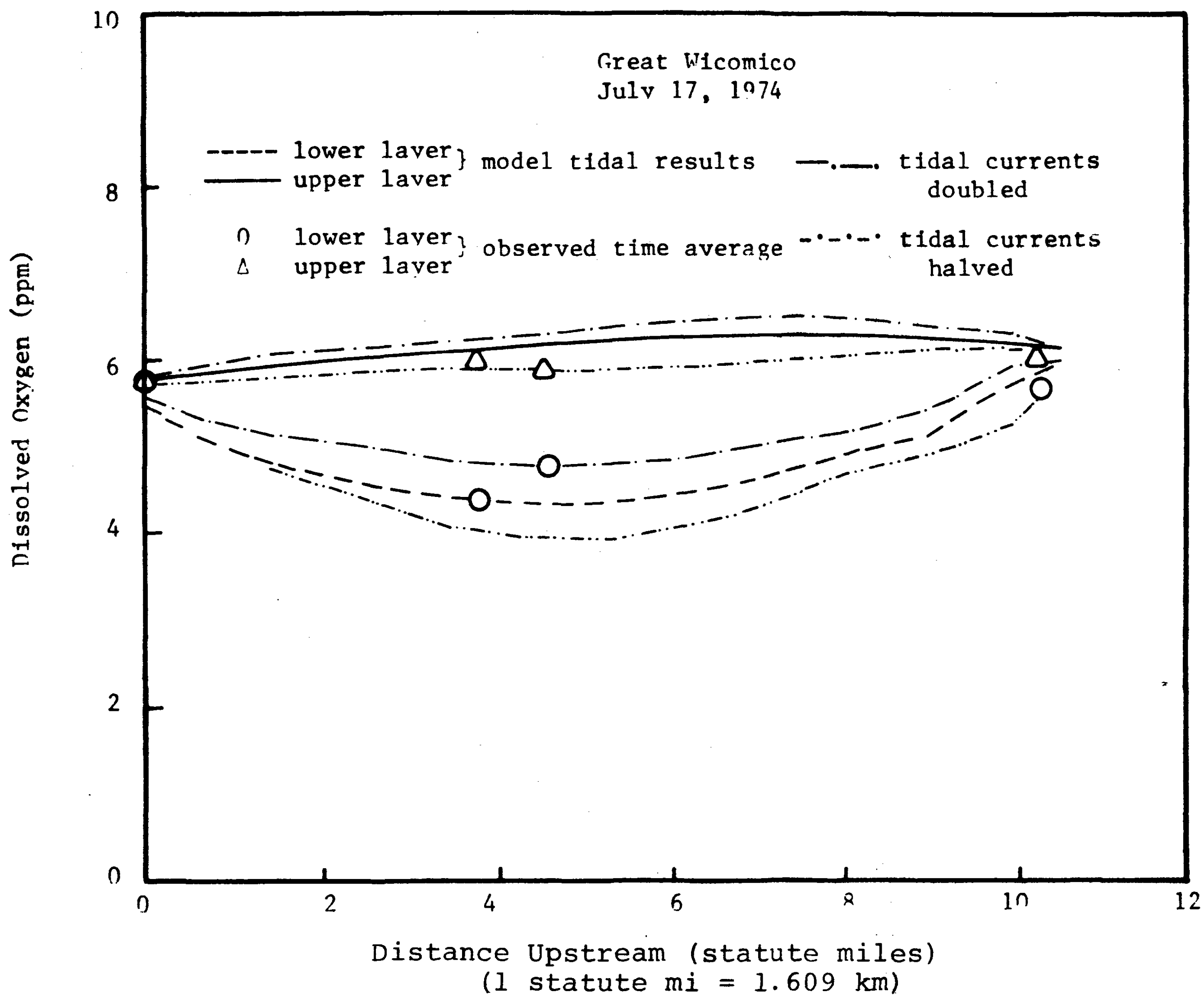


Figure 23. Model runs with tidal currents double those observed and half of those observed.

that the dissolved oxygen sag in the surface layer in Cockrell Creek is due primarily to the presence of point source loadings, since mitigation or removal of the point source greatly affects the extent of sag. Reduction of carbonaceous decay rate does not greatly affect dissolved oxygen, since oxygen consumption is proportional to the product of carbonaceous decay rate times CBOD. Reduction in decay rate tends to raise the CBOD level, and thus stabilize the product of the two. Reduction of bottom oxygen demand tends to improve oxygen levels in the lower layer but not to affect the surface layer. However it is not possible to say at this time to what extent the bottom deposits are man-derived or to state the future prognosis. The task of the model is to predict the result of a given set of input conditions.

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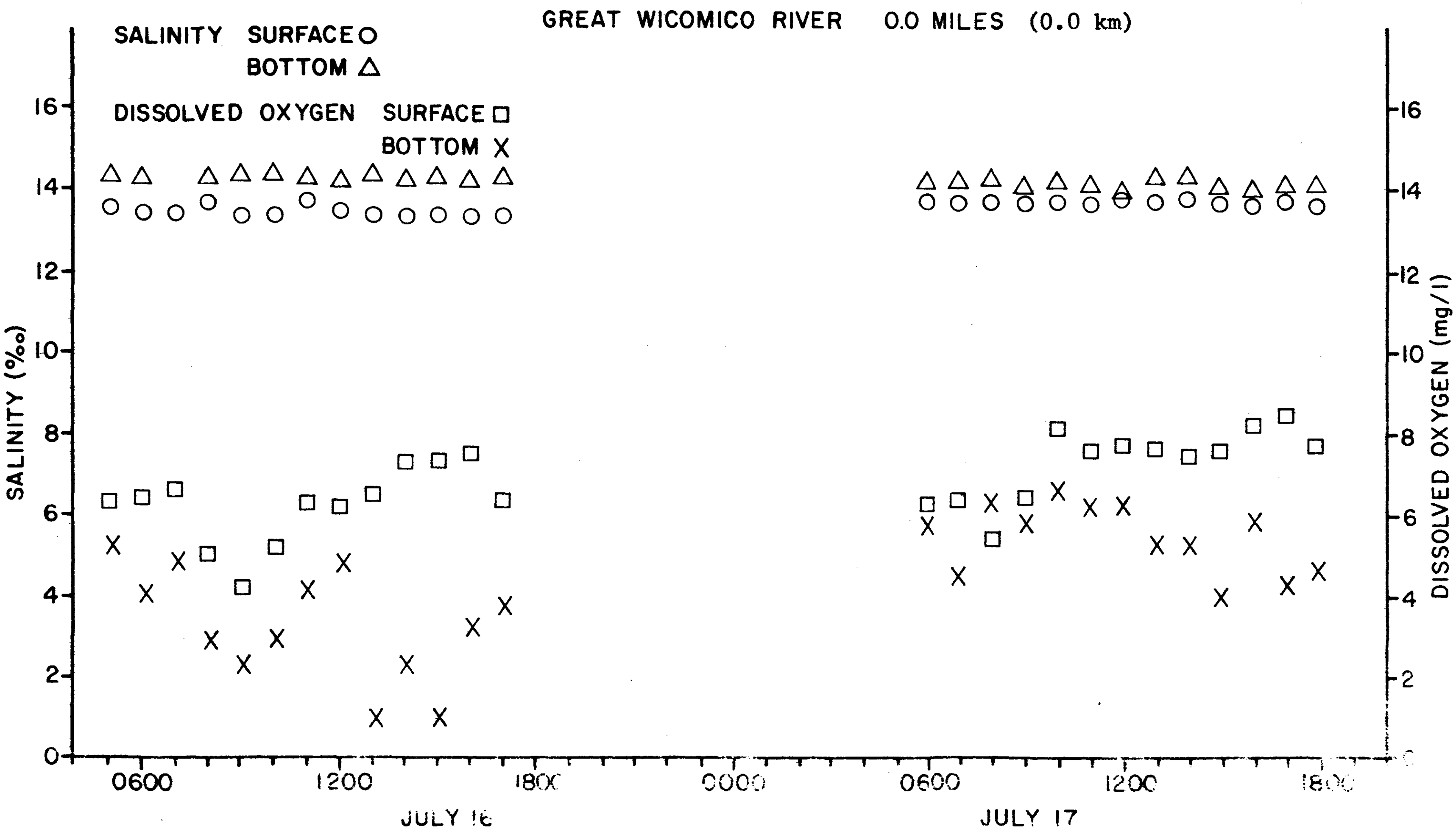
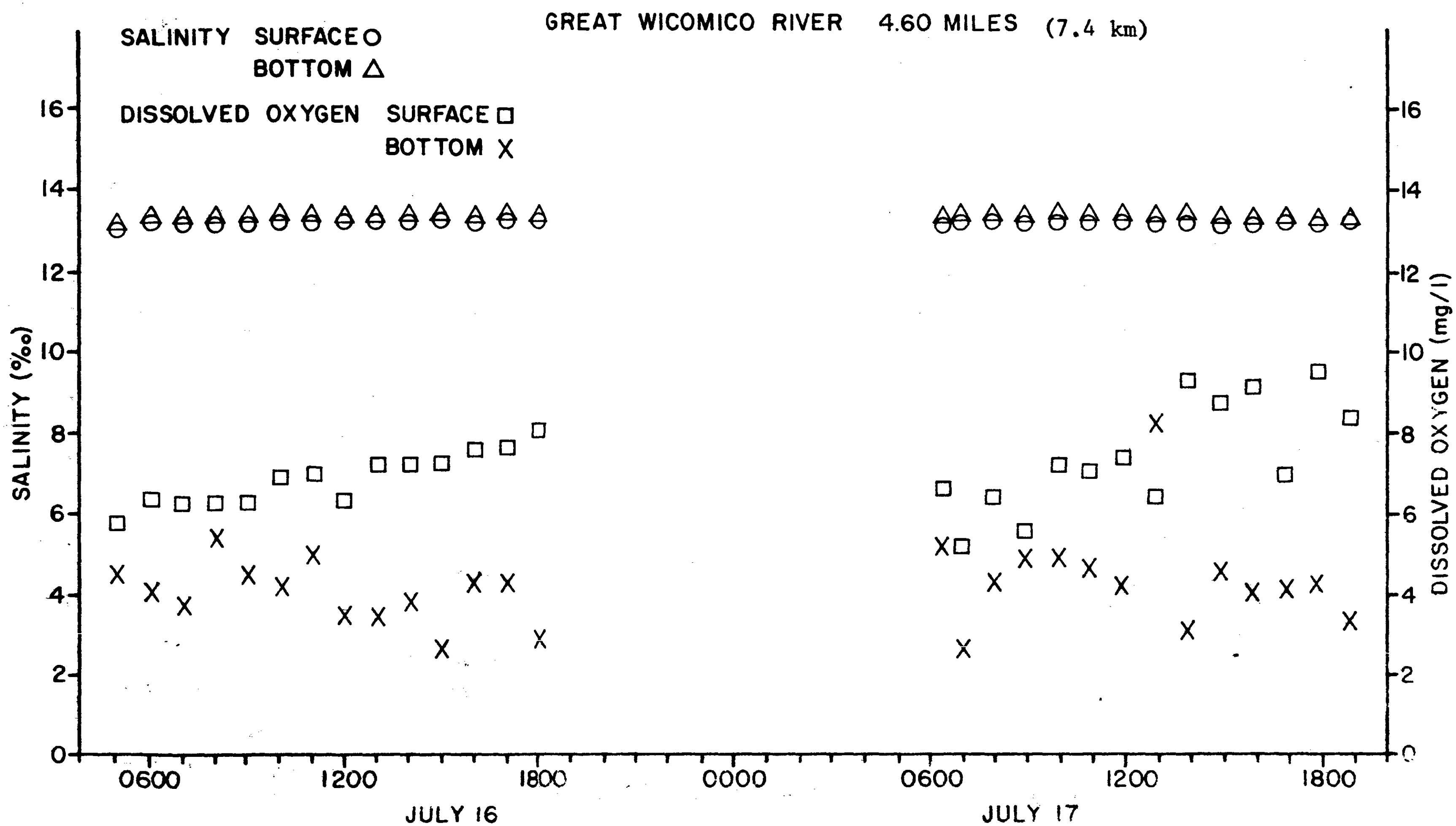
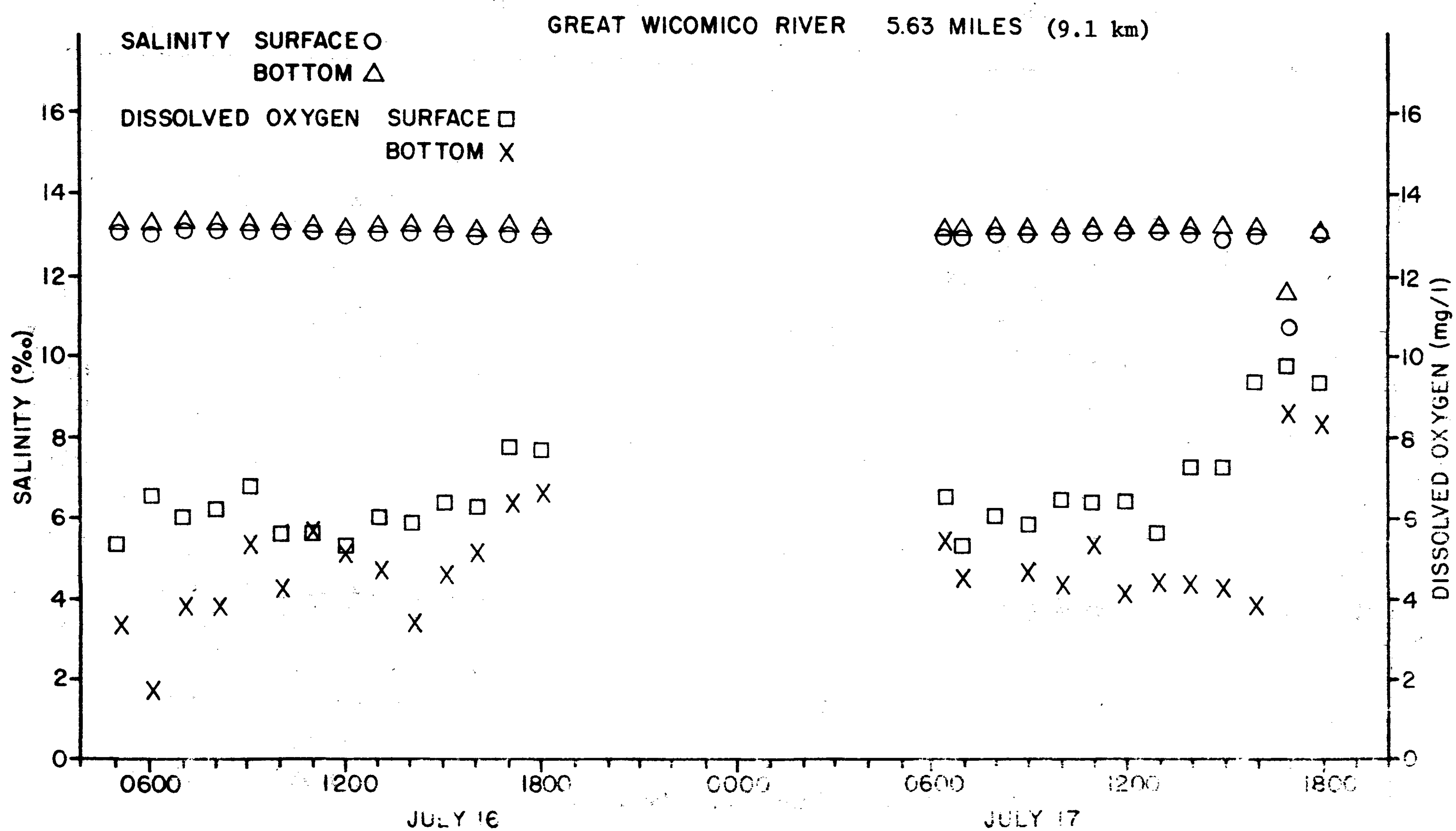
Appendix A

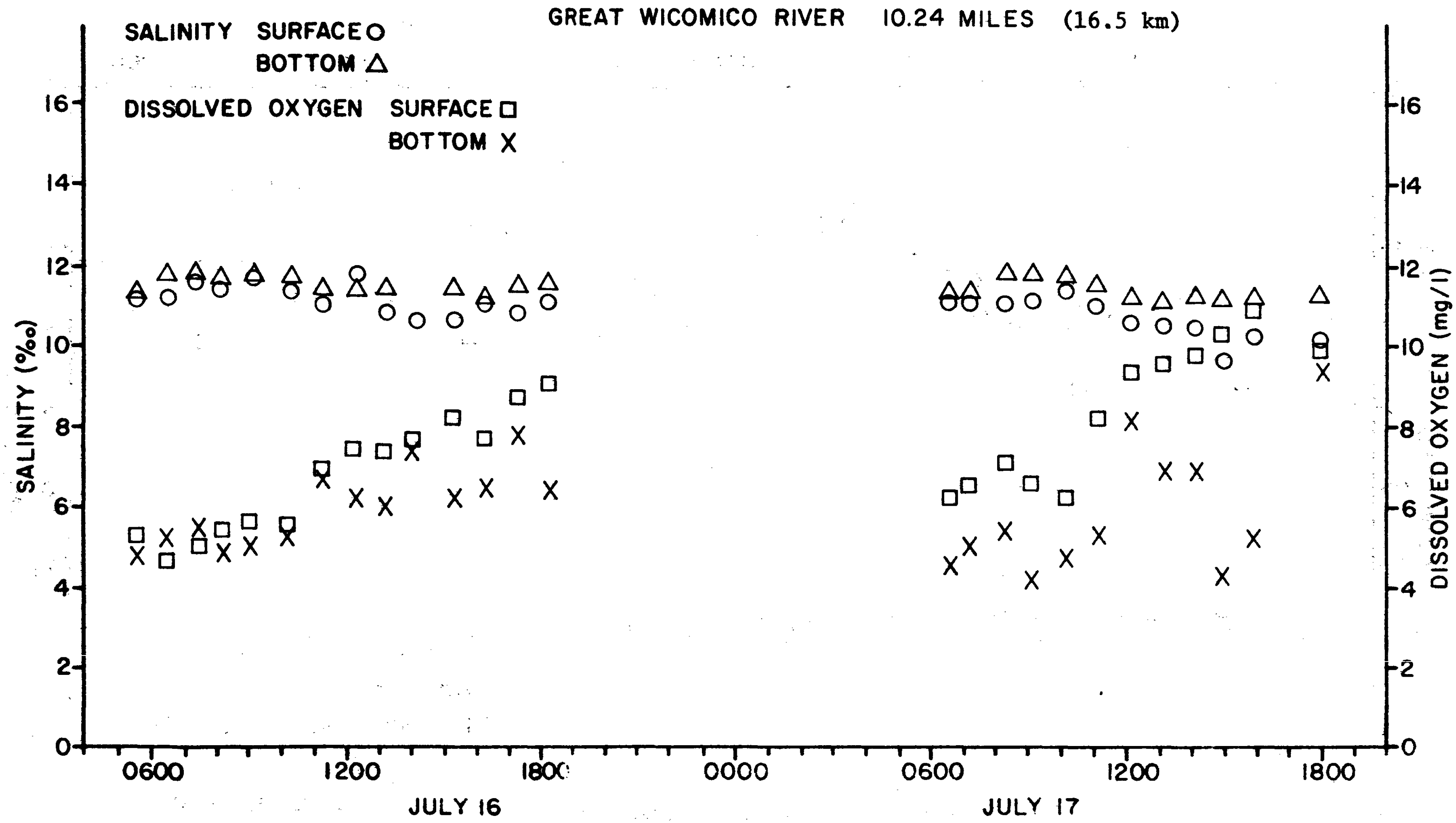
Graphical Summary of Results of Water Quality Survey

July 1974

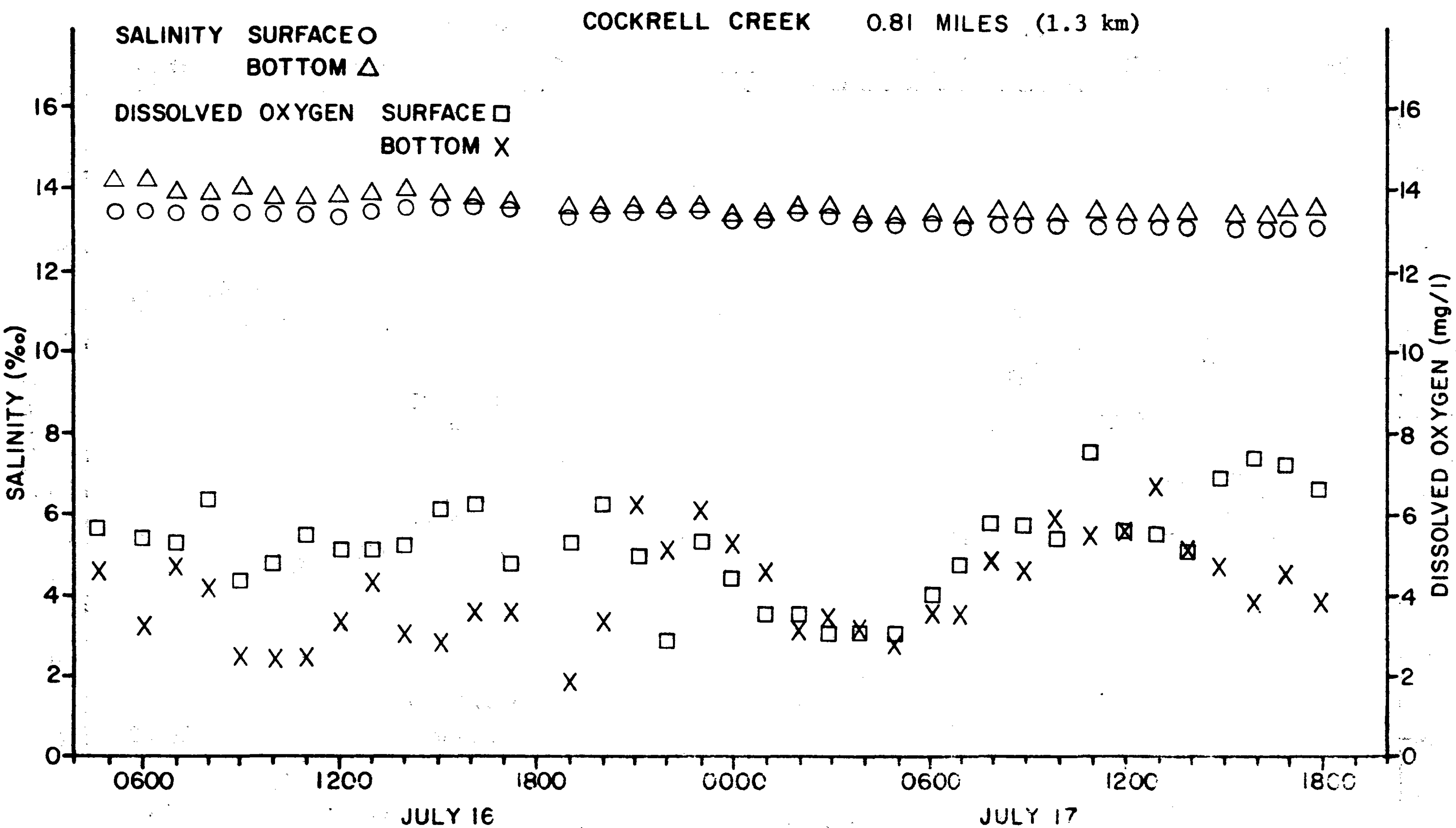

GREAT WICOMICO RIVER 0.0 MILES (0.0 km)
SALINITY SURFACE ○
BOTTOM △
DISSOLVED OXYGEN SURFACE □
BOTTOM X
SALINITY (‰)
DISSOLVED OXYGEN (mg/l)
0
2
4
6
8
10
12
14
16
0600
1200
1800
0000
0600
1200
1800
JULY 16
JULY 17

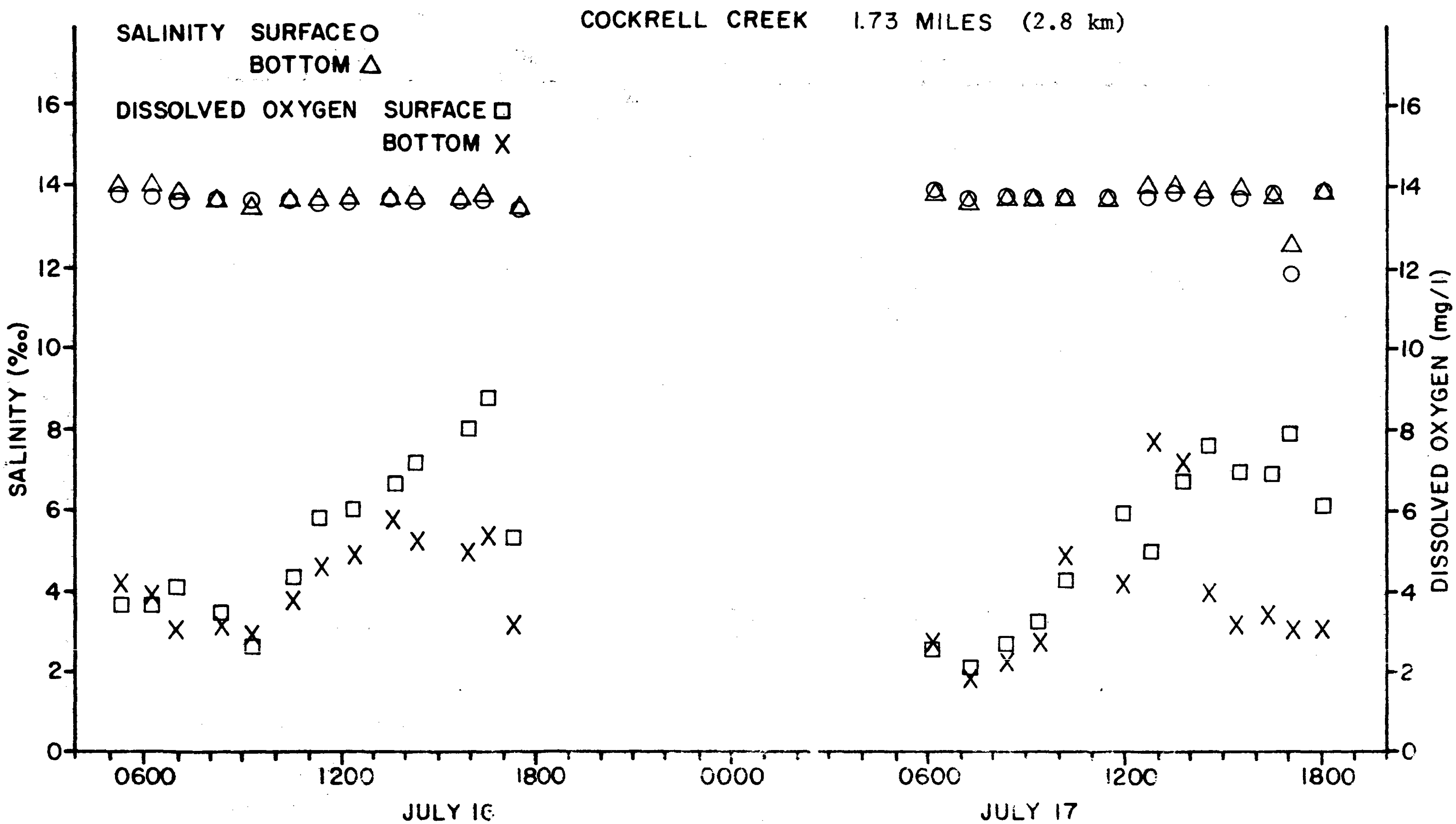

GREAT WICOMICO RIVER 4.60 MILES (7.4 km)
SALINITY SURFACE ○
BOTTOM △
DISSOLVED OXYGEN SURFACE □
BOTTOM X
SALINITY (‰)
DISSOLVED OXYGEN (mg/l)
0600
1200
1800
0000
0600
1200
1800
JULY 16
JULY 17

