6-1989

Hypoxia in the Lower Rappahannock Estuary

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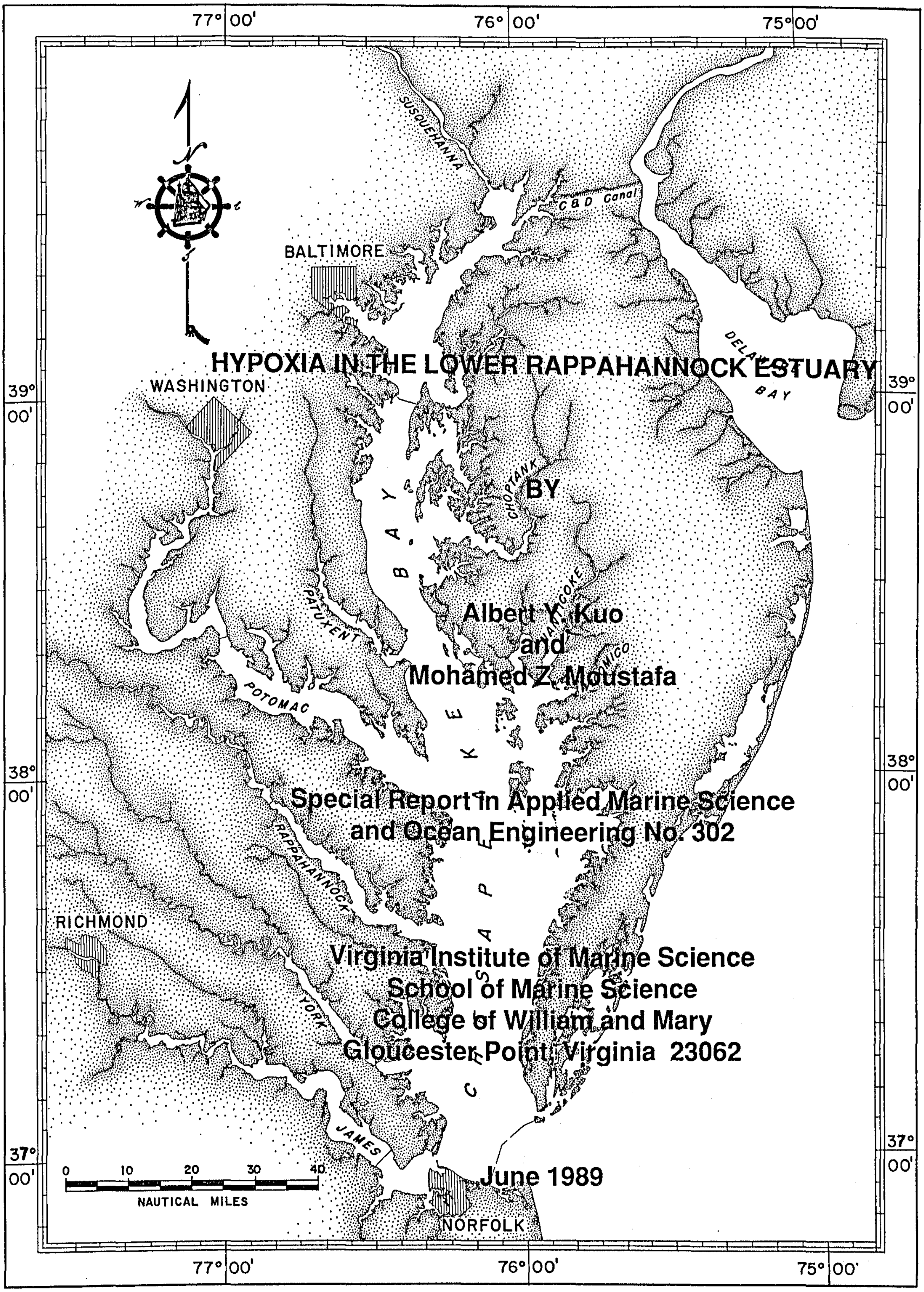

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Special Report in Applied Marine Science
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ACKNOWLEDGEMENTS

Funding of this project was jointly supported by the Virginia State Water Control Board and the Virginia Institute of Marine Science through the Cooperative State Agencies program.

We thank the technical staff of the Division of Physical Oceanography of the Virginia Institute of Marine Science for their participation in the field study and data reduction. We would also like to express our appreciation to Mr. Robert Siegfried, formerly of the Virginia State Water Control Board, for providing the data from the EPA Chesapeake Bay monitoring program.

I. INTRODUCTION

The Rappahannock River is a major tributary of Chesapeake Bay (Figure 1). The tidal portion of the river extends 172 kilometers from the river mouth in a generally north-west direction to the 'fall line' at Fredericksburg (Division of Water Resources, 1970). The average tidal range at the mouth is 37 cm, increasing to 55 cm at Bowlers Rock (55 km upstream), decreasing slightly to 46 cm at Leedstown (99 km upstream) and increasing again to 85 cm at Fredericksburg (N.O.S., 1988). The tidal portion of the river drains an area of 2,613 km^2. The drainage area above the fall line is 4,120 km^2. The discharge ranges from 0.14 to 3,960 m^3/s, with an average flow of 47 m^3/s (USGS, Water Resources Data for Virginia, 1986).

The lowest portion of the Rappahannock River is a partially mixed estuary. The hydrodynamic characteristics are similar to those in other Chesapeake bay tributaries like the Potomac, York and James Rivers (Ulanowicz and Flemer, 1978). Fresh and salt water mix over a broad transition zone seaward of Tappahannock and stratification is relatively weak. Water movement in this estuary follows a two-layered pattern with a net seaward flow through the upper layer and net landward flow through the lower layer (Nichols, 1973). A sill is present at the mouth of the Rappahannock River and restricts water exchange with the bay.

Since the estuary empties into Chesapeake Bay, salinity in the estuary is moderated by the remoteness from the ocean and the effect of freshwater flow from other tributaries to the bay, especially the Susquehanna River.

A. Background

The dissolved oxygen concentration (DO) in an estuary is dependent on several physical and biochemical factors. The solubility of oxygen is influenced mainly by water temperature and salinity. In addition, turbulence affects atmospheric reaeration rates. Respiration by marine organisms and the decomposition of organic material exert demands on the available oxygen. Dissolved oxygen values in the Rappahannock estuary have shown a seasonal pattern from previous observations (Brooks, 1983). The highest values, around 10 mg/l, were reported during the winter seasons when low temperatures result in high oxygen solubility as well as reduced oxygen demand. The level of dissolved oxygen decreases through the spring and reaches a minimum in the summer when both temperature and salinity are high. The minimum value of 0.0 mg/l has been frequently observed in the deep waters near the river mouth during the summer season.

Aquatic organisms are highly dependent on the DO in the water column. In recent years a great concern has been devoted to the study of oxygen deficiency, i.e. hypoxic and anoxic conditions, and the identification of these areas in estuarine and coastal waters. Hypoxia is defined as a condition of reduced DO, while anoxia is defined as absence of dissolved oxygen. These conditions are more likely to occur in deep bottom water rather than surface water where oxygen is more readily available from the atmosphere. Seliger et al. (1985) have concluded that oxygen deficiency appears to have significant ecological impacts on aquatic organisms.

Despite the fact that Virginia's tributary estuaries have similar hydrodynamic characteristics, hypoxia has been observed frequently in the lowest reach of the Rappahannock and York Rivers but seldom in the corresponding portion of the James River. Kuo and Neilson (1987) reported that when water temperatures exceeded 20° C (typically May through September), DO below 5 mg/l were observed in about 95% of the 58 surveys (CSA program, slackwater surveys since 1971) in the Rappahannock, 75% of the 65 surveys in the York, but only 7% of the 60 surveys in the James. The hypoxic conditions appeared earliest and lasted longest in the Rappahannock. Furthermore, the minimum DO in the Rappahannock was less than 4 mg/l on all but one of the summer surveys.

B. Study Goals

There are several objectives to this study. The immediate objective is to collect a comprehensive and consistent set of field observations to better describe the hypoxic condition in the Rappahannock River. Other objectives can be classified as short and long term goals.

Long term

(1) Identify and quantify the processes contributing to the dissolved oxygen budget in deep waters, and explain the variabilities among the three Virginia major tributary estuaries.

(2) Provide information for resource management so that the James River can be protected from hypoxic problems and, perhaps, the problems in the York and Rappahannock Rivers can be alleviated.

Short term

(1) Is the hypoxic condition in the Rappahannock River just an extension of that in Chesapeake Bay, or does it originate locally within the river?

(2) Does the hypoxic condition in the Rappahannock River persist throughout the summer, or is there occasional oxygenation as observed in the York River?

II. FIELD SURVEYS AND DATA PRESENTATION

Field data for this study were collected during the summer season of 1987. Data collection can be divided into four major groups as follow:

A. Slackwater surveys.

B. Time-series measurements of dissolved oxygen, salinity and temperature.

C. Current measurements.

D. Tide measurements.

A. Slackwater Surveys

Since previous studies (Kuo and Neilson, 1987) have shown hypoxic conditions to exist only in the lower portion of the estuary and mostly during the summer season, June through September, all slackwater surveys covered this portion of the river and this period. A total of 13 slackwater surveys were conducted from 2 June to 14 September 1987 at a slack water phase of the tide, e.g. slack water before ebb (SBE), as it propagated upstream from the estuary mouth. During each survey, temperature, conductivity and dissolved oxygen measurements were taken at designated stations along the river, including one in Chesapeake Bay. Station locations for these surveys are shown in Figure 2. In this figure, station designation (e.g. 0.00, 9.80) refers to distance from the river mouth in kilometers. Station designation preceeded by letters (e.g CB6.1) refers to the Chesapeake Bay station. Stations for slackwater surveys are located at the deepest point of these transects.

Temperature and conductivity were measured with an Applied Micro System Conductivity-Temperature-Depth probe (CTD). Continuous vertical profiles, top to bottom, for these variables were obtained at each designated station. On the other hand, DO was measured using a probe made by Yellow Springs Instruments. Dissolved oxygen measurements were taken every meter from the surface to 15 meters depth, then measurements were taken every 2 meters until the bottom was reached.

Conductivity measurements were converted to salinities employing UNESCO algorithm (1983). Salinity, temperature and dissolved oxygen data for the river stations are displayed as isooconcentration contours in the vertical-longitudinal plane in Appendix A. A table listing the data for the bay station (CB-6.1) is also included in Appendix A.

B. Time Series Measurement of DO, Temperature and Salinity

1. Measurement with DO meters

Time-series measurements of temperature, conductivity and dissolved oxygen were taken at two stations, R0.0 and R16.6, by a Hydrolab DataSounde 1. Deployment depth at station R0.0 was 11.8 meters, while at station R16.6 they were deployed at mid-depth, 7.5 m, and at the bottom, 16.2 m. The meter was deployed at station R0.0 from 5 August to 2 September, during this period, it was repeatedly serviced, calibrated and then deployed for a period ranging from 7 to 10 days. Battery life and fouling restrict the deployment period. The meters at station R16.6 were not deployed until August 25 because of availability.

All meters were set to record temperature, conductivity and dissolved oxygen at half-hour intervals. Conductivity readings were converted to salinity following the procedure used for slackwater survey data. Errors in dissolved oxygen measurements are estimated by the manufacturer to be ± 5.0%. The highest DO observed was about 10.0 mg/l, and hence, an error of ± 0.5 mg/l is introduced. Since the largest instrument error possible from these observations is not more than 0.5 mg/l, it was decided to acknowledge the error introduced by the instrument in reading the DO values rather than correcting the raw data. Time series plots of DO, salinity and temperature data for station R0.0 are presented in Figures 3a, 3b and 3c respectively. The gaps shown in these figures represent the times at which the dissolved oxygen meter was being serviced. At station R16.6 only 8 days of data were retrieved because the meters broke loose from mooring after first service. Time series plots of DO, temperature and salinity at station R16.6 are presented in Figures 4 and 5 respectively for depths 7.5 and 16.2 m.

2. Measurement with S4 current meters

Time-series measurements of temperature, pressure and conductivity were also taken by the S4 meters deployed at station R0.0 and R16.6. Average values of all variables were recorded every 30 minutes. Conductivity readings were converted following the procedure as described previously for the slack water data. Tables 1 and 2 provide length of time-series and the depth at which temperature and salinity data were collected. Duration for these variables are the same as the current meter measurements described in the next section.

Time-series plots of the half hourly measurements are displayed in Figures 6 through 11. These time series data were then subjected to a low-pass (36 hour) filter to remove tidal and other high frequency signals. The non-tidal temperature and salinity fluctuations are also displayed in Figures 6 through 11.

C. Current Measurements

Current velocities were measured with in-situ, self recording meters that were deployed with taut wire moorings at station R0.0 and R16.6. Two types of current meters were used, the Ruz meter and the Inter-Ocean S4 meter. The Ruz meter is a modified Braincon Histogram meter, which measures current magnitude by a savonius rotor, with a vane attached for direction measurement. The original photographic recording system was replaced by solid state memory. These meters were set to record current direction and magnitude every 34 minutes.

The S4 meter is an electromagnetic type current meter with solid state memory. It is also equipped with temperature, conductivity and pressure sensors. The average values of all variables were recorded every 30 minutes.

At station R0.0, current velocities were measured at 3 depths. Two S4 meters were deployed near the surface, 1.20 m, a Ruz meter at 6.60 m and an S4 meter at 9.70 m. The two near surface S4 meters, i.e. meters # 746 and # 922, were deployed at the same depth consecutively. Meter # 746 was deployed first and later was replaced by meter # 922. A brief description of the mooring at station R0.0 is presented in Table 1. At station R16.6, a total of five current meters, three S4 and two Ruz meters, were deployed. Table 2 provides information describing station R16.6

Table 1, Mooring at station R0.0

Meter #	Depth (meter)	starting time	ending time	speed	direction	temp	cond
S4#746	1.20	0919 8/03/87	1219 8/21/87	X	X	X	X
S4#922	1.20	1302 8/21/87	1032 9/02/87	X	X	X	X
Ruz#258	6.60	1021 8/3/87	1940 9/02/87	X	X	-	-
S4#786	9.70	0946 8/03/87	1516 9/02/87	X	X	X	X

X = indicates that variables have been measured.

\- = indicates that no measurement of such a variable took place.

Table 1, Mooring at station R0.0

Meter #	Depth (meter)	starting time	ending time	speed	direction	temp	cond
S4#746	1.20	0919 8/03/87	1219 8/21/87	X	X	X	X
S4#922	1.20	1302 8/21/87	1032 9/02/87	X	X	X	X
Ruz#258	6.60	1021 8/3/87	1940 9/02/87	X	X	-	-
S4#786	9.70	0946 8/03/87	1516 9/02/87	X	X	X	X

X = indicates that variables have been measured.

\- = indicates that no measurement of such a variable took place.

Table 2, Mooring at station R16.6

Meter #	Depth (meter)	starting time	ending time	speed	direction	temp	cond
S4#789	1.20	1127 8/03/87	0957 8/30/87	X	X	X	X
RUZ#269	5.90	1134 8/03/87	1456 9/03/87	X	X	-	-
S4#749	10.00	1053 8/03/87	1053 9/03/87	X	X	X	X
RUZ#316	13.90	1215 8/03/87	0241 9/03/87	X	X	-	-
S4#747	18.70	1054 8/03/87	0850 9/03/87	X	X	X	X

X = indicates that variables have been measured.

\- = indicates that no measurement of such a variable took place.

Current speeds and directions obtained from all Ruz meters were unsatisfactory. Visual inspection and comparison with measurements from nearby S4 meters indicate either unreliable data or very short length of reasonable data, i.e. less than 6 days. Hence, all Ruz meters are excluded from analyses.

Current velocities measured with the S4 meters are presented as stick plots in Figures 12 and 13 respectively for stations R0.0 and R16.6. Data obtained from each current meter were analyzed to determine the principal axis of the flows, i.e. the dominant direction of ebb and flood flows at that location. Figures 14 and 15 present polar plots for current data at each station with direction of principal axis indicated. Each point in the plot represents the magnitude and direction of a half-hourly current measurement. An axis along the direction of the principal axis is the natural choice as the principal axis of a coordinate system for any further current data analysis. The procedure to determine the principal axis direction, α, is done by resolving velocity data into the east-west component, u, and the north-south component, v. At each station, an angle α was determined by the following equation.

$$\alpha = 0.5 \tan^{-1} \left(\frac{2 \, \overline{u \cdot v}}{\overline{v^2} - \overline{u^2}} \right)$$

in which the over bar represents averaging over all data points.

The angle α represents the direction along which the sum of absolute values of velocity components from all data points attains maximum. This direction would be the direction of the principal axis if flood and ebb flows are diametrically opposed. In order to justify such an assumption, data points were split into two groups by a line perpendicular to the direction of angle α. From these two data groups two angles, α_e and α_f, were determined separately employing the same equation with each group. The resulting two directions represent the direction of ebb and flood flows. Since the difference between these two angles and the principal direction was less than 5 degrees in all cases, implying that the ebb and flood flows are almost diametrically opposed to each other, the principal direction was taken as the longitudinal axis for a coordinate system for further current analysis.

The time series plots of the longitudinal velocity component are presented in Figures 16 and 17 respectively for station R0.0 and R16.6. The time series data of the longitudinal velocity component were then subjected to a low-pass filter with a 1/36 hour cut-off frequency. This process removes the tidal current and currents of higher frequency. These results are presented in Figures 16 and 17.

D. Tide Measurements

Three tide gauges were installed during this study at the locations shown in Figure 2. Tide gauges were maintained at Deltaville and Urbanna from July 22 to September 8, and at Tappahannock from August 18 to September 8. Tidal heights were recorded every six minutes. These raw data were then converted to hourly tidal elevations. Time series of hourly tidal heights are displayed in Figures 18 through 20. These time series data were then subjected to a low-pass (36 hour) filter to remove tidal and other high frequency signals. The non-tidal water surface fluctuations are presented in Figures 18 through 20. Tide heights at Deltaville have been adjusted such that the heights are relative to NGVD (National Geodetic Vertical

Datum). Since the other two gauges, Urbanna and Tappahannock, were not surveyed, the heights were adjusted to mean tide level during the period of measurements.

III. DATA INTERPRETATIONS AND RESULTS

A. Hydrographic Conditions

The freshwater discharge in the Rappahannock River was lower than normal during summer 1987. The monthly mean flows at the fall line were 22.8, 7.3 and 4.4 m^3/s respectively for June, July and August, well below the long-term means of 35, 25 and 32 m^3/s respectively. In particular, the flows in July and August were so low and steady that they did not contribute to the variabilities in water circulation and salinity stratification in the saline portion of the river. The hydrographic conditions described in the following were mainly influenced by tide, wind and the conditions in the bay.

All time series data of current velocity and surface elevation contain a strong semi-diurnal component associated with the astronomical tide (Figures 16-20); the tidal amplitude varied fortnightly through the spring-neap cycle. The data also show that spring tides alternate between stronger and weaker amplitudes, implying that strongest mixing occurred on a 29-day interval.

The sub-tidal component of surface elevation was of the same order of magnitude as the tidal component (see Figures 18-20). The sub-tidal component varied on time scales ranging from two to ten days, and mainly was forced by meteorological conditions. The sub-tidal currents were much smaller than tidal currents and less than 10 cm/s most of the time (Figures 16 and 17). Despite being variable in time, the sub-tidal currents show outflow near the surface and inflow near the river bottom, a circulation pattern characteristic of coastal plain estuaries. At the river mouth the net velocity averaged over record lengths was 0.0 and -6.2 cm/s at 1.2 and 9.7 m depths respectively where positive value designates downriver direction. The net velocity at 16.6 km upriver was 2.9, -3.0 and -3.7 cm/s respectively at depths of 1.2, 10 and 18.7 m. These imply that the water mass at the river bottom originated mainly from the bay.

The salinity and temperature time series (Figures 3-11) show a significant semi-diurnal component induced by the tide, however, the magnitude of these variations were much smaller than longer-term sub-tidal variations. As seen in Figures 6-11, the sub-tidal component has time scales ranging from two to ten days, with longer time scale variations dominant. Since the source of salinity in the river is the bay, this implies that the mechanisms of bay-tributary interaction are highly variable.

B. Real-Time DO Variations

Three sets of DO time series data, measured at half hourly intervals, are available. The data from the bottom water at the river mouth are presented in Figure 3a. Because there are data gaps when the instrument was retrieved for service and cleaning, no low-pass filtering of the data was performed. The figure indicates that the magnitude of semi-diurnal tidal variations may be as big as the sub-tidal variations, especially during periods of lower DO. Therefore, the phase of the tide selected for slackwater surveys would have significant effect on the data at this location. Any results derived from slackwater survey data should be treated with caution.

Because of the problem of instrument calibration, only eight days of DO data are available at station R16.6. These data are presented in Figures

4a and 5a respectively for DO at mid-depth and near bottom. There was little sub-tidal variation at mid-depth where DO was above 5 mg/l most of the time. On the contrary, DO in the bottom water had a decrease of about 2 mg/l starting August 29, following the trend that occurred about three days earlier at the river mouth (Figure 3a). Figure 5a also indicates that the tidal variation of DO in the deep basin is of the order of 0.5 mg/l. Therefore, the tidal phase of slackwater surveys would have little effect on the data.

C. Spatial Extent of Hypoxic Condition

There is no widely accepted quantitative definition of hypoxia: DO below 5 mg/l is considered hypoxic for the purpose of the following discussions. The Commonwealth of Virginia has adopted water quality standards of 5 mg/l daily average with no observation below 4 mg/l in estuarine waters. Many other states have comparable standards. Additionally, all of the slackwater survey data are daytime DO values, which are higher than the daily average in general. Thus, 5 mg/l is a reasonable quantitative definition from the water quality management standpoint.

A total of 13 slackwater surveys were conducted from 2 June to 14 September 1987. The data are presented as constant value contours of dissolved oxygen, salinity and temperature in a vertical-longitudinal plane along the river axis in the Appendix. The 5 mg/l DO contour was highlighted in these figures. Comparison of these figures with those of previous years suggests that the spatial extent of the hypoxic condition in 1987 was more widespread than in the past. The hypoxia existed in the lower portion of the water column and extended upriver from the mouth beyond the station at km 58, where the water depth is less than 8 m. The hypoxic waters were never observed to reach the water surface, however, they often occupied more than half of the water column. In early summer, the most severe DO condition occurred on the sloping bottom between km 40 and 50, where anoxic conditions existed. The location of minimum DOs progressed downriver until it reached the bottom waters around km 30 in the middle of July and remained in that region for the rest of the summer.

In the segment of the river downstream from km 46 where the river deepens sharply, hypoxia was observed in each of the 13 surveys at all stations except that at the mouth. The station at the river mouth is only 13 m deep and there bottom DO was above 5 mg/l on some surveys. Furthermore, continuous monitoring of bottom DO at the river mouth from 5 August to 2 September (Figure 3a) indicates that it exceeded 5 mg/l more than 50% of the time. On the contrary, the bottom DO at the station in the bay was observed to be below 5 mg/l at every survey throughout the summer.

D. Temporal Variation of Hypoxic Condition

Some differences in DO distribution between times of spring and neap tides are evident in the figures presented in Appendix. The DO distribution during neap tide (e.g. June 4, July 8 and Aug. 4) was highly stratified throughout this lower portion of the estuary, while some degree of vertical mixing occurred soon after spring tide (e.g. June 18, July 16 and Aug. 17). Tidal mixing during spring tides was strong enough to completely mix the water at the river mouth, however, the mixing of water in the deep basin was limited so that the vertical gradient of DO remained strong.

The effect of periodic intense mixing by spring tides can be demonstrated much clearer with constant value contours of DO and salinity in a depth-time plane. Figures 21 to 24 depict the time history of the vertical distributions of DO and salinity at four stations: one at the river mouth, two at the deep basin inside the river, and one in the bay off the river mouth. Reoxygenation of bottom water following spring tides was evident at station R0.0, the river mouth (Figure 21a). Dissolved oxygen concentrations became fairly uniform (5 to 6 mg/l) throughout the water column at roughly monthly intervals after the stronger spring tide. In the period between spring tides, bottom DO dropped to as low as 2 mg/l, while surface DO increased to 8 mg/l. Salinity distribution (Figure 21b) also underwent the destratification-stratification cycle following the spring-neap cycling. One exception occurred in the period between 20 and 30 August when both DO and salinity distributions failed to restratify during neap tide before the 24 August survey. Mixing by strong winds on 22 and 23 August may offer the explanation. Only a partial reoxygenation of bottom waters was observed at stations inside the river (Figures 22a and 23a), and none at the station in the bay (Figure 24a). Hypoxic conditions existed in bottom waters of the deep basin and the bay continuously from May to September. Figures 22b, 23b and 24b also show that the mixing by spring tides was not strong enough to eliminate salinity stratification at these locations.

To present the temporal variation of the overall DO condition in the deep basin, a quantity is defined to represent spatial extent of hypoxic condition as percentage of water column with DO less than 5 or 2 mg/l. The total water area of the vertical plane along the river axis from river mouth to 60 km upriver is 8.47×10^5 m^2, obtained from figures in the Appendix. The areas with DO less than 5 and 2 mg/l respectively were calculated for each DO contour plot, and expressed in terms of percentages of total water area. The percentages were plotted as a function of time in Figure 25. It is to be noted that these values so obtained only serve to provide relative quantities to demonstrate temporal variation. Because of the non-uniform depth variation across the river and the lack of information on the transverse variation of DO, these values represent only a rough estimate of the volume of hypoxic waters.

The hypoxic condition first appeared at the upriver end of the deep basin around late April (Figure 23a), about 20 days before it was first observed at the bay station (Figure 24a). By early June, 68% of the water column in the deep basin became hypoxic and 28% of water column had DO below 2 mg/l. Figure 25 shows that there were short-term variations superimposed on the longer-term seasonal trend. The short-term variations were the result of periodic intense mixing during the spring tide period, which temporarily reduced the spatial extent of hypoxic waters. Except for these temporary reductions, the spatial extent of hypoxic condition was relatively constant in June and July and then started to decrease in early August.

E. Bay-Tributary Interaction

A quantitative assessment of the effect of the hypoxic condition in the bay on that in the Rappahannock River can be made only from the measurement of DO flux through the transect at the river mouth. This requires simultaneous measurements of DO and current velocity at 10 or more sampling points in the transect at time intervals on the order of an hour. The amount of field work involved was beyond the scope of this study.

As a first attempt, a self recording DO meter was deployed near the bottom of the station at the river mouth. Dissolved oxygen was measured at half hour intervals for about one month while current velocity was measured. As a reference, the mid-depth and bottom DO at station R16.6 were also measured, however, the measurements lasted for less than 10 days because of instrument calibration problems. Figures 3 to 5 present the DO time series. Figure 3a shows that DO was highly variable at the river mouth, implying that the bay-tributary interaction was very dynamic. The DO stayed above 5 mg/l most of the time, and dropped to the 2 to 5 mg/l range for periods lasting 2 to 3 days. On the contrary, the DO of the bottom waters in the deep basin (Figure 5a) was much less variable. It stayed hypoxic continuously for the 9-day period when the data were available.

The net estuarine circulation transports water into the estuary along the bottom and out of the estuary near the surface. Figure 16 shows that though the sub-tidal (low-pass filtered) current at the bottom of the river mouth was variable, it was directed into the river most of the time. On the other hand, Figure 3a indicates that the intrusion of hypoxic bay water into the river might occur only during the several brief periods when bottom DO at the mouth dropped below 5 mg/l. These periods lasted only about two to three days at each occurrence. This implies that the water mass transported into the river has distinct properties at different times, perhaps from different origins in the bay.

Some characteristics of bay-tributary interaction may be inferred from the examination of time series data of DO, salinity and velocity at the bottom of the river mouth. It is apparent from Figures 3a and 3b that there was a strong correlation between DO and salinity. During the several brief periods when DO dropped below 5 mg/l, there were corresponding increases in salinity. Comparison of Figures 3a and 16b further shows that these low DO, high salinity waters always arrived at the river mouth when the net upriver circulation was particularly strong, 10-20 cm/s. On the other hand, the upriver net circulation did not always bring in water with low DO. It may be concluded that the transport of hypoxic waters from the bay into the river is an intermittent phenomenon.