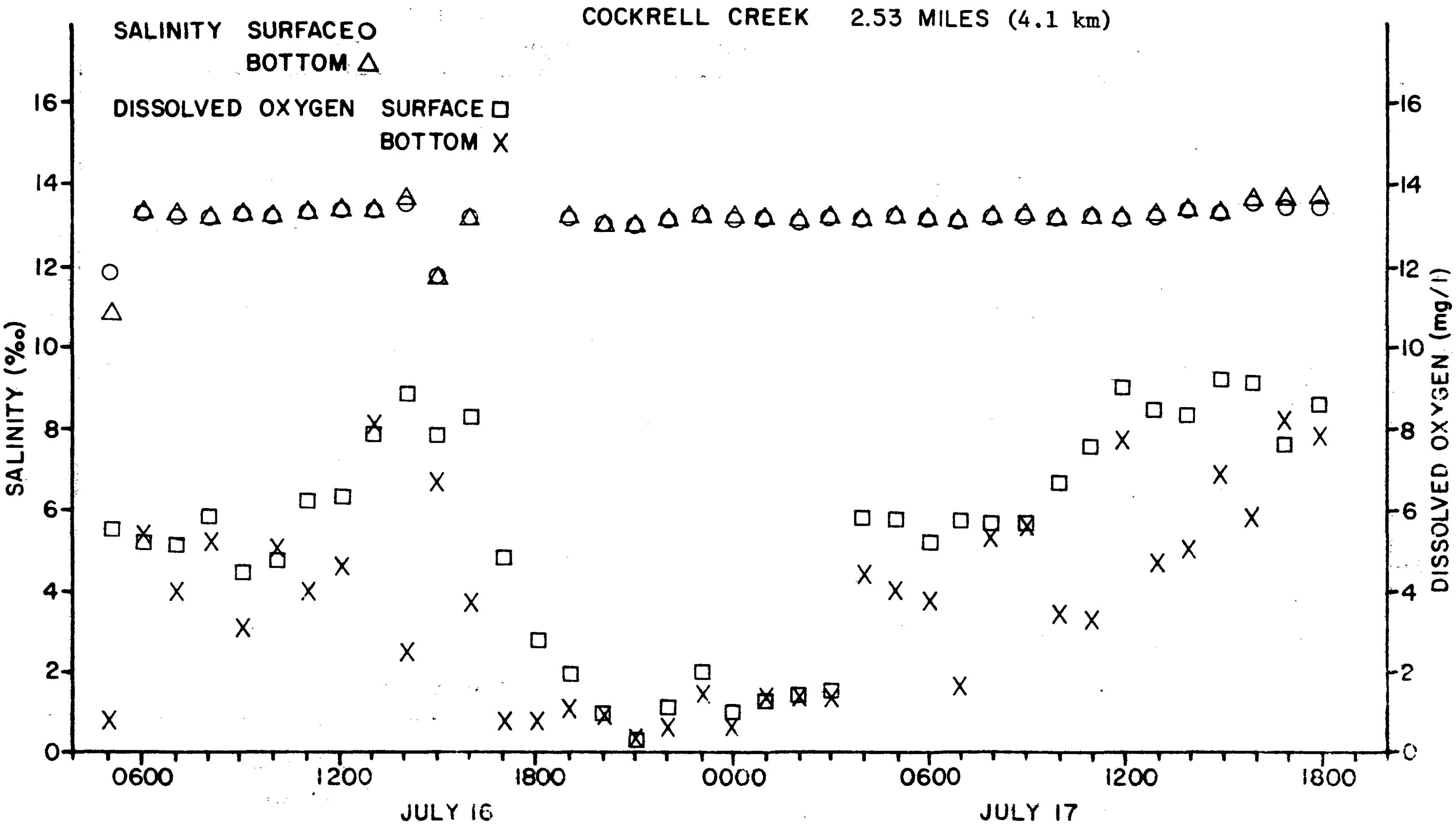

GREAT WICOMICO RIVER 5.63 MILES (9.1 km)
SALINITY SURFACE ○
BOTTOM △
DISSOLVED OXYGEN SURFACE □
BOTTOM X
SALINITY (‰)
DISSOLVED OXYGEN (mg/l)
0
2
4
6
8
10
12
14
16
0600
1200
1800
0000
0600
1200
1800
JULY 16
JULY 17

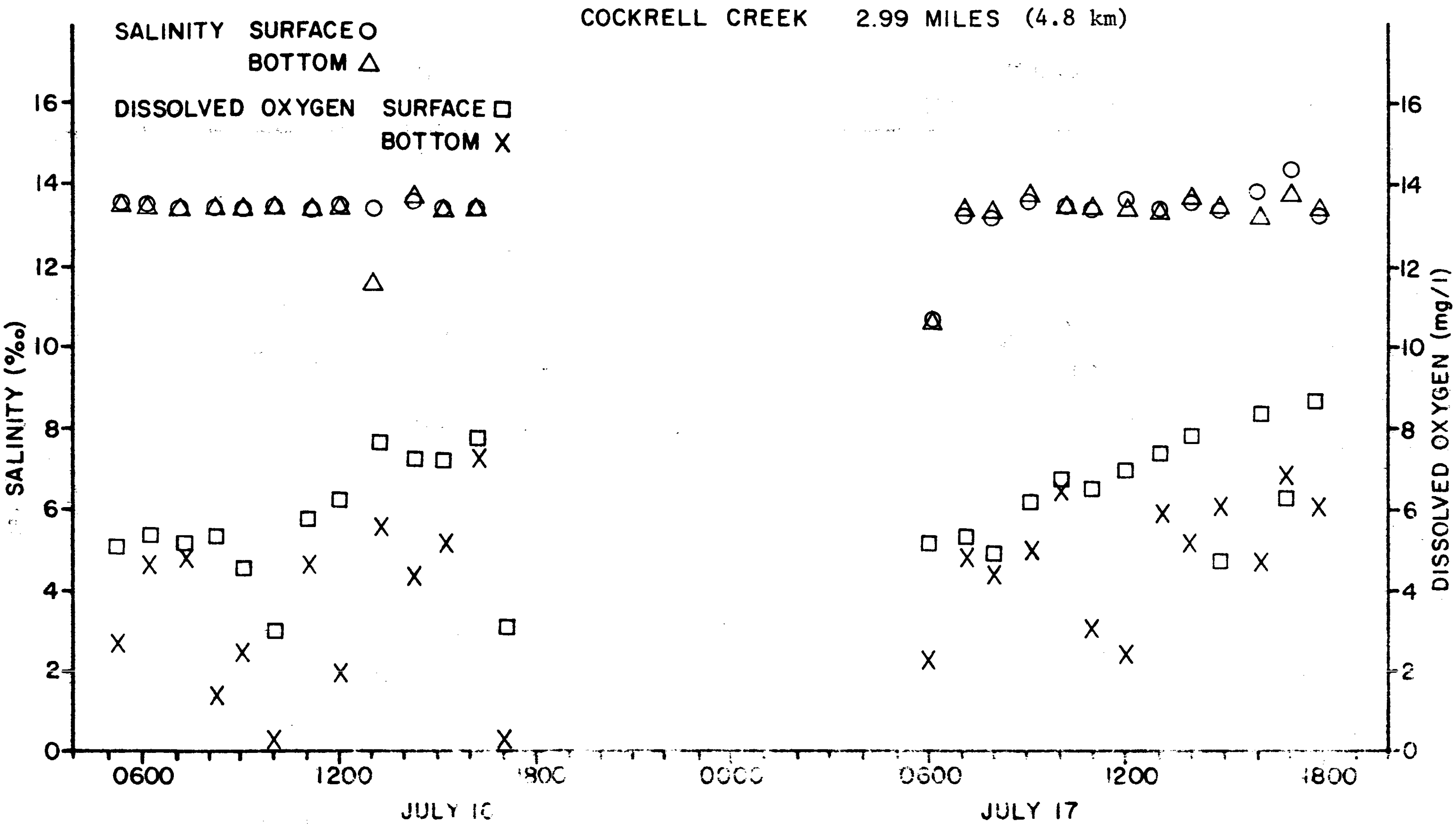


GREAT WICOMICO RIVER 10.24 MILES (16.5 km)
SALINITY SURFACE ○
BOTTOM △
DISSOLVED OXYGEN SURFACE □
BOTTOM X
SALINITY (‰)
DISSOLVED OXYGEN (mg/l)
0
2
4
6
8
10
12
14
16
0600
1200
1800
0000
0600
1200
1800
JULY 16
JULY 17

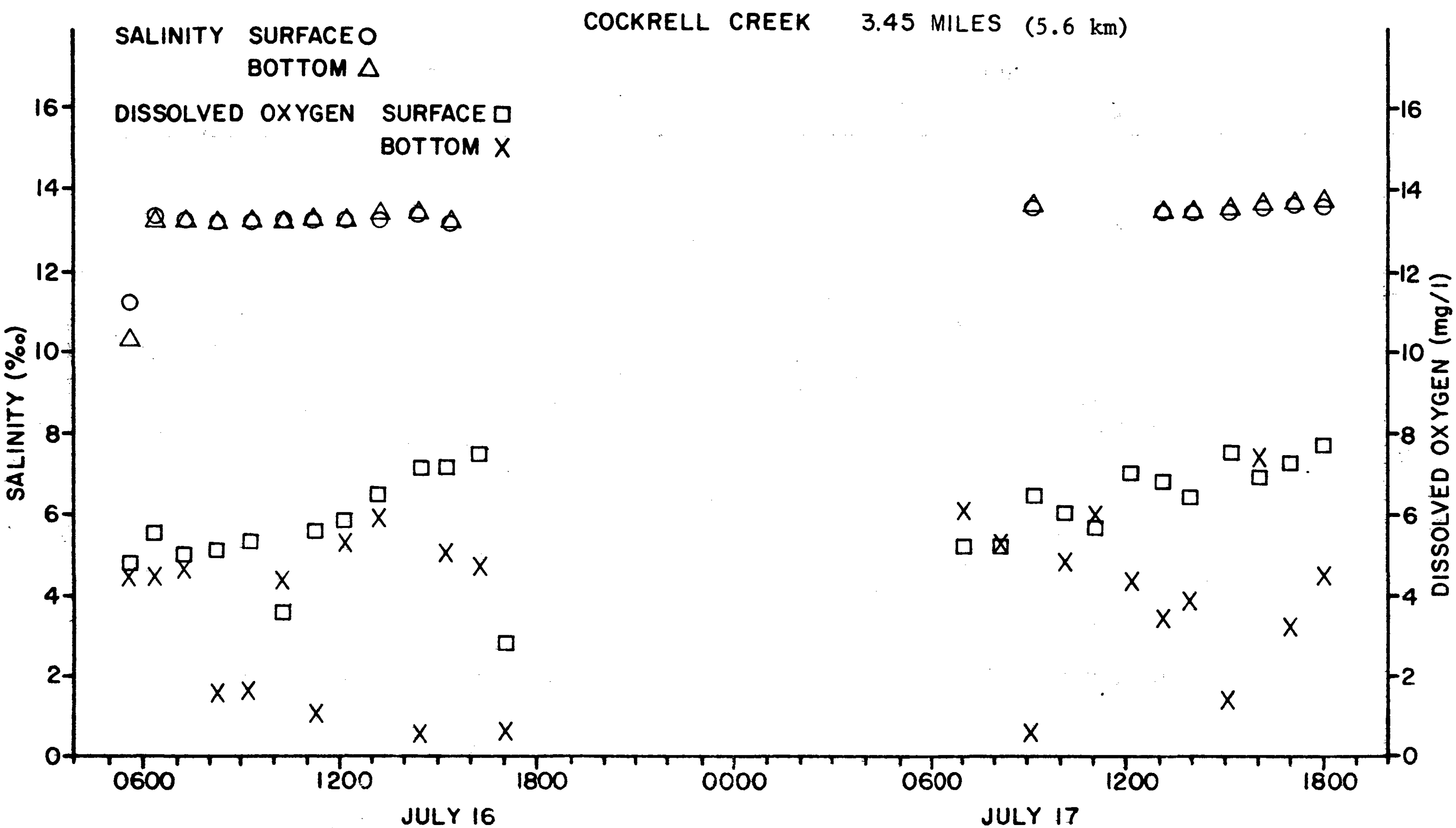

COCKRELL CREEK 0.81 MILES (1.3 km)
SALINITY SURFACE ○
BOTTOM △
DISSOLVED OXYGEN SURFACE □
BOTTOM X
SALINITY (‰)
DISSOLVED OXYGEN (mg/l)
0
2
4
6
8
10
12
14
16
0600
1200
1800
0000
0600
1200
1800
JULY 16
JULY 17


COCKRELL CREEK 1.73 MILES (2.8 km)
SALINITY SURFACE ○
BOTTOM △
DISSOLVED OXYGEN SURFACE □
BOTTOM X
SALINITY (‰)
DISSOLVED OXYGEN (mg/l)
0
2
4
6
8
10
12
14
16
0600
1200
1800
0000
0600
1200
1800
JULY 16
JULY 17

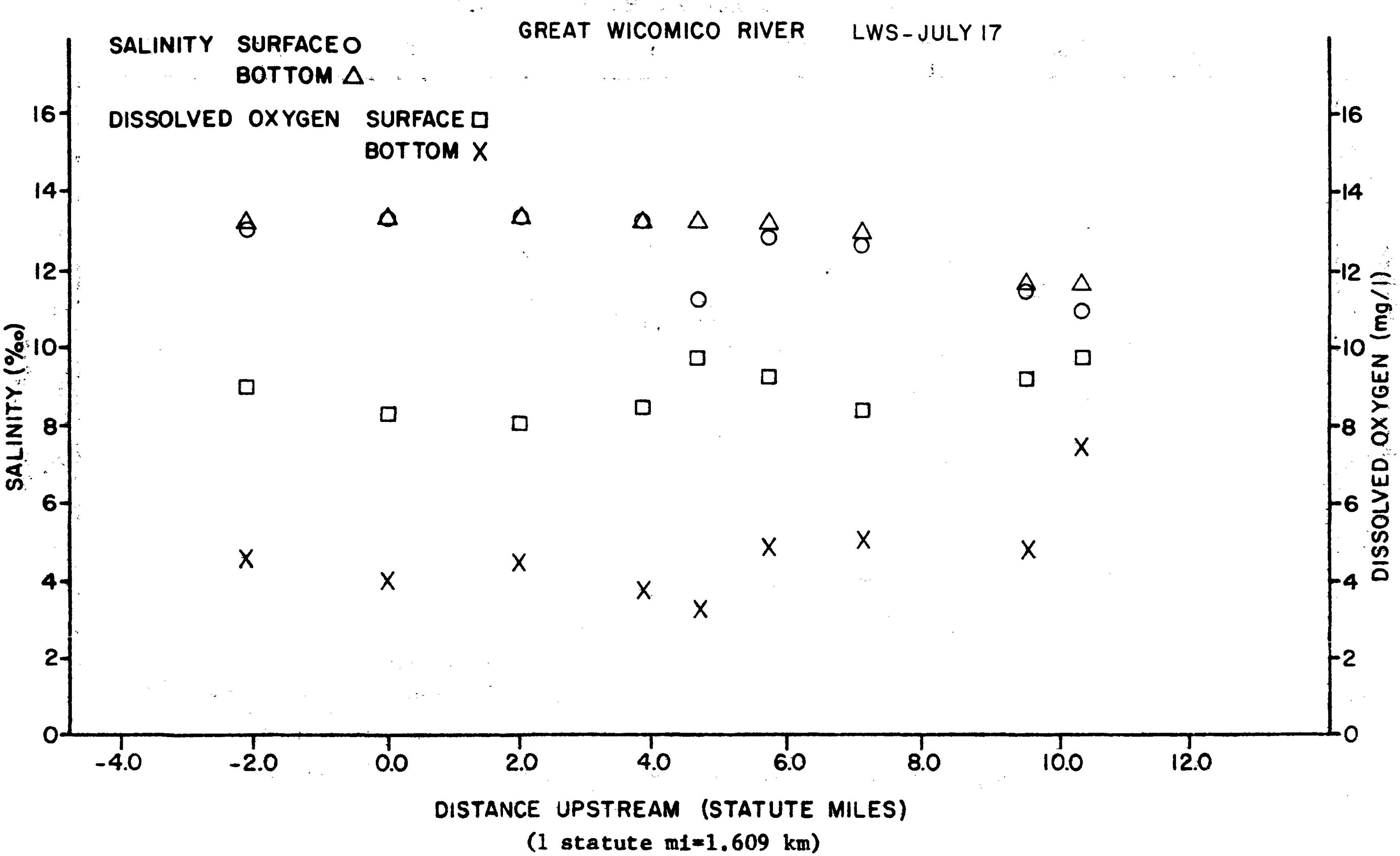

COCKRELL CREEK 2.53 MILES (4.1 km)
SALINITY SURFACE ○
BOTTOM △
DISSOLVED OXYGEN SURFACE □
BOTTOM X
SALINITY (‰)
DISSOLVED OXYGEN (mg/l)
0600
1200
1800
0000
0600
1200
1800
JULY 16
JULY 17

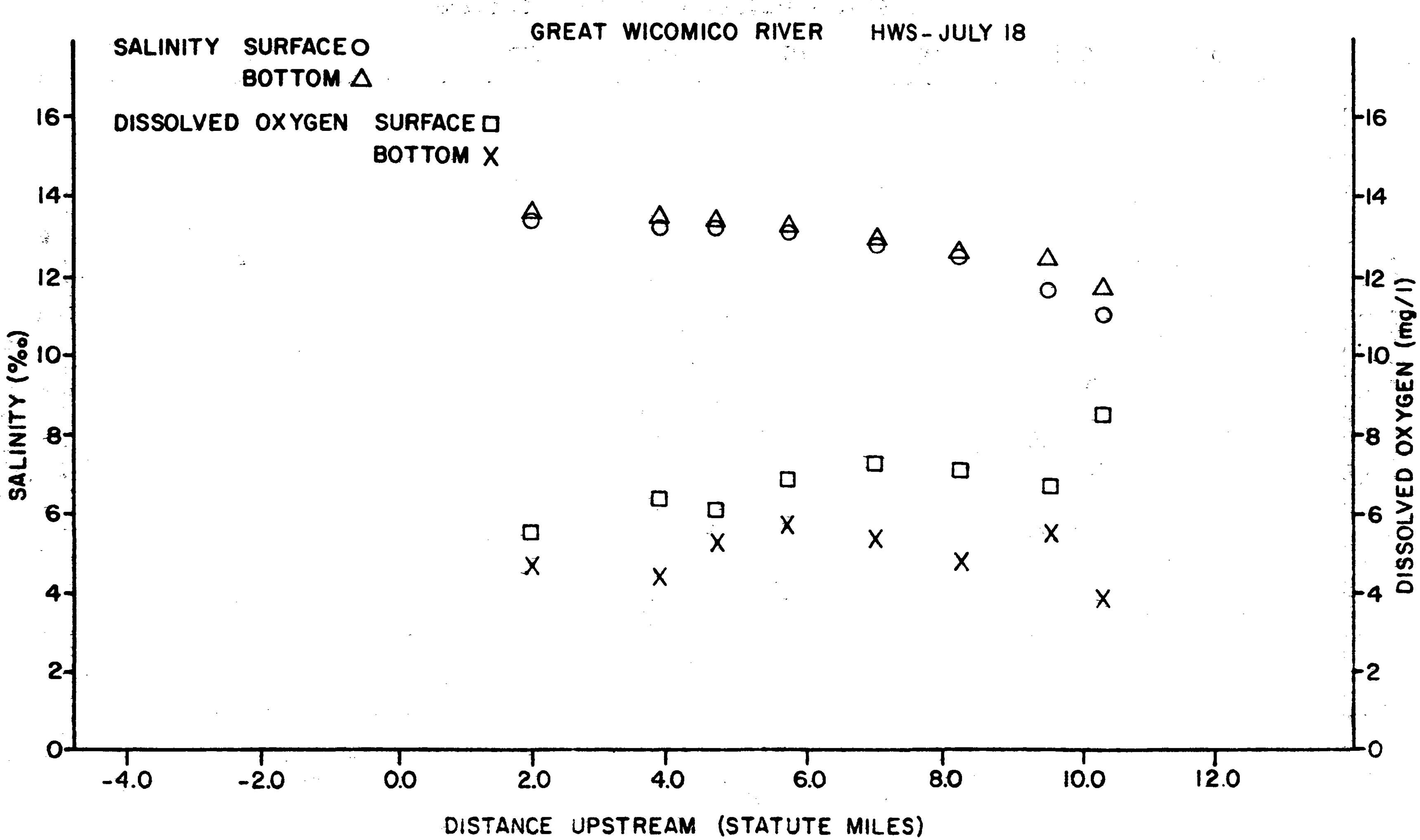


COCKRELL CREEK 2.99 MILES (4.8 km)
SALINITY SURFACE ○
BOTTOM △
DISSOLVED OXYGEN SURFACE □
BOTTOM X
SALINITY (‰)
DISSOLVED OXYGEN (mg/l)
0
2
4
6
8
10
12
14
16
0600
1200
1800
0000
0600
1200
1800
JULY 16
JULY 17

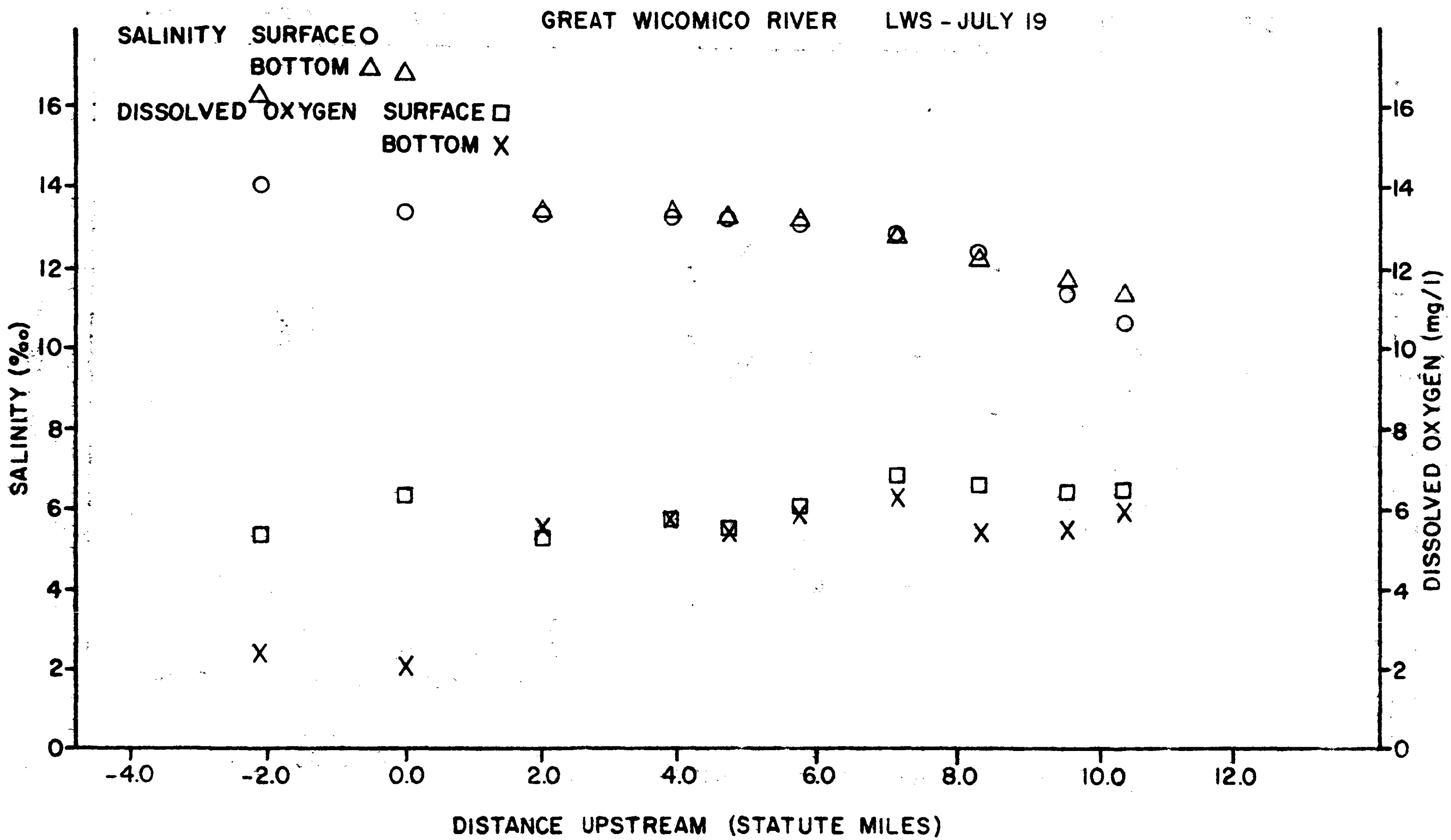


COCKRELL CREEK 3.45 MILES (5.6 km)
SALINITY SURFACE ○
BOTTOM △
DISSOLVED OXYGEN SURFACE □
BOTTOM X
SALINITY (‰)
DISSOLVED OXYGEN (mg/l)
0600
1200
1800
0000
JULY 16
JULY 17

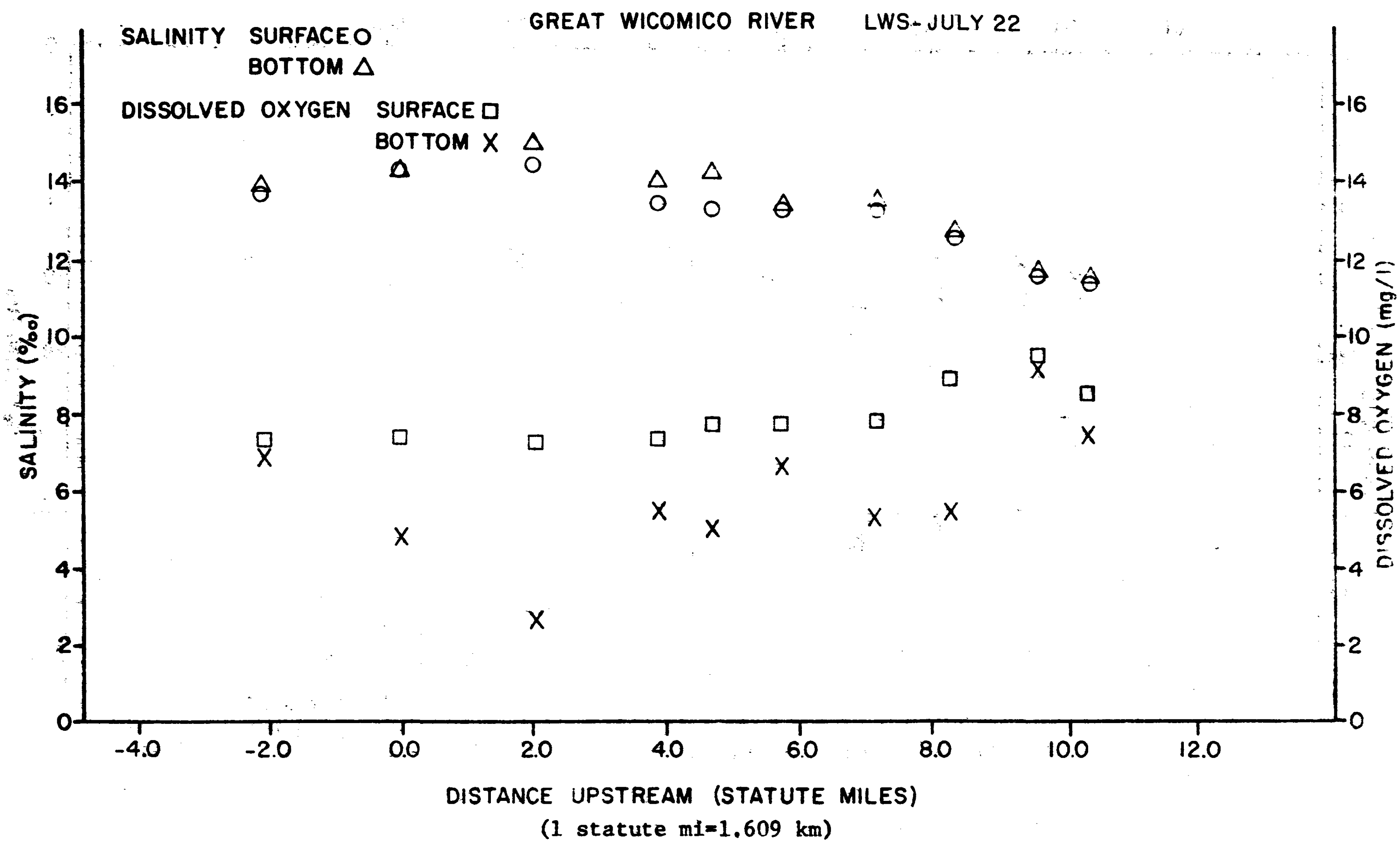

GREAT WICOMICO RIVER LWS-JULY 17
SALINITY SURFACE ○
BOTTOM △
DISSOLVED OXYGEN SURFACE □
BOTTOM X
SALINITY (‰)
DISSOLVED OXYGEN (mg/l)
0
2
4
6
8
10
12
14
16
-4.0
-2.0
0.0
2.0
4.0
6.0
8.0
10.0
12.0
DISTANCE UPSTREAM (STATUTE MILES)
(1 statute mi=1.609 km)

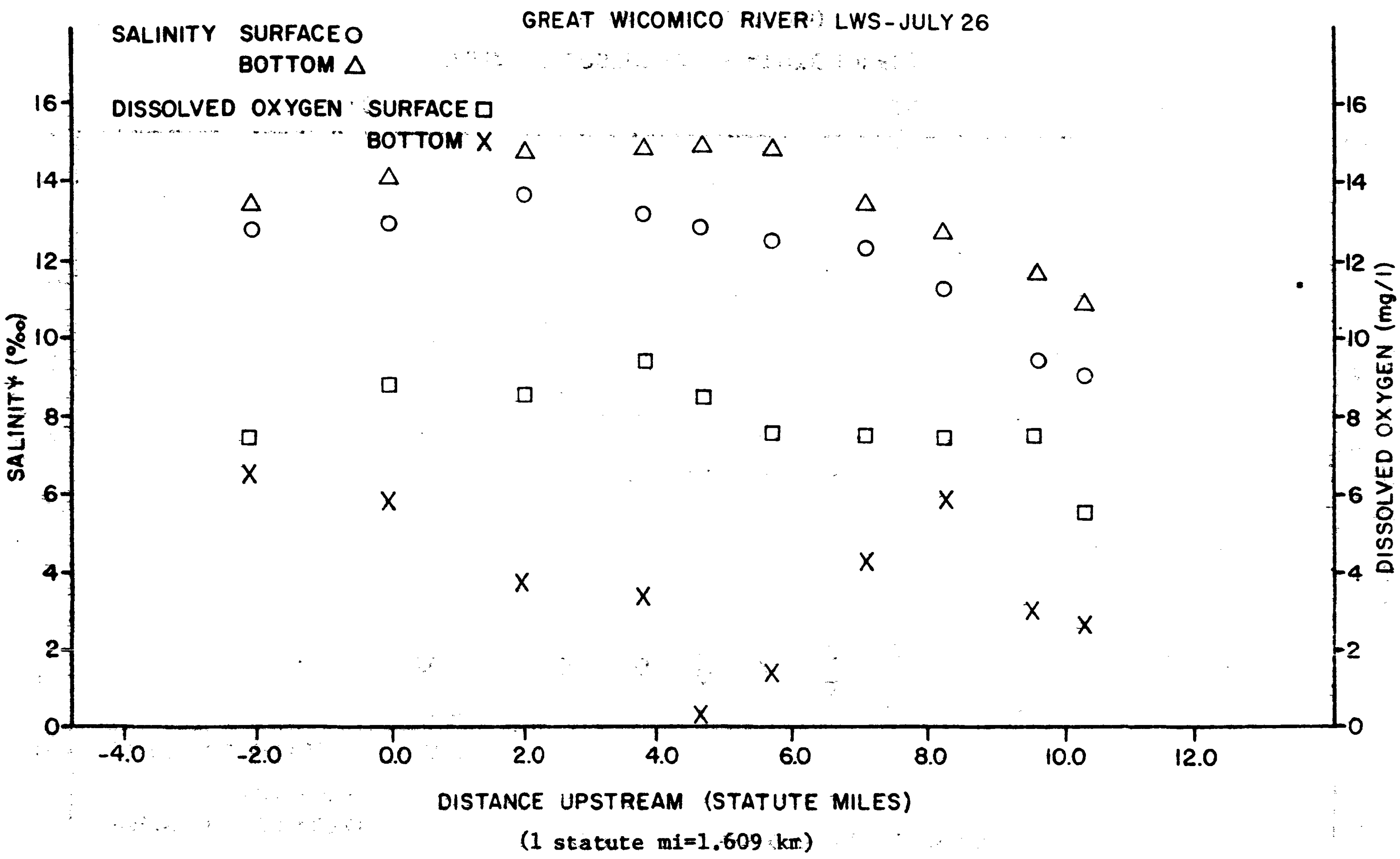


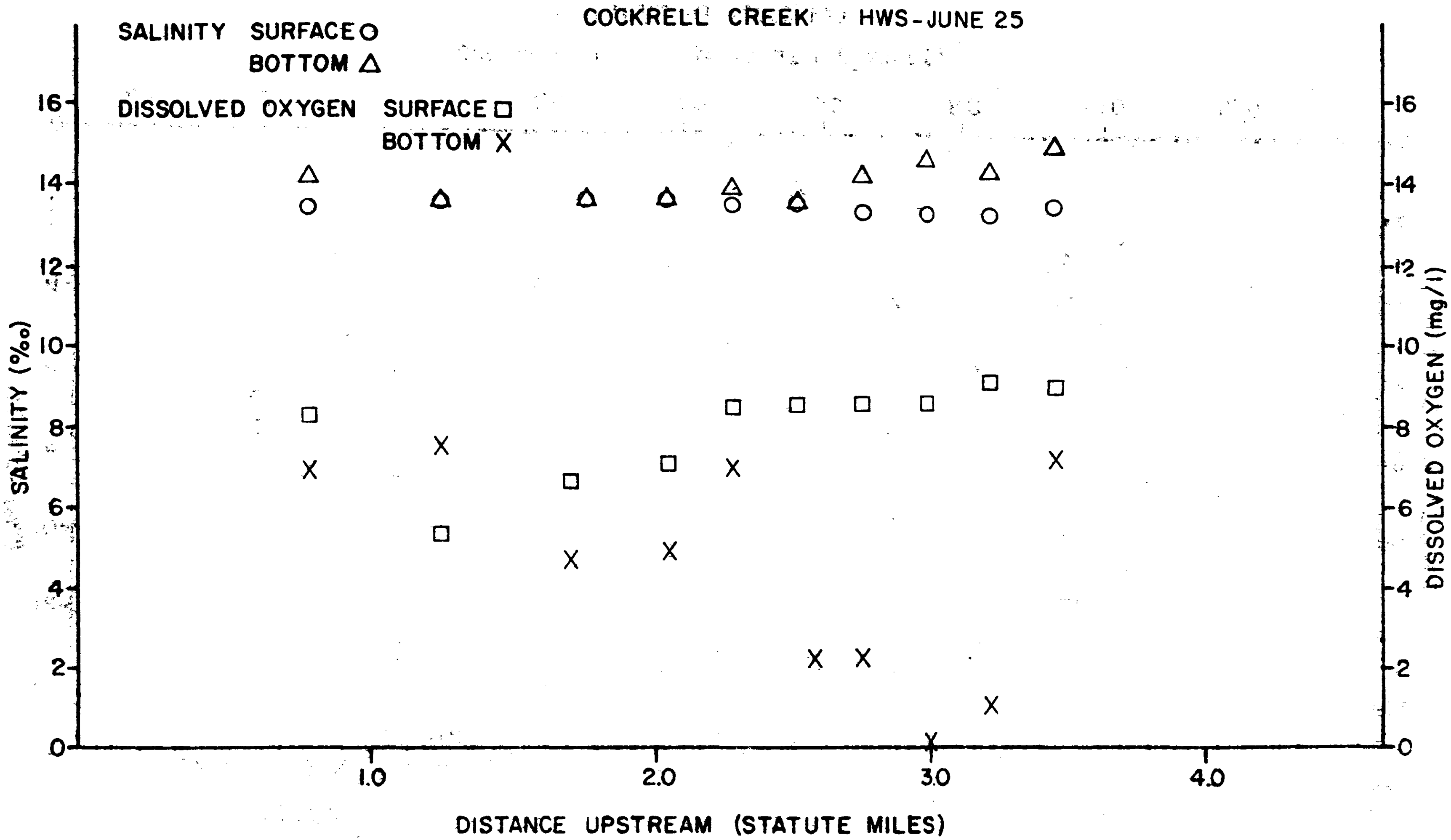
(1 statute mi=1.609 km)



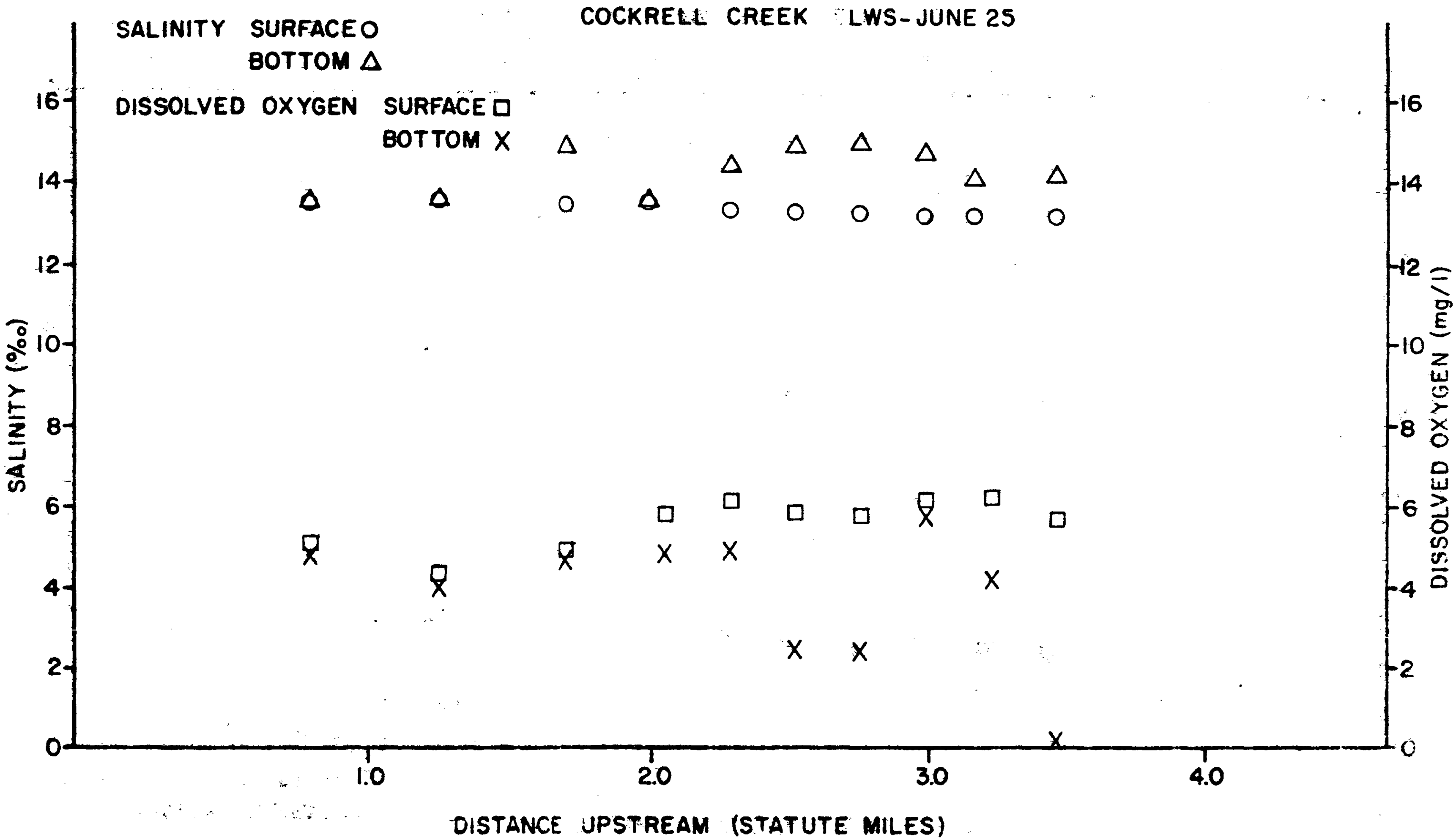
(1 statute mi=1.609 km)


GREAT WICOMICO RIVER LWS-JULY 22
SALINITY SURFACE ○
BOTTOM △
DISSOLVED OXYGEN SURFACE □
BOTTOM X
SALINITY (‰)
DISSOLVED OXYGEN (mg/l)
0
2
4
6
8
10
12
14
16
-4.0
-2.0
0.0
2.0
4.0
6.0
8.0
10.0
12.0
DISTANCE UPSTREAM (STATUTE MILES)
(1 statute mi=1.609 km)

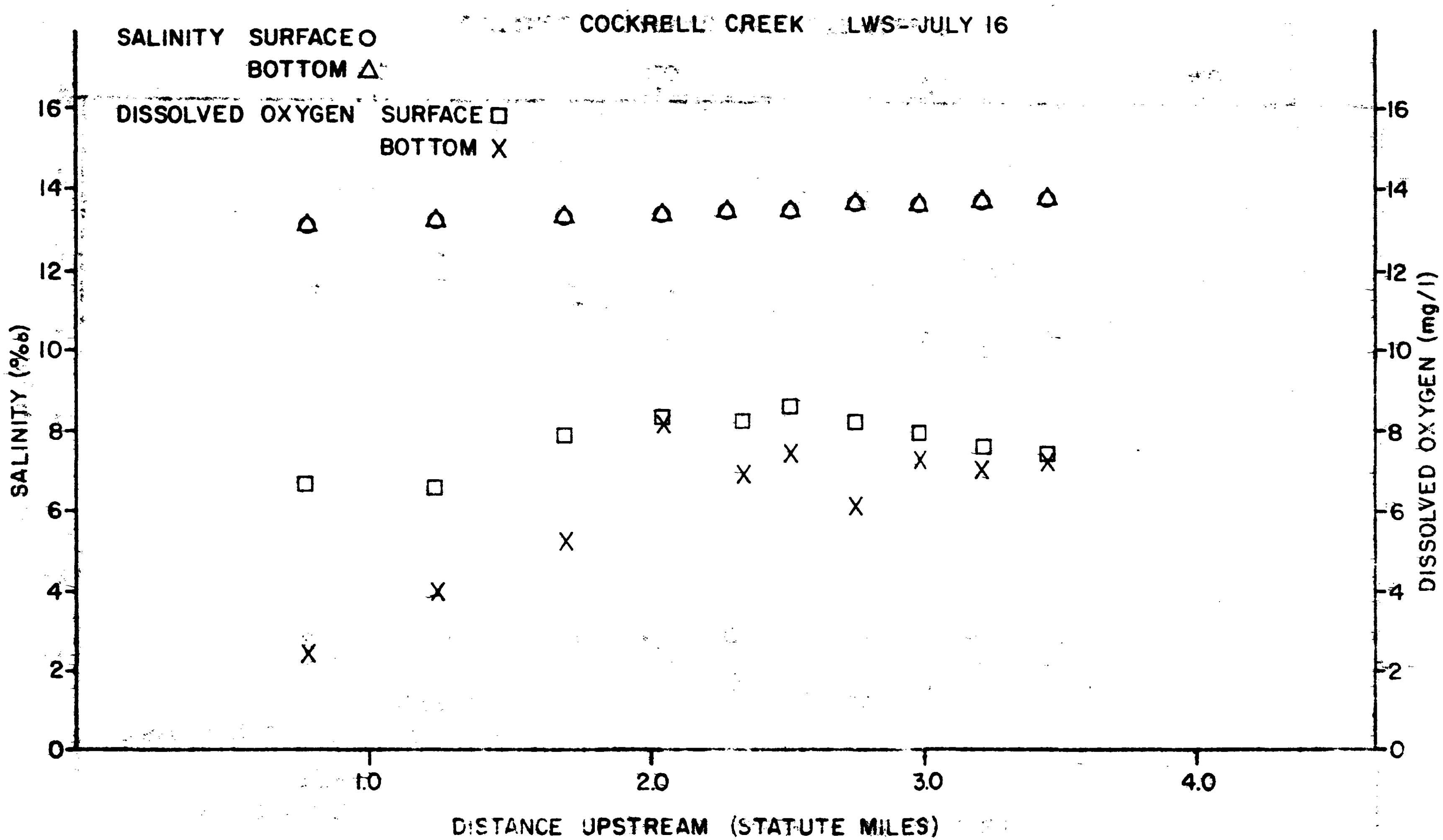

GREAT WICOMICO RIVER LWS-JULY 26
SALINITY SURFACE ○
BOTTOM △
DISSOLVED OXYGEN SURFACE □
BOTTOM X
SALINITY (‰)
DISSOLVED OXYGEN (mg/l)
0
2
4
6
8
10
12
14
16
-4.0
-2.0
0.0
2.0
4.0
6.0
8.0
10.0
12.0
DISTANCE UPSTREAM (STATUTE MILES)
(1 statute mi=1.609 km)



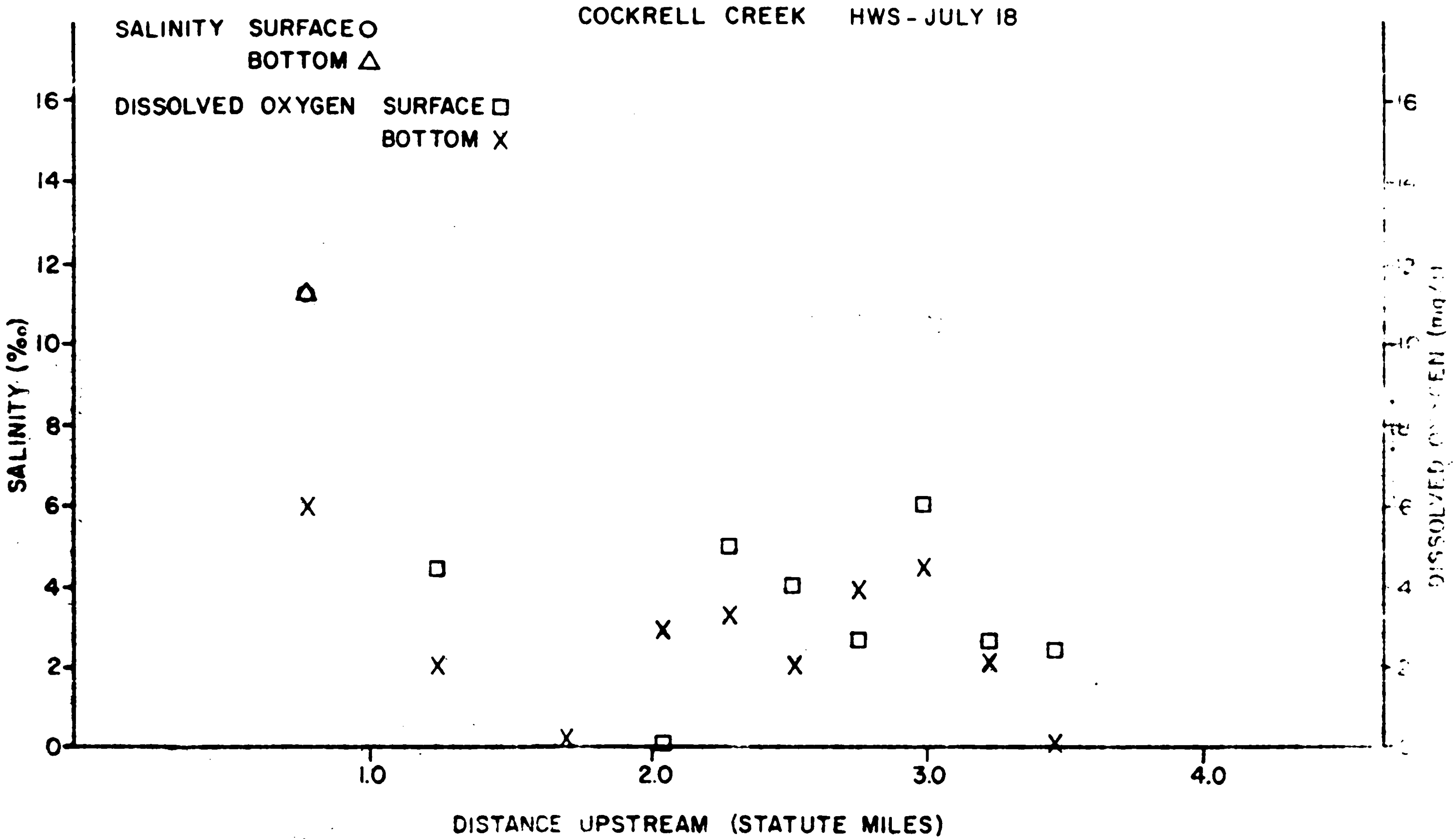
(1 statute mi=1.609 km)



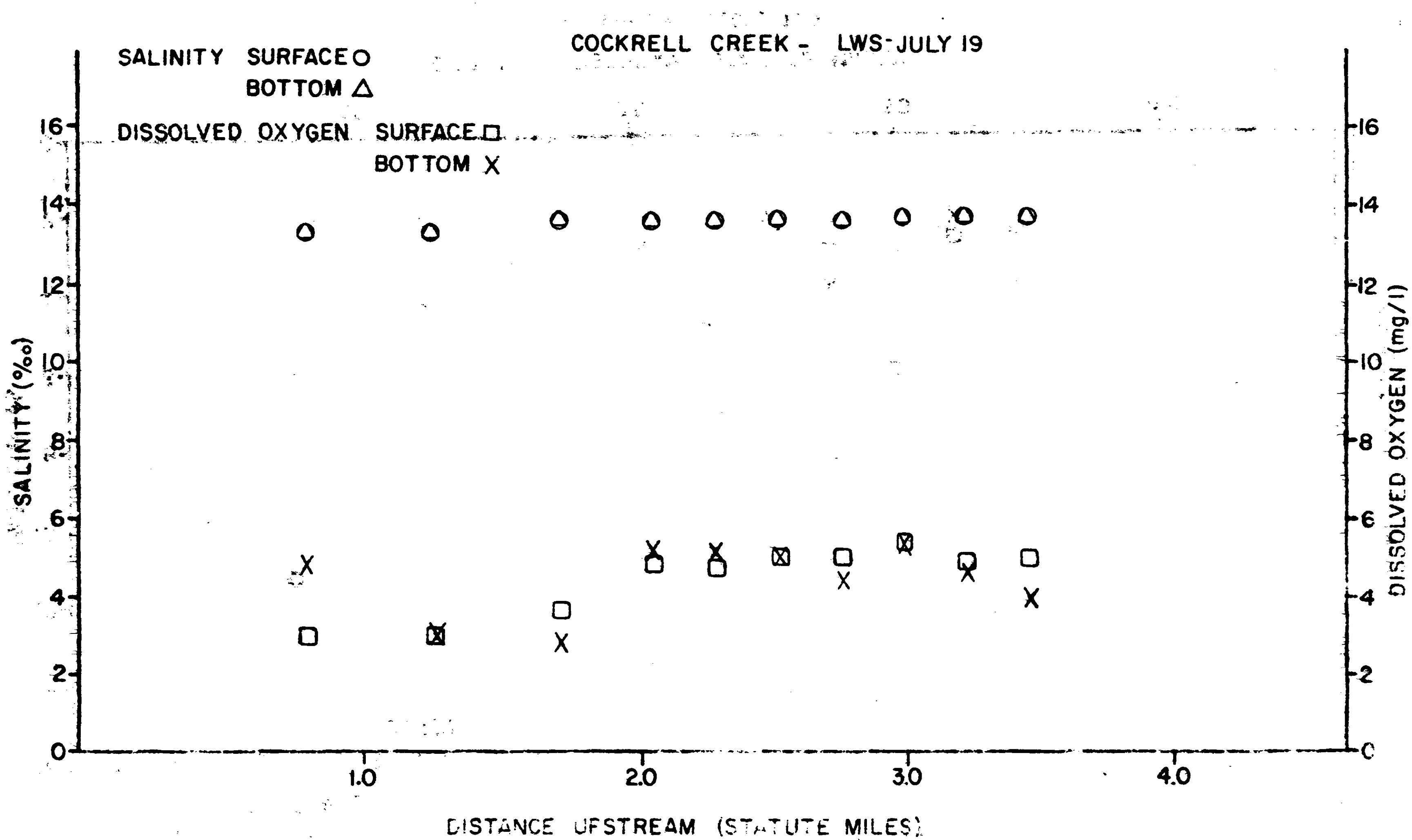
(1 statute mi=1.609 km)



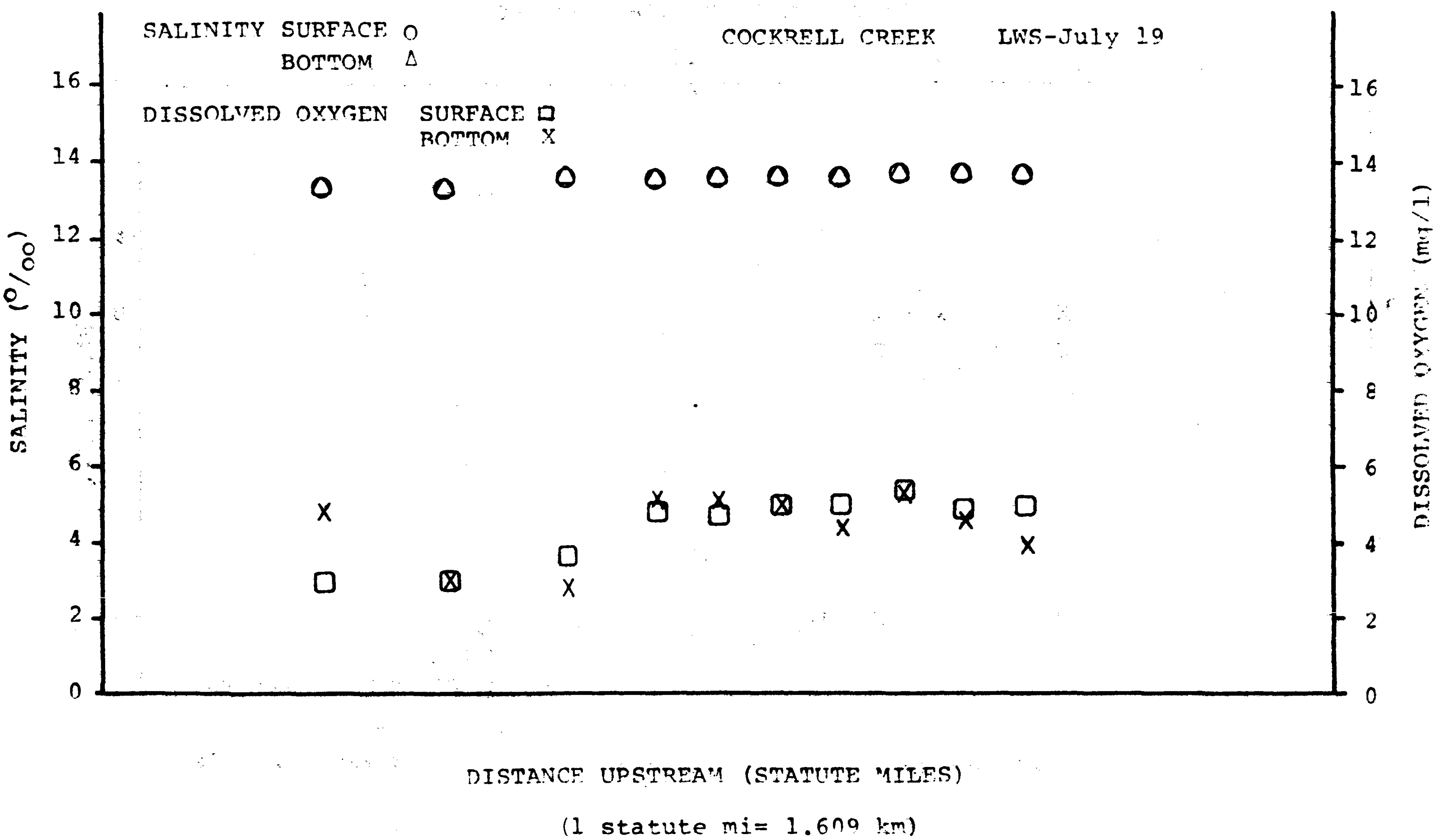
(1 statute mi=1.609 km)