With the data from the simultaneous measurements of current velocity and DO, the average DO of the water transported into the Rappahannock was calculated to be 5.1 mg/l. This was about 2 mg/l below saturation value, and yet about 2 mg/l or more above the bottom water DO in the river. Therefore, the hypoxic condition in the deep basin of the river was more locally driven than just an extension of that in Chesapeake Bay. The same conclusion may be drawn by comparing the timing and degree of DO depression at the bay station (Figure 24a) and those at stations in the river (Figures 22a and 23a). The bottom DO in the river dropped below 2 mg/l around 10 May while that in the bay maintained above 2 mg/l until mid-June. Anoxia occurred in the river, but was not observed in the bay off the mouth of the river.

CONCLUSIONS

Hypoxia, a condition where dissolved oxygen concentrations are less than 5 mg/l, was observed to exist in the deep basin (from river mouth to 46 km upriver) of the lower Rappahannock estuary as early as April. It first occurred on the sloping bottom at the upriver end of the deep basin, where the water became anoxic in early summer. Although hypoxic water often occupied a major portion of the water column, it never reached the water surface. Dissolved oxygen in the deep basin remained depressed throughout the summer despite the periodic decrease in the spatial extent of hypoxic water resulting from stronger mixing by spring tides.

The net estuarine circulation transports water into the estuary along the bottom and out of the estuary near the surface. Time series data measured at the bottom of the river mouth indicate that the DO of the water transported from the bay into the river was highly variable. In addition to intratidal fluctuations, it also fluctuated widely at sub-tidal time scales. The tidal average DO at the bottom of the river mouth stayed above 5 mg/l most of the time in August 1987 when time series data were taken. It dropped to an average of about 3 mg/l for several brief periods, each lasting about 2 to 3 days. These periods of low DO coincided with periods of higher salinity and stronger upriver circulation. This implies that the transport of hypoxic bottom water from the bay into the river was intermittent.

The average DO of the water entering the river along its bottom in August 1987 was calculated to be 5.1 mg/l. This was 2 mg/l or more above the DO of bottom water in the river. Therefore, the hypoxic condition in the deep basin of the river was more locally driven than being an extension of that in the bay. Anoxia was observed in the deep basin, while not at the station off the river mouth in the bay.

REFERENCES

Brooks, T. J. 1983, Rappahannock river slack water data report, temperature, salinity and dissolved oxygen 1970-1980 data report # 18. Virginia Institute of Marine Science, Gloucester Point, Virginia.

Division of Water Resources, Virginia Department of Conservation and Economic Development. 1970. Rappahannock River Basin Comprehensive Water Resources Plan. Volume 1 - Introduction. Planning Bulletin 219. Richmond, Virginia.

Kuo, A. Y. and B. J. Neilson. 1987. Hypoxia and salinity distributions in Virginia estuaries. Estuaries, Vol. 10, No 4.

National Ocean Survey, National Oceanic and Atmospheric Administration. 'Tide Tables', 1988. U.S. Government Printing Office.

Nichols, M. and G. Thompson. 1973. Development of the turbidity maximum in a coastal plain estuary. Special Scientific Report 75, Virginia Institute of Marine Science, Gloucester Point, Virginia

Seliger, H. H., J. A. Boggs, and J. A. Biggley. 1985. Catastrophic anoxia in the Chesapeake Bay in 1984. Science 228:70-73.

Ulanowicz, R. E. and D. A. Flemer. 1978. A synoptic view of a coastal plain estuary. In: J. Nihoul, ed., Hydrodynamics of Estuaries and Fjords, Elsevier, Amsterdam, p. 1-26.

United Nations Educational, Scientific and Cultural Organization. 1983. UNESCO Technical Papers in Marine Science, 44.

U.S. Geological Survey. 1986. Water Resources Data for Virginia Water Years 1970-1981. Richmond, Virginia.

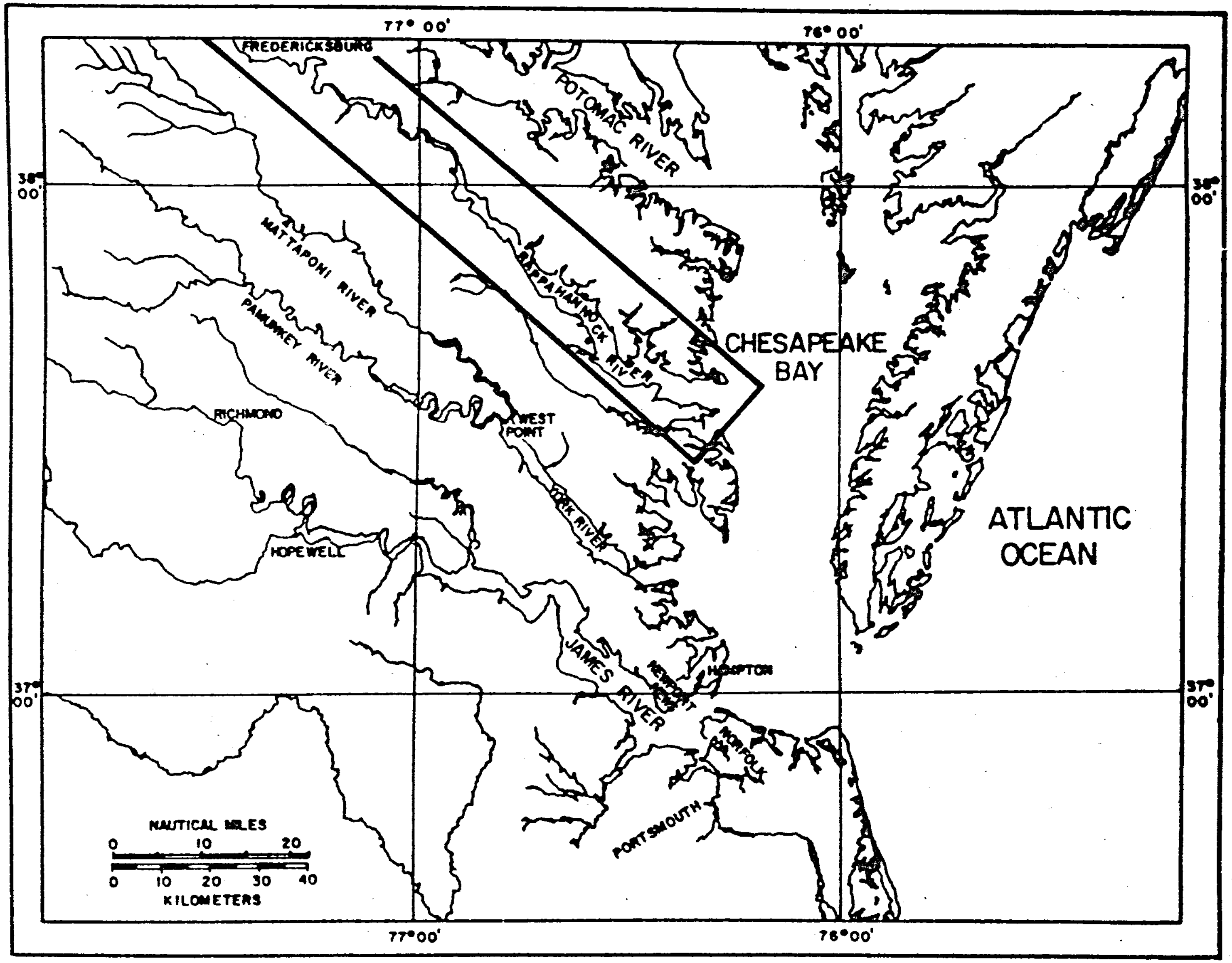


Figure 1. Map Locating the Rappahannock River Within Virginia

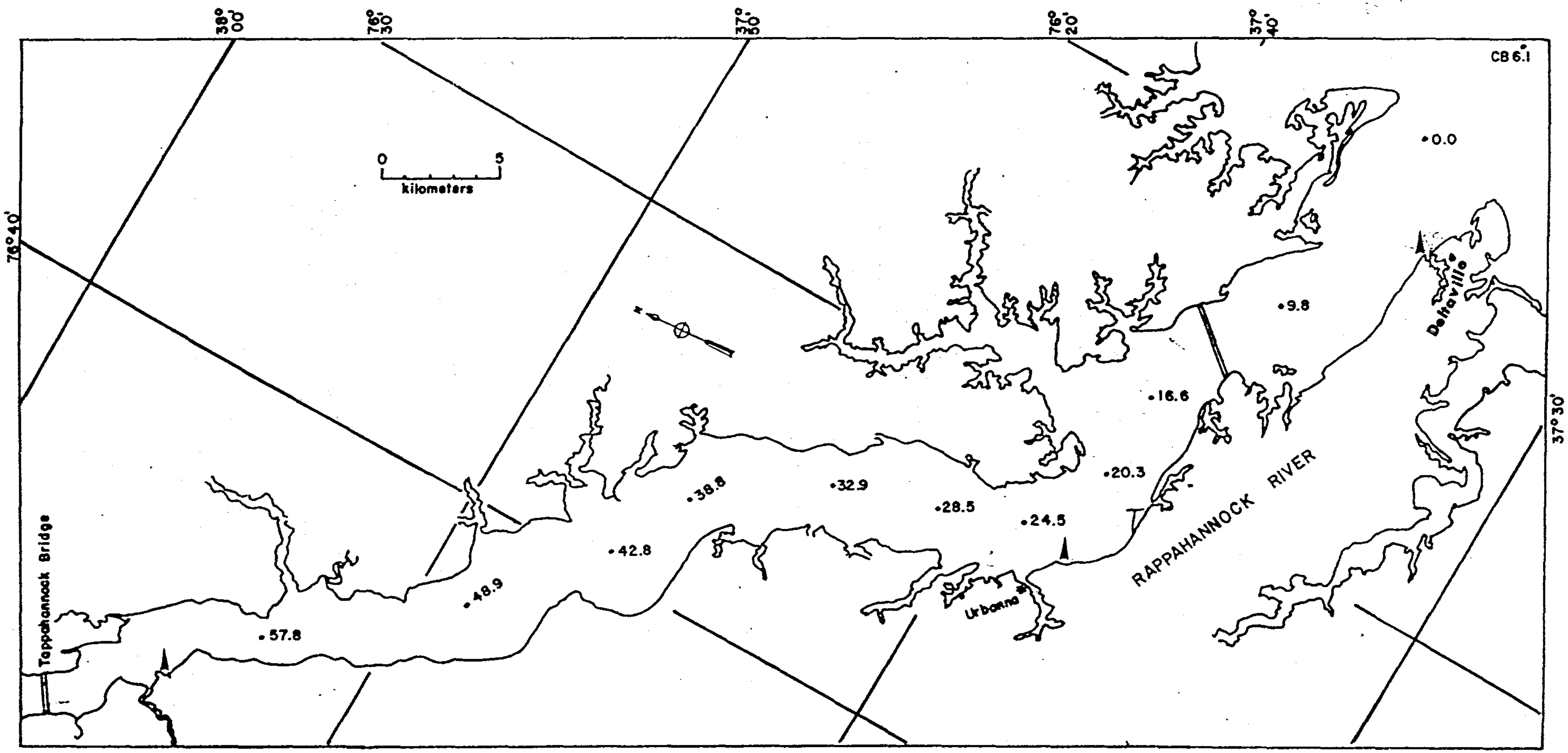


Figure 2. Sampling stations for slackwater surveys (the station designations are distances from river mouth in kilometers, ▲ designates tide gauge location).

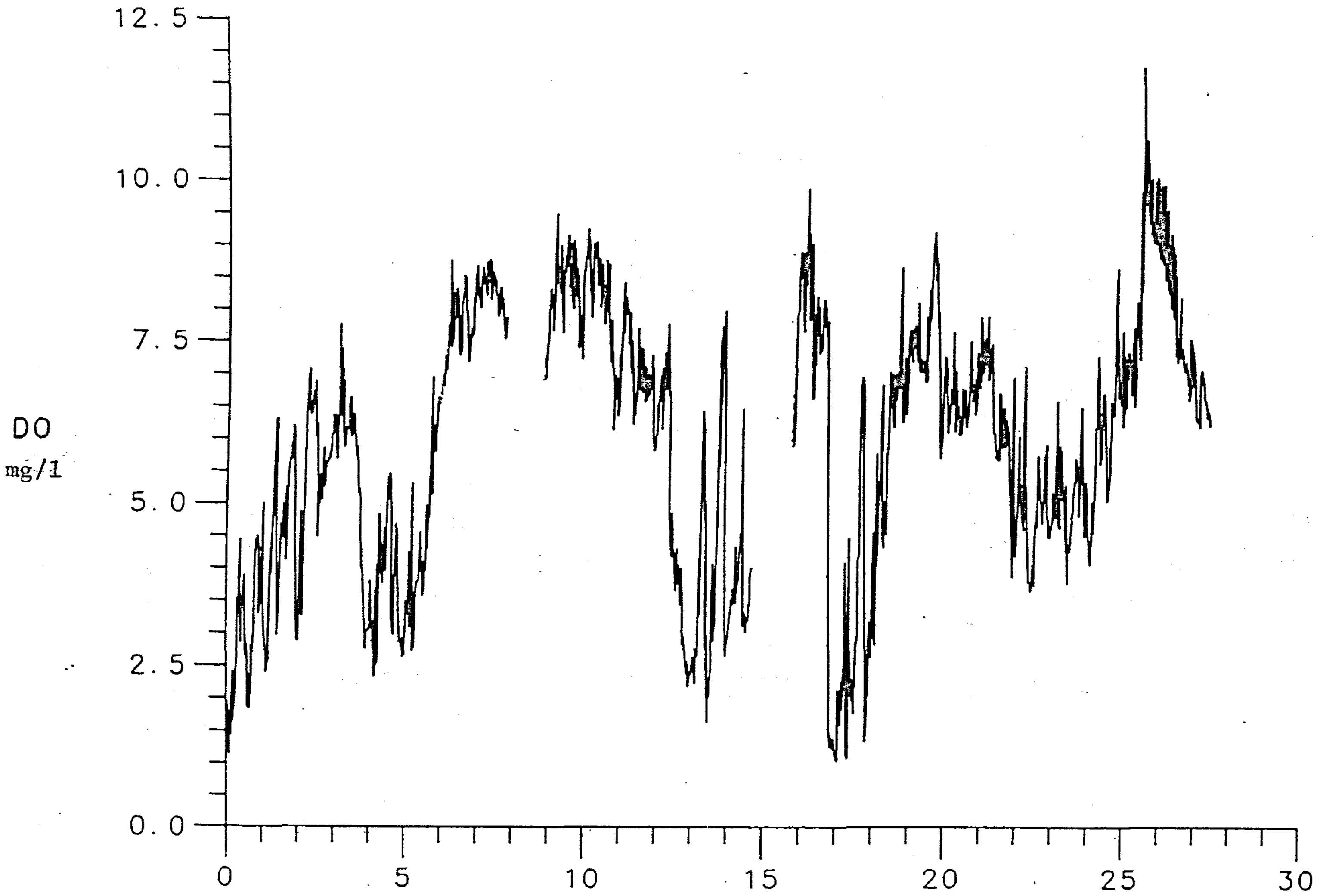


Figure 3a. Dissolved oxygen concentration at station R0.0, depth 11.8 m (1130 hr, 5 August to 2 September 1987).

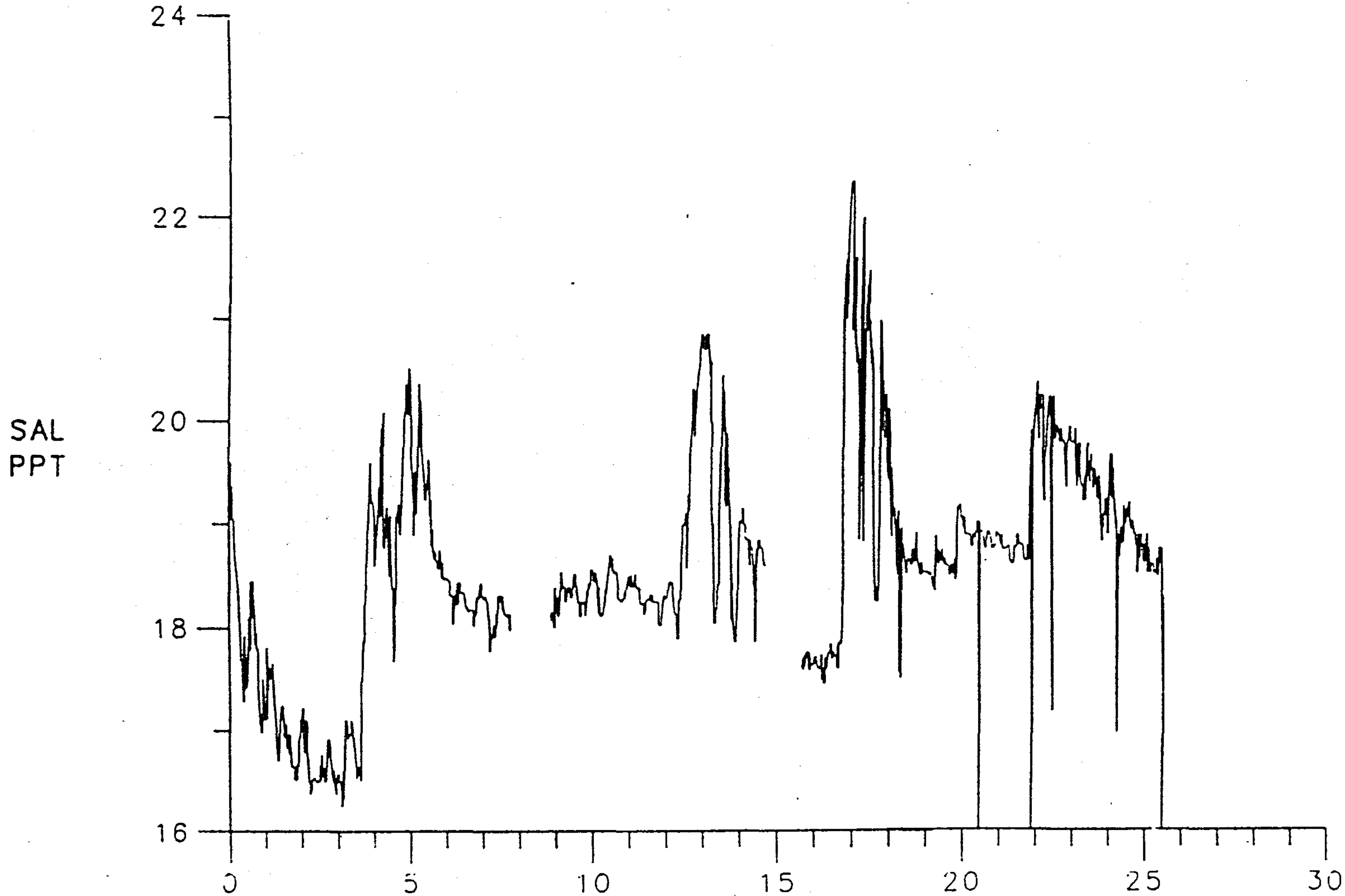


Figure 3b. Salinity at station R0.0, depth 11.8 m (1130 hr, 5 August to 2 September 1987).

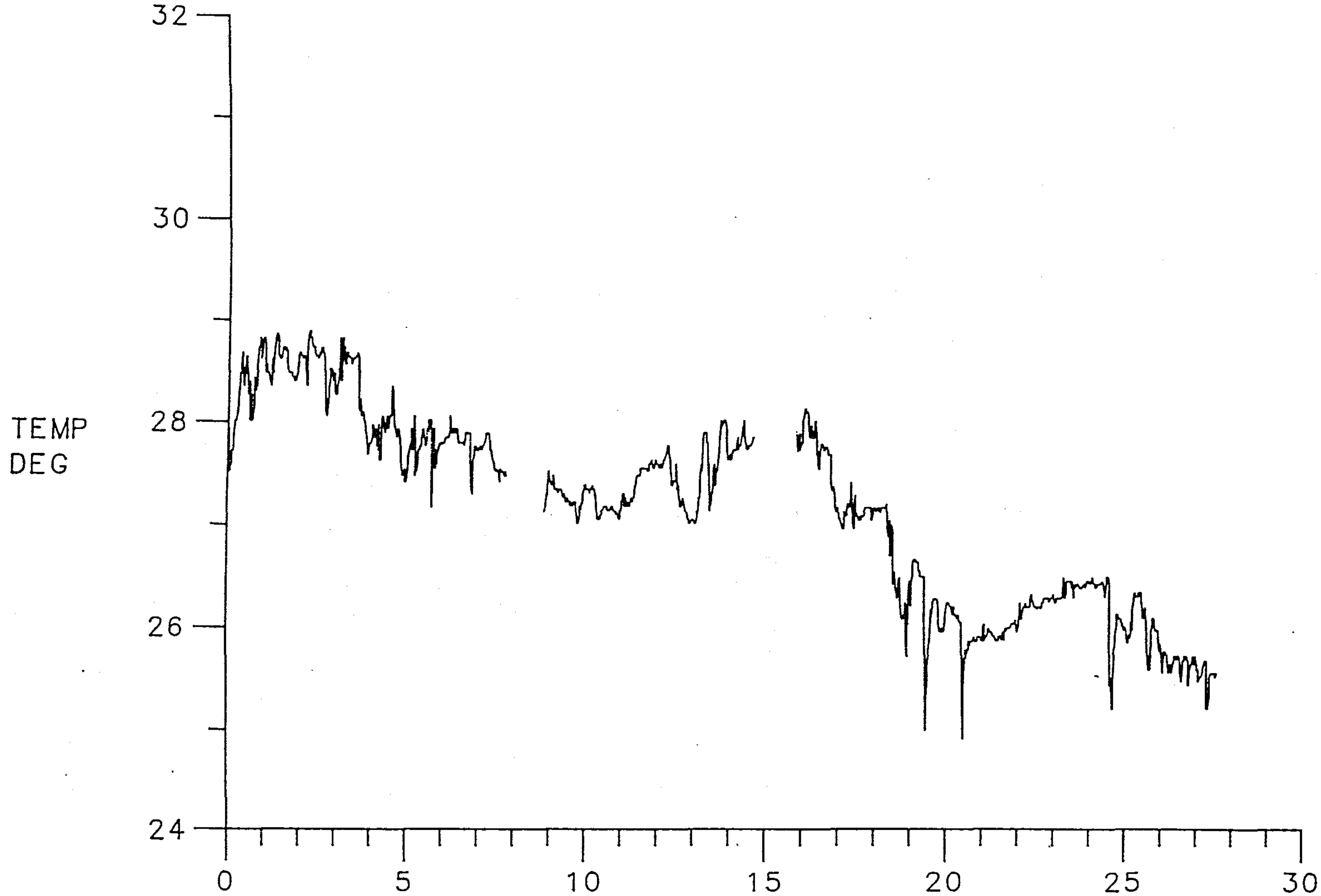


Figure 3c. Temperature at station R0.0, depth 11.8 m (1130 hr, 5 August to 2 September 1987).

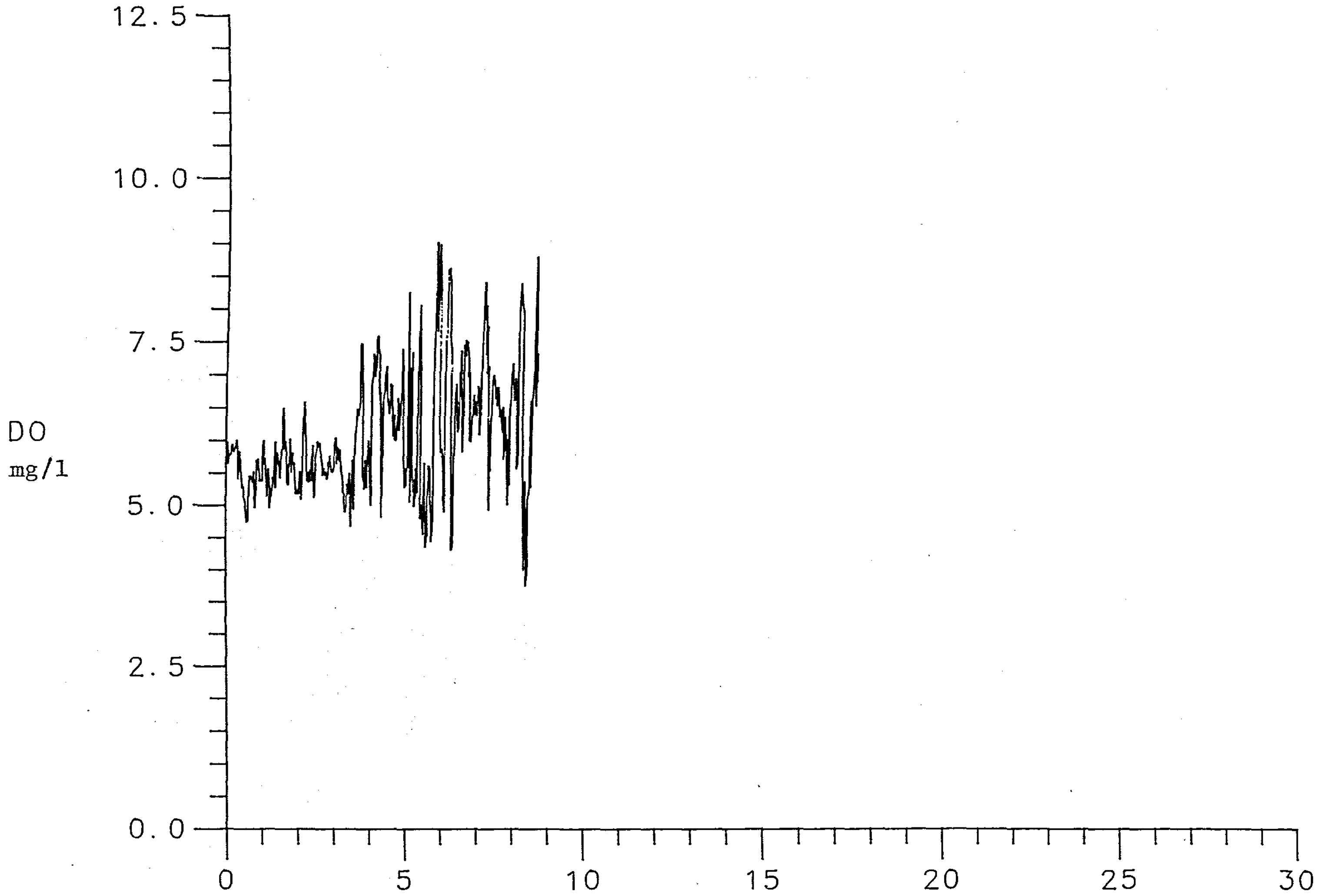


Figure 4a. Dissolved oxygen at station R16.6, depth 7.5 m (1330 hr, 25 August to 3 September 1987).

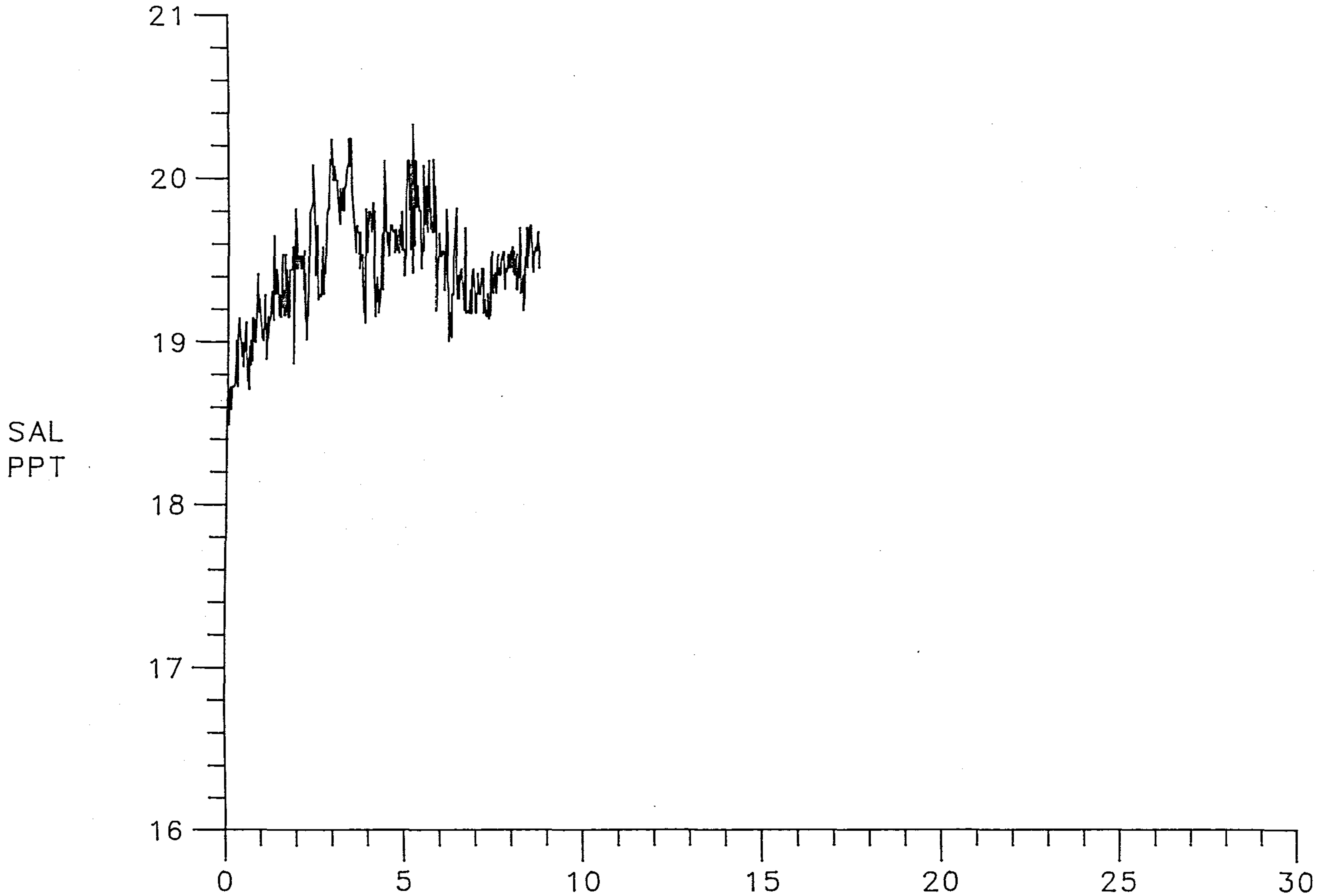


Figure 4b. Salinity at station R16.6, depth 7.5 m (1330 hr, 25 August to 3 September 1987).