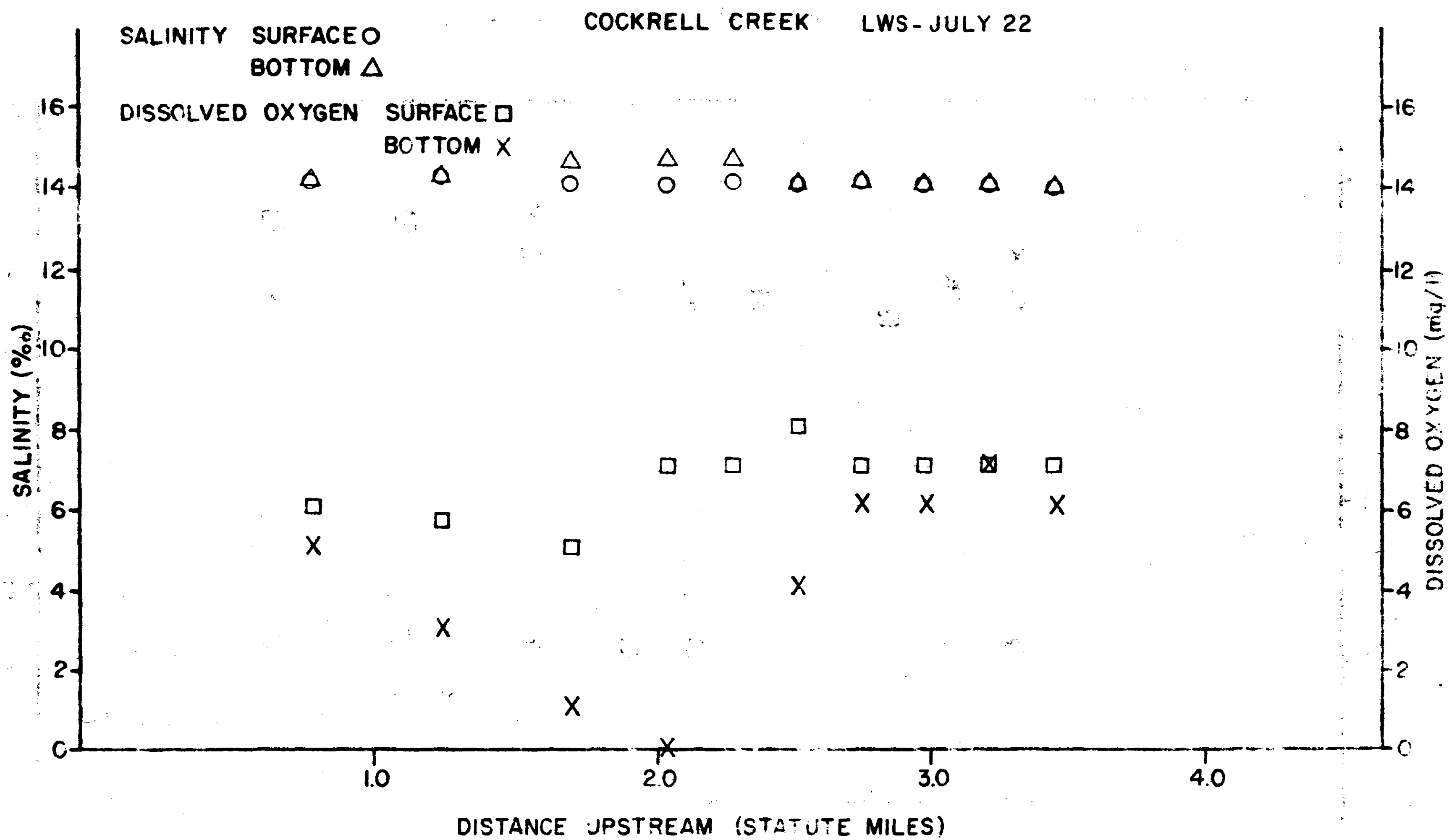
(1 statute mi=1.609 km)



(1 statute mi = 1.609 km)



SALINITY SURFACE O
BOTTOM Δ
DISSOLVED OXYGEN SURFACE □
BOTTOM X
COCKRELL CREEK
LWS-July 19
SALINITY (°/oo)
DISSOLVED OXYGEN (mg/l)
0
2
4
6
8
10
12
14
16
DISTANCE UPSTREAM (STATUTE MILES)
(1 statute mi= 1.609 km)

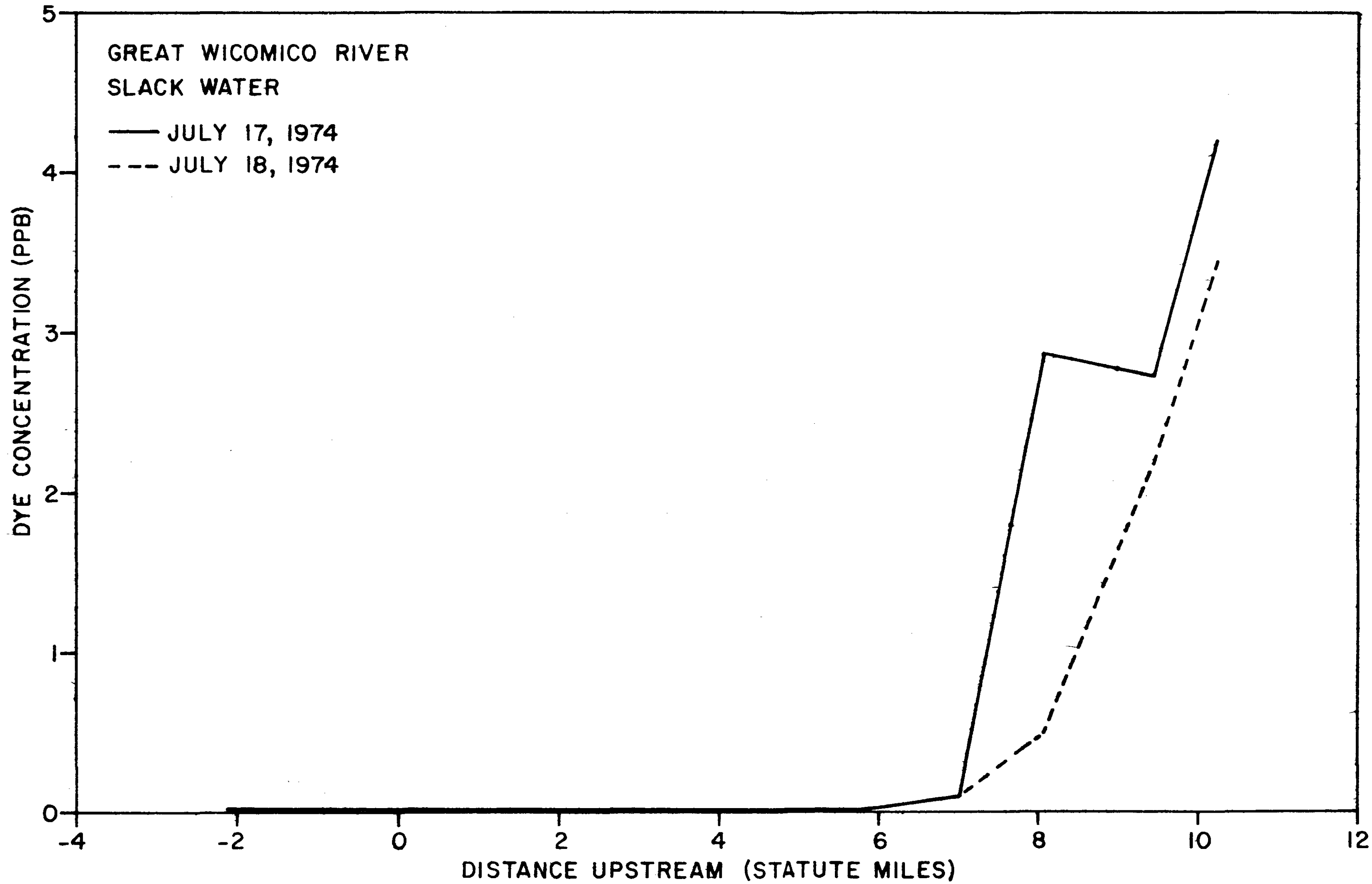


(1 statute mi=1.609 km)

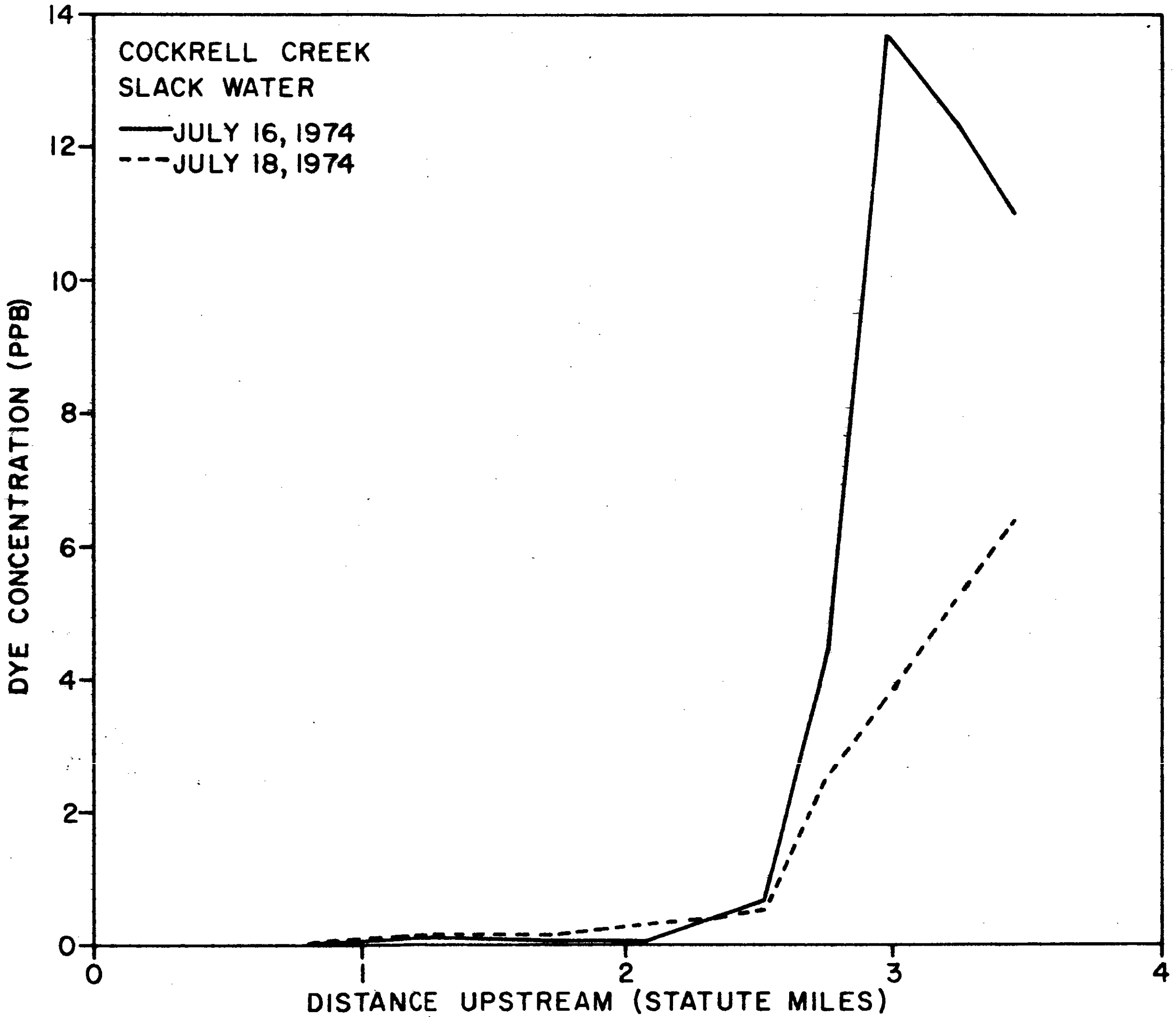
Appendix B

Graphical Summary of Results of Dye Studies

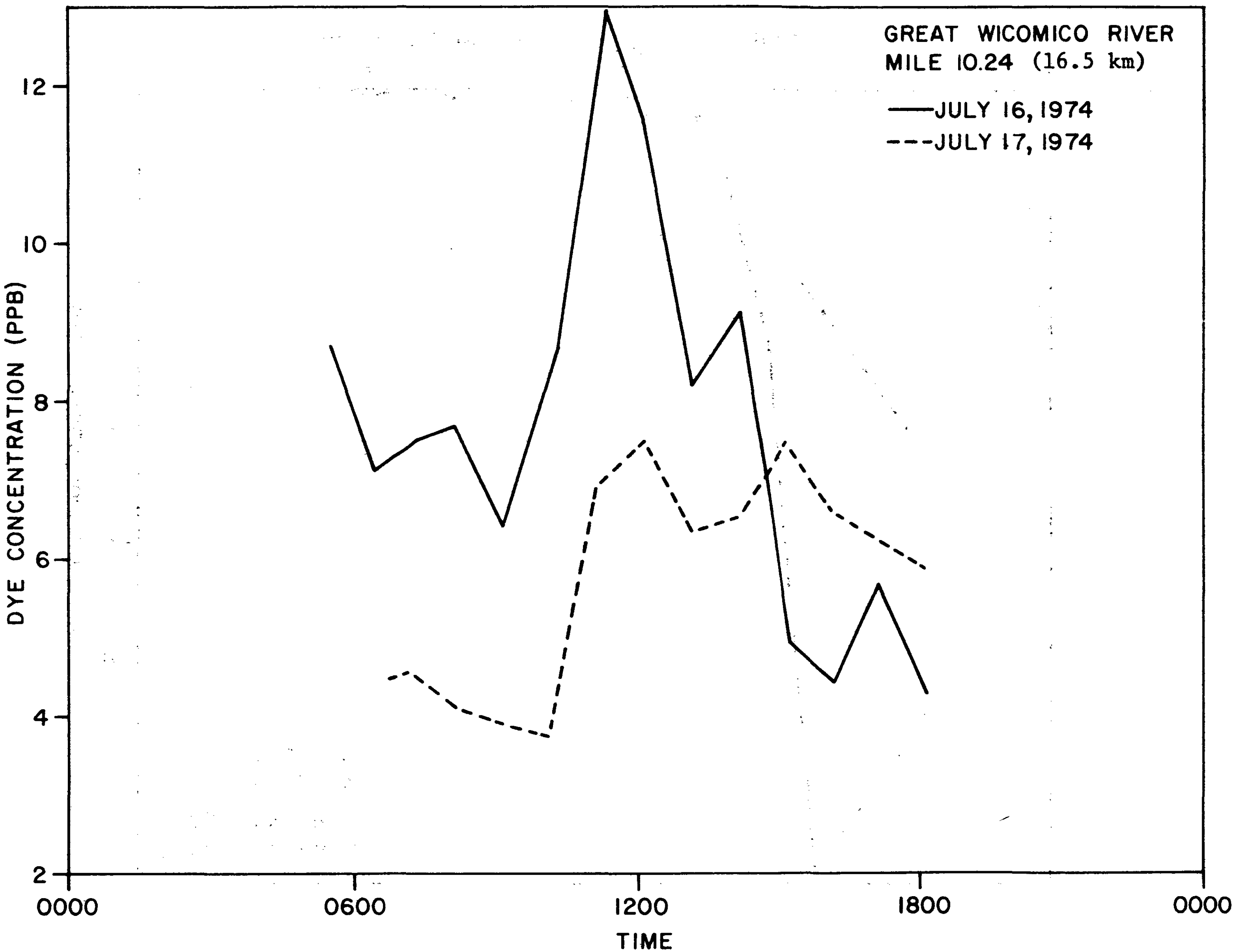
July 17 & 18, 1974

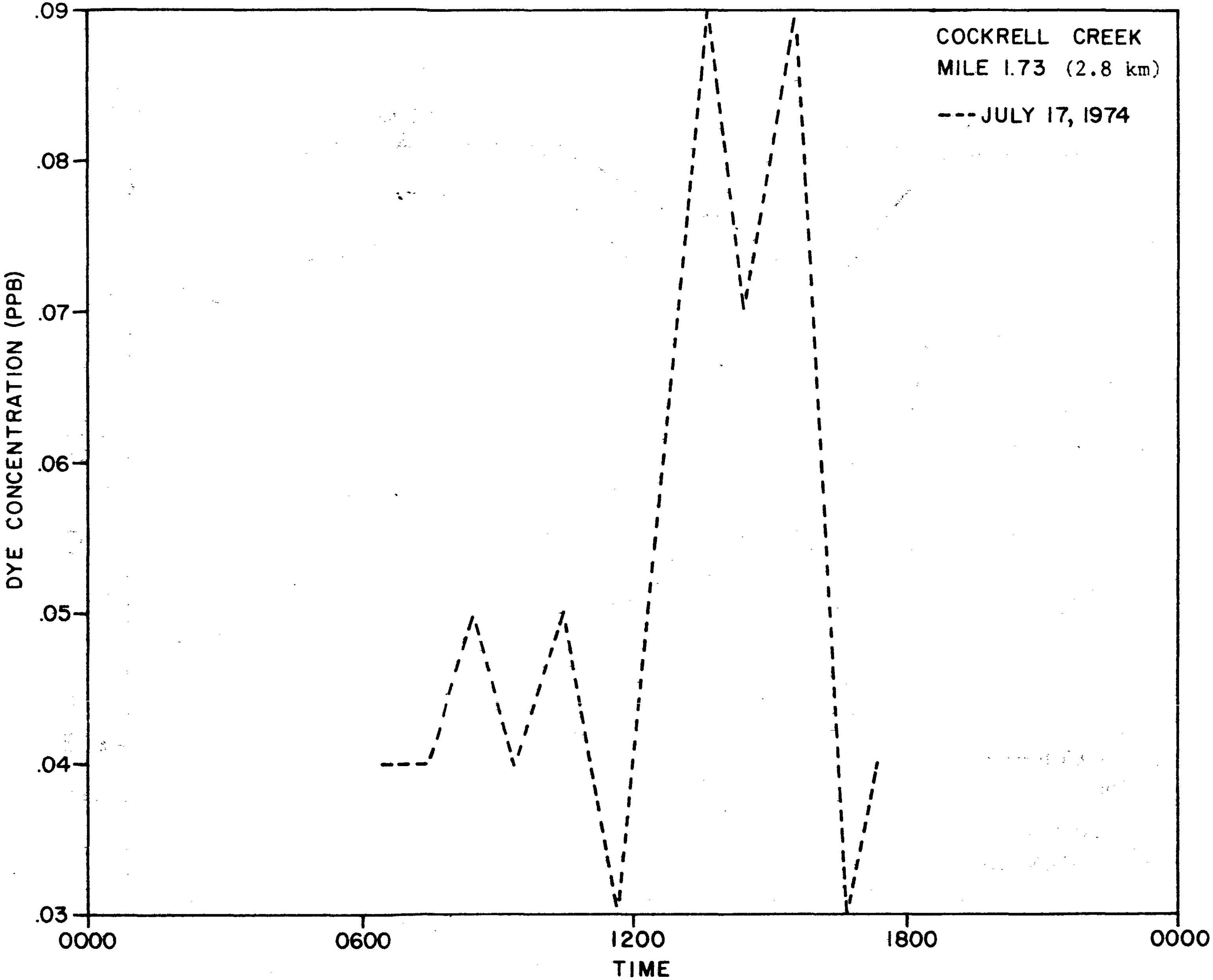


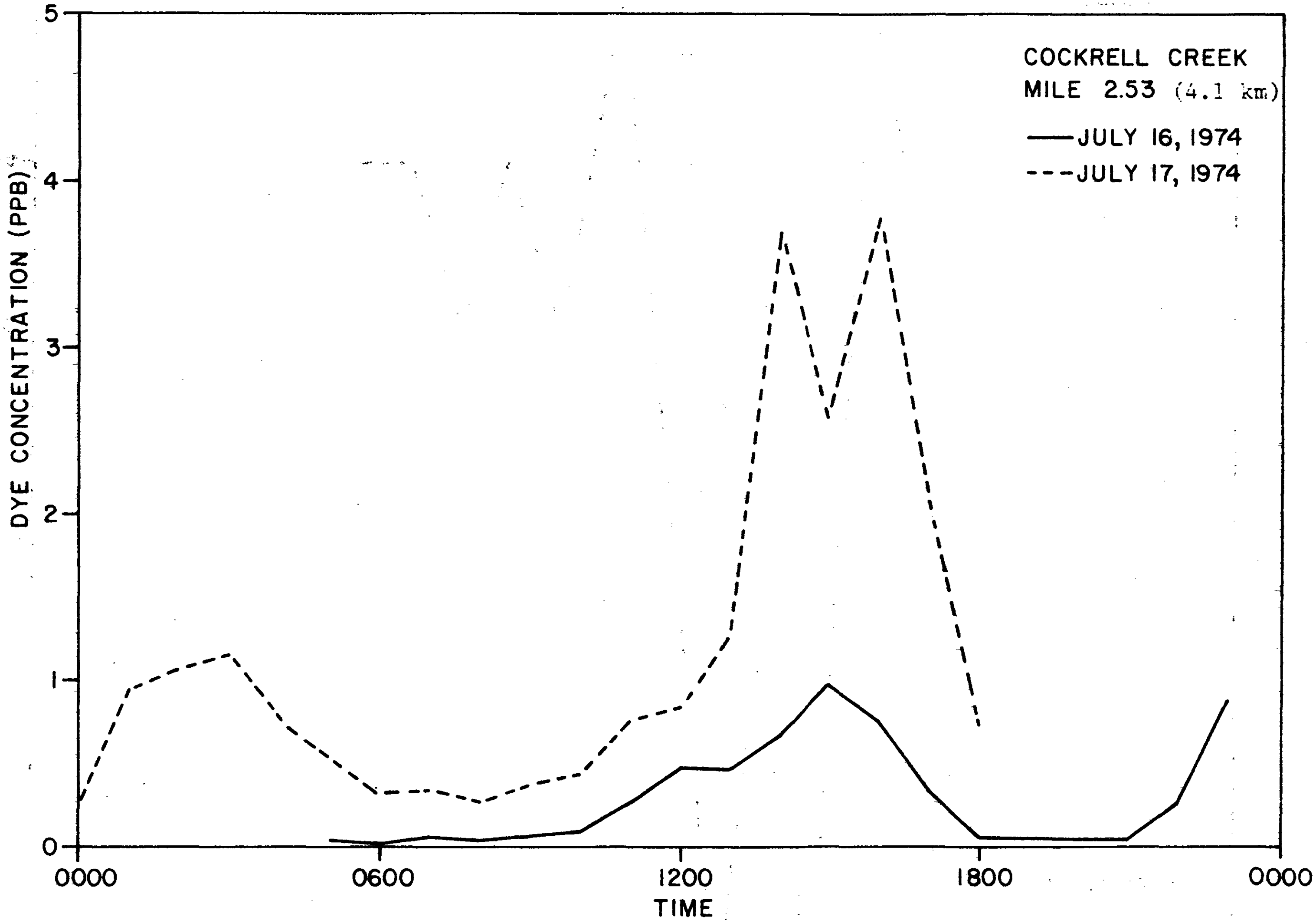
(1 statute mi=1.609 km)



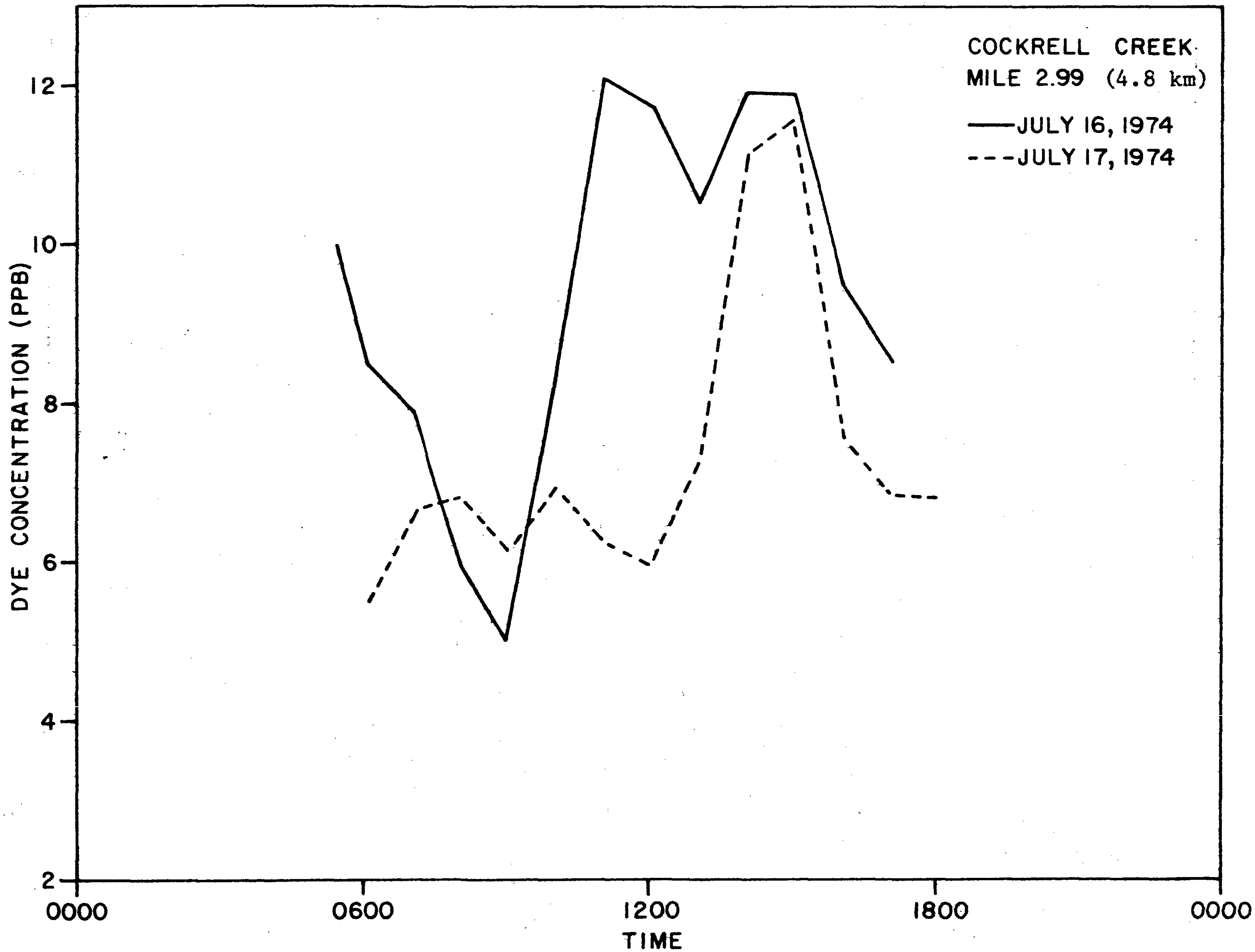
(1 statute mi=1.609 km)

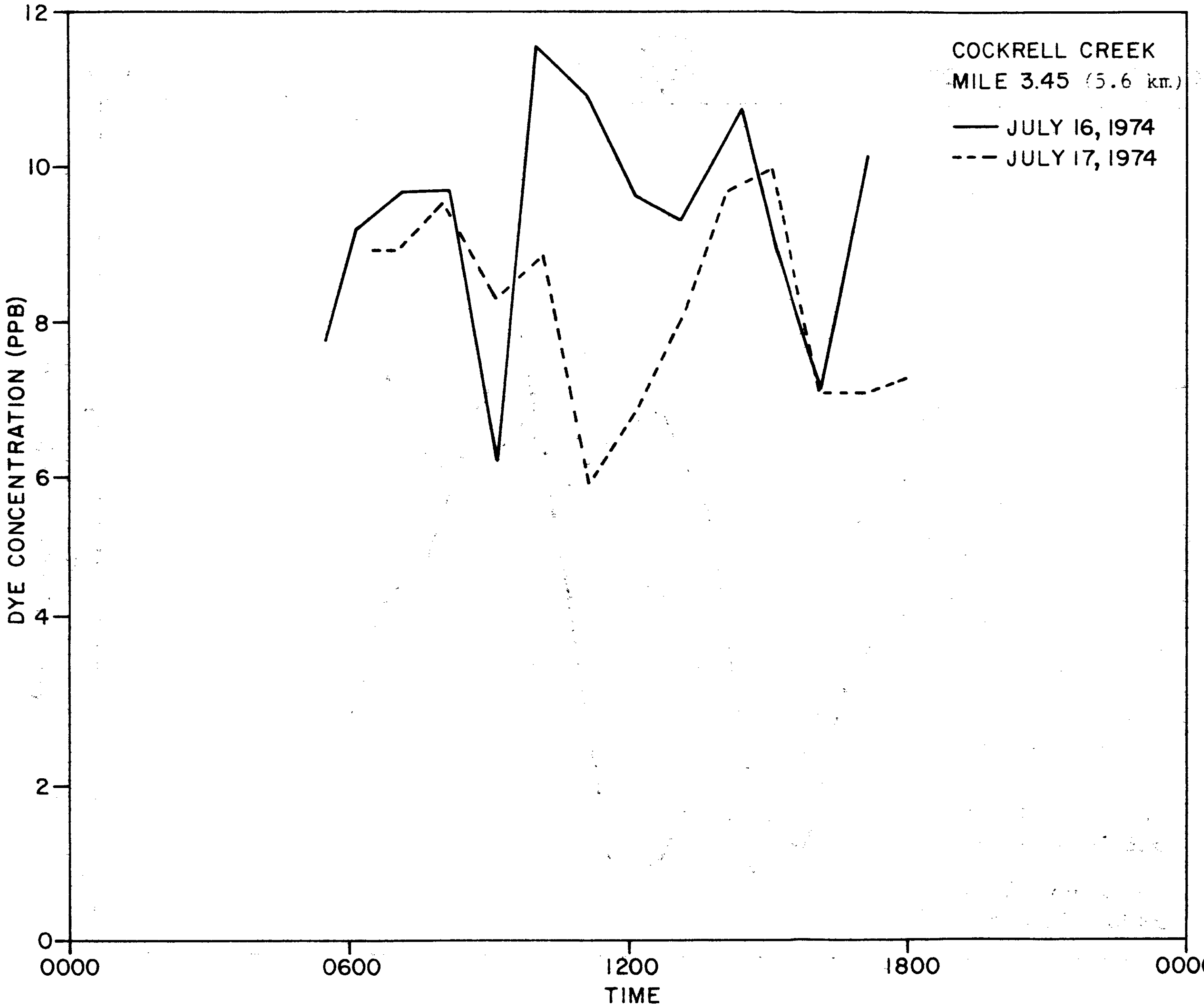

GREAT WICOMICO RIVER
MILE 10.24 (16.5 km)
JULY 16, 1974
JULY 17, 1974
DYE CONCENTRATION (PPB)
12
10
8
6
4
2
0000
0600
1200
1800
0000
TIME


COCKRELL CREEK
MILE 1.73 (2.8 km)
JULY 17, 1974
DYE CONCENTRATION (PPB)
.09
.08
.07
.06
.05
.04
.03
0000
0600
1200
1800
0000
TIME



COCKRELL CREEK
MILE 2.53 (4.1 km)
JULY 16, 1974
JULY 17, 1974
DYE CONCENTRATION (PPB)
TIME
0000
0600
1200
1800
0000
0
1
2
3
4
5

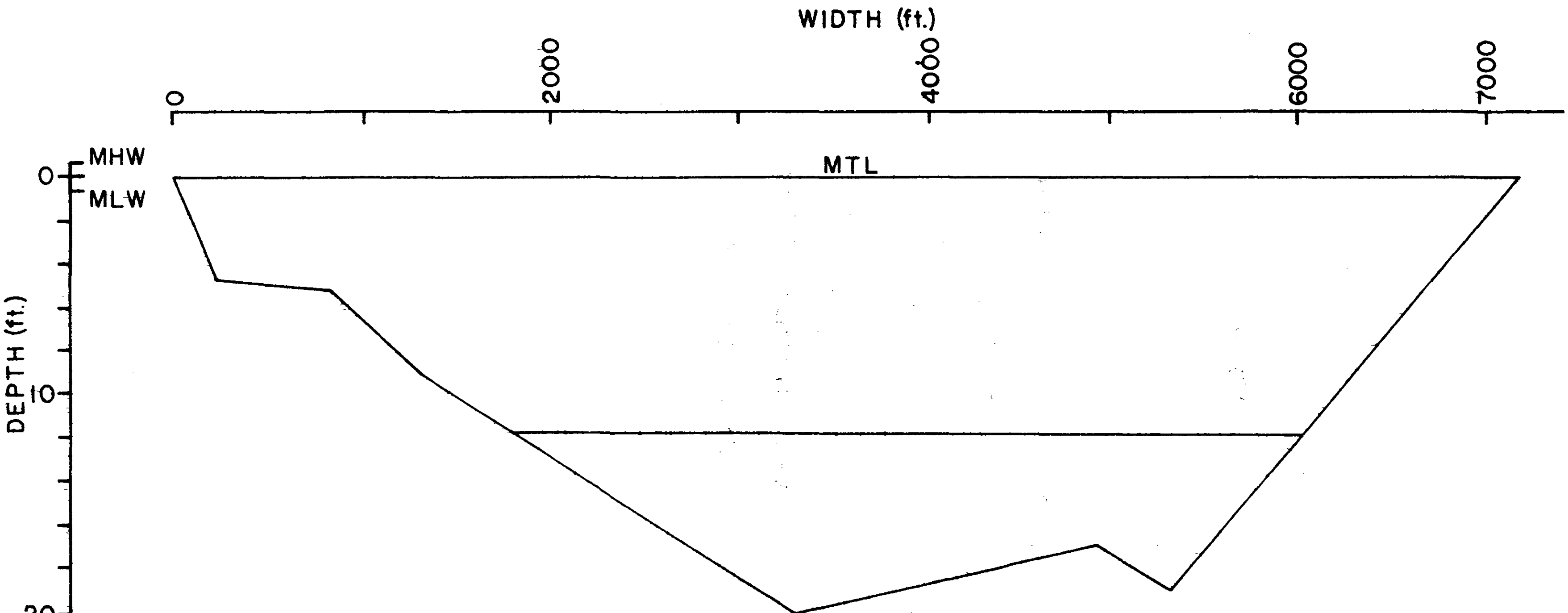

COCKRELL CREEK
MILE 2.99 (4.8 km)
JULY 16, 1974
JULY 17, 1974
DYE CONCENTRATION (PPB)
12
10
8
6
4
2
0000
0600
1200
1800
0000
TIME


COCKRELL CREEK
MILE 3.45 (5.6 km.)
JULY 16, 1974
JULY 17, 1974
DYE CONCENTRATION (PPB)
TIME
0
2
4
6
8
10
12
0000
0600
1200
1800
0000

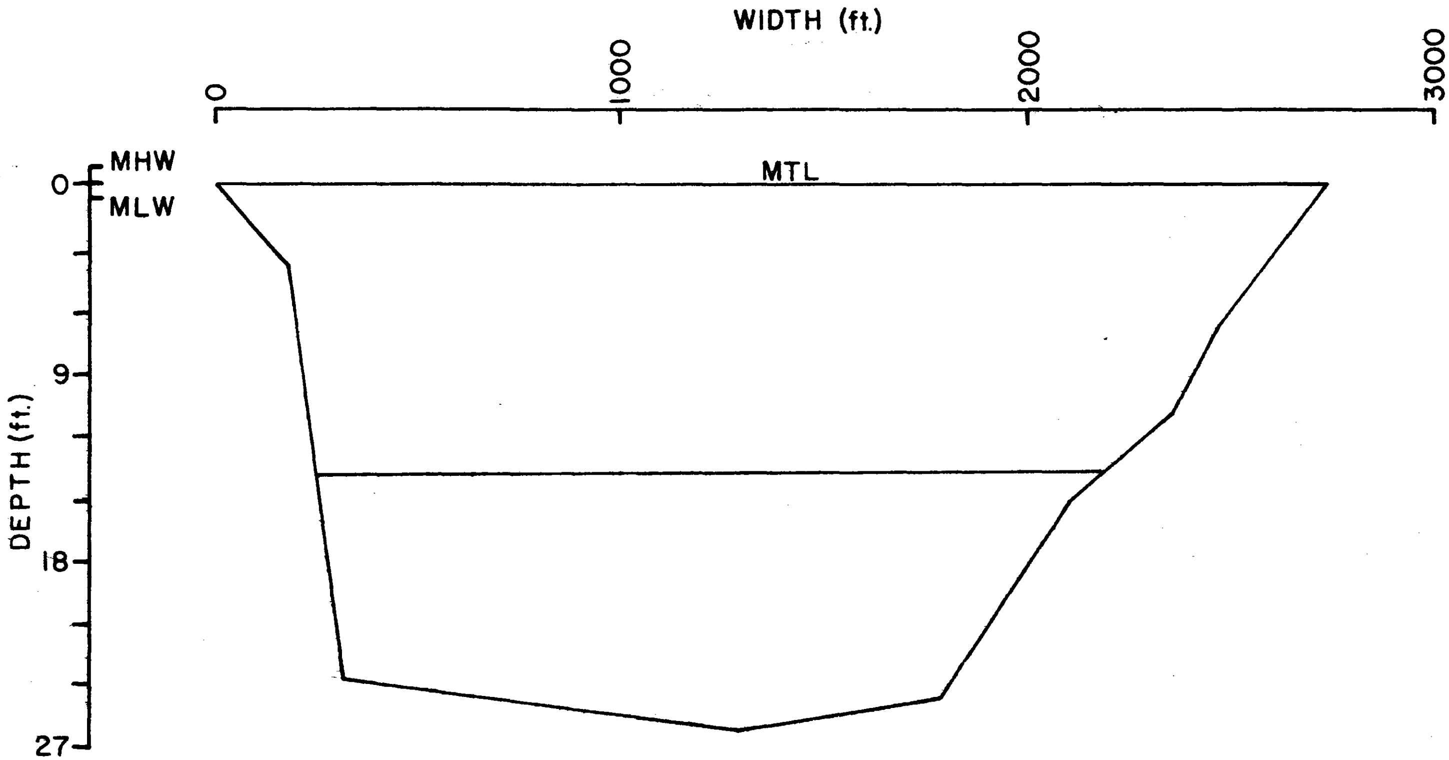
Appendix C

Bottom Cross-Section
Profiles

Great Wicomico River
Cockrell Creek

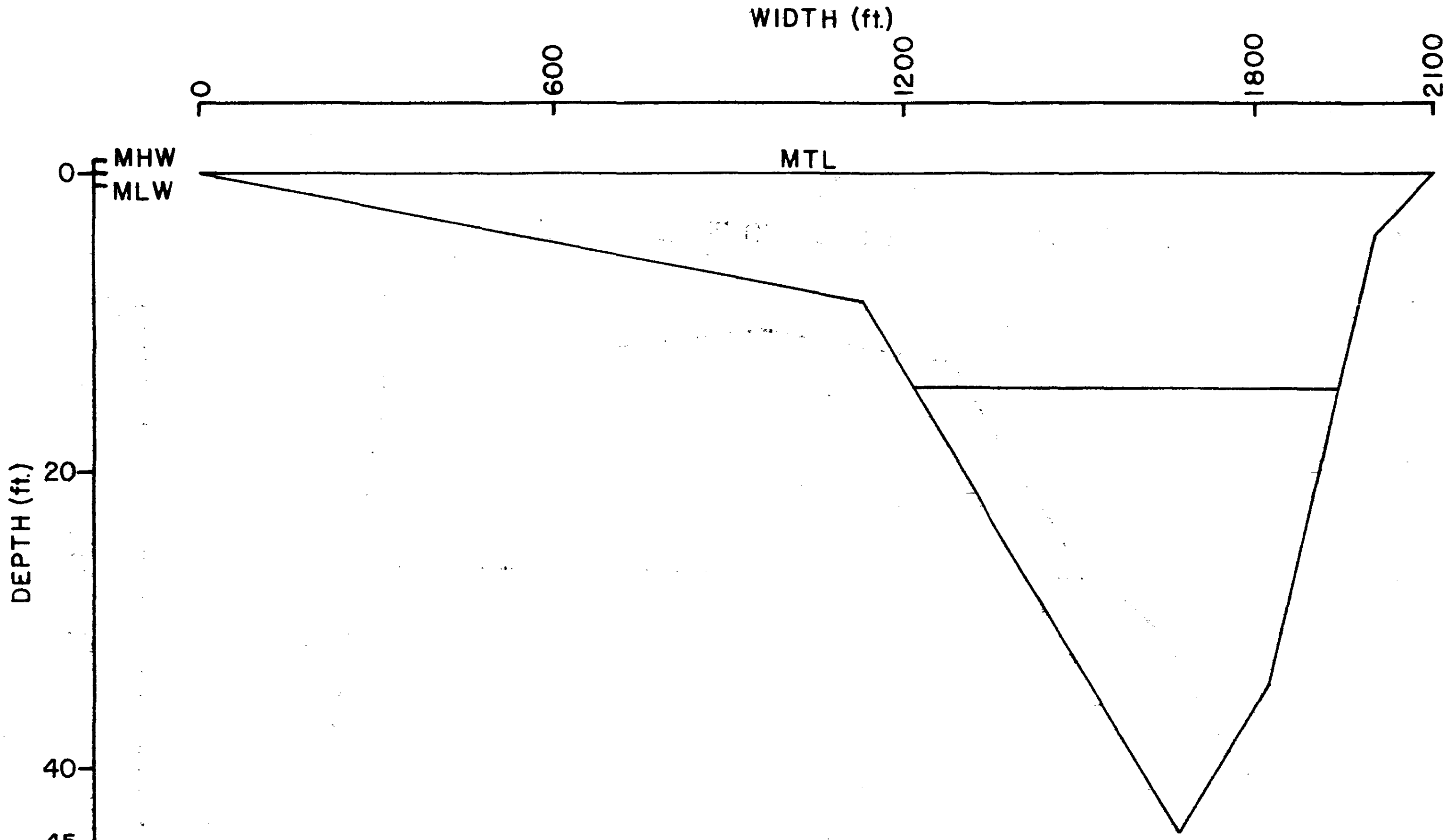


GREAT WICOMICO RIVER 0.0 MILES (0.0 km)
(1 ft=0.305 m)



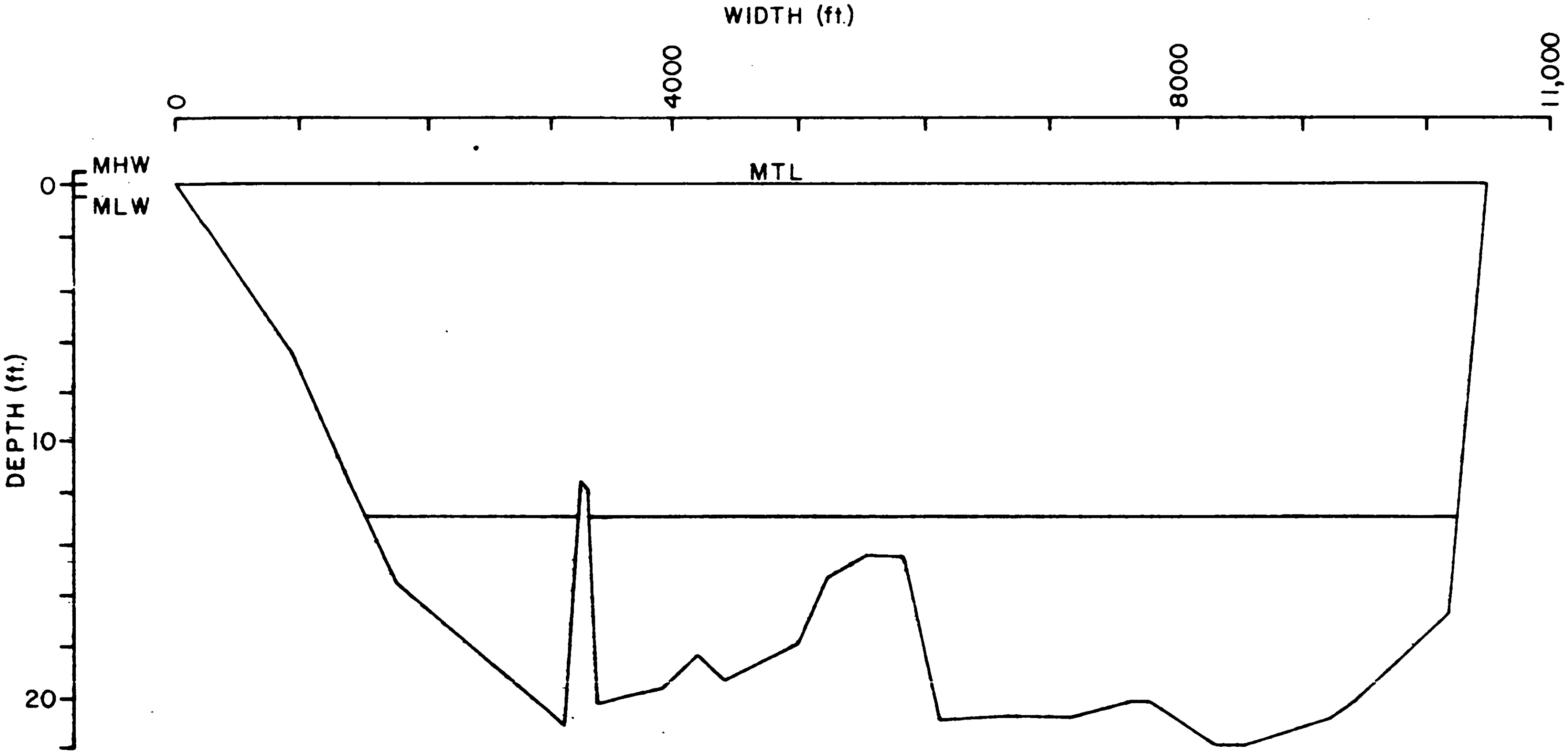
GREAT WICOMICO RIVER 0.92 MILES (1.5 km)

(1 ft=0.305 m)



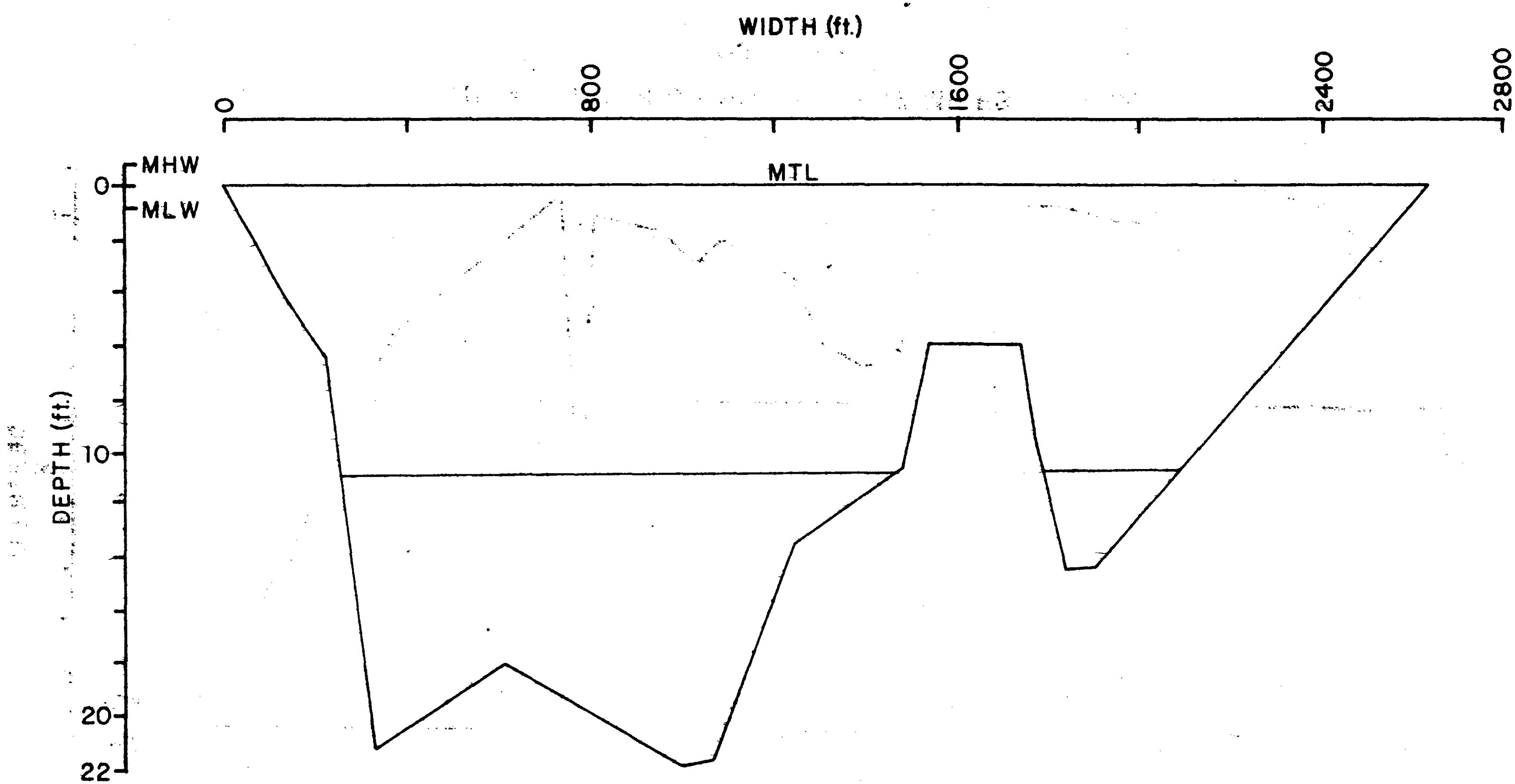
GREAT WICOMICO RIVER 1.96 MILES (3.1 km)

(1 ft=0.305 m)



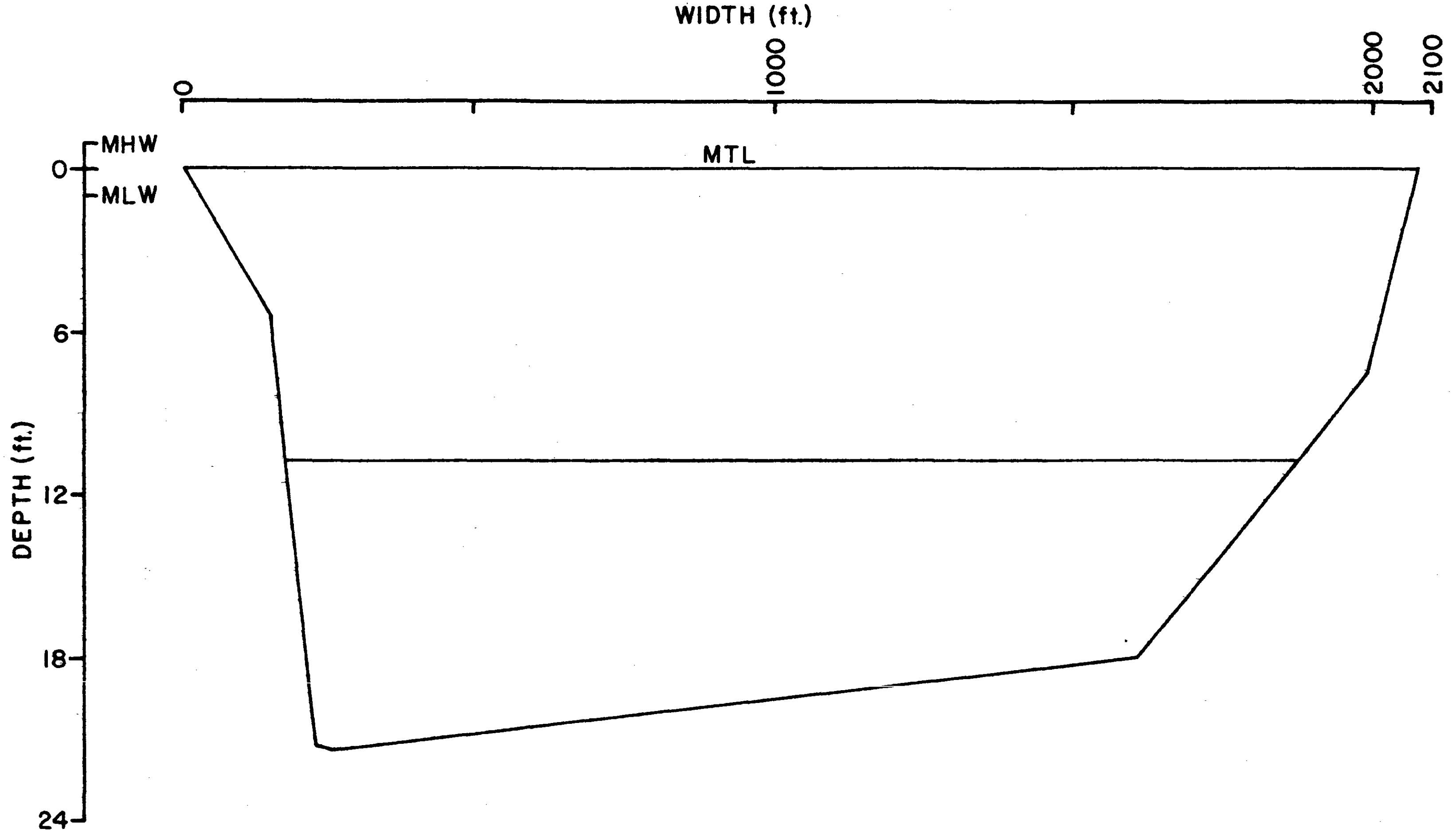
GREAT WICOMICO RIVER 2.07 MILES (3.3 km)

(1 ft=0.305 m)