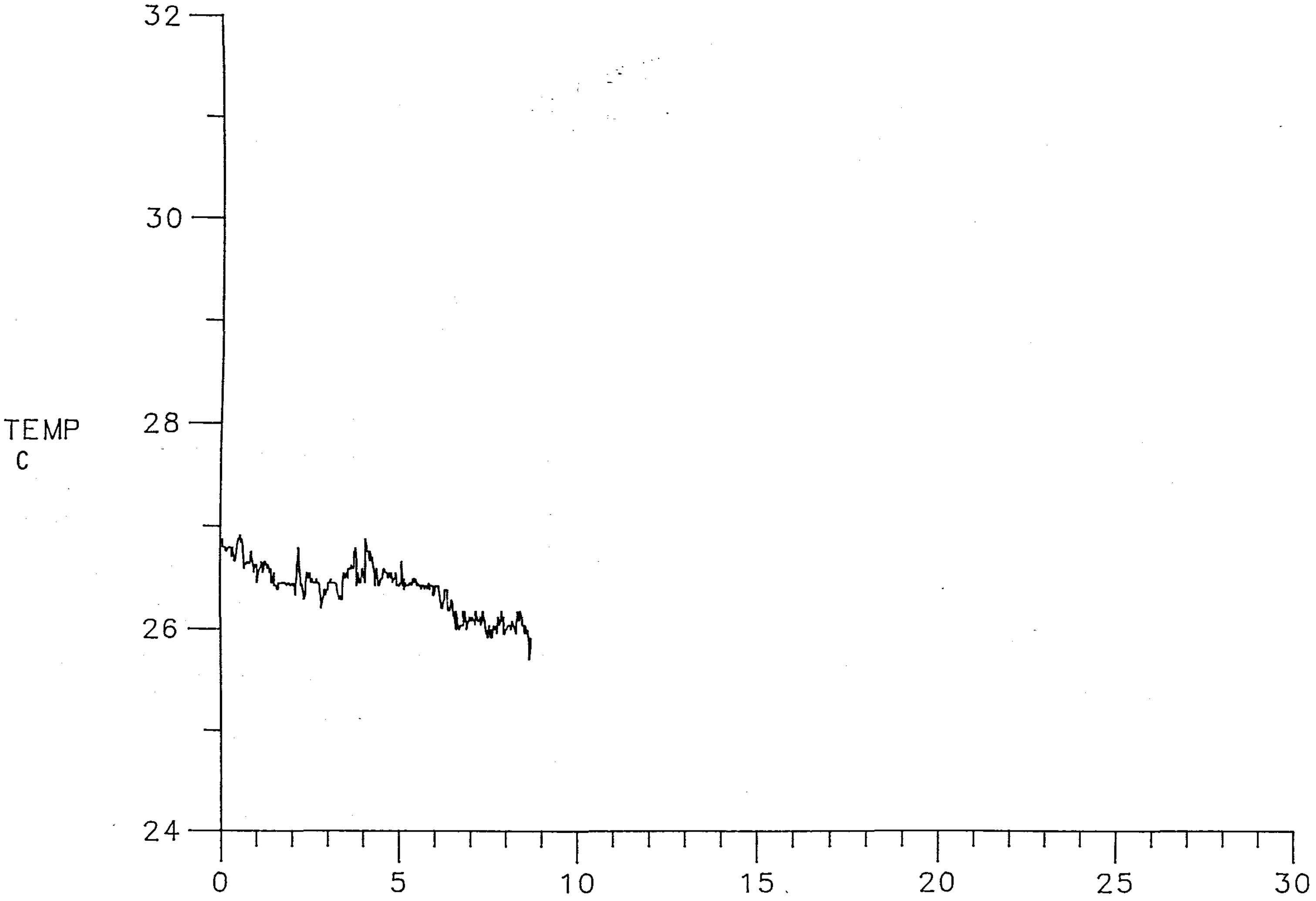


Figure 4c. Temperature at station R16.6, depth 7.5 m (1330 hr, 25 August to 3 September 1987).

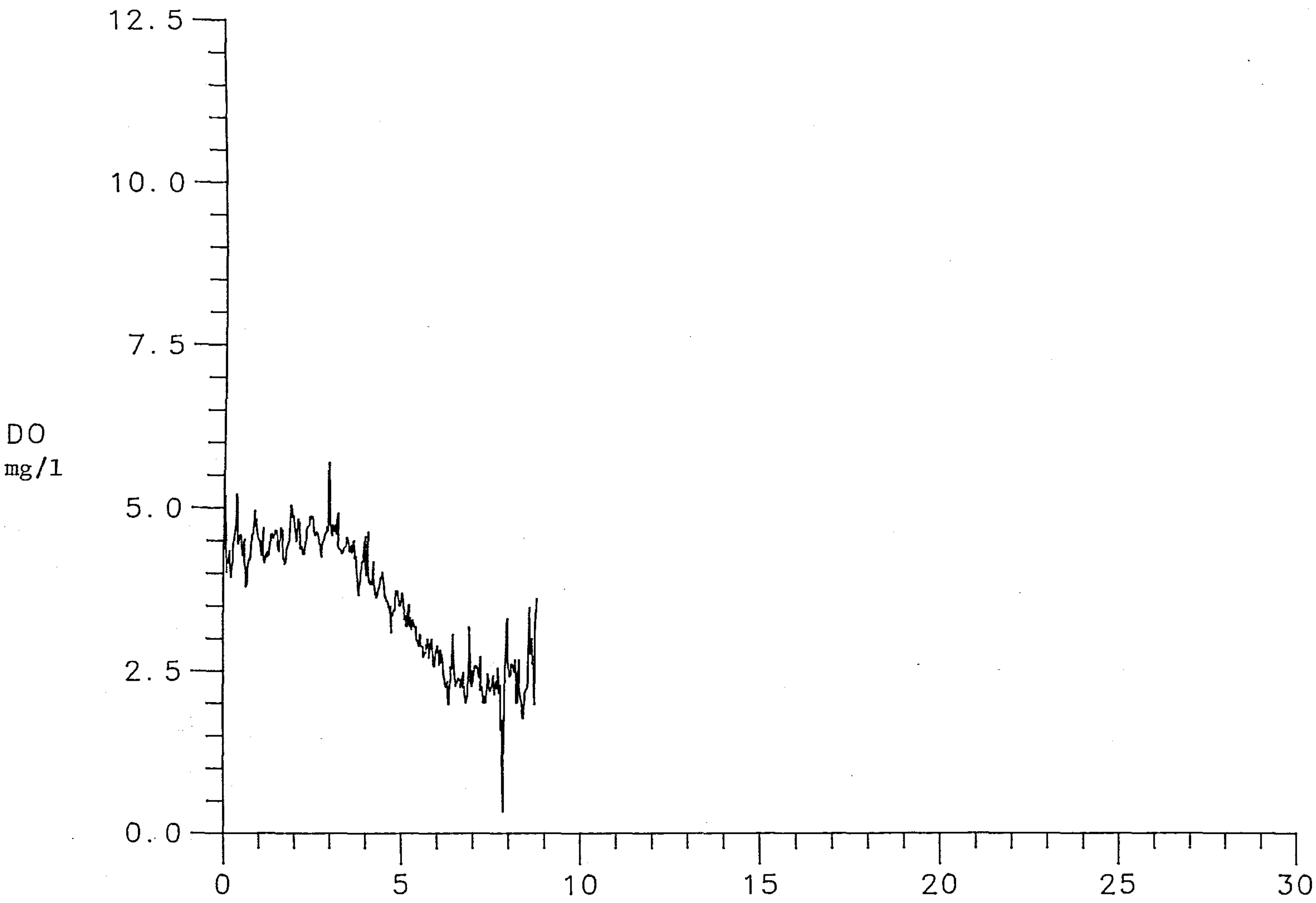


Figure 5a. Dissolved oxygen concentration at station R16.6, depth 16.2 m (1330 hr, 25 August to 3 September 1987).

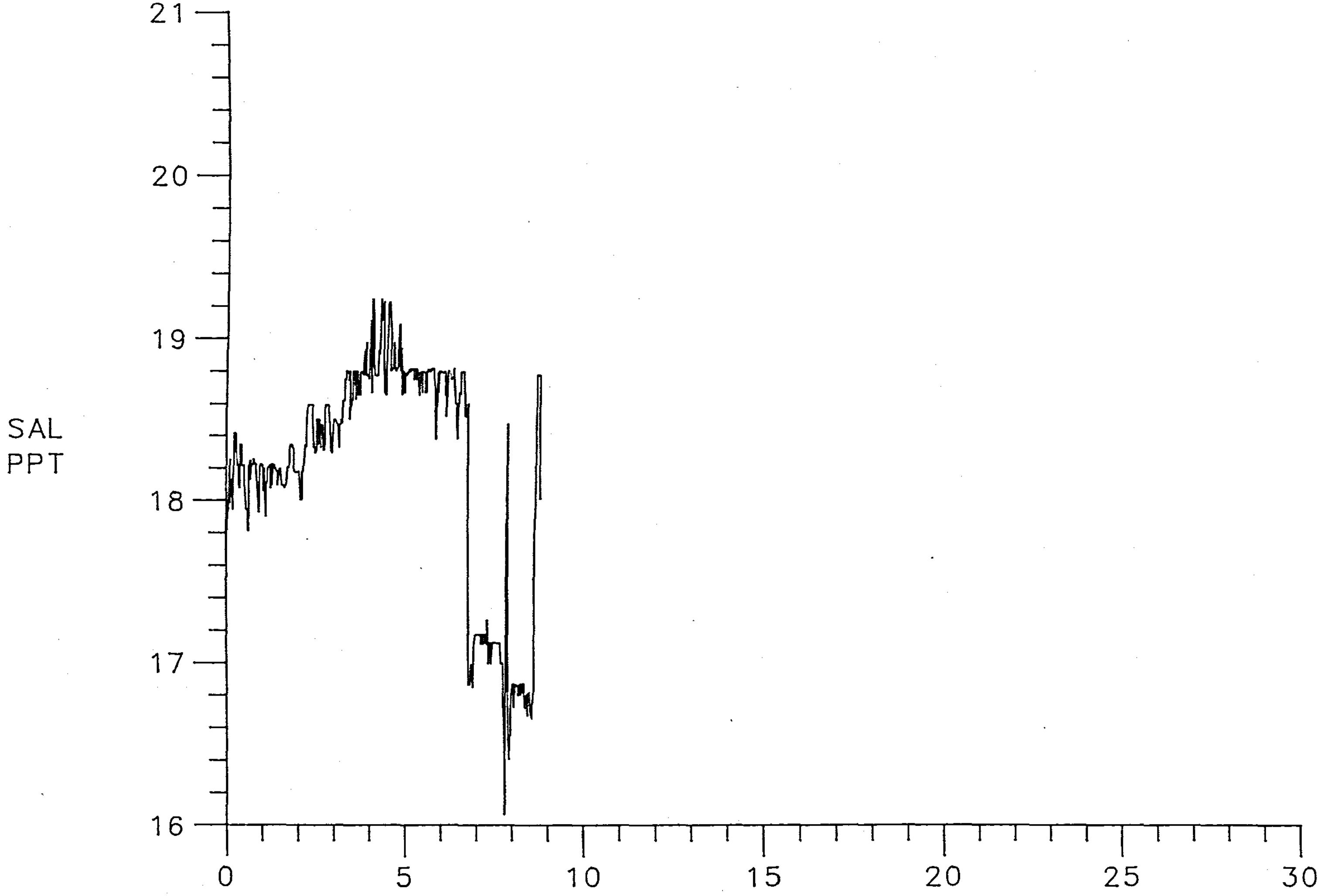


Figure 5b. Salinity at station R16.6, depth 16.2 m (1330 hr, 25 August to 3 September 1987).

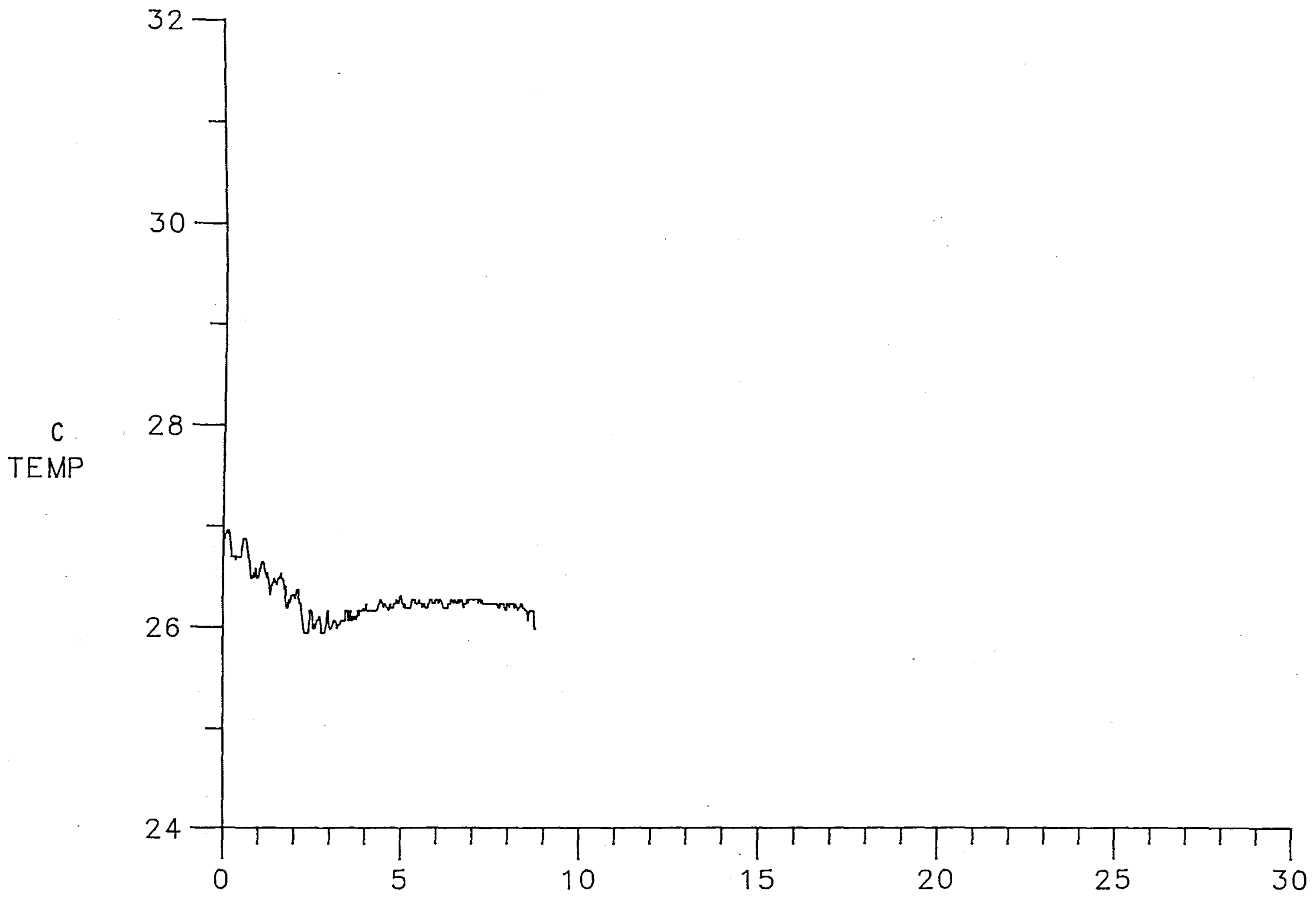


Figure 5c. Temperature at station R16.6, depth 16.2 m (1330 hr, 25 August to 3 September 1987).

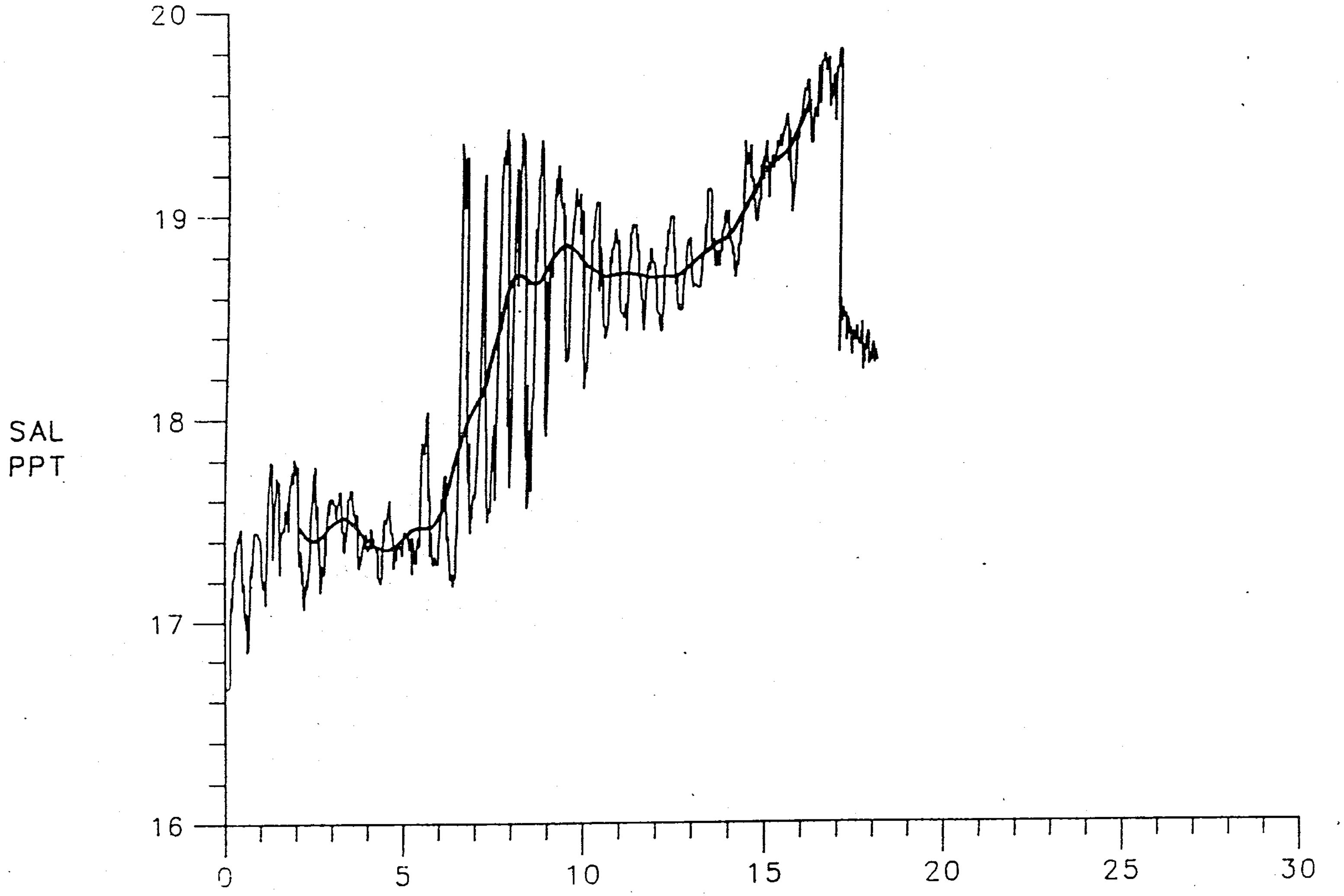


Figure 6a. Salinity at station R0.0, depth 1.2 m (0919 hr, 3 August to 21 August 1987, meter # 746).

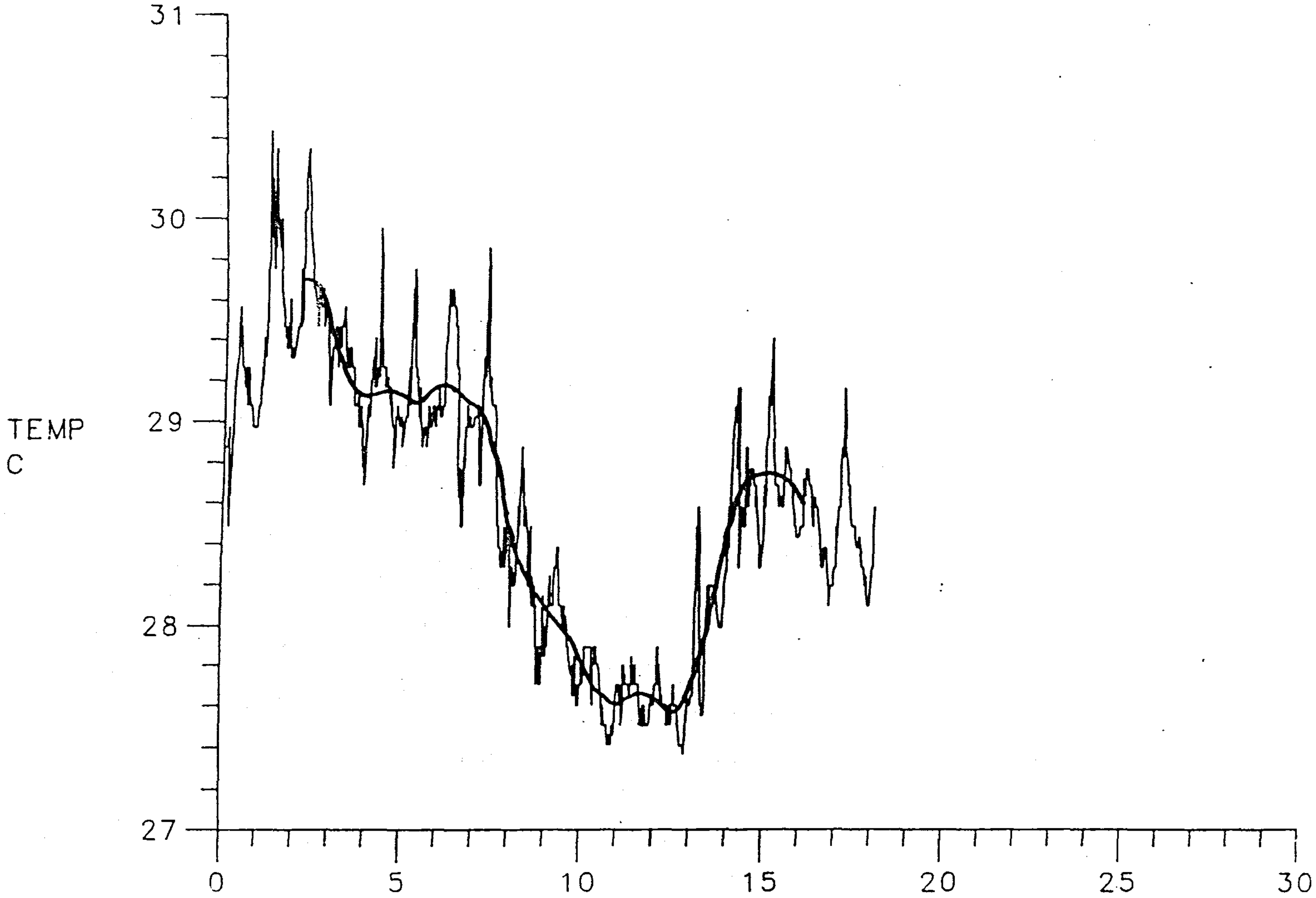


Figure 6b. Temperature at station R0.0, depth 1.2 m (0919 hr, 3 August to 21 August 1987, meter # 746).

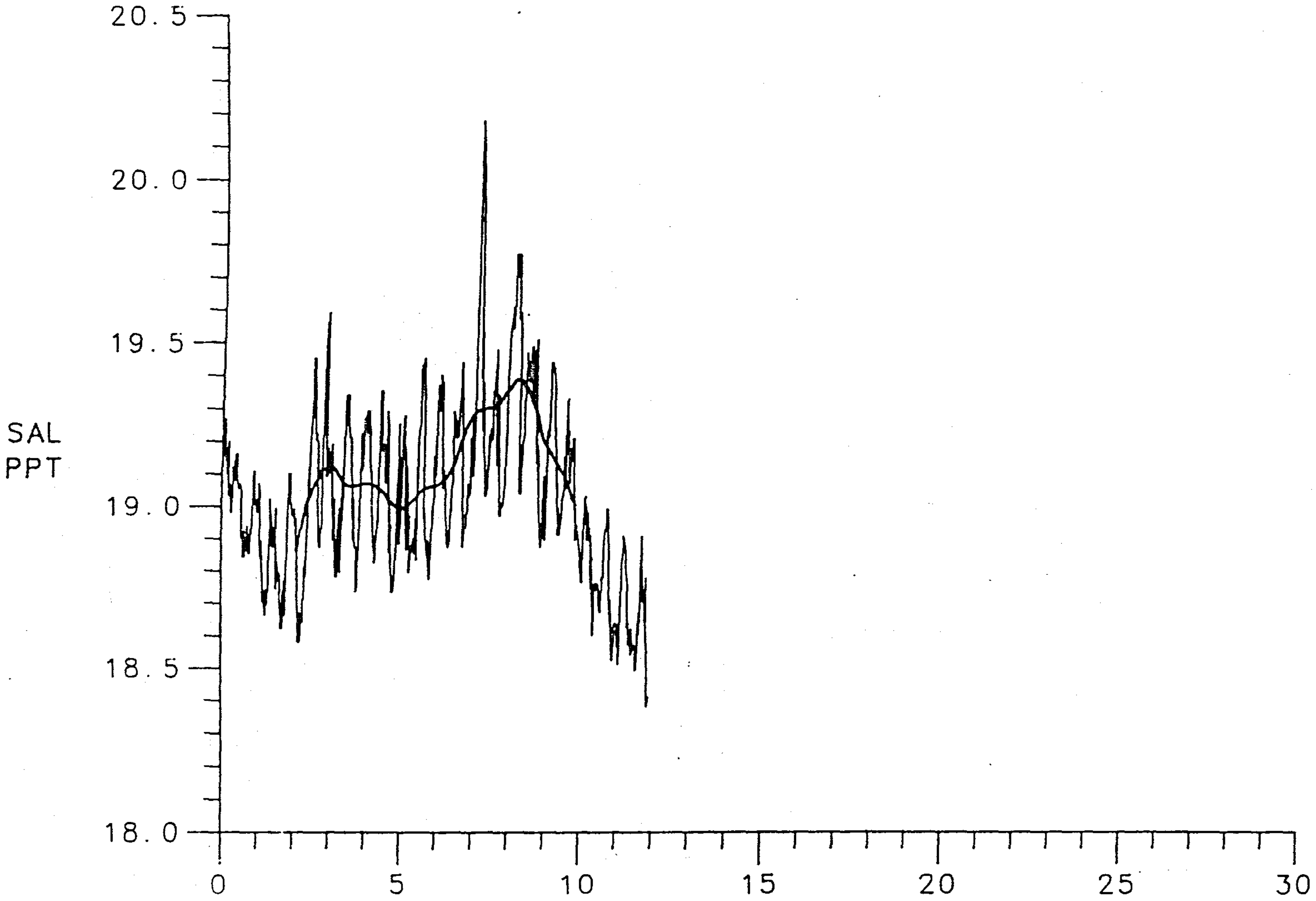


Figure 7a. Salinity at station R0.0, depth 1.2 m (1302 hr, 21 August to 2 September 1987, meter # 922).