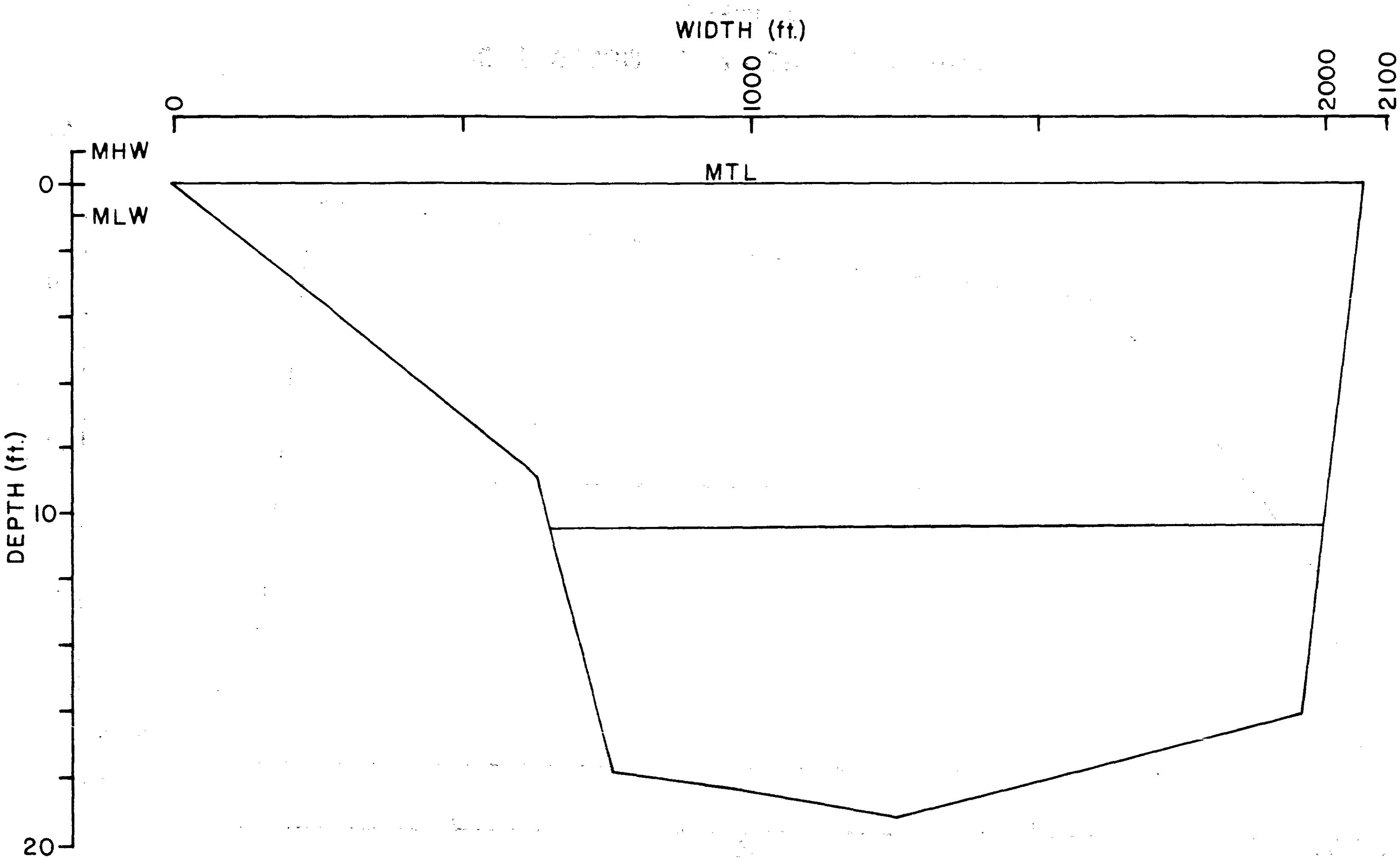
GREAT WICOMICO RIVER 2.99 MILES (4.8 km)

(1 ft=0.305 m)



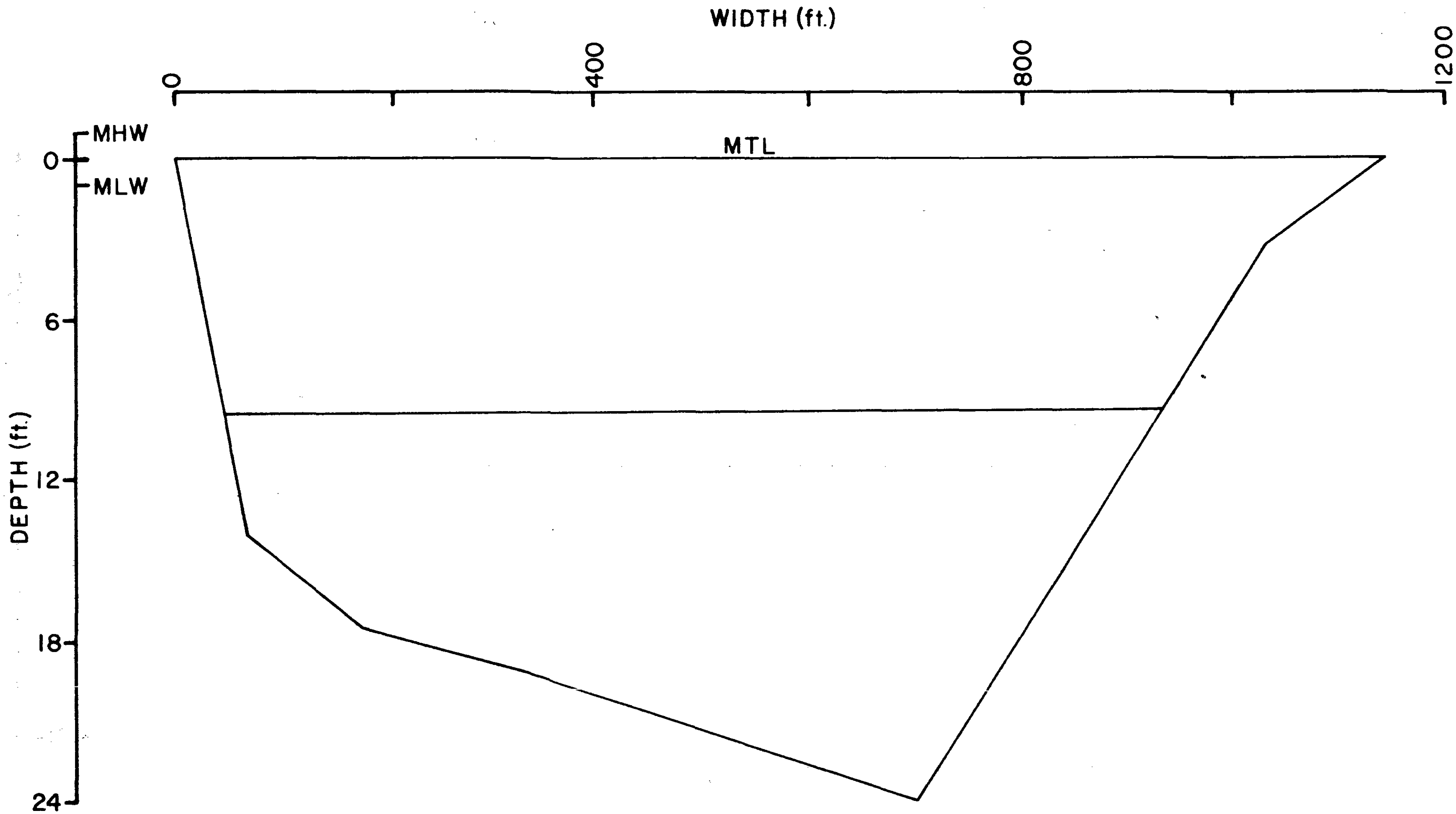
GREAT WICOMICO RIVER 3.80 MILES (6.1 km)

(1 ft=0.305 m)

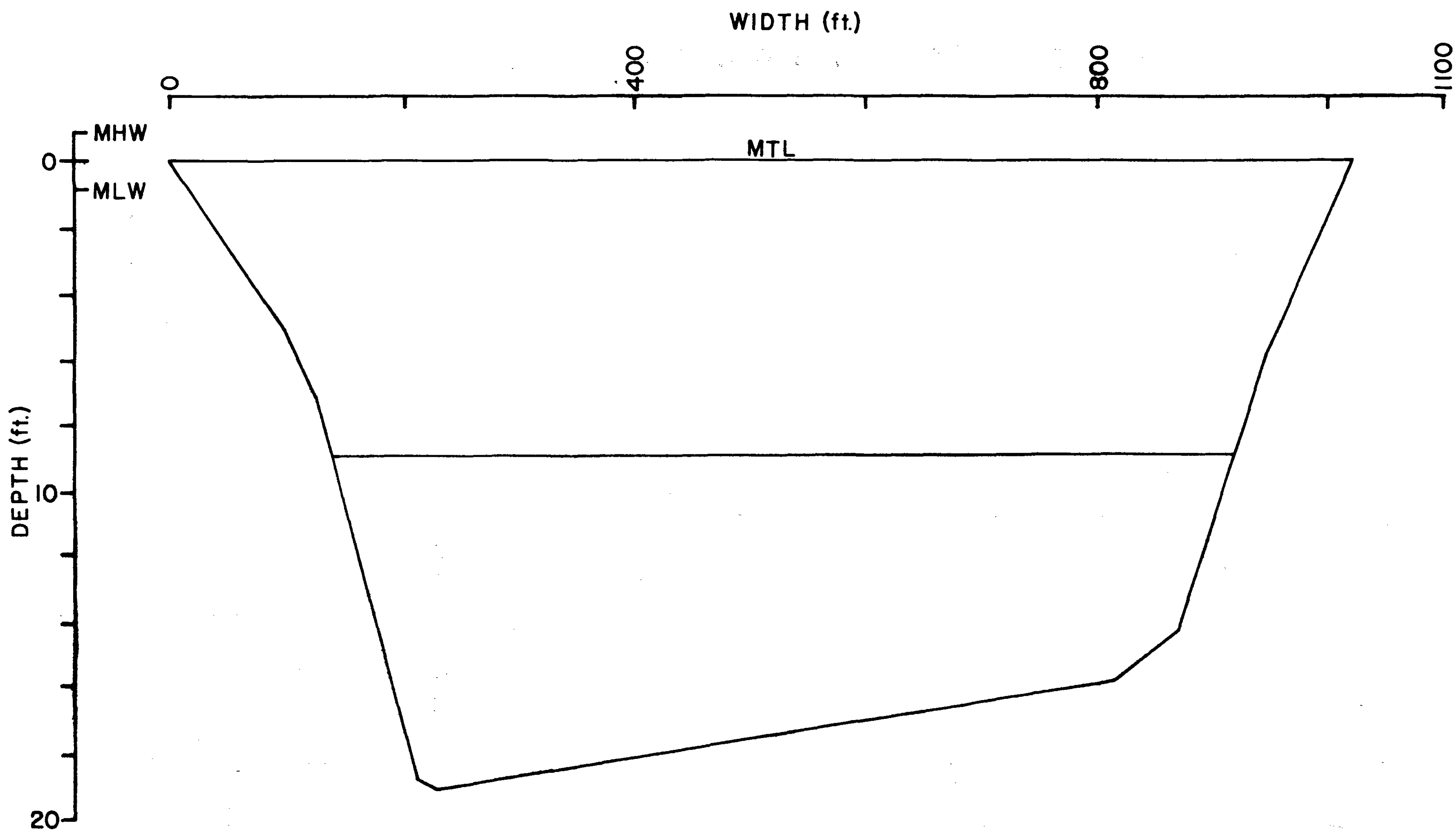


GREAT WICOMICO RIVER 4.60 MILES (7.4 km)

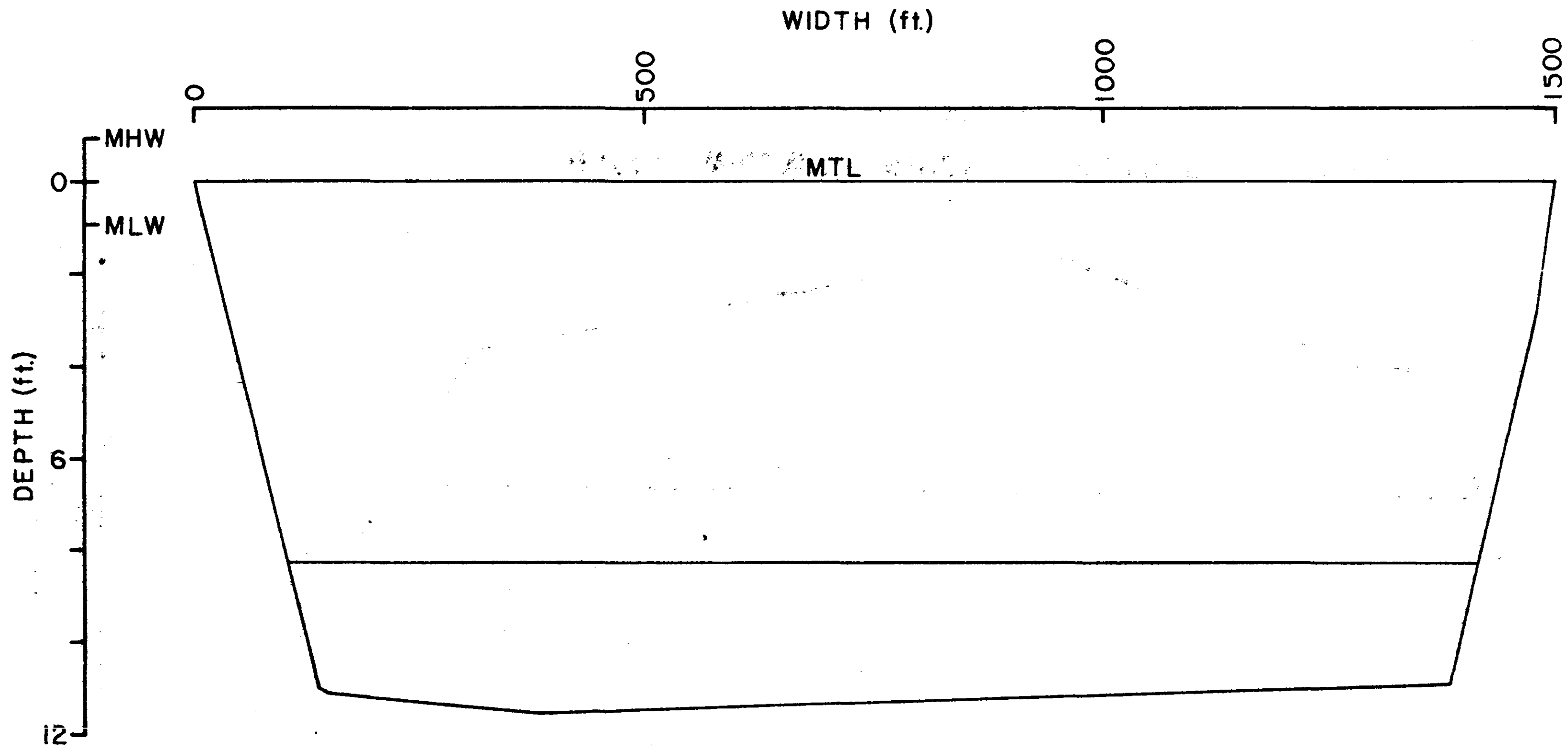
(1 ft=0.305 km)



GREAT WICOMICO RIVER 5.63 MILES (9.1 km)
(1 ft=0.305 km)

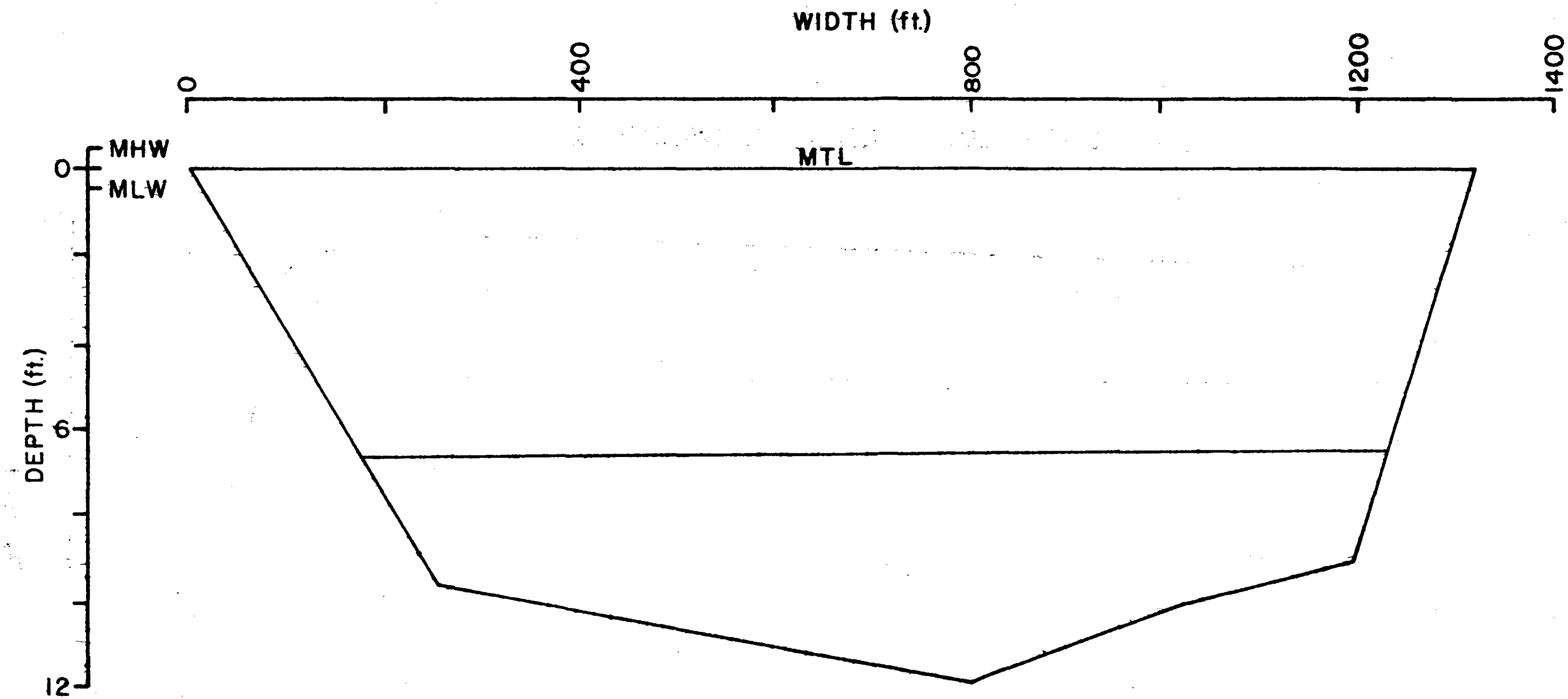


GREAT WICOMICO RIVER 6.27 MILES (10.1 km)
(1 ft=0.305 m)



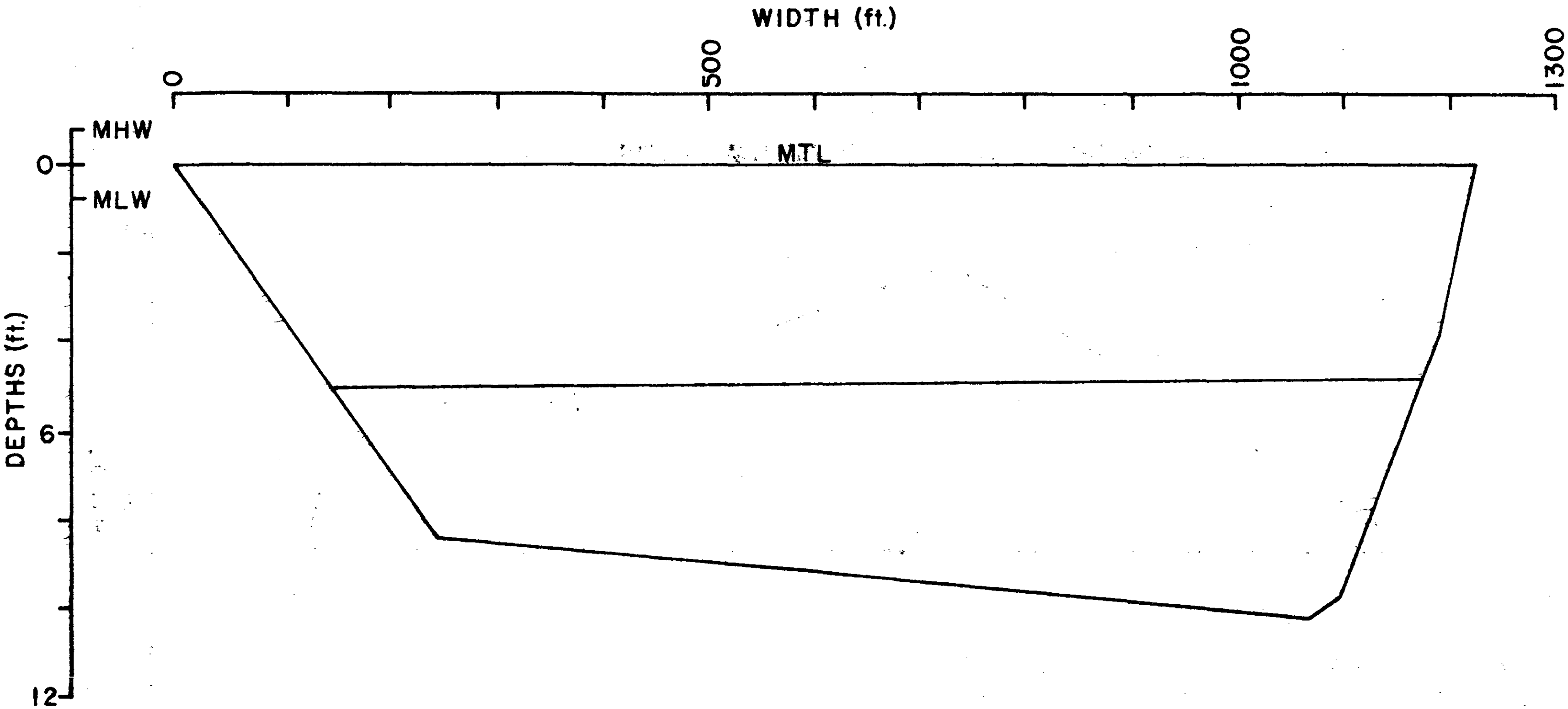
GREAT WICOMICO RIVER 7.02 MILES (11.3 km)

(1 ft=0.305 m)



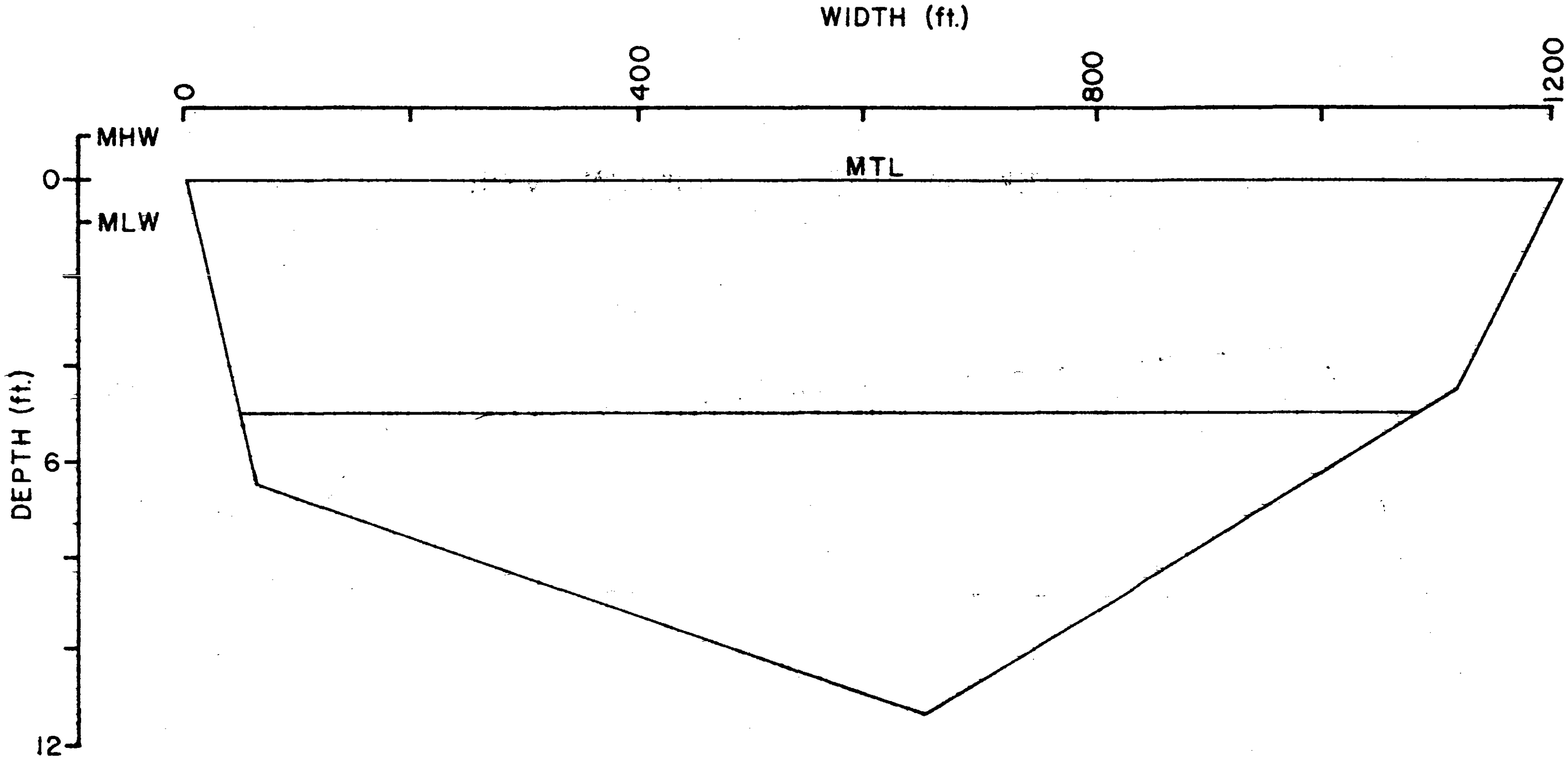
GREAT WICOMICO RIVER 7.60 MILES (12.2 km)

(1 ft=0.305 m)



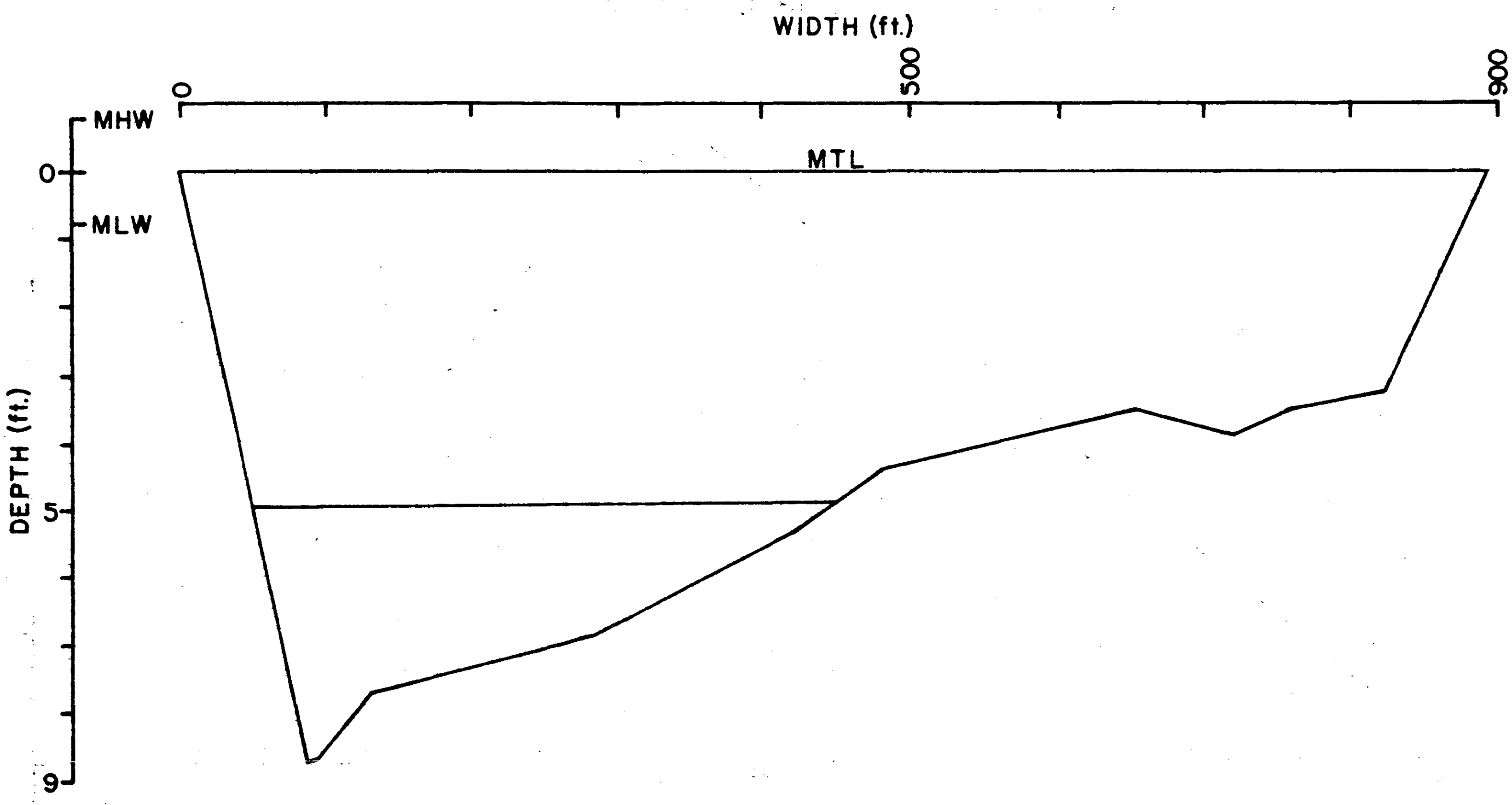
GREAT WICOMICO RIVER 8.17 MILES (13.1 km)

(1 ft=0.305 m)



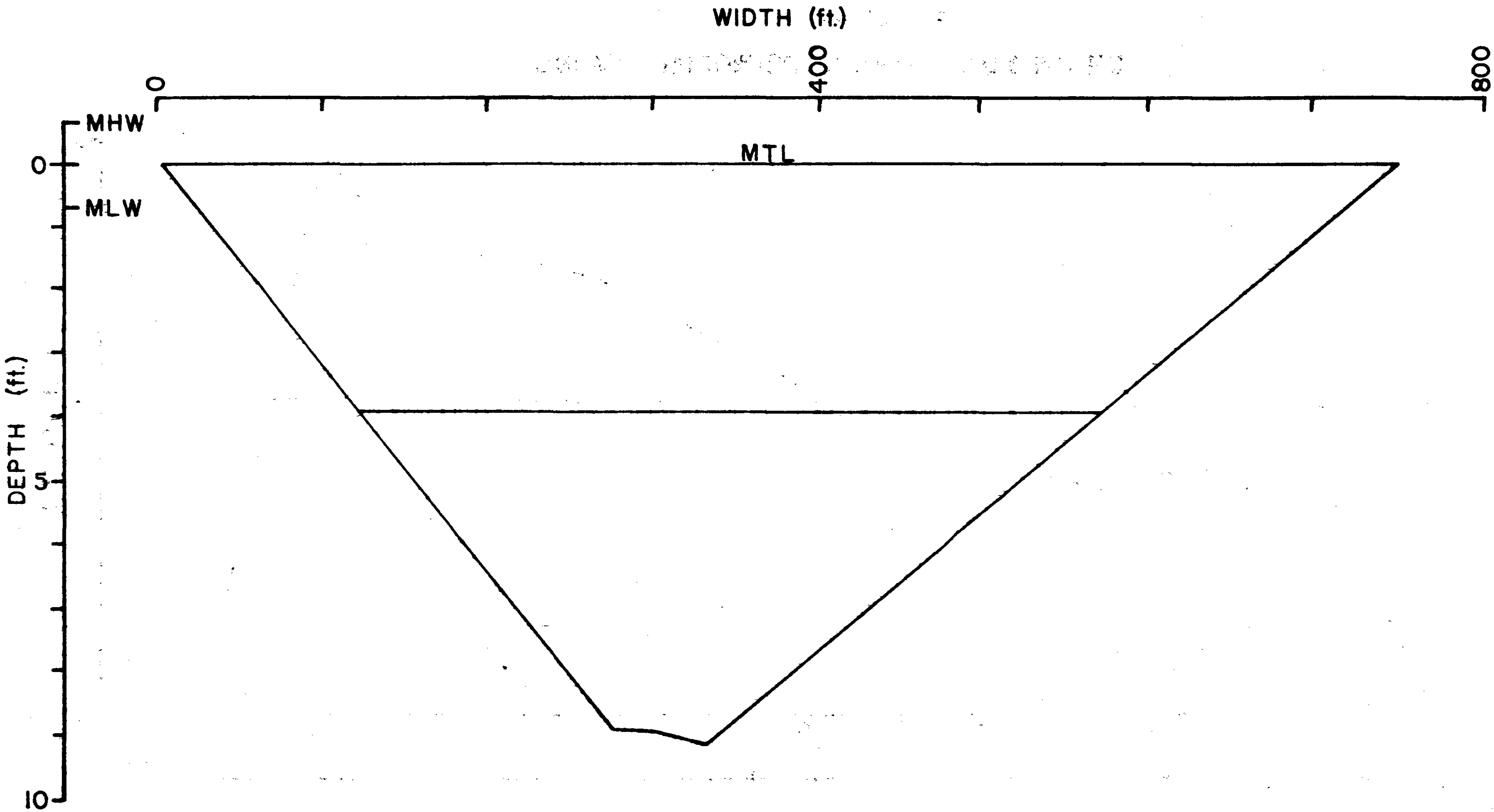
GREAT WICOMICO RIVER 8.64 MILES (13.9 km)

(1 ft=0.305 m)



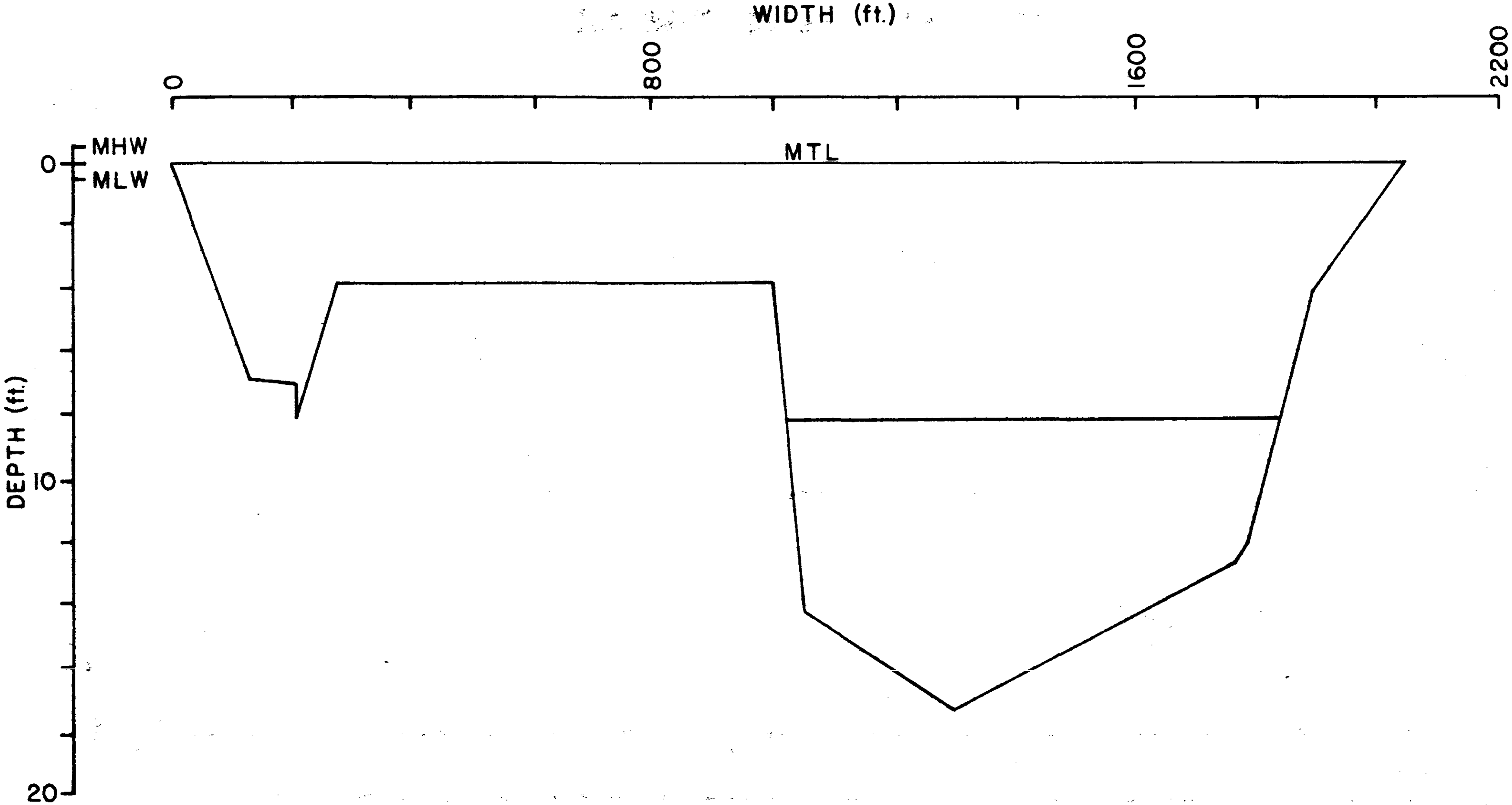
GREAT WICOMICO RIVER 9.44 MILES (15.2 km)

(1 ft=0.305 m)



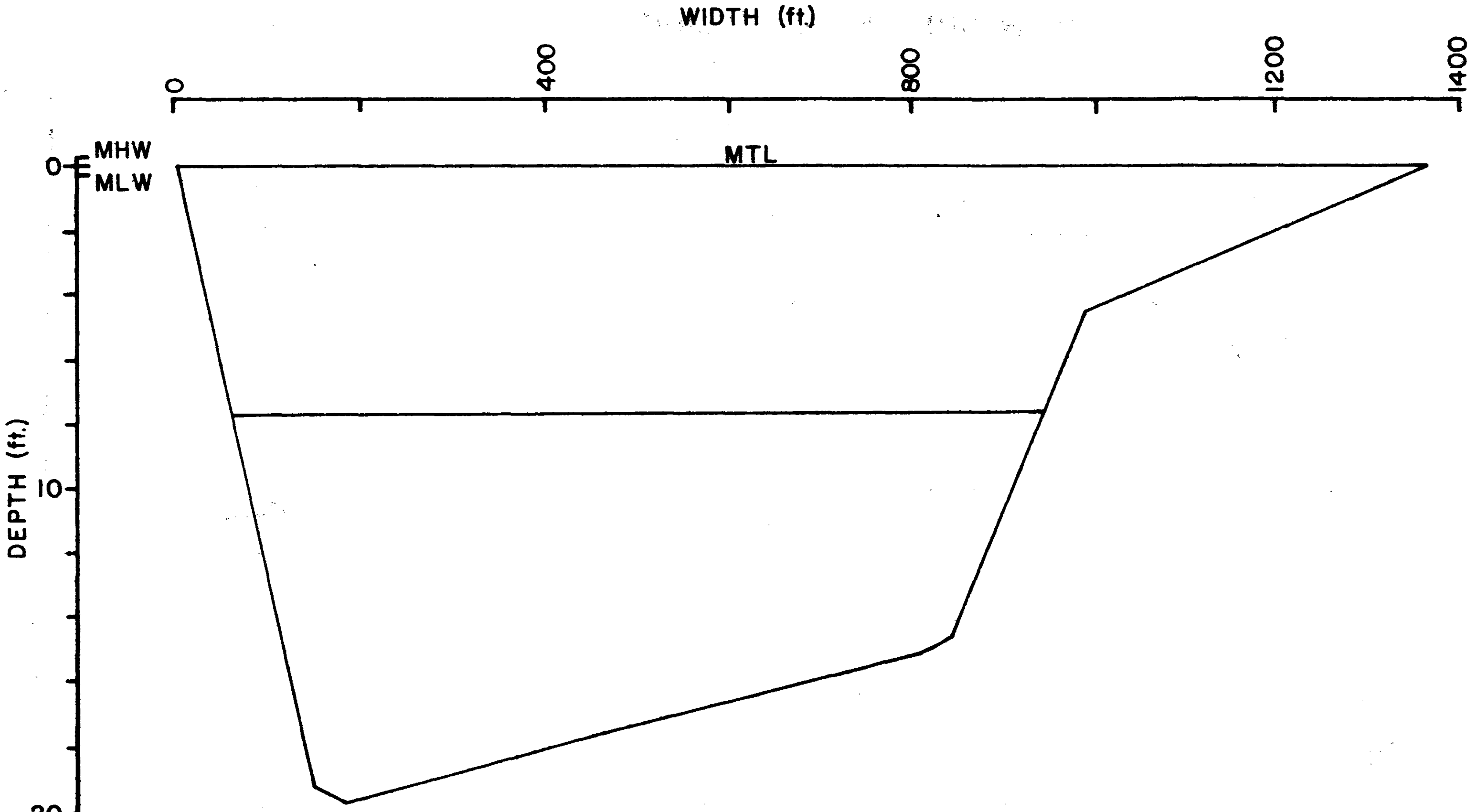
GREAT WICOMICO RIVER 10.24 MILES (16.5 km)

(1 ft=0.305 m)



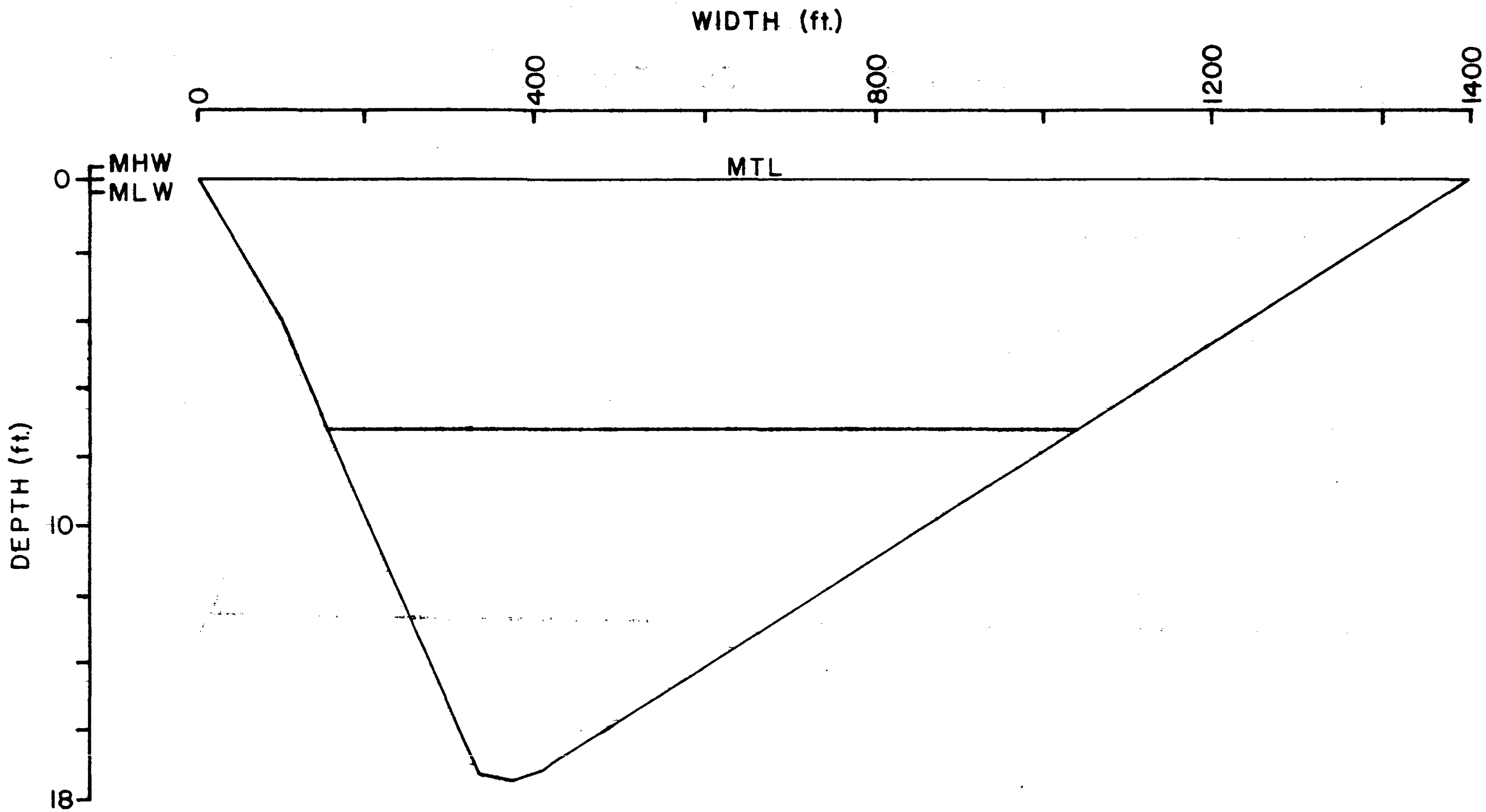
COCKRELL CREEK 0.81 MILES (1.3 km)

(1 ft=0.305 m)



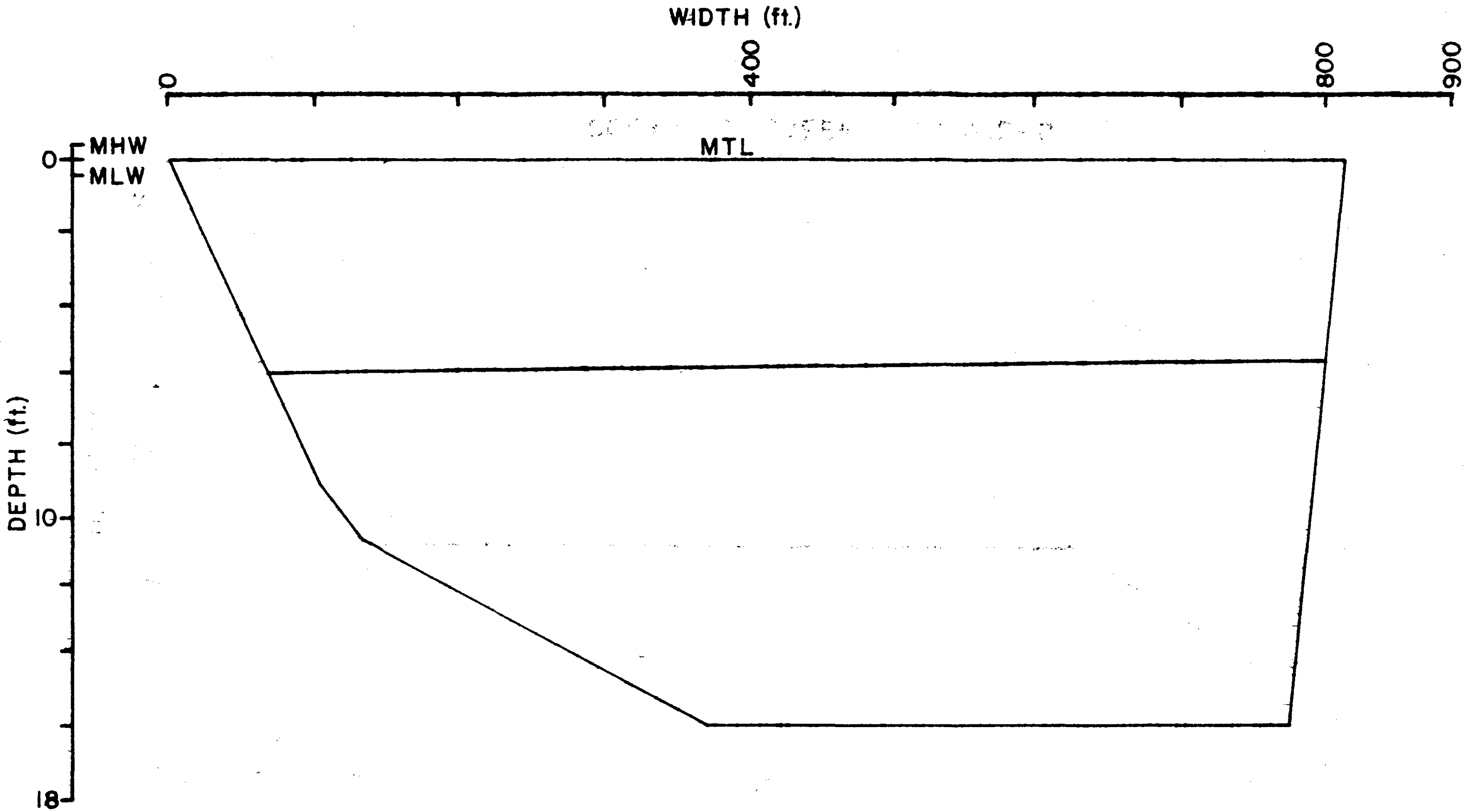
COCKRELL CREEK 1.04 MILES (1.7 km)

(1 ft=0.305 m)



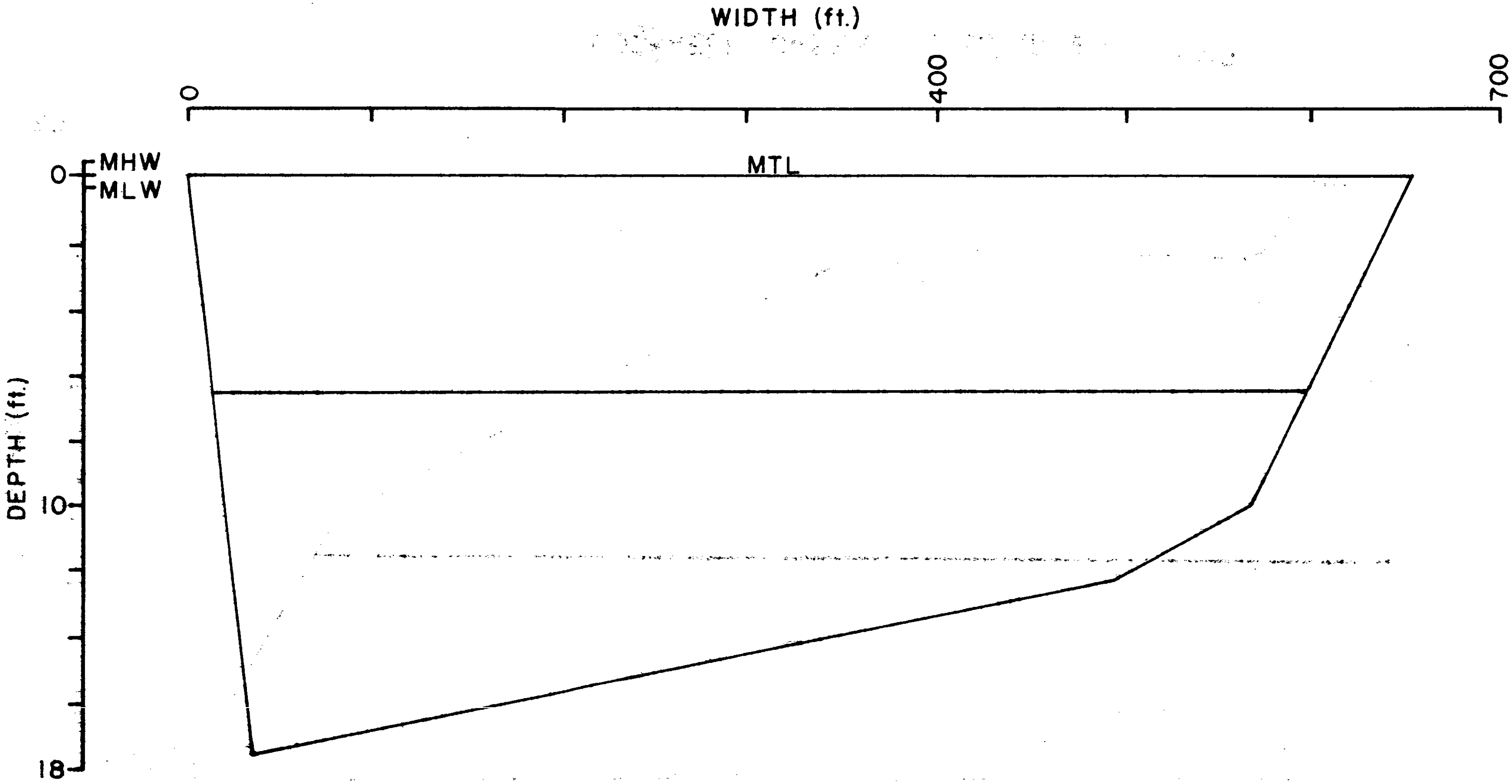
COCKRELL CREEK 1.27 MILES (2.0 km)

(1 ft=0.305 m)

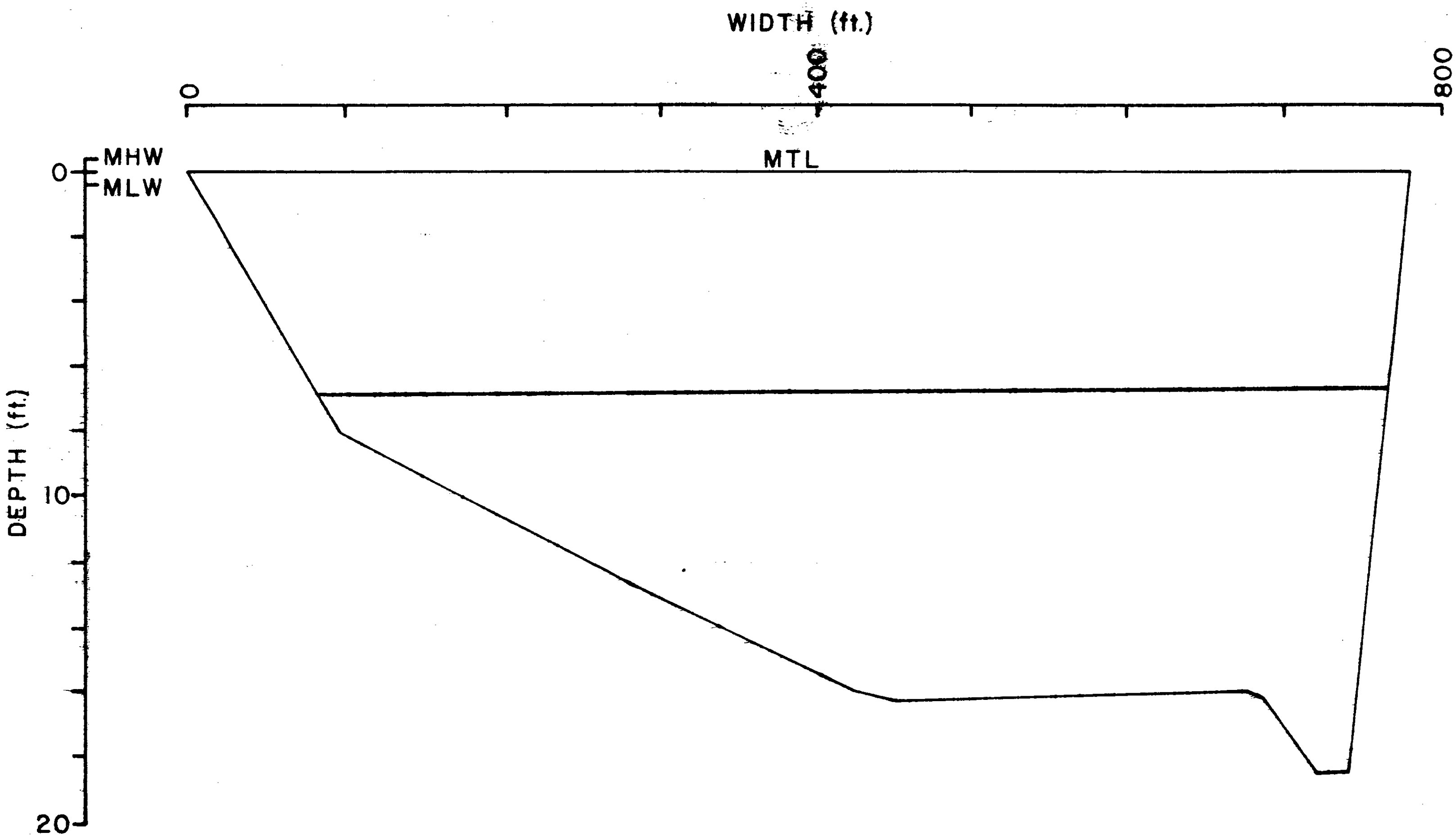


COCKRELL CREEK 1.73 MILES (2.8 km)