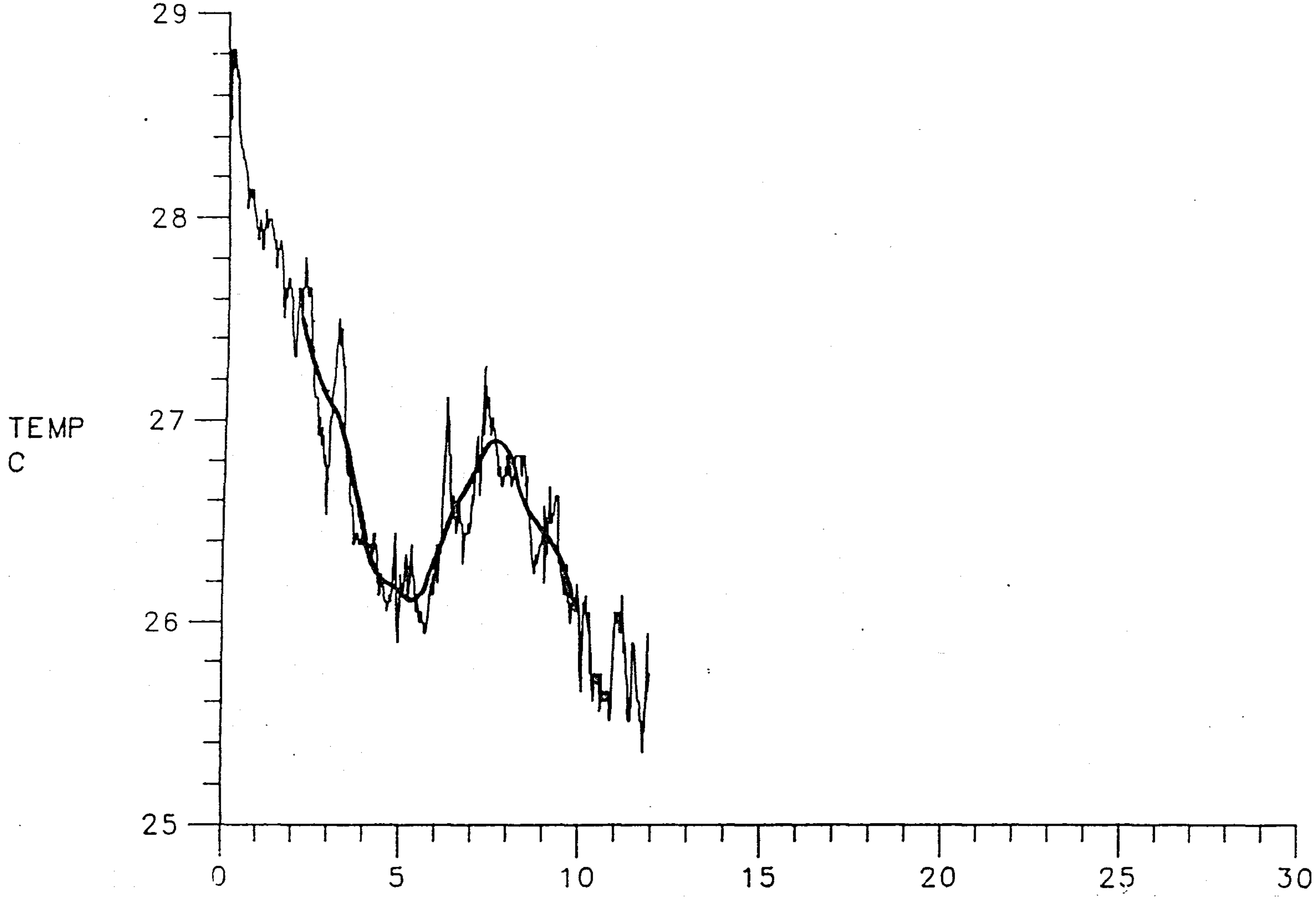


Figure 7b. Temperature at station R0.0, depth 1.2 m (1302 hr, 21 August to 2 September 1987, meter # 922).

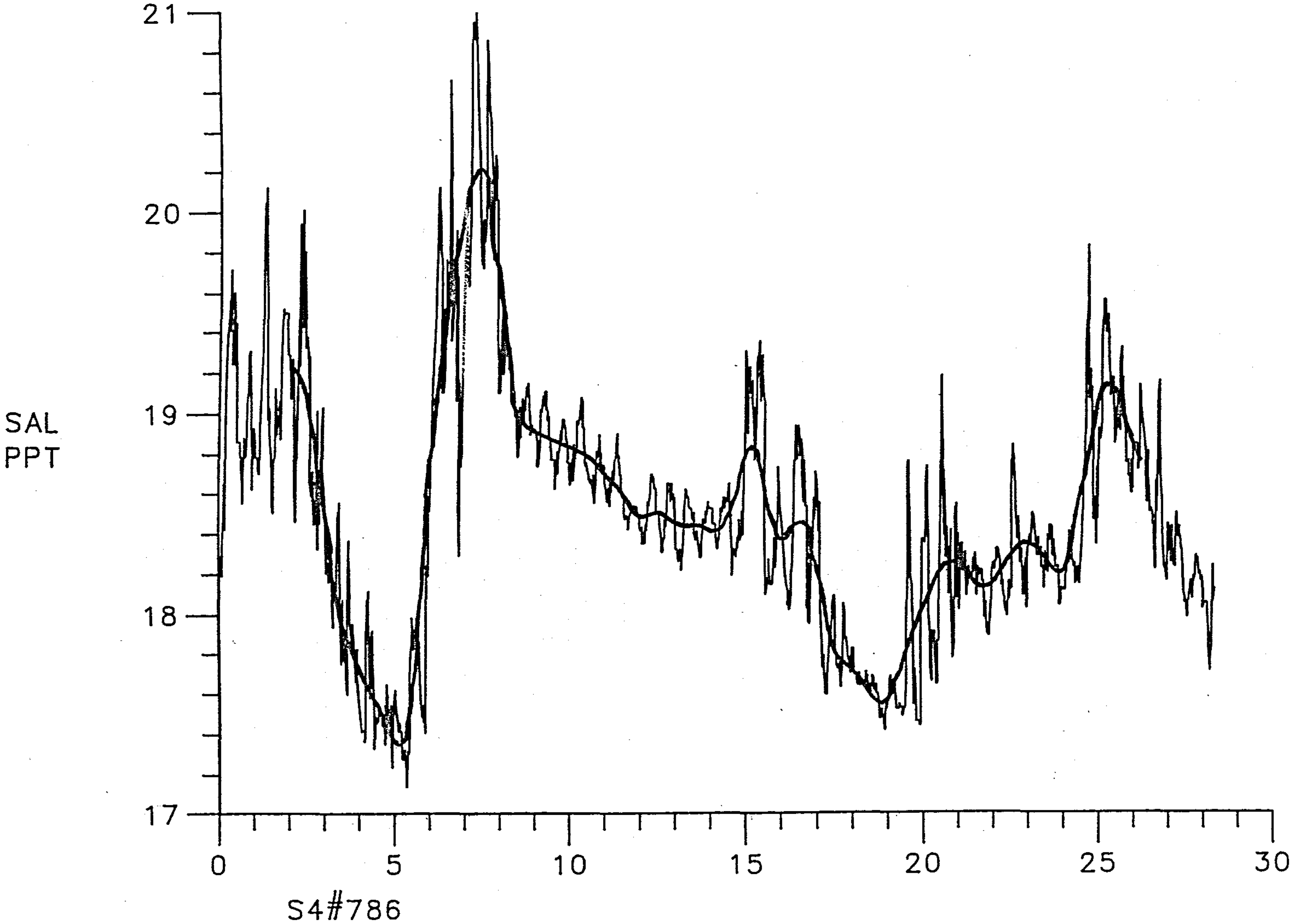


Figure 8a. Salinity at station R0.0, depth 9.7 m (1302 hr, 3 August to 2 September 1987).

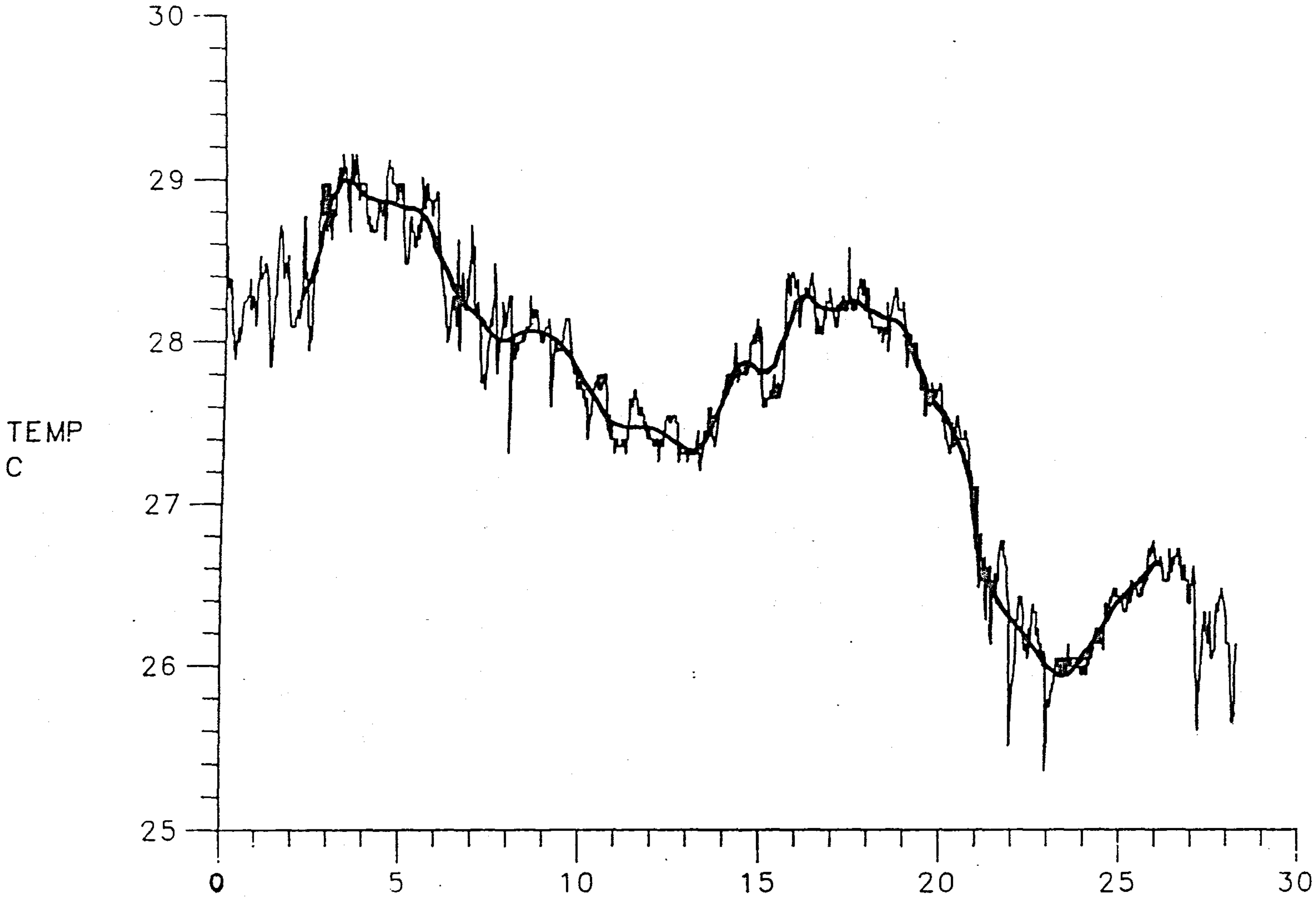


Figure 8b. Temperature at station R0.0, depth 9.7 m (1302 hr, 3 August to 2 September 1987).

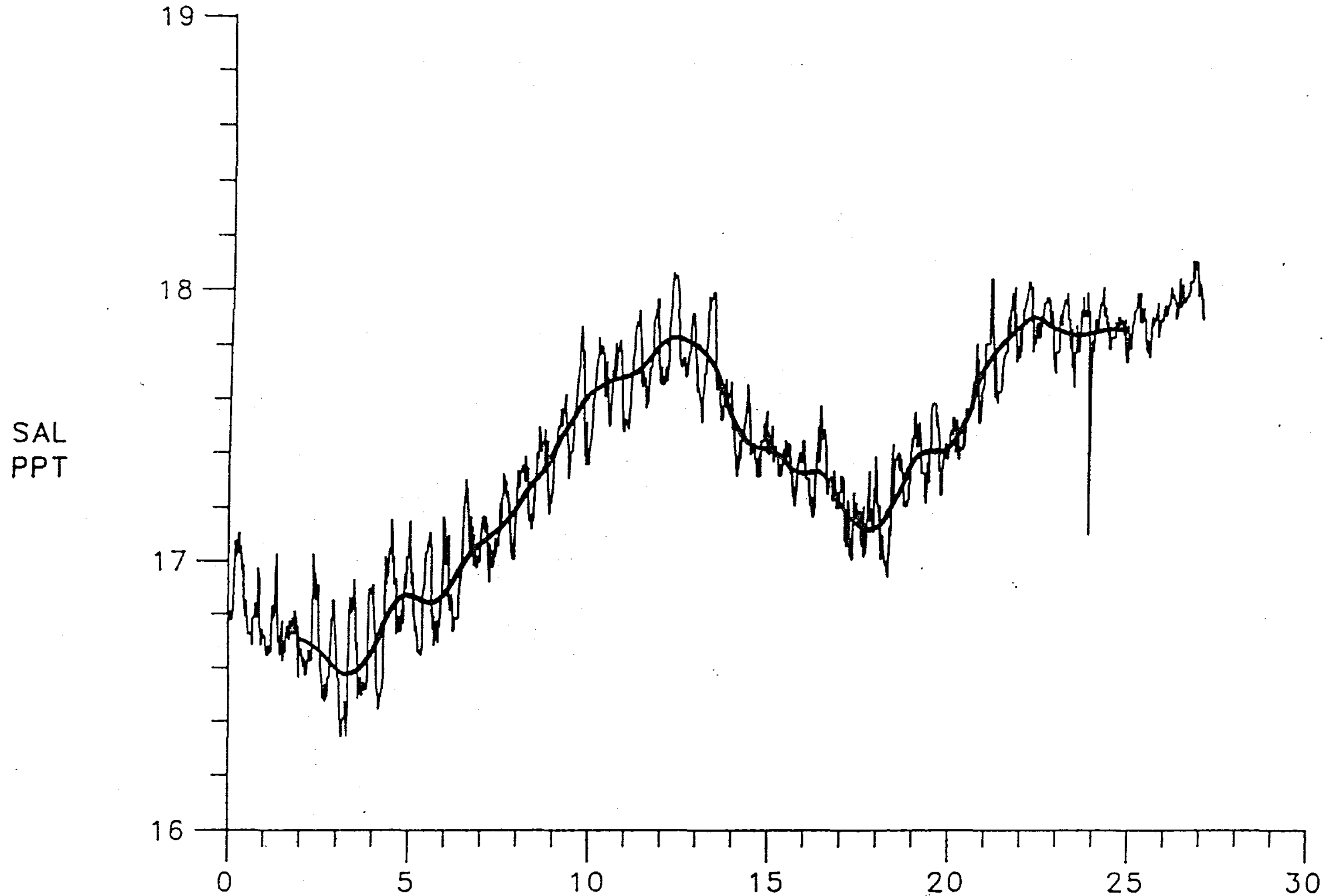


Figure 9a. Salinity at station R16.6, depth 1.2 m (1127 hr, 3 August to 31 August 1987).

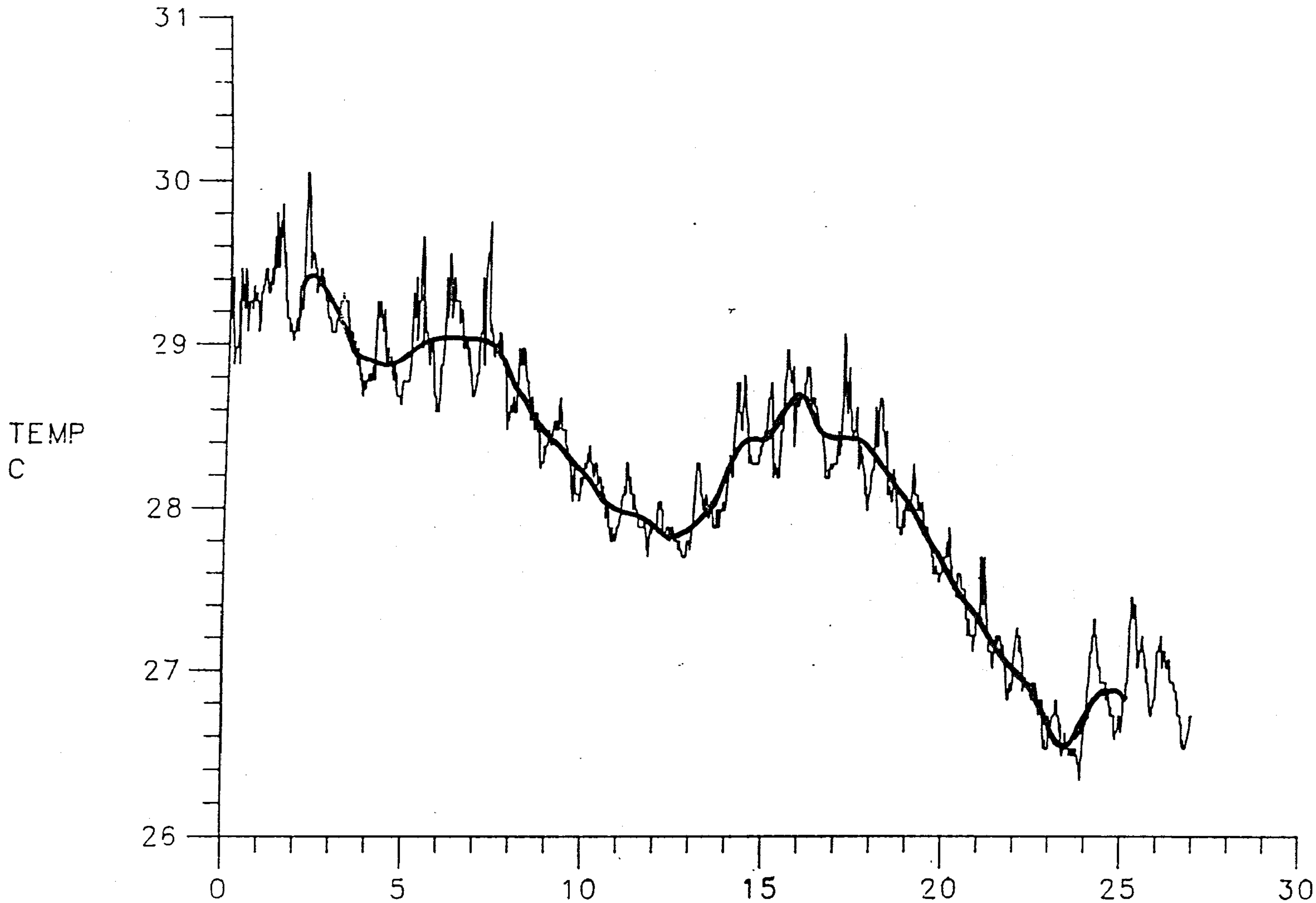


Figure 9b. Temperature at station R16.6, depth 1.2 m (1127 hr, 3 August to 31 August 1987).

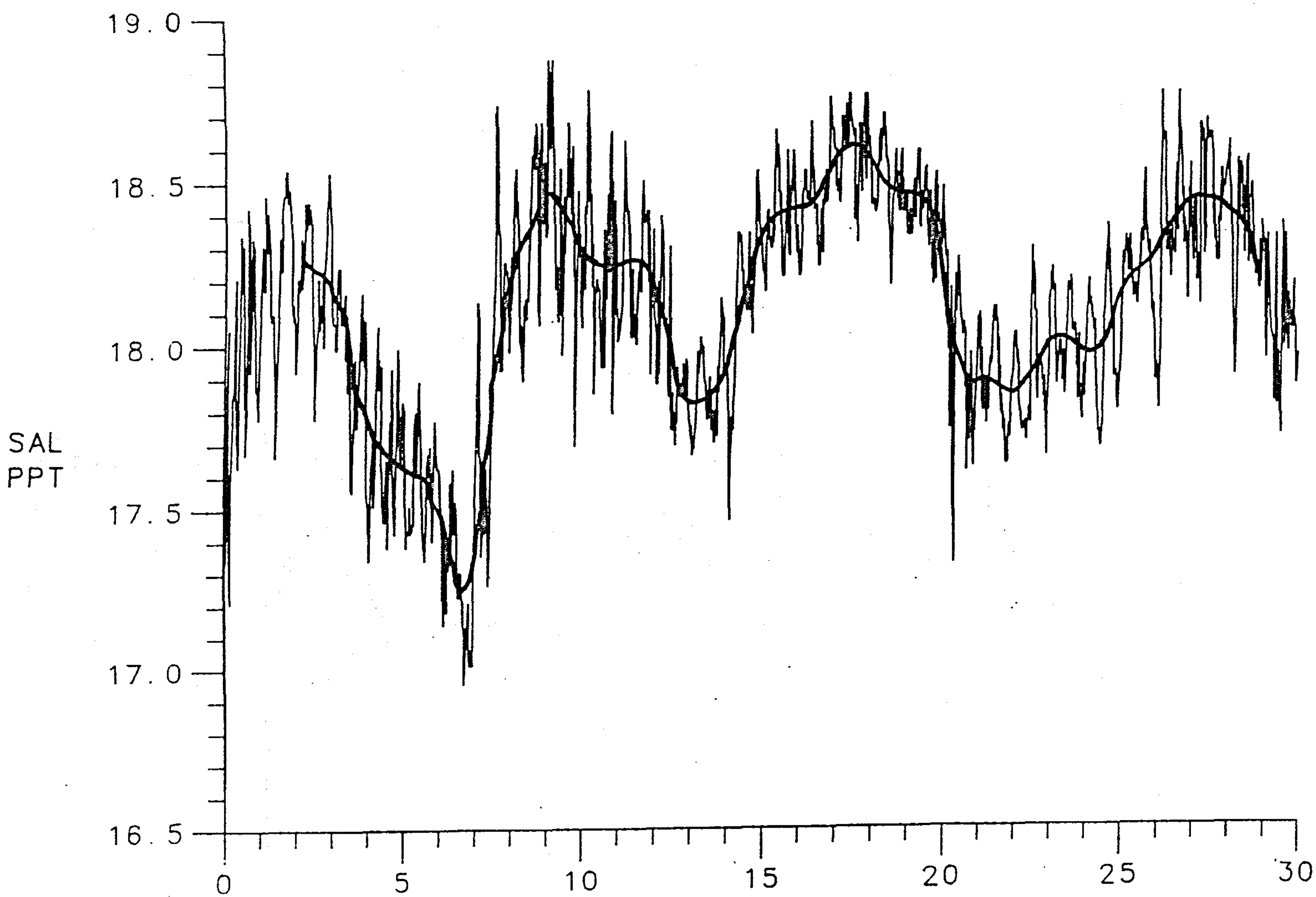


Figure 10a. Salinity at station R16.6, depth 10 m (1123 hr, 3 August to 2 September 1987).

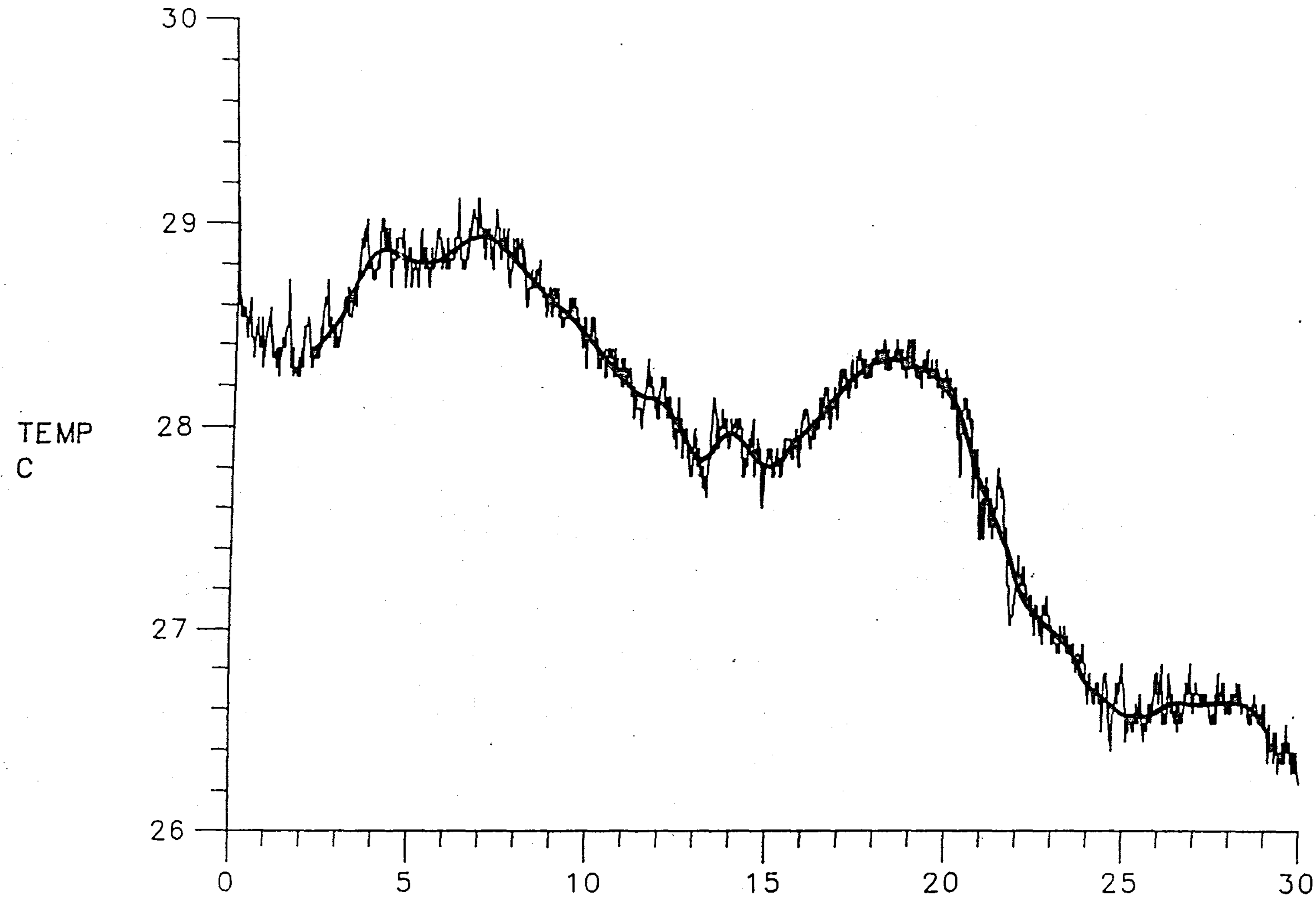


Figure 10b. Temperature at station R16.6, depth 10 m (1123 hr, 3 August to 2 September 1987).

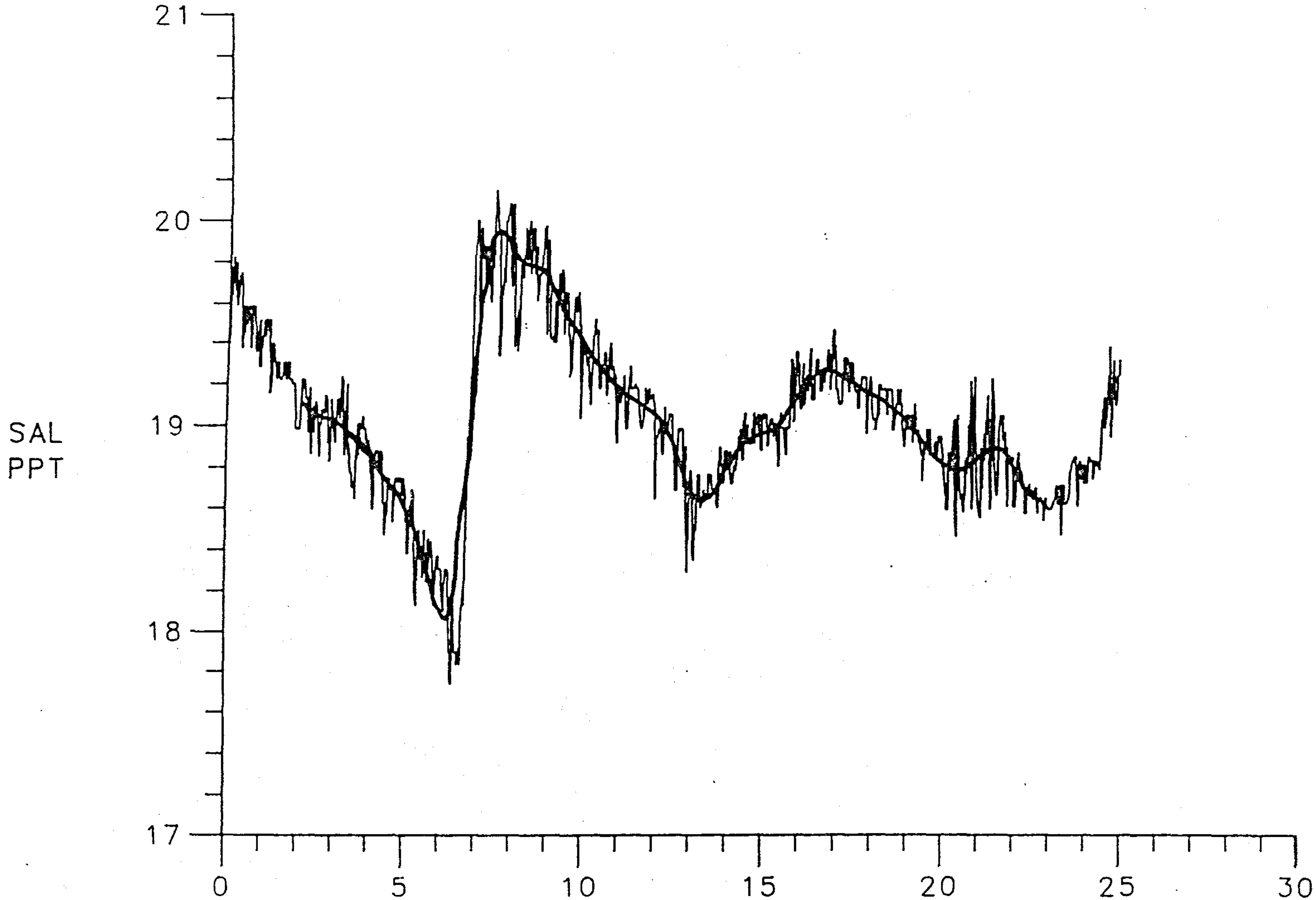


Figure 11a. Salinity at station R16.6, depth 18.7 m (1124 hr, 3 August to 30 August 1987).

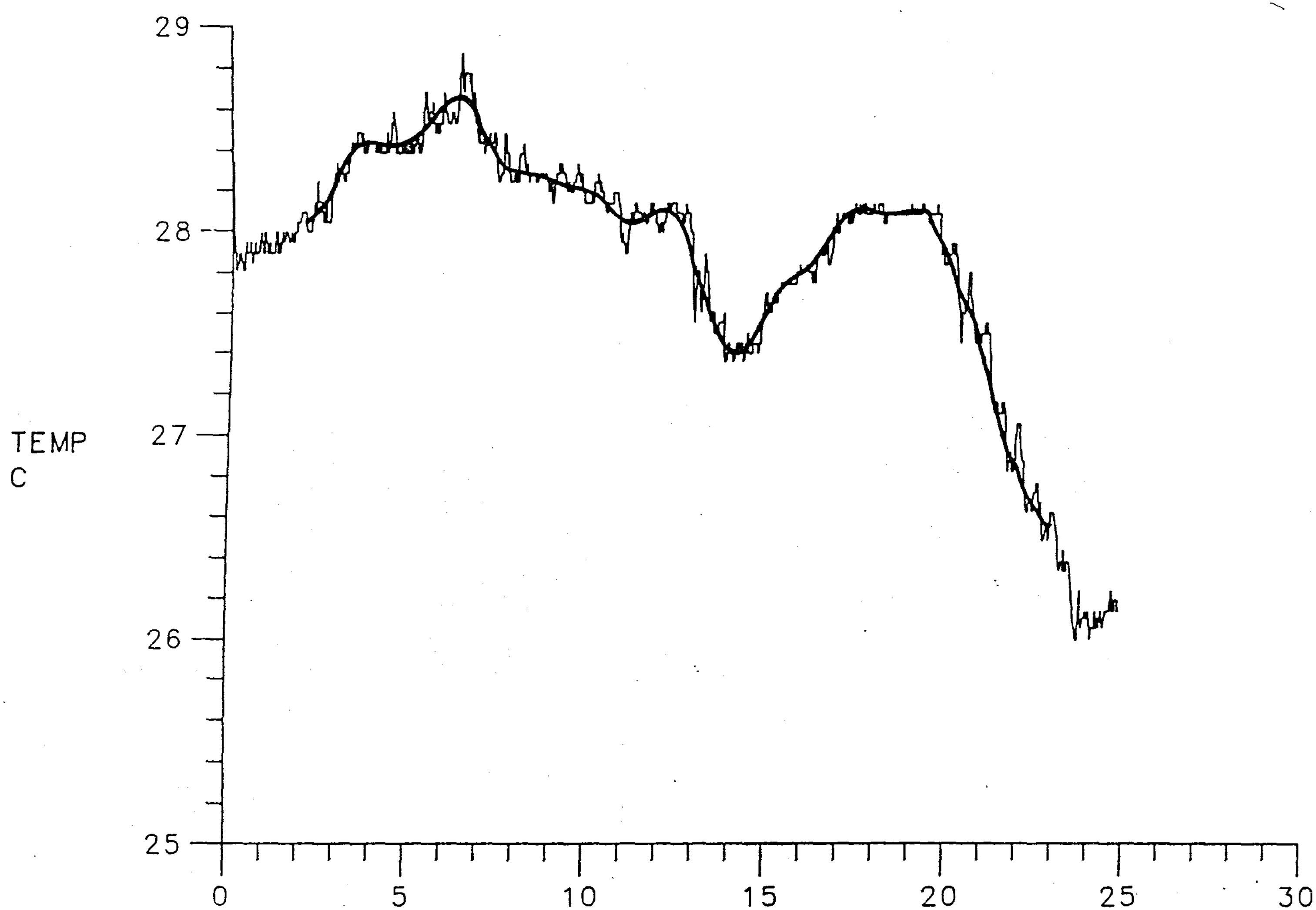


Figure 11b. Temperature at station R16.6, depth 18.7 m (1124 hr, 3 August to 30 August 1987).

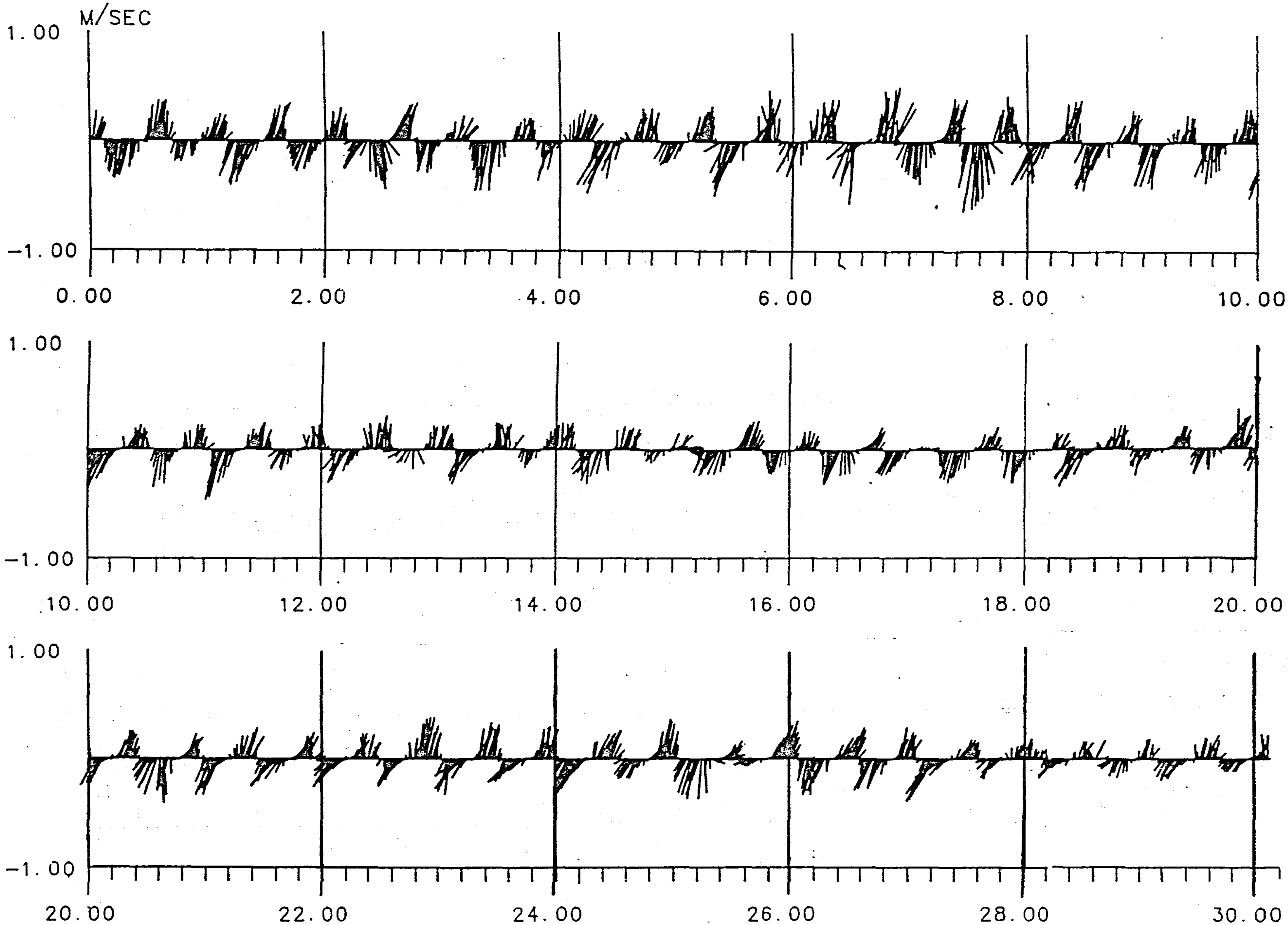


Figure 12a. Velocity at station R0.0, depth 1.2 m (0919 hr, 3 August to 2 September 1987, x-axis is to the south).

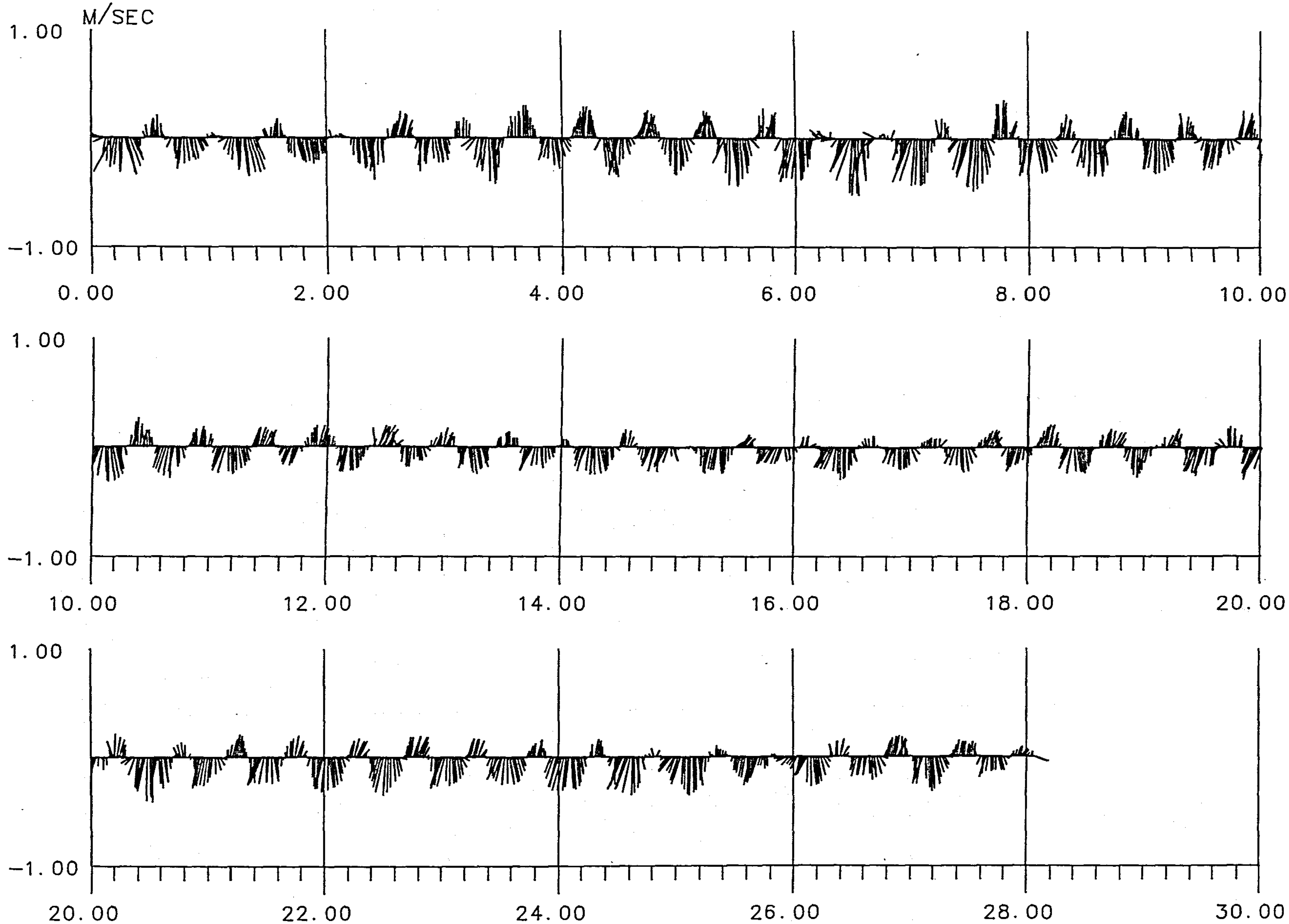


Figure 12b. Velocity at station R0.0, depth 9.7 m (0946 hr, 3 August to 2 September 1987, x-axis is to the south).

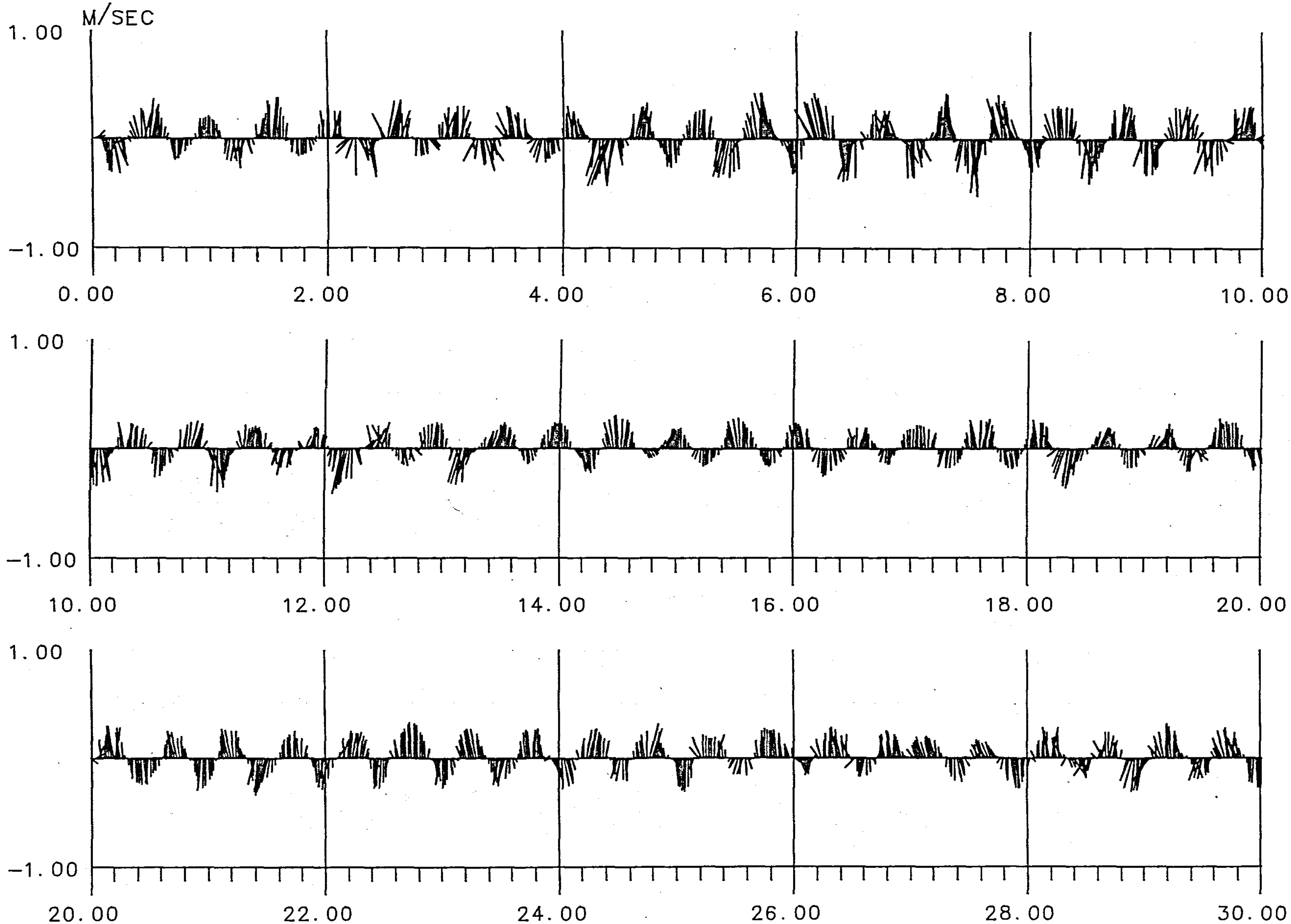


Figure 13a. Velocity at station R16.6, depth 1.2 m (1127 hr, 3 August to 3 September 1987, x-axis is to the south).

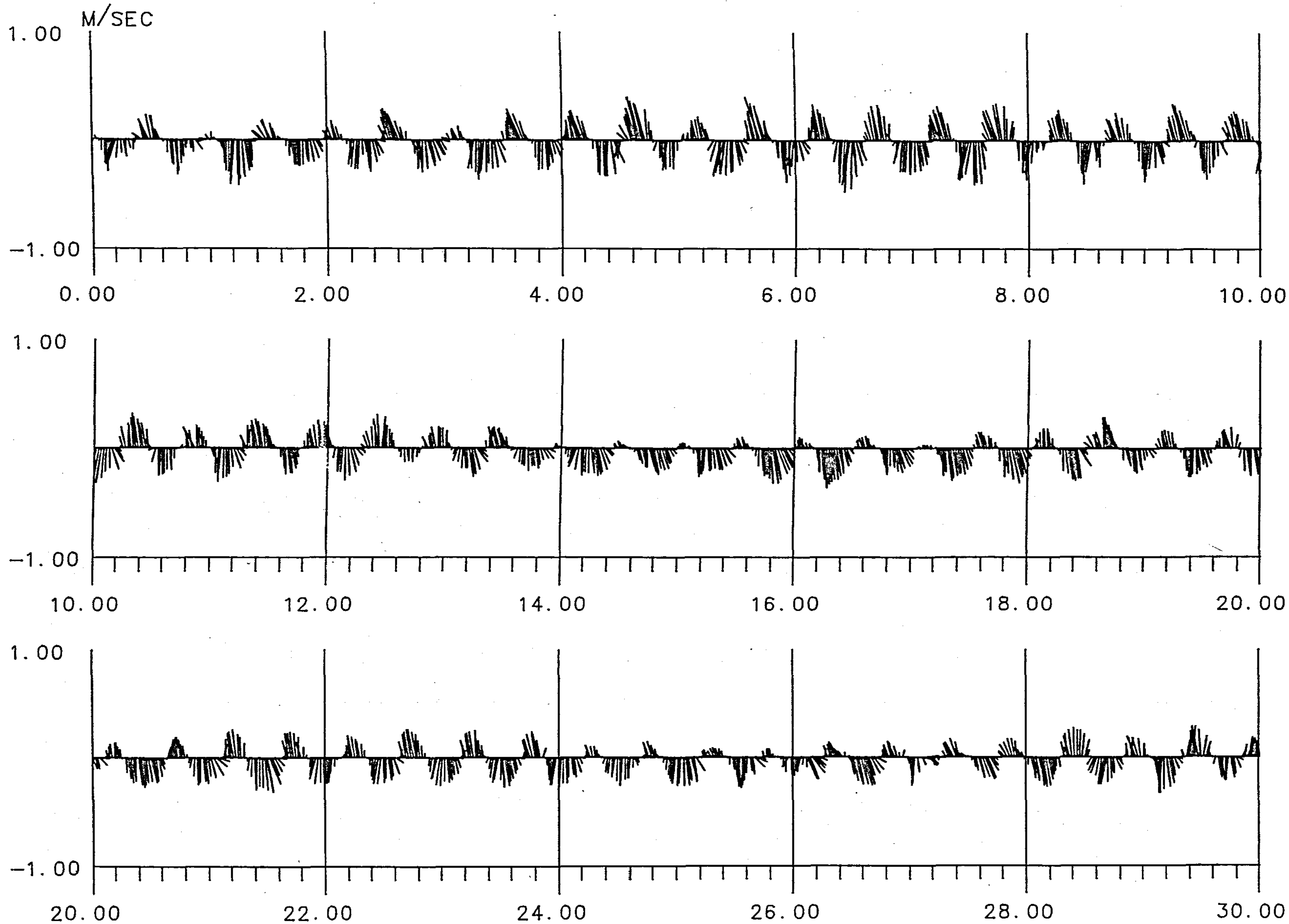


Figure 13b. Velocity at station R16.6, depth 10 m (1053 hr, 3 August to 3 September 1987, x-axis is to the south).

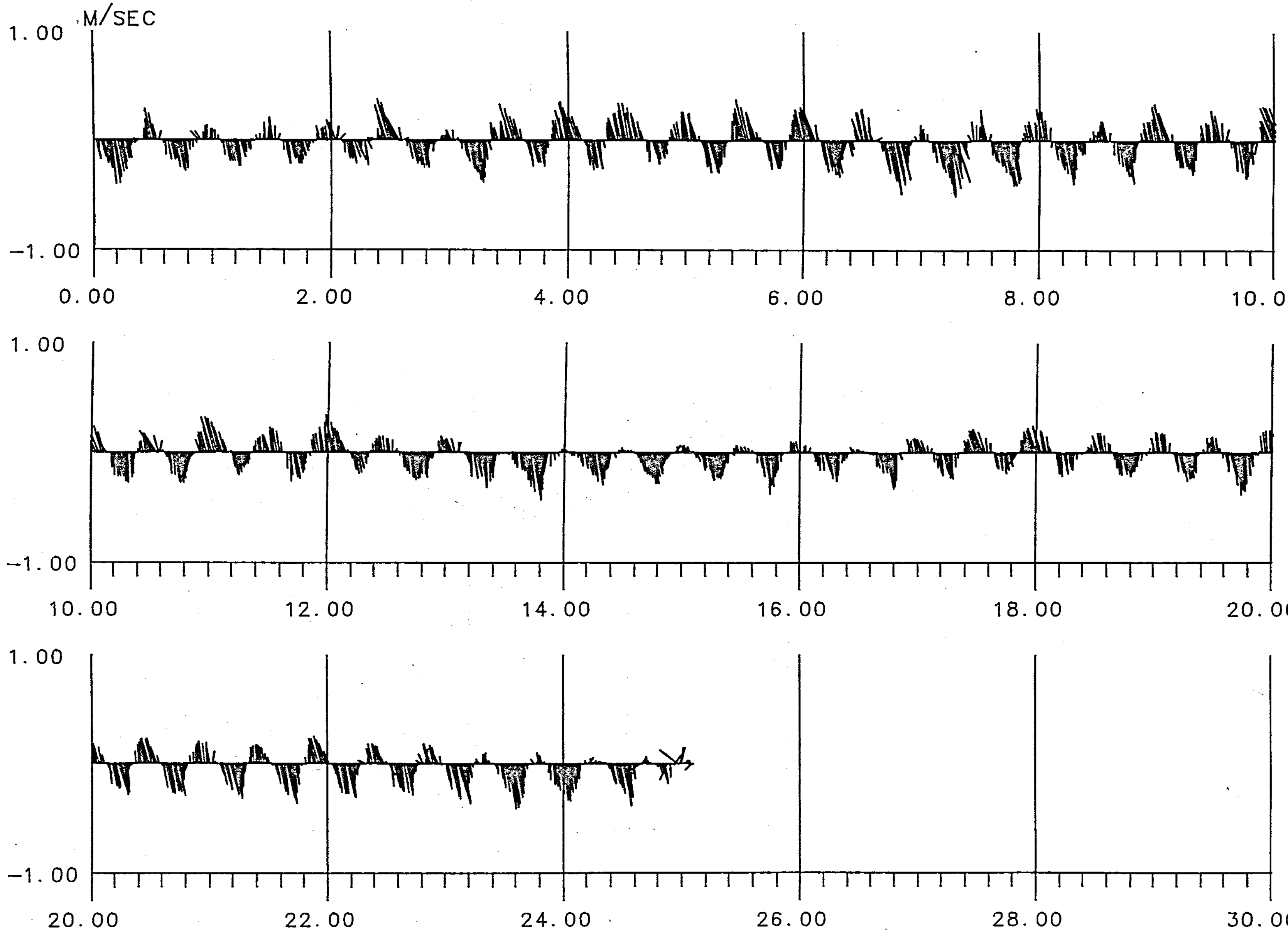


Figure 13c. Velocity at station R16.6, depth 18.7 m (1054 hr, 3 August to 3 September 1987, x-axis is to the south).

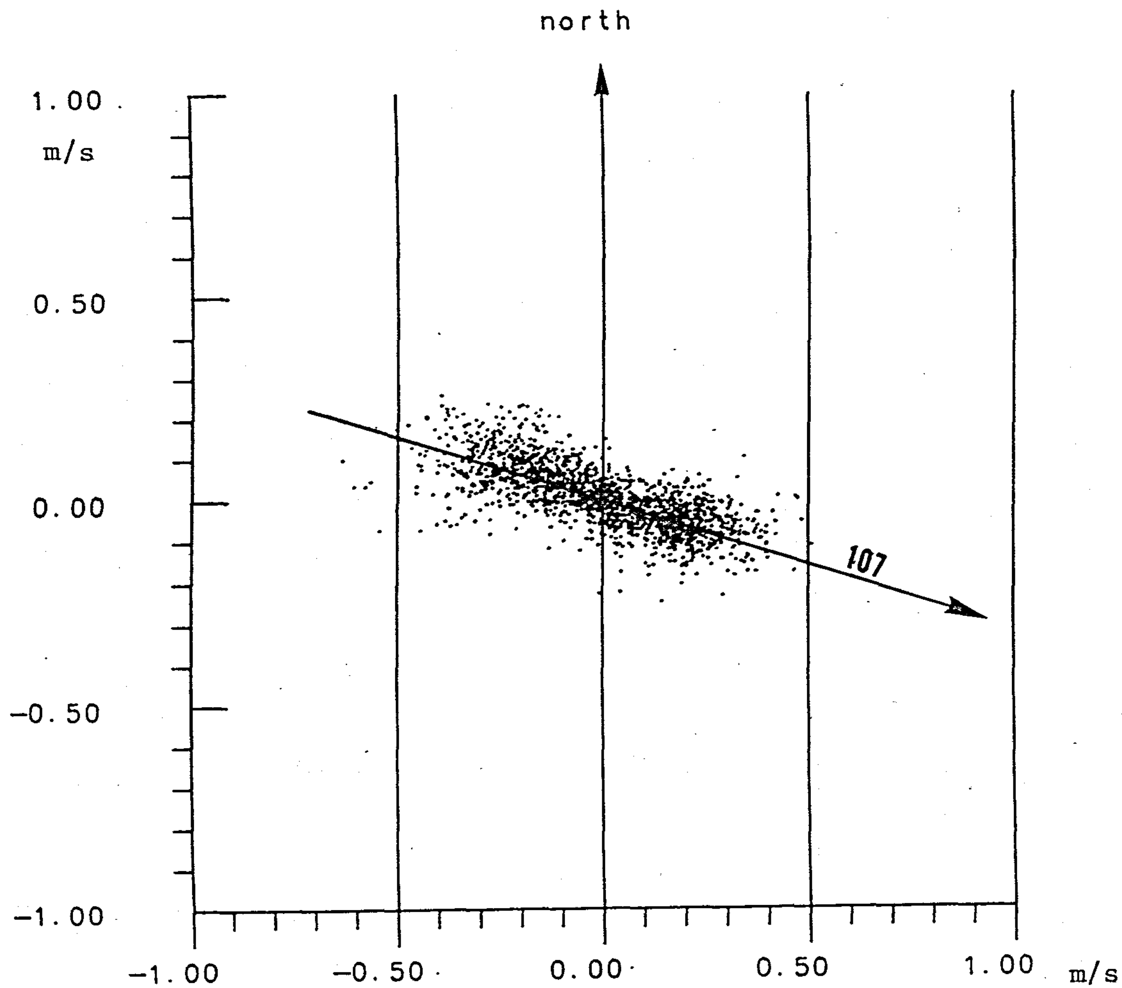


Figure 14a. Polar plot for velocity at station RO.0, depth 1.2 m.

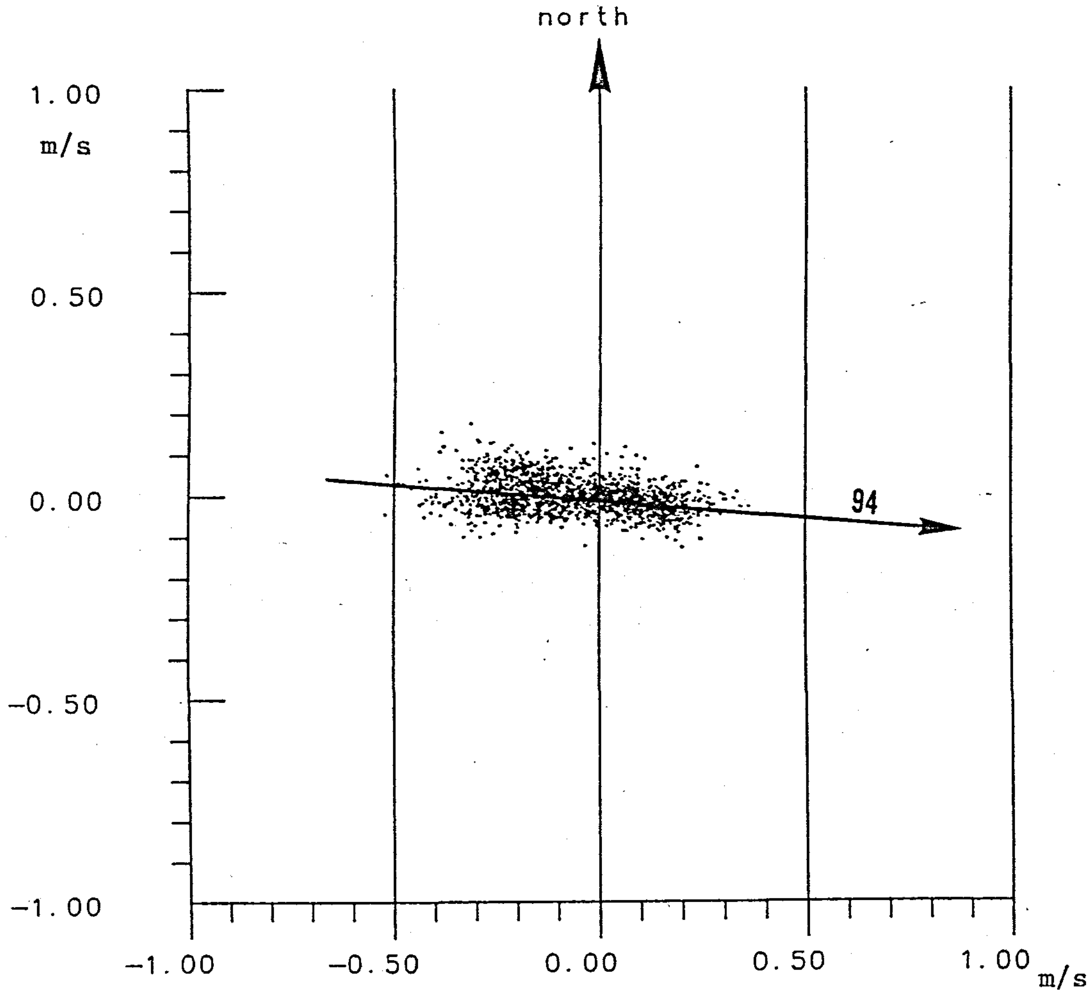


Figure 14b. Polar plot for velocity at station R0.0, depth 9.7 m.

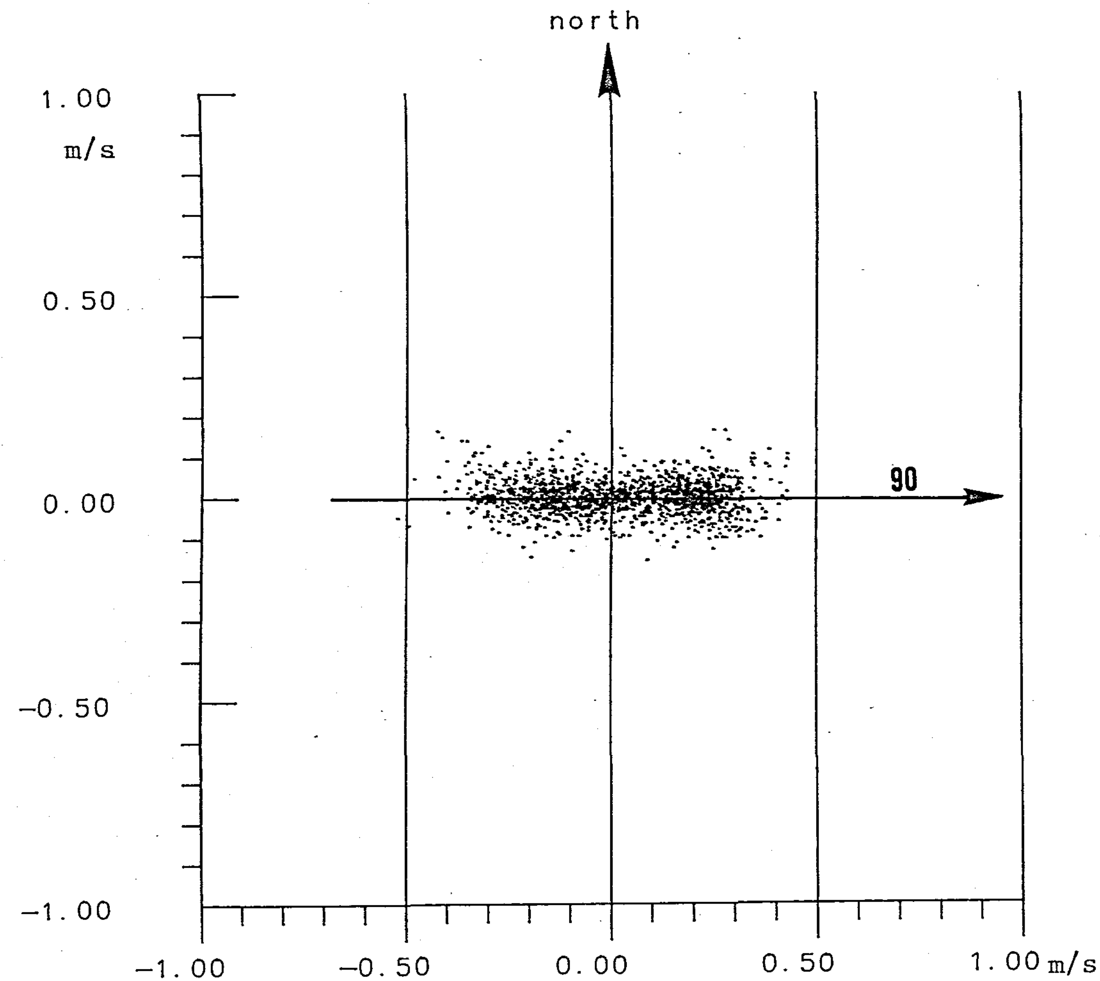


Figure 15a. Polar plot for velocity at station R16.6, depth 1.2 m.

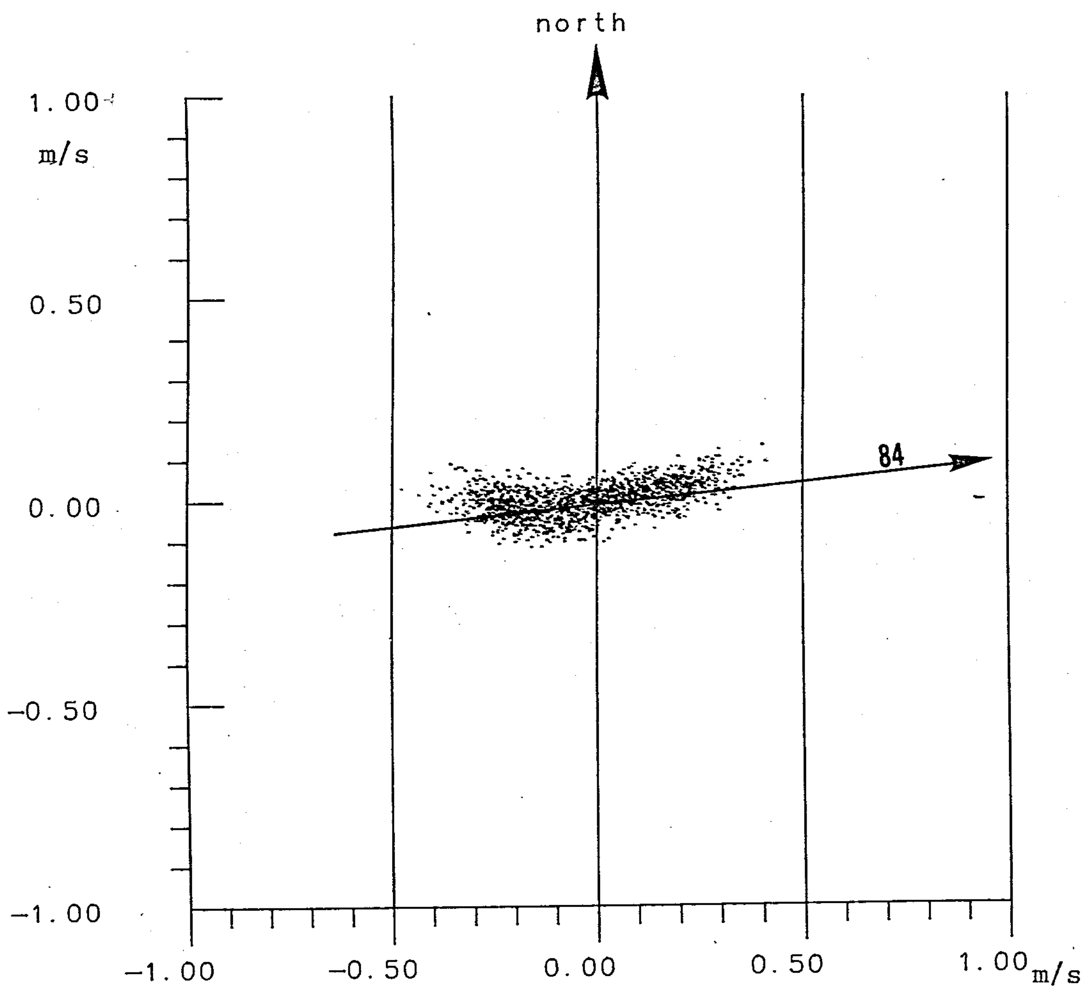


Figure 15b. Polar plot for velocity at station R16.6, depth 10 m.

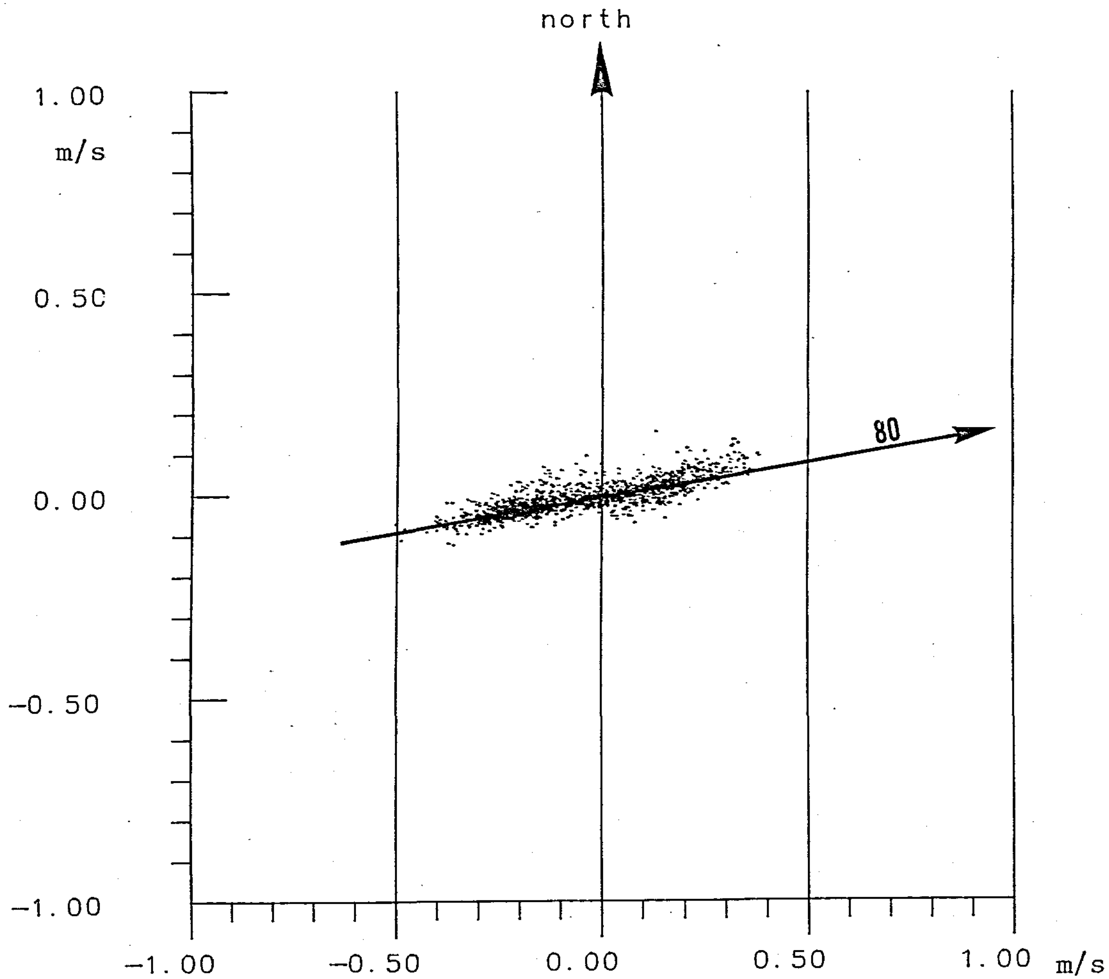


Figure 15c. Polar plot for velocity at station R16.6, depth 18.7 m.

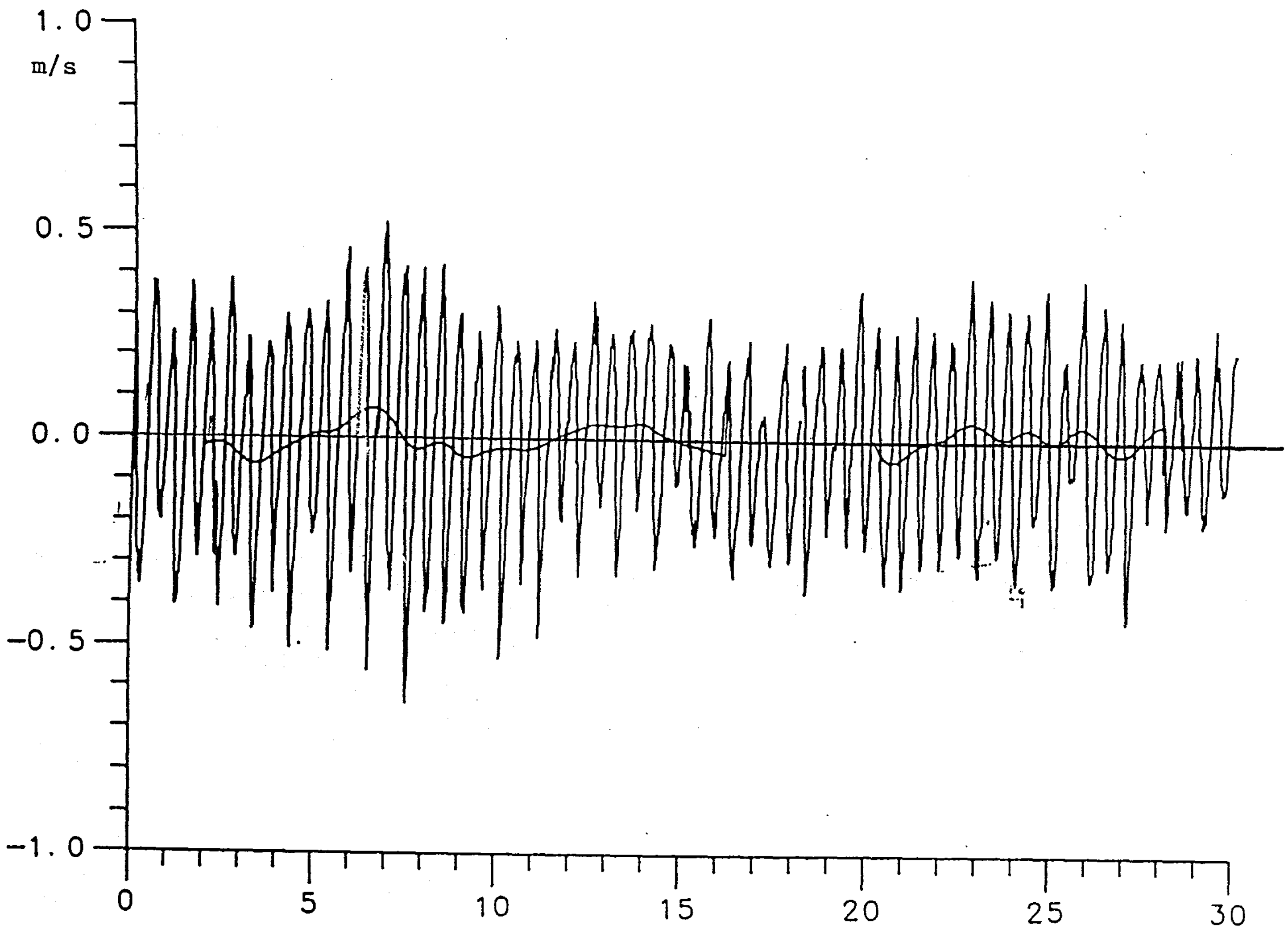


Figure 16a. Filtered and unfiltered longitudinal velocity component at station R0.0, depth 1.2 m (0919 hr, 3 August to 2 September 1987, positive is in ebb direction).

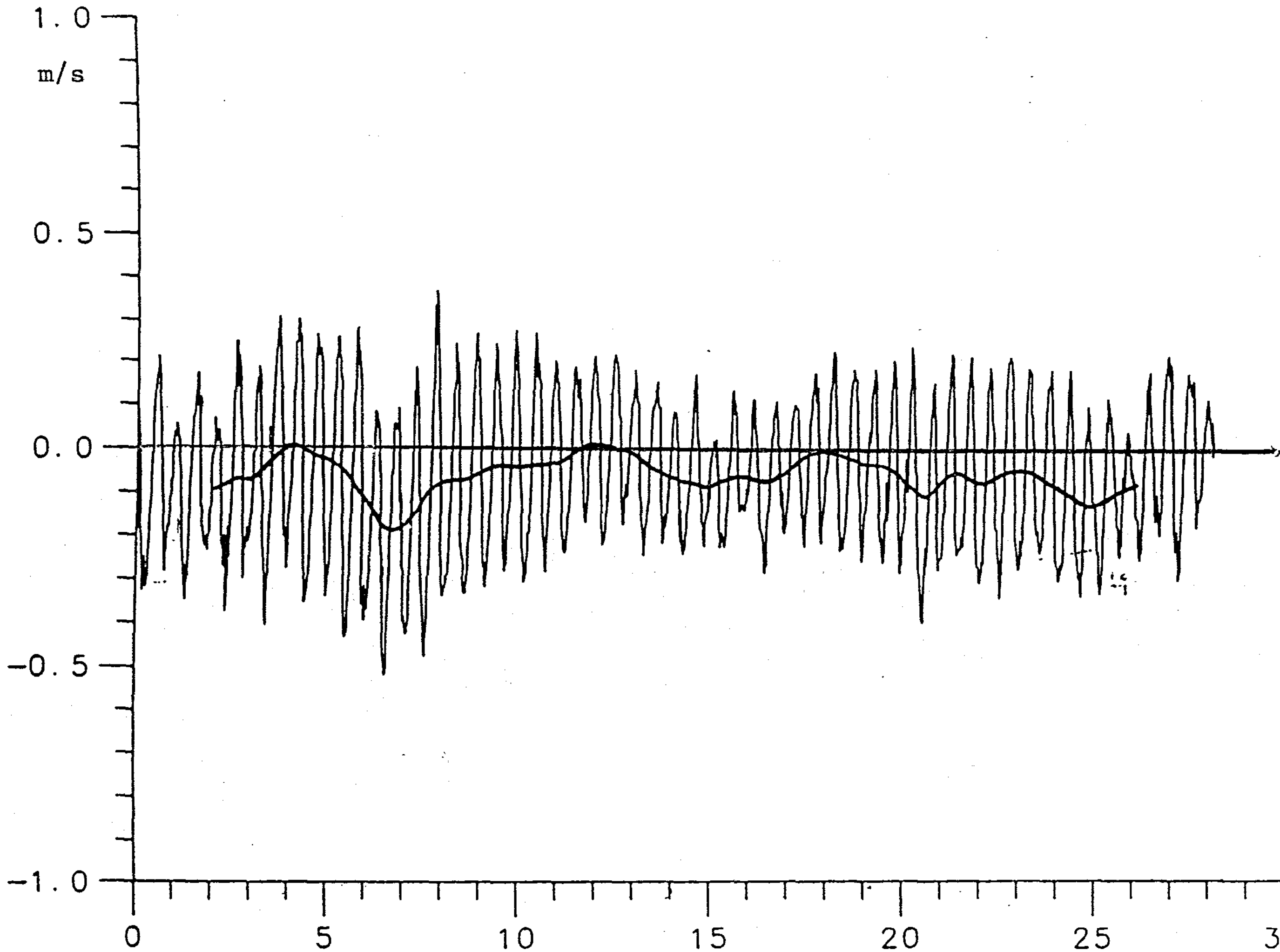


Figure 16b. Filtered and unfiltered longitudinal velocity component at station R0.0, depth 9.7 m (0946 hr, 3 August to 2 September 1987, positive is in ebb direction).

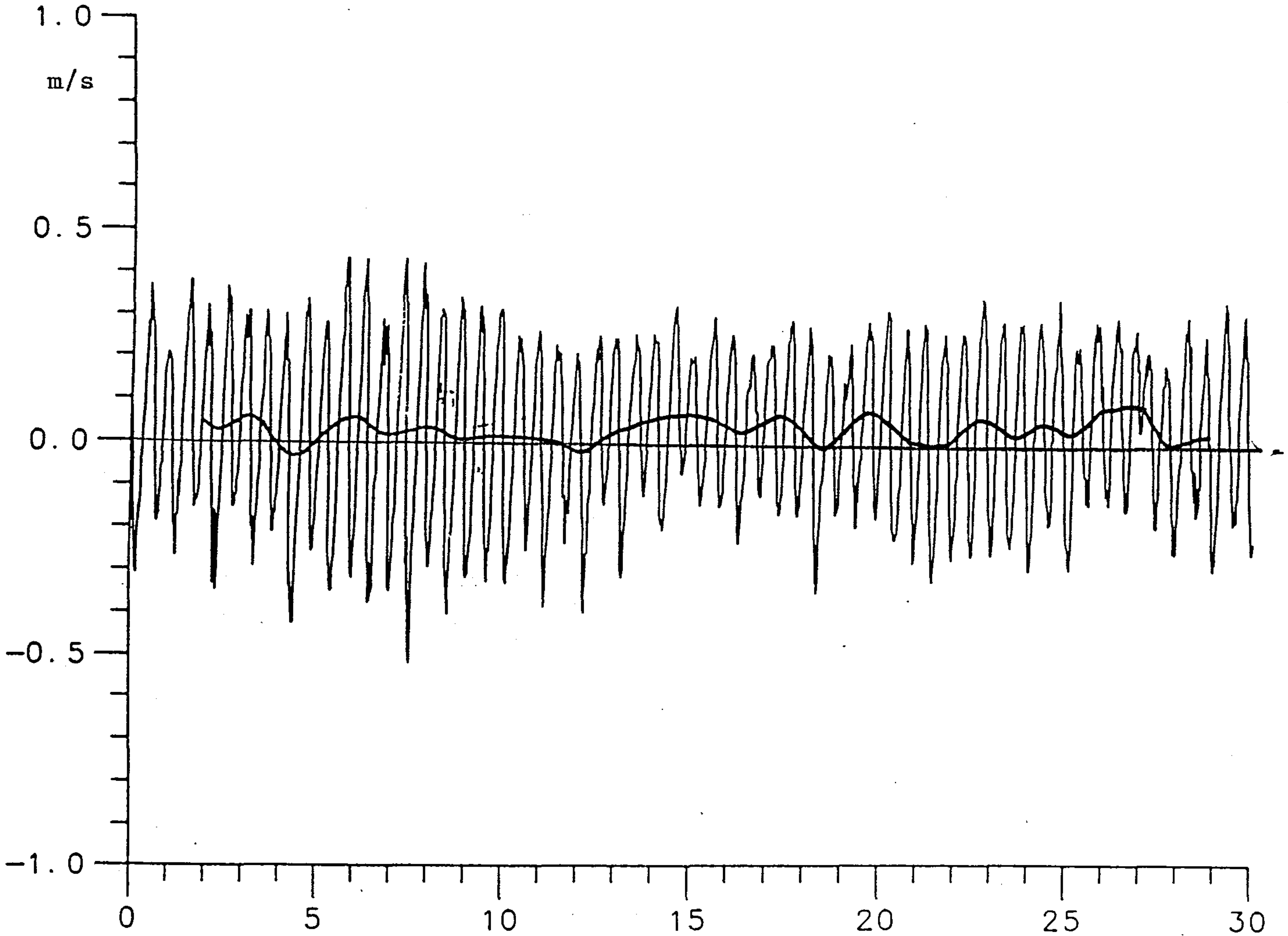


Figure 17a. Filtered and unfiltered longitudinal velocity component at station R16.6, depth 1.2 m (1127 hr, 3 August to 3 September, 1987, positive is in ebb direction).

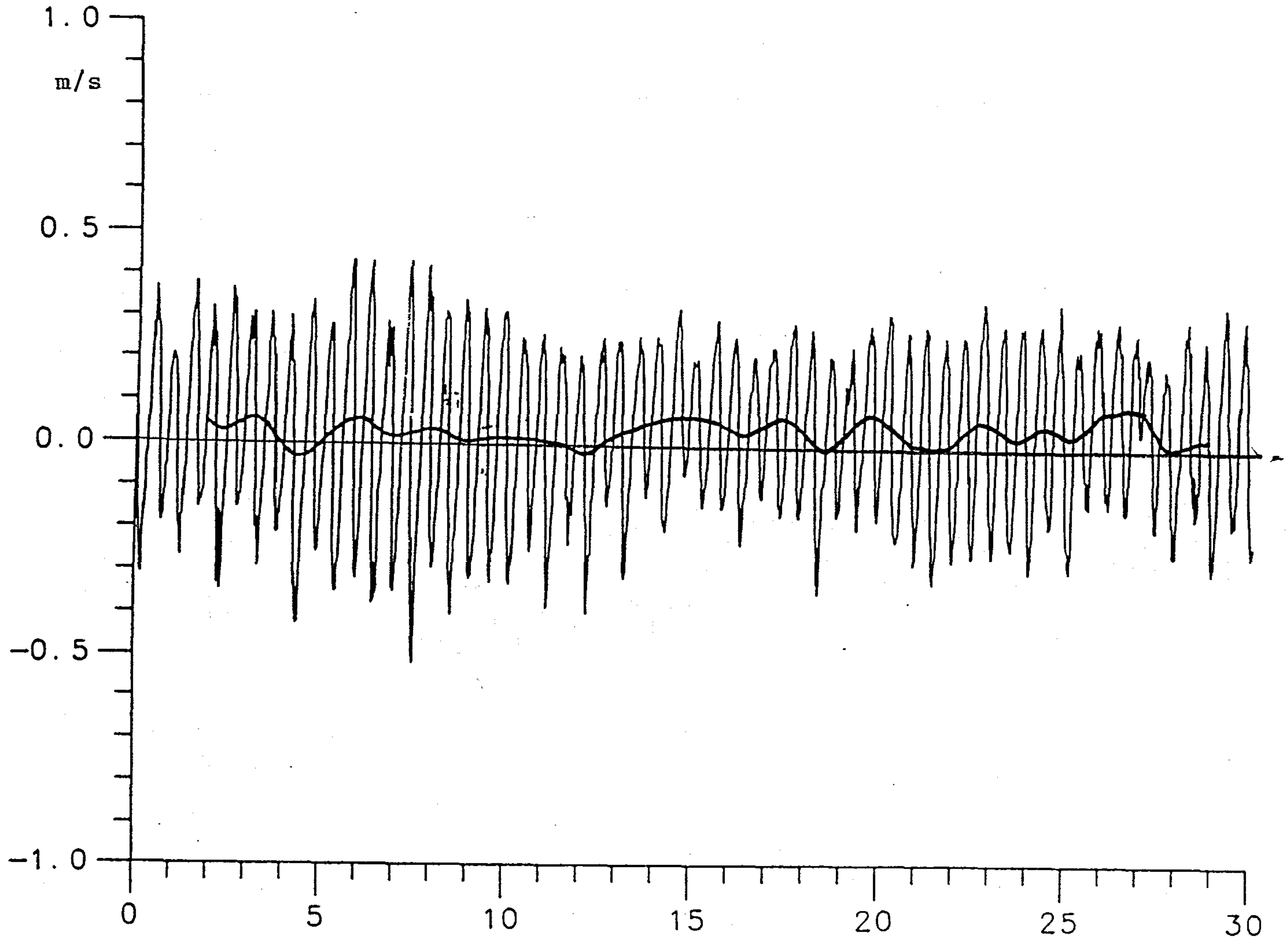


Figure 17a. Filtered and unfiltered longitudinal velocity component at station R16.6, depth 1.2 m (1127 hr, 3 August to 3 September, 1987, positive is in ebb direction).

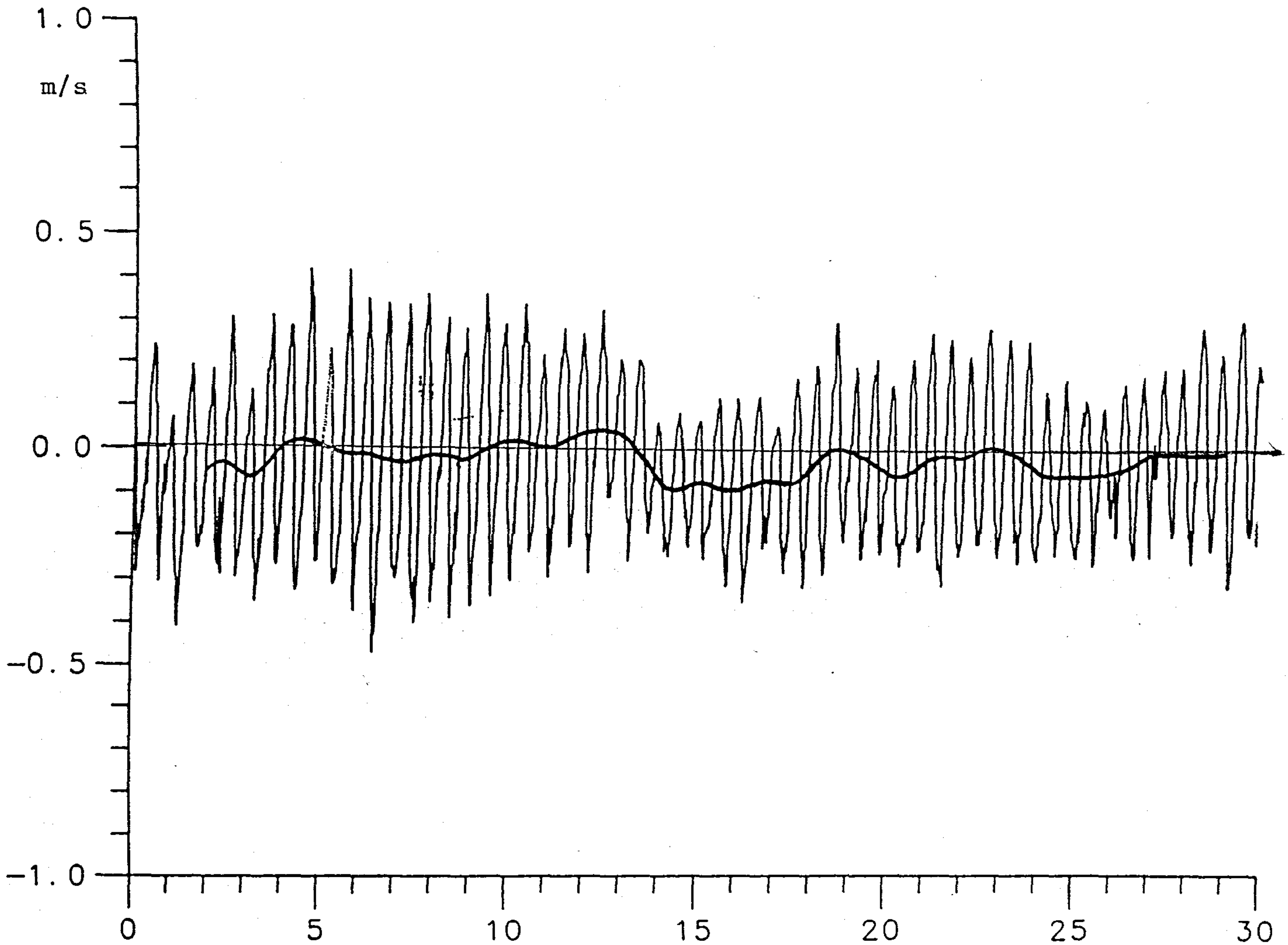


Figure 17b. Filtered and unfiltered longitudinal velocity component at station R16.6, depth 10 m (1053 hr, 3 August to 3 September 1987, positive is in ebb direction).

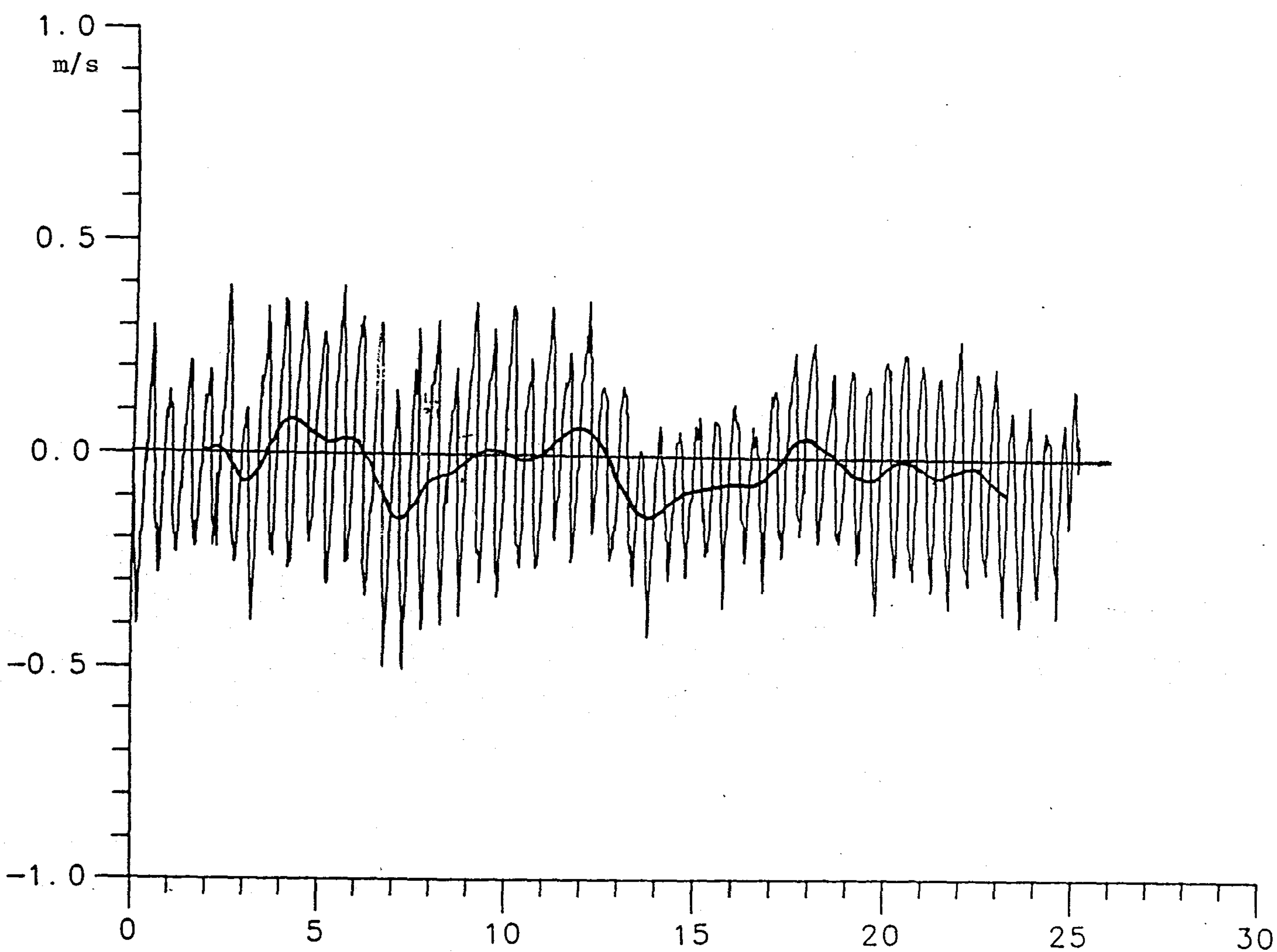


Figure 17c. Filtered and unfiltered longitudinal velocity component at station R16.6, depth 18.7 m (1054 hr, 3 August to 3 September 1987, positive in in ebb direction).

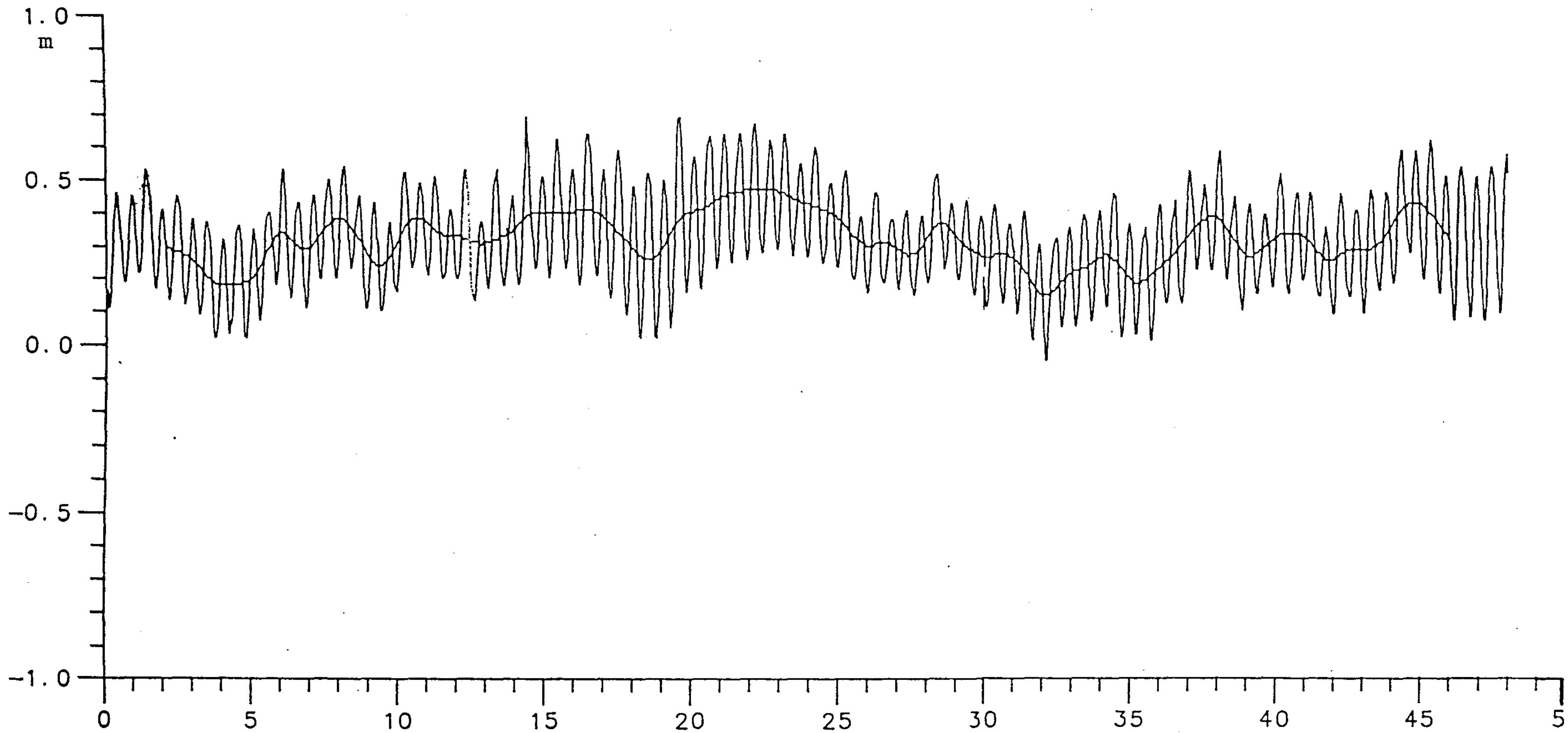


Figure 18. Tidal height and filtered signal at Deltaville (1300 hr, 22 July to 8 September 1987).

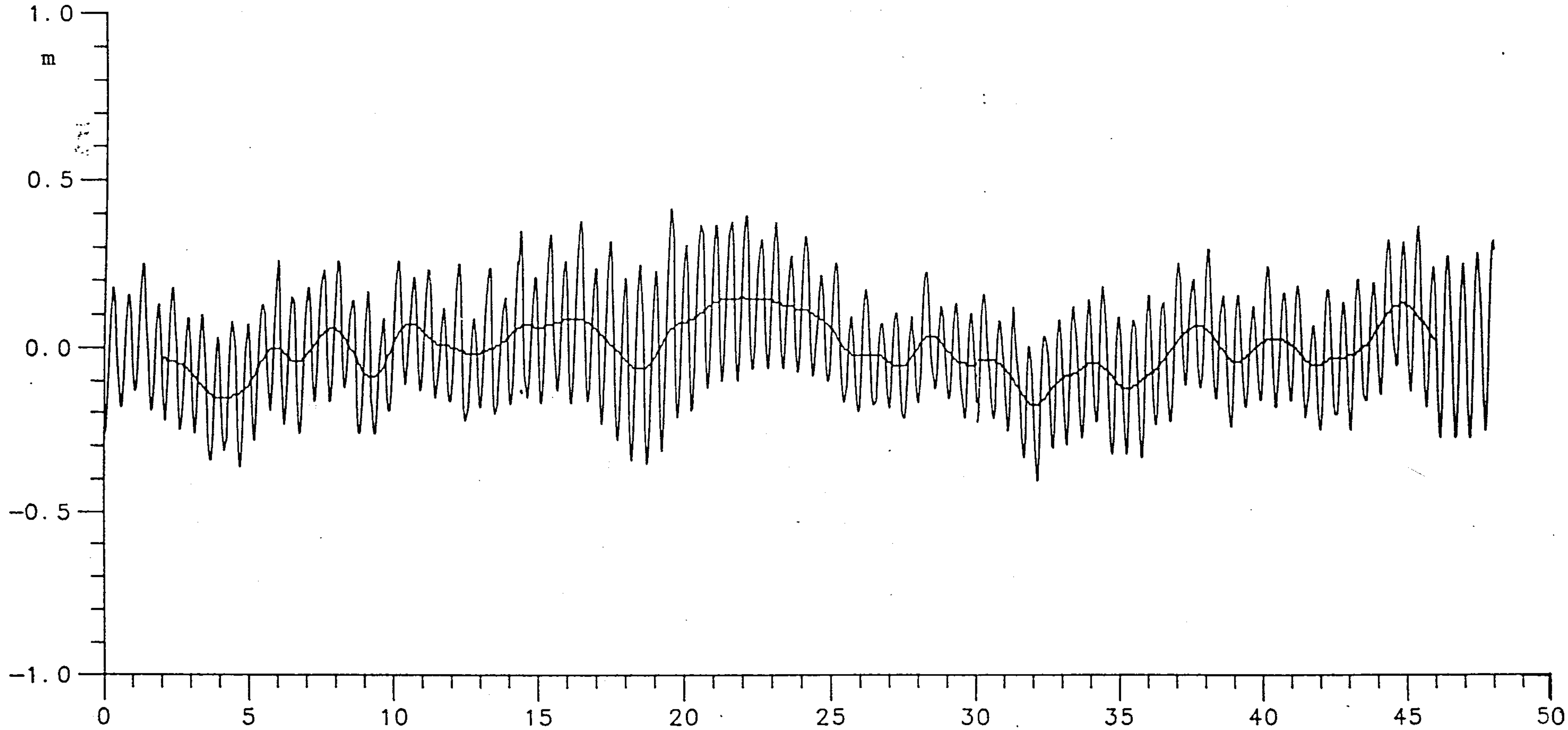


Figure 19. Tidal height and filtered signal at Urbanna (1400 hr, 22 July to 8 September 1987).

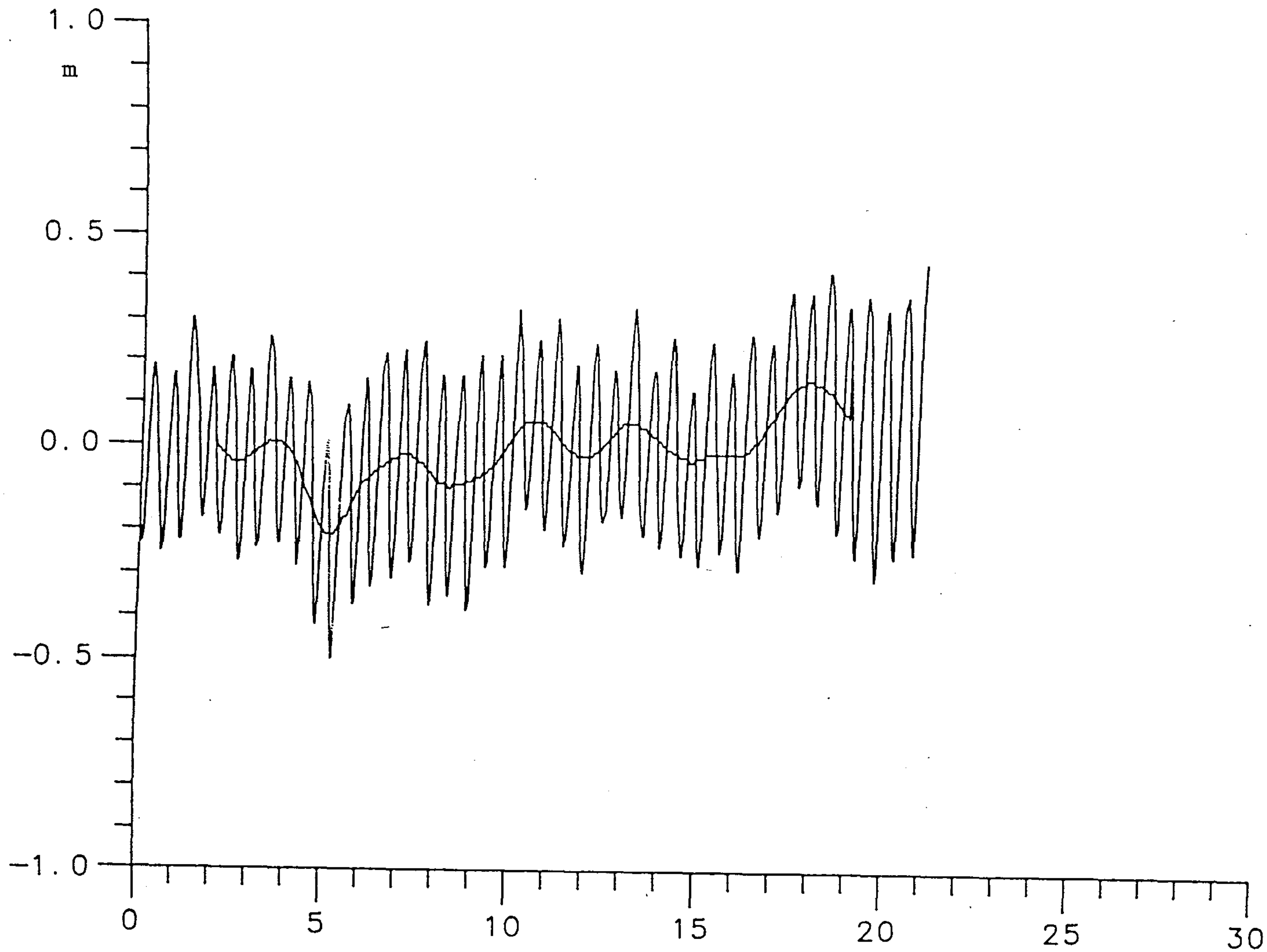


Figure 20. Tidal height and filtered signal at Tappahannock (1300 hr, 18 August to 8 September 1987).

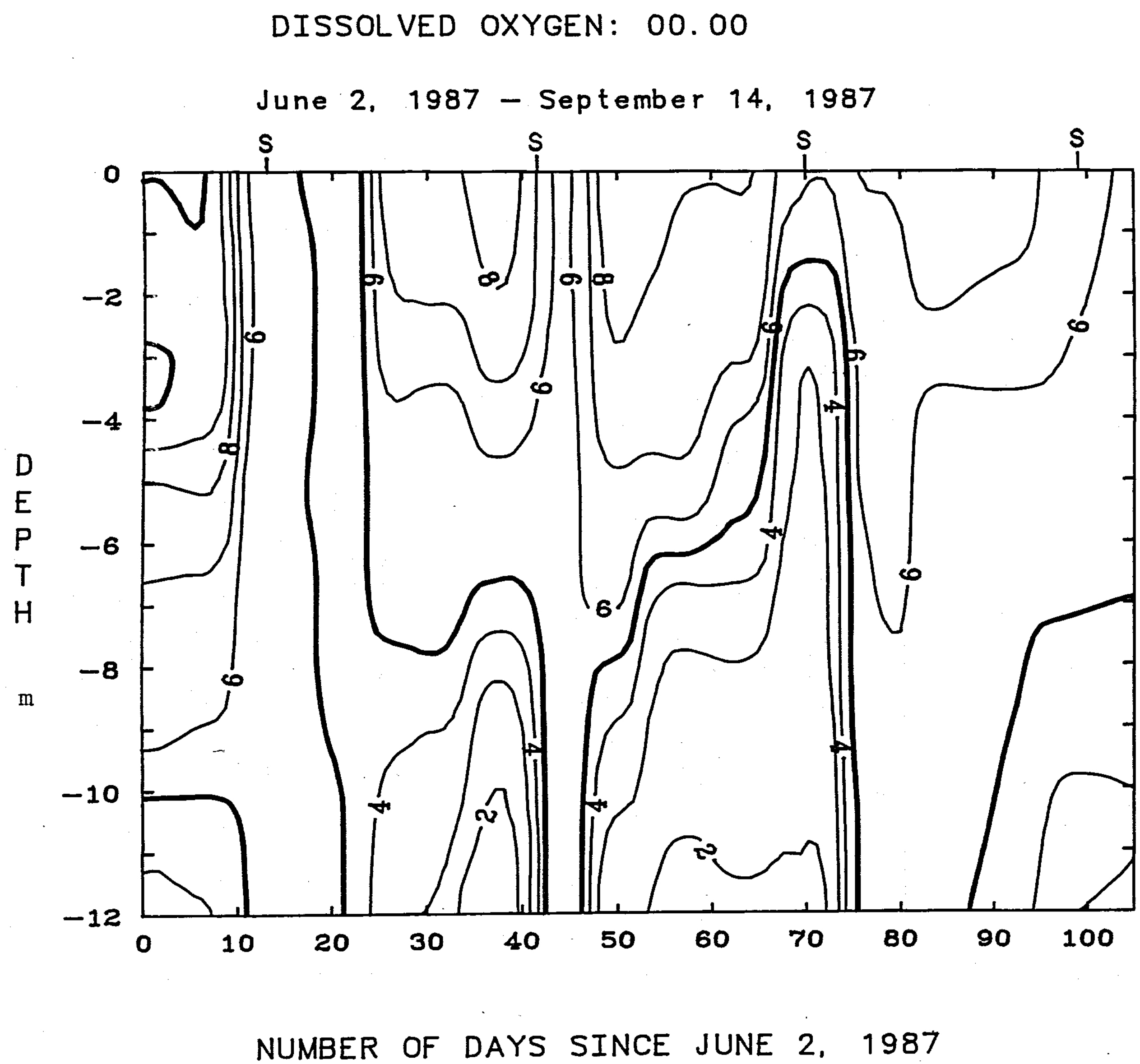


Figure 21a. Constant value contours of DO in depth-time plane at station R0.0 (s on the top of the figure indicates time of stronger spring tide).

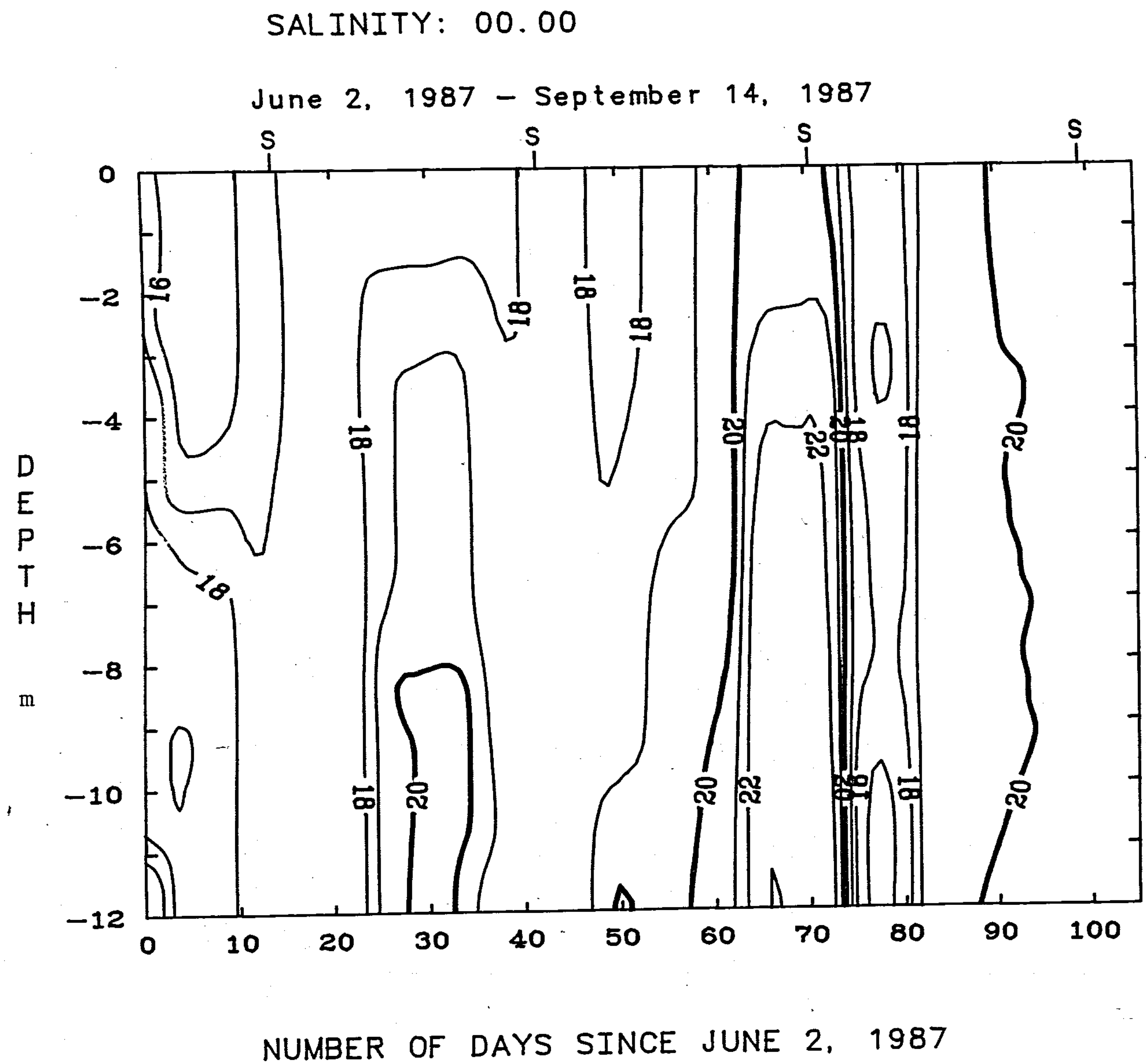


Figure 21b. Constant value contours of salinity in depth-time plane at Station R0.0.

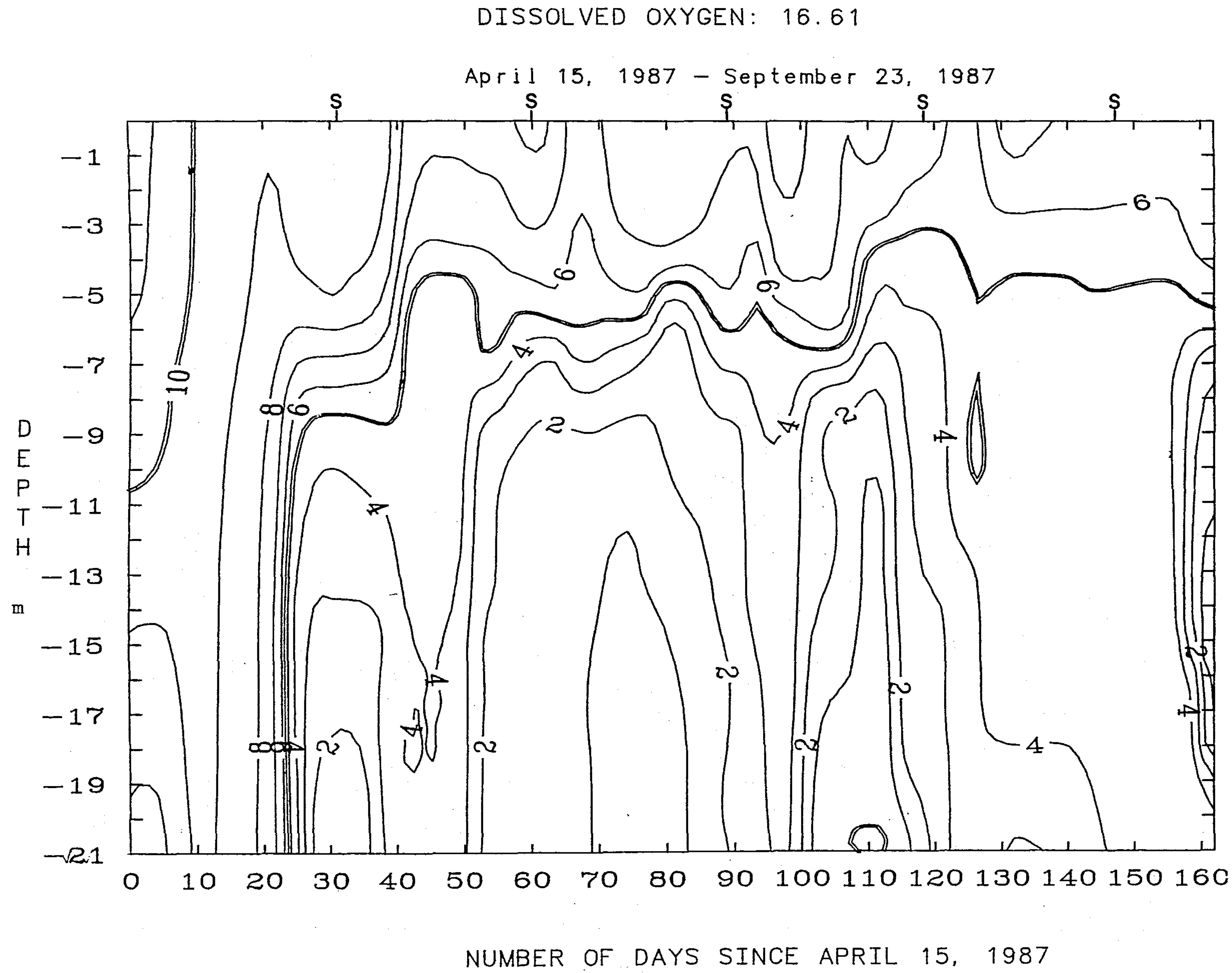


Figure 22a. Constant-value contours of DO in depth-time plane at station R16.6.

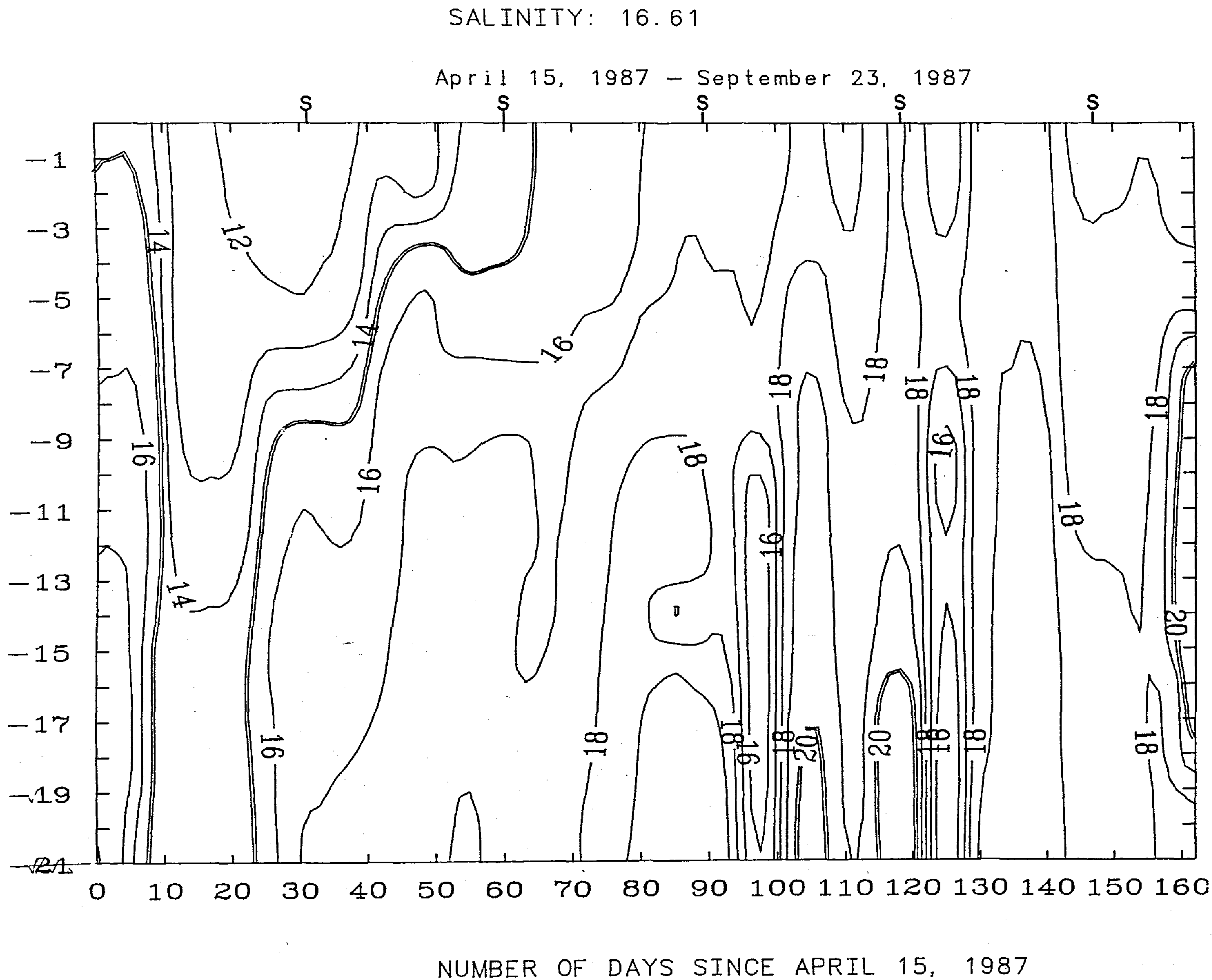


Figure 22b. Constant value contours of salinity in depth-time plane at station R16.6.

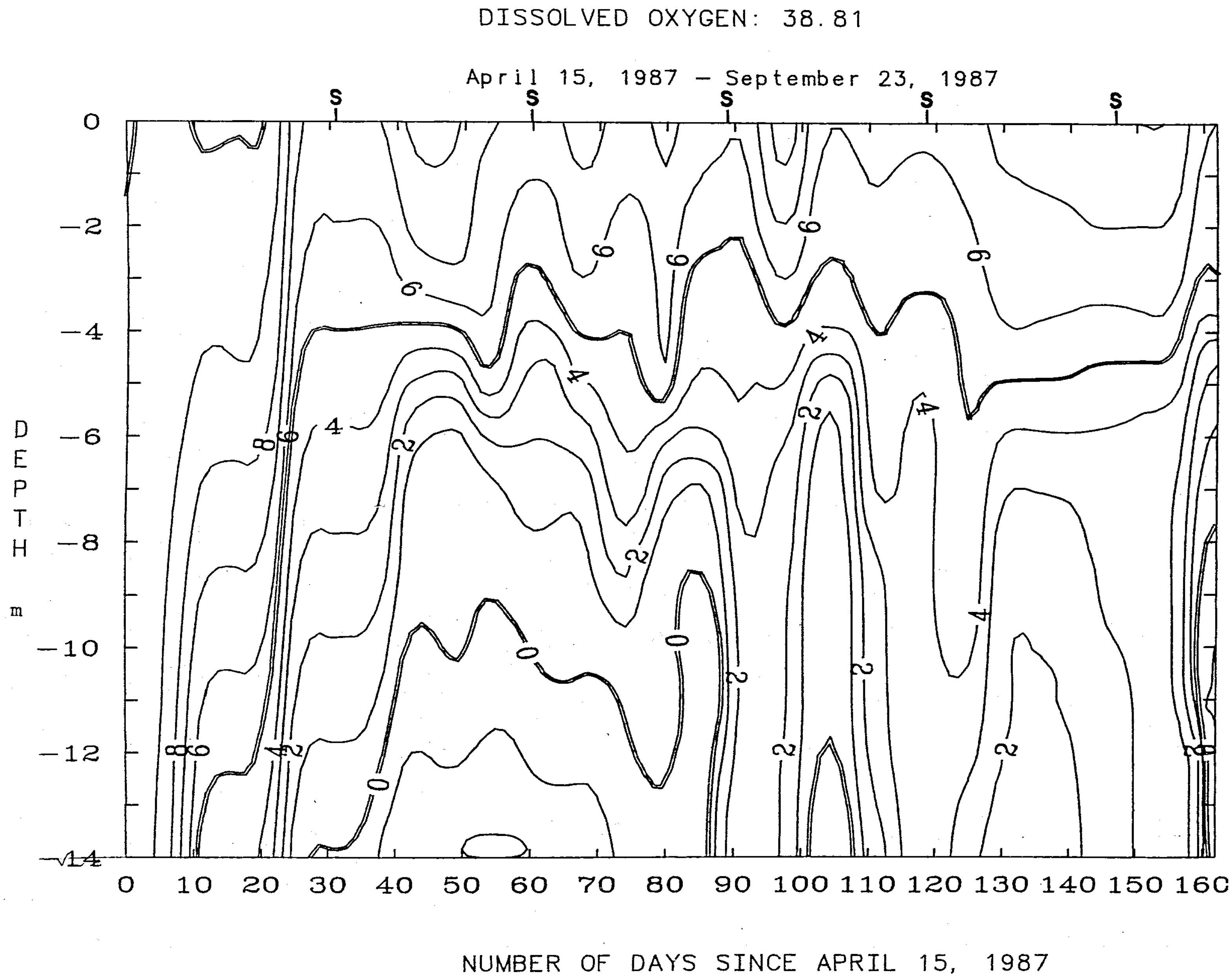


Figure 23a. Constant value contours of DO in depth-time plane at station R38.8.

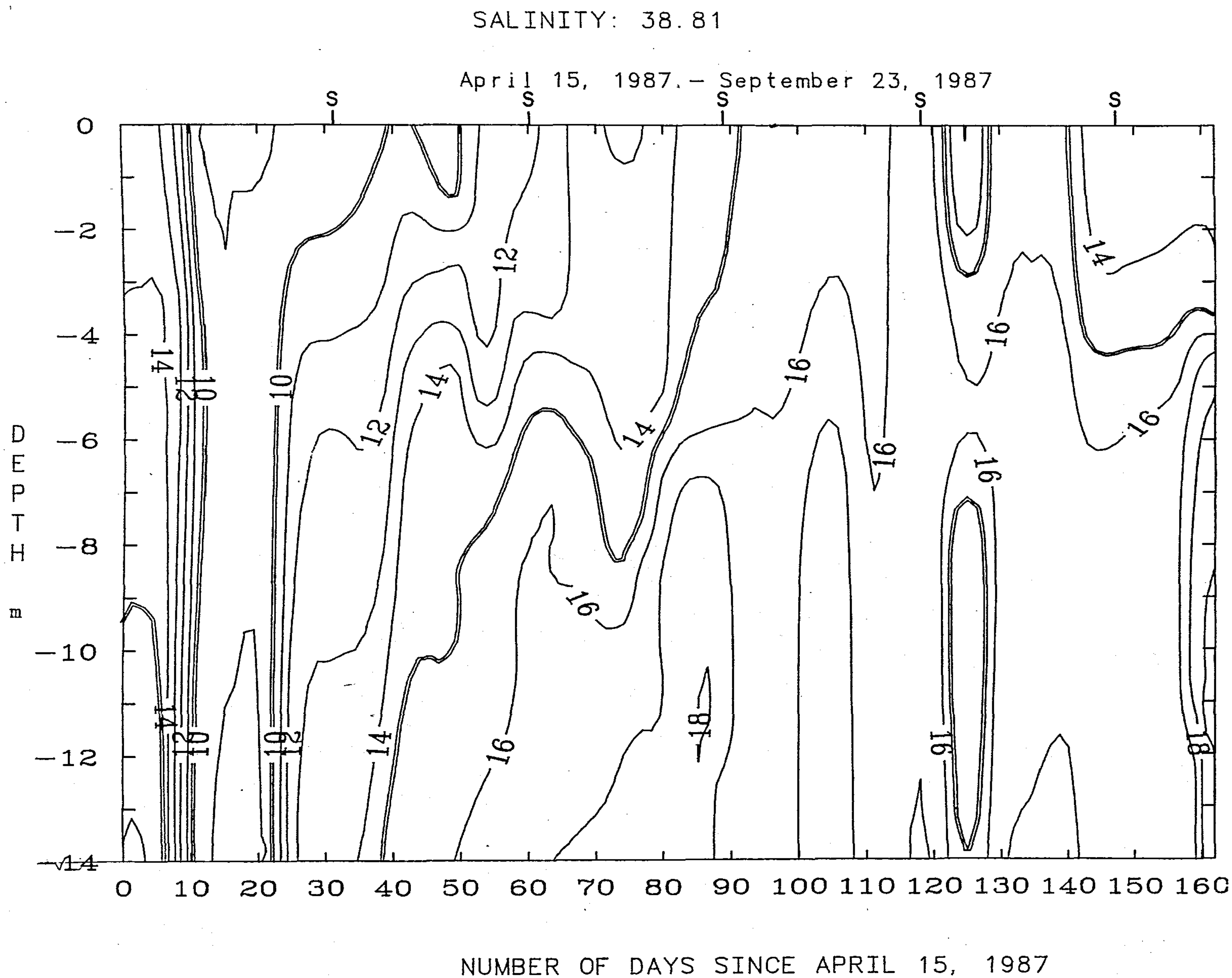


Figure 23b. Constant value contours of salinity in depth-time plane at station R38.8.

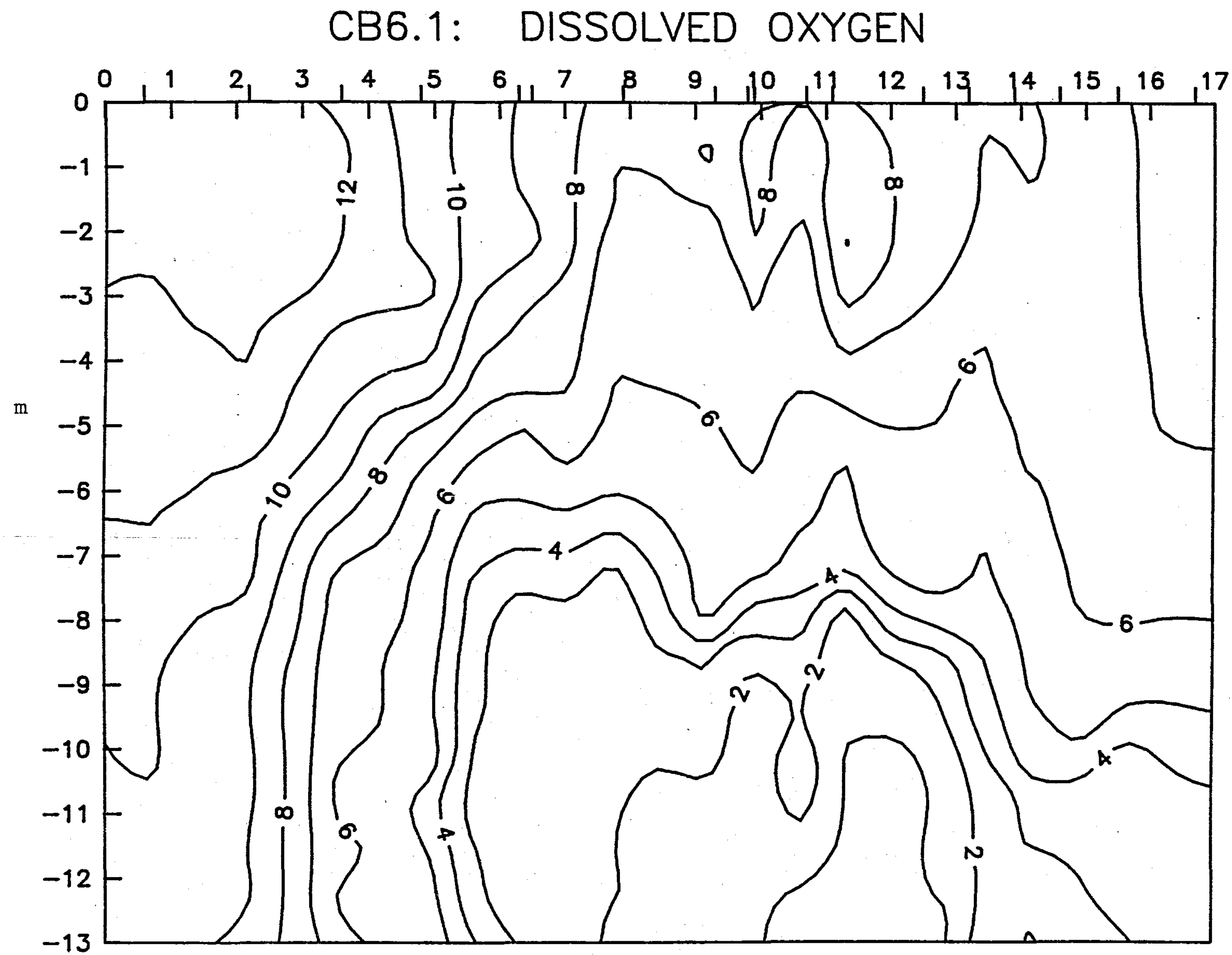


Figure 24a. Constant value contours of DO in depth-time plane at station in the bay off river mouth. (The abscissa is in number of 10 days since April 1, 1987).

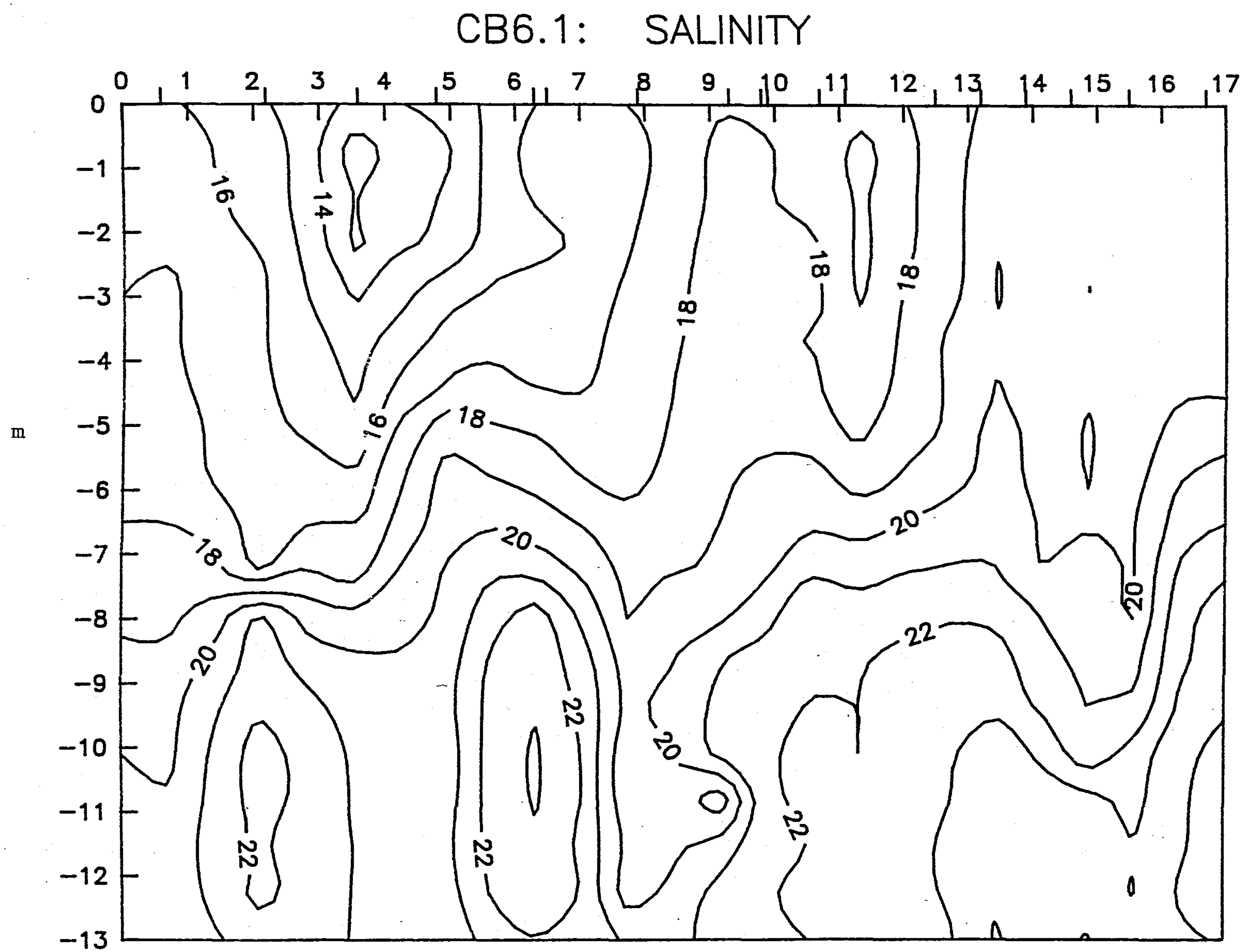


Figure 24b. Constant value contours of salinity in depth-time plane at station in the bay off river mouth. (The abscissa is in number of 10 days since April 1, 1987).

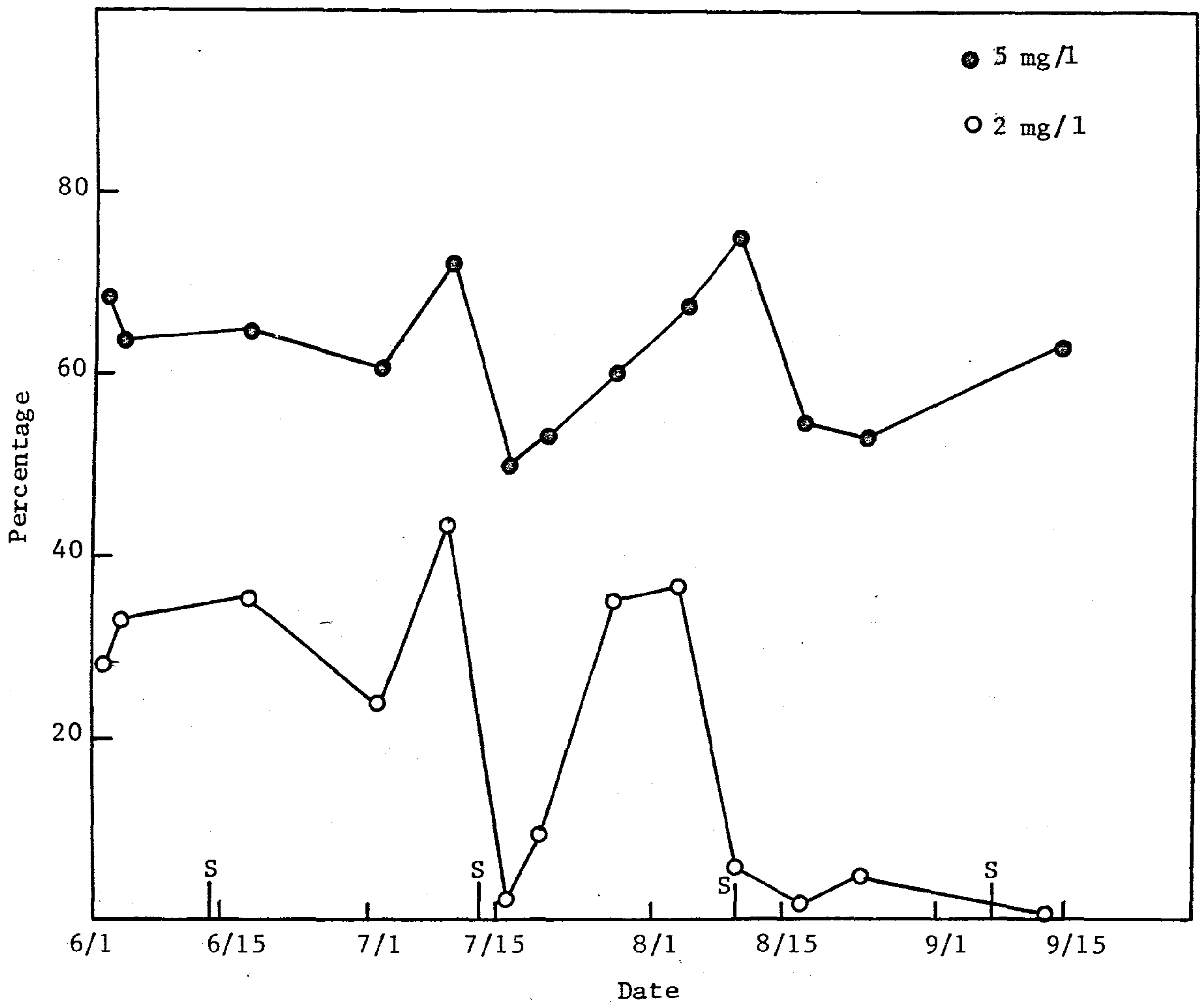