(1 ft-0.305 m)

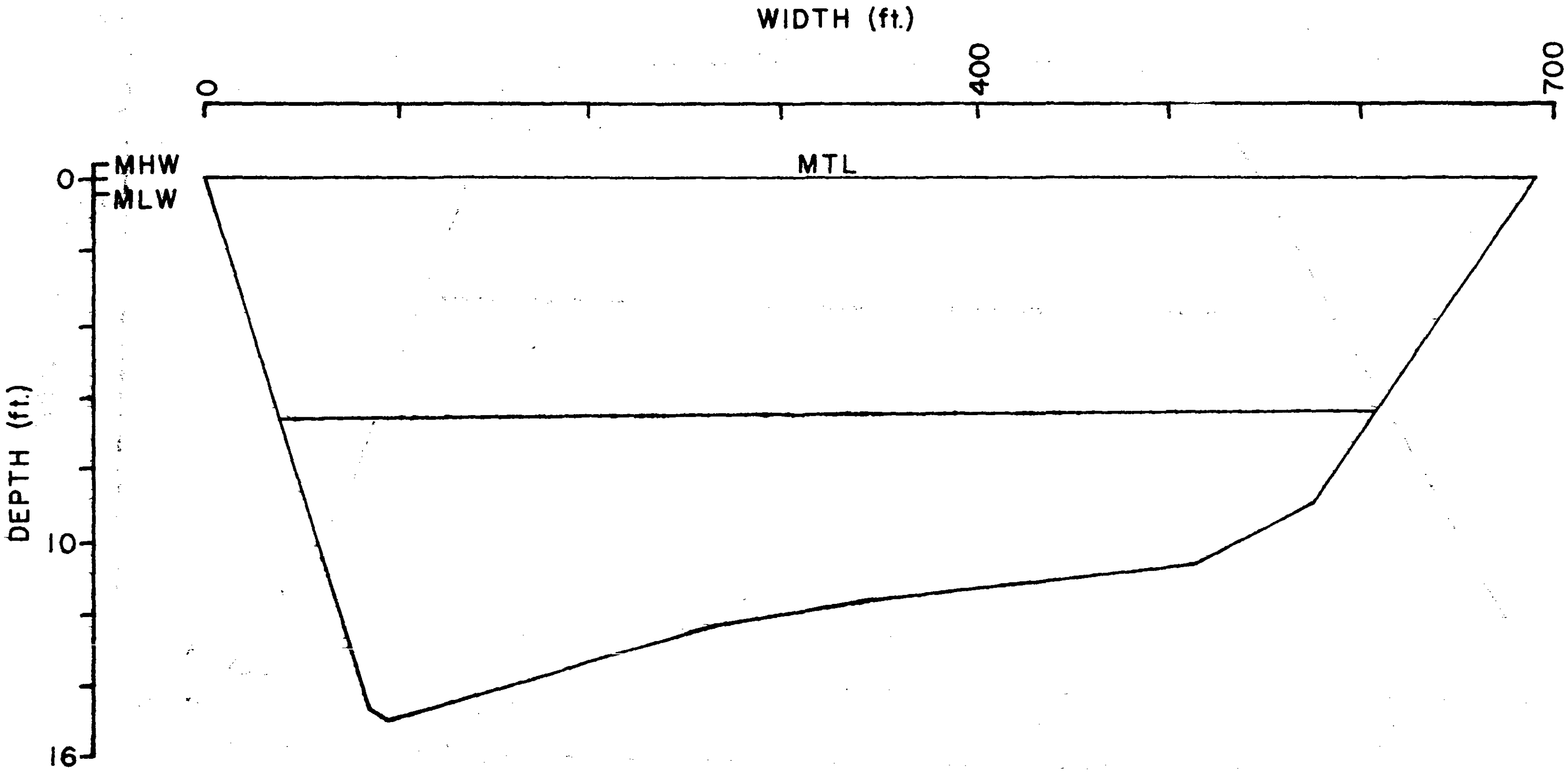


COCKRELL CREEK 2.07 MILES (3.3 km)
(1 ft=0.305 m)



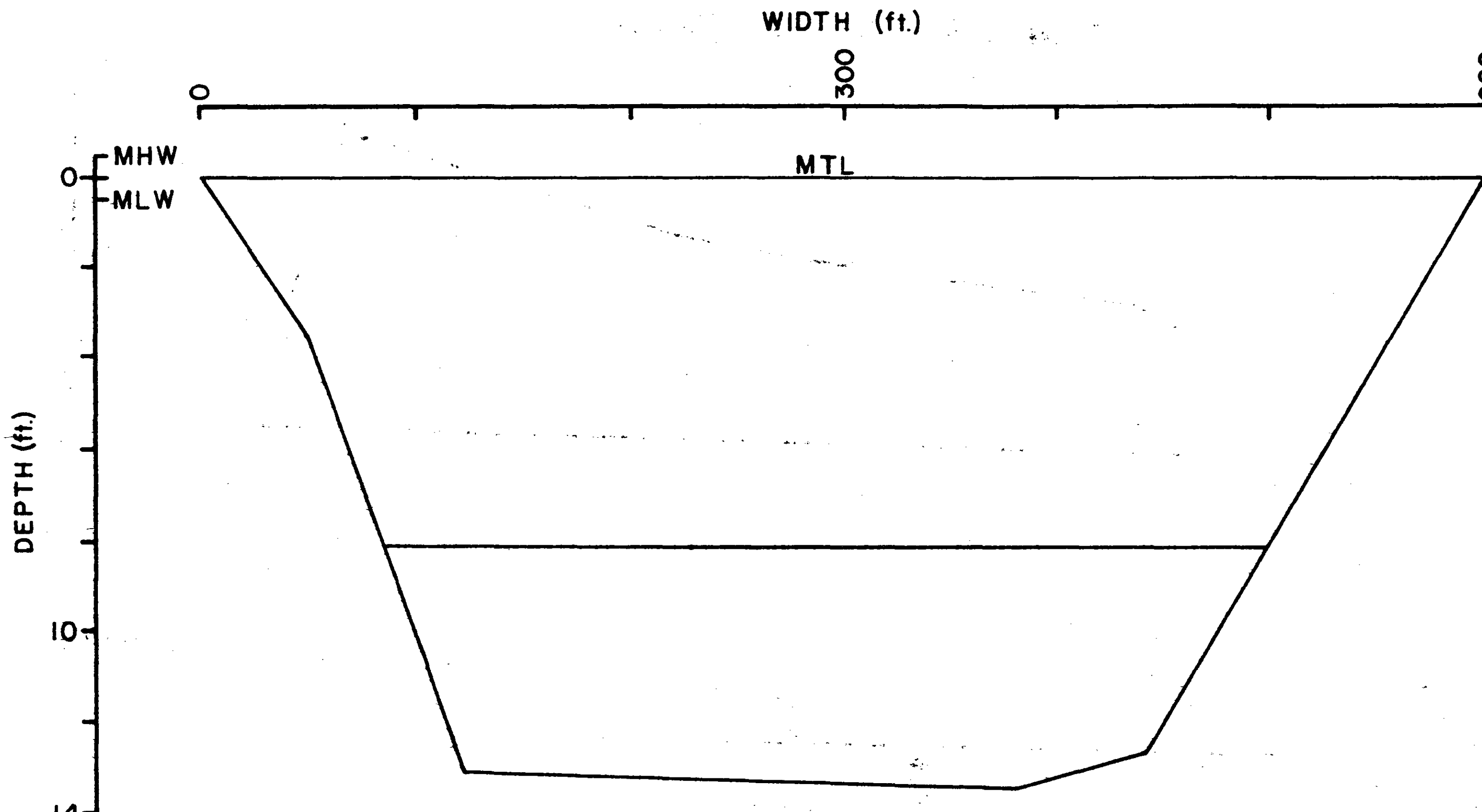
COCKRELL CREEK 2.30 MILES (3.7 km)

(1 ft = 0.305 m)



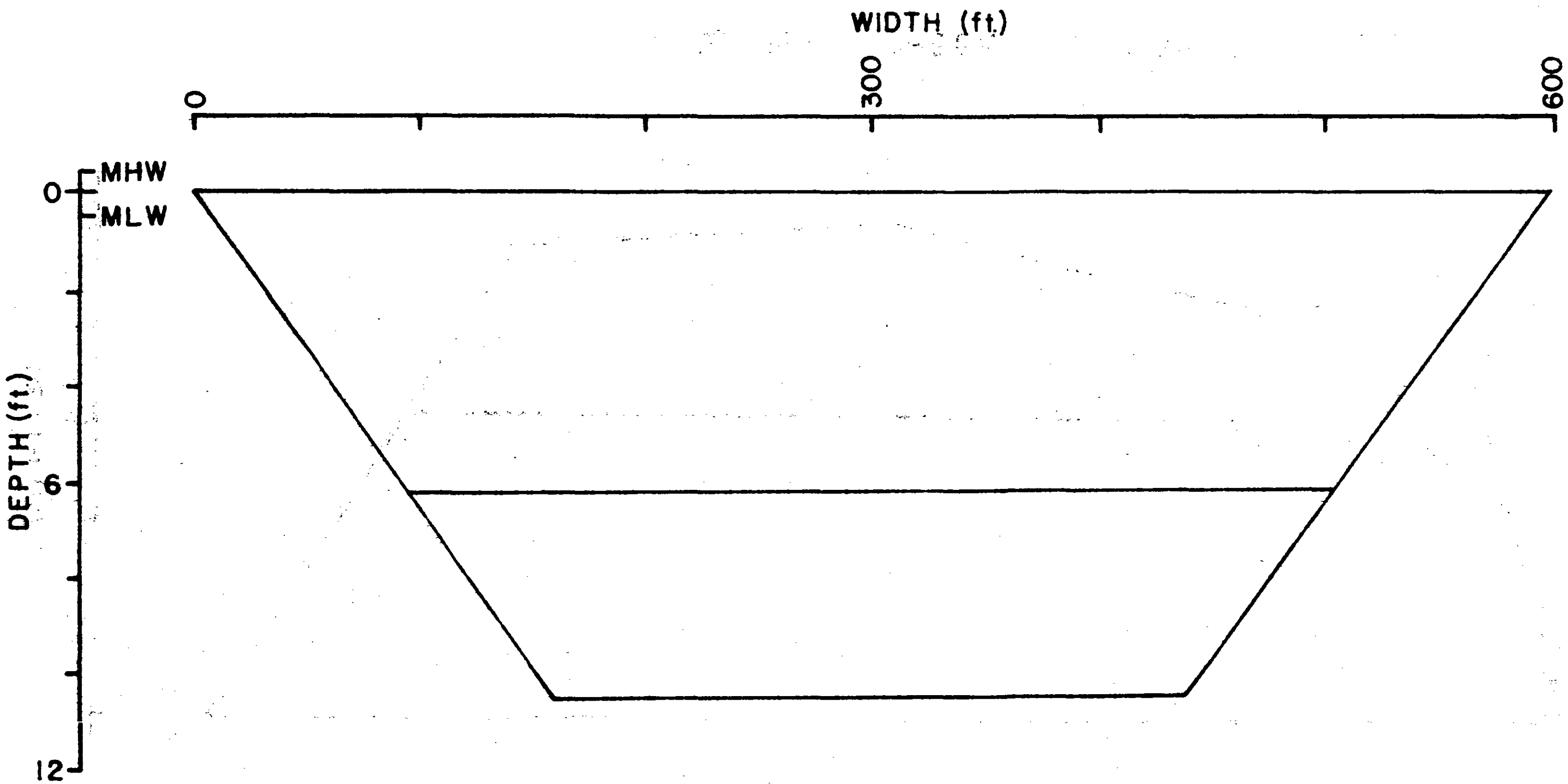
COCKRELL CREEK 2.53 MILES (4.1 km)

(1 ft=0.305 m)



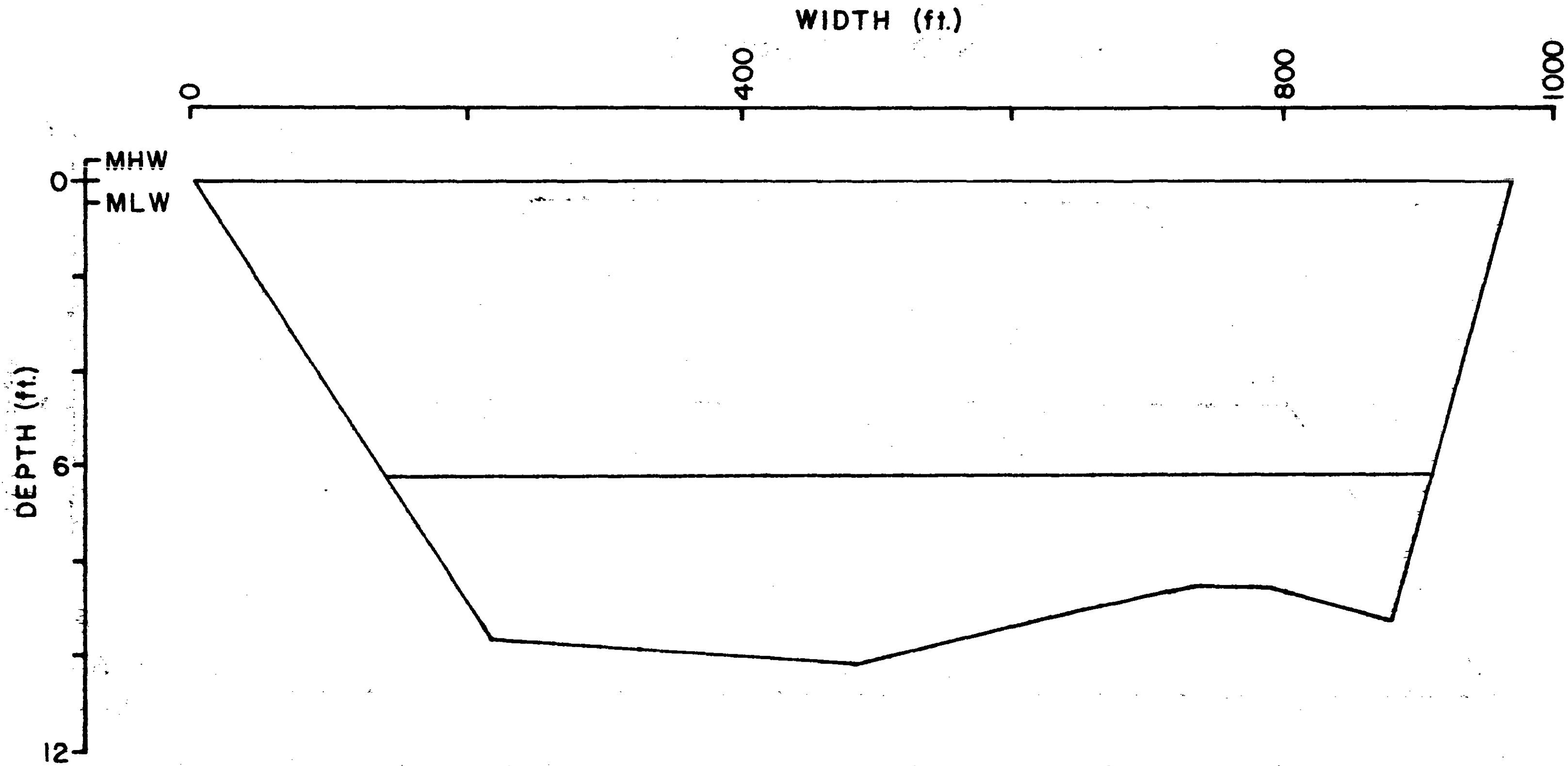
COCKRELL CREEK 2.76 MILES (4.4 km)

(1 ft=0.305 m)



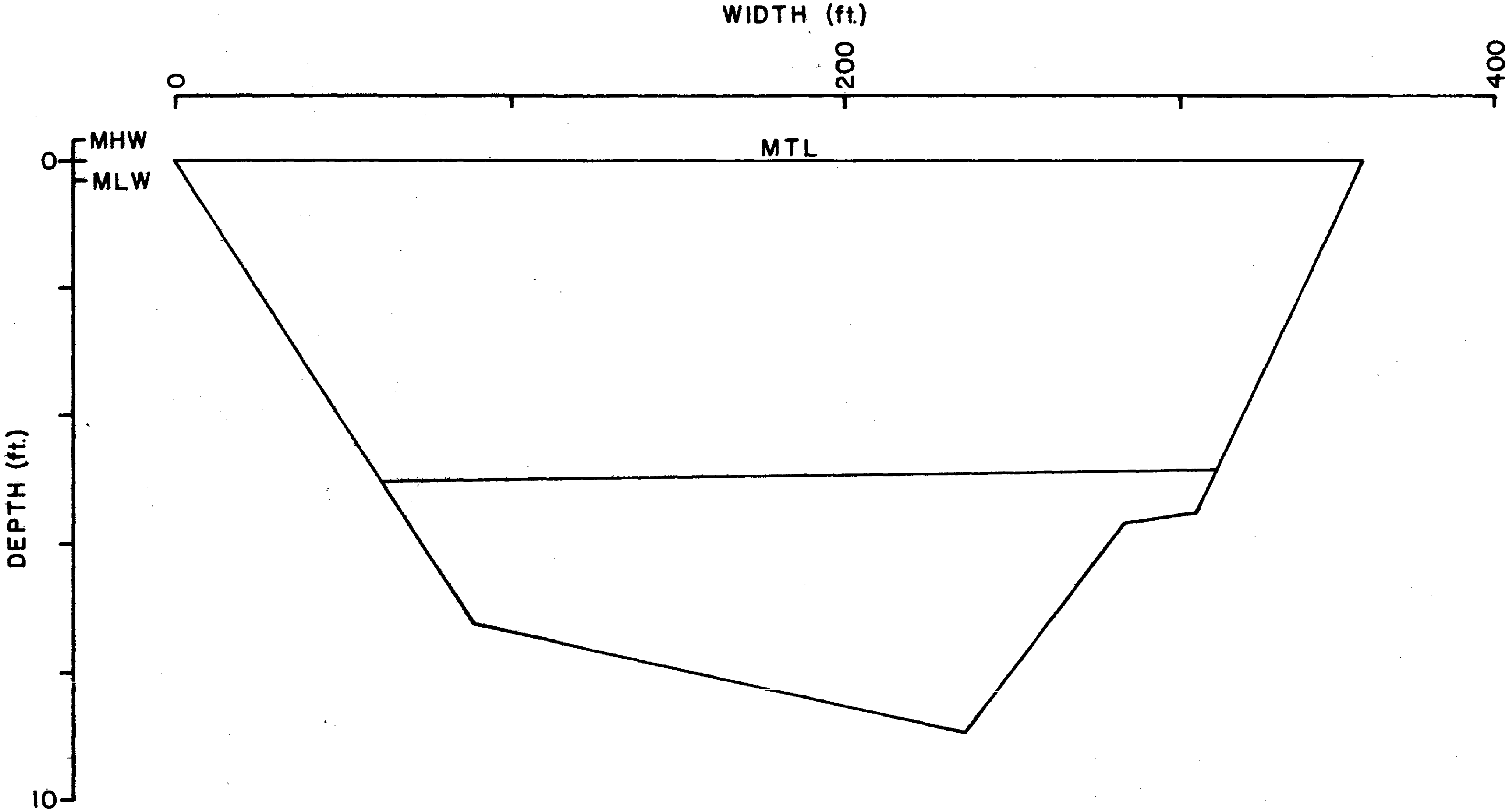
COCKRELL CREEK 2.99 MILES (4.8 km)

(1 ft=0.305 m)



COCKRELL CREEK 3.22 MILES (5.2 km)

(1 ft=0.305 m)



COCKRELL CREEK 3.45 MILES (5.6 km)

(1 ft=0.305 m)

Appendix D

Users' Manual for Two-Layer Model

The following is a list of the input data necessary for the two-layer water quality model, complete with the necessary format for each card.

A. Main Program

1. Title Format: 20A4

2. NS: number of reaches

   NPRNT: number of times results will be printed out

   Format: 2I5

3. TCYC: total duration of run in tidal cycles

   DT: time step, also in tidal cycles

   DNB: time in hours from 0600 to computation starting time. Used to take into account the phase of diurnal photosynthesis and respiration cycle

   TB: time in hours from low water slack at the most upstream transect to computation starting time. May be set to zero for most cases

   Format: 8F10.2

4. QGAGE: freshwater flow at gauge, if any; otherwise freshwater flow into farthest upstream reach

   AGAGE: drainage area upstream of flow gauge, if any; otherwise drainage area upstream of farthest upstream transect.

   AHEAD: drainage area between flow gauge and farthest upstream transect; if no flow gauge, set to zero.

   FIE(1): tidal advection weighting factor for salinity: never less than 0.5 or more than 1.0.

   FIE(2): tidal advection weighting factor for other constituents: never less than 0.5 or more than 1.0.

   Format: 8F10.2

5. TCCKC: Temperature correction coefficient for CBOD decay.

TCCKN: Temperature correction coefficient for nitrogenous BOD decay.

TCBEN: Temperature correction coefficient for bottom oxygen demand.
Format: 3F10.3

B. Subroutine INPUT

1. TPR(I), I=1, NPRNT: times at which integration results are to be printed out
Format: 14F5.2

2,3,4,5,6. IDG: number of data group

NI: number of inputs

Comment: comment or useful information concerning data group
Format: 2I5, 15A4

2. datagroup 1 - Geometric data. NI $\geq$ NS+1

2.1 X(I),I=1,NI: transect locations in statute miles
Format: 7F10.5

2.2 A(1,I),I=1,NI: cross-sectional areas of upper layer portion of transect
Format: 7F10.5

2.3 A(2,I),I=1,NI: cross-sectional areas of lower layer portion of transect
Format: 7F10.5

2.4 ACON(I),I=1,NI: conveyancy area in upper layer
Format: 7F10.5

2.5 H(1,I),I=1,NI: mean depth of upper layer portion of inter-transect reach
Format: 7F10.5

2.6 H(2,I),I=1,NI: mean depth of lower layer portion of inter-transect reach
Format: 7F10.5

2.7 V(1,I),I=1,NI: volume of upper layer portion of inter-transect reach
Format: 7E10.2

2.8 V(2,I),I=1,NI: volume of lower layer portion of inter-transect reach
Format: 7E10.2

3. data group 2 - hydraulic inputs. NI $\geq$ NS+1

3.1 UT(1,I),I=1,NI: tidal current amplitude at I transect in upper layer
Format: 7F10.2

3.2 UT(2,I),I=1,NI: tidal current amplitude at I transect in lower layer
Format: 7F10.2

3.3 FITI(1,I),I=1,NI: tidal phase in hours for upper layer at transect I
Format: 7F10.2

3.4 FITI(2,I),I=1,NI: tidal phase in hours for lower layer at transect I
Format: 7F10.2

3.5 DRAER(I),I=1,NI: drainage area for each reach, in square miles
Format: 7510.5

3.6 EUP(I),I=1,NI: vertical exchange dispersion coefficient, in square miles
Format: 7510.5

4. data group 3 - biochemical inputs. NI$\geq$ NS

4.1 TEMP(1,I),I=1,NI: upper - layer temperature
Format: 14F5.2

4.2 TEMP(2,I),I=1,NI: lower-layer temperature
Format: 14F5.2

4.3 DKAYC(1,I),I=1,NI: carbonaceous decay rate for upper layer
Format: 14F5.2

4.4 DKAYC(2,I),I=1,NI: carbonaceous decay rate for lower layer
Format: 14F5.2

4.5 DKAYN(1,I),I=1,NI: nitrogenous decay rate for upper layer
Format: 14F5.2

4.6 DKAYN(1,I),I=1,NI: nitrogenous decay rate for lower layer
Format: 14F5.2

4.7 FJC(I),I=1,NI: carbonaceous point-source loading in pounds per day
Format: 7F10.5

4.8 FJN(I),I=1,NI: nitrogenous point-source loading in pounds per day
Format: 7F10.5

4.9 BOTDM(I),I=1,NI: bottom oxygen demand in $gm/m^2/day$
Format: 14F5.2

4.10 FOTOS(I),I=1,NI: photosynthesis amplitude in $gm/m^2/day$
Format: 14F5.2

5. data group 4 - initial conditions [illegible]

5.1 upstream boundary conditions

BSU: upstream surface salinity;

BSL: upstream bottom salinity;

BDU: upstream surface DO;

BDL: upstream bottom DO;

BU: upstream surface carbonaceous BOD;

BL: upstream bottom carbonaceous BOD;

BNU: upstream surface nitrogenous BOD;

BNL: upstream bottom nitrogenous BOD.
Format: 14F5.2

5.2 downstream boundary conditions

ESU: downstream surface salinity;

ESL: downstream bottom salinity;

EDU: downstream surface DO;

EDL: downstream bottom DO;

EU: downstream surface carbonaceous BOD;

EL: downstream bottom carbonaceous BOD;

ENU: downstream surface nitrogenous BOD;

ENL: downstream bottom nitrogenous BOD.
Format: 14F5.2

5.3 SU(I),I=1,NI: initial surface salinity;
Format: 14F5.2

5.4 SL(I),I=1,NI: initial bottom salinity;
Format: 14F5.2

5.5 DOU(I),I=1,NI: initial surface DO;
Format: 14F5.2

5.6 DOL(I),I=1,NI: initial bottom DO;
Format: 14F5.2

5.7 CBDU(I),I=1,NI: initial bottom carbonaceous BOD;
Format: 14F5.2

5.8 CBDL(I),I=1,NI: initial bottom carbonaceous BOD;
Format: 14F5.2

5.9 BDNU(I),I=1,NI: initial surface nitrogenous BOD;
Format: 14F5.2

5.10 BDNL(I),I=1,NI: initial bottom nitrogenous BOD.
Format: 14F5.2

6. data group 5 - background concentrations. NI not needed

6.1 BKS: background salinity concentration;

BKD: background DO concentration;

BKC: background carbonaceous BOD concentration;

BKN: background nitrogenous BOD concentration.
Format: 7F10.5

7. IDG=99 Causes exit from subroutine
Format: 25

C. Subroutine CONST.

1. FNURA: estuarine circulation parameter;

QNORM: normal flow at gauge;

FLNORM: salinity intrusion length for case of normal flow.
Format: 7F10.5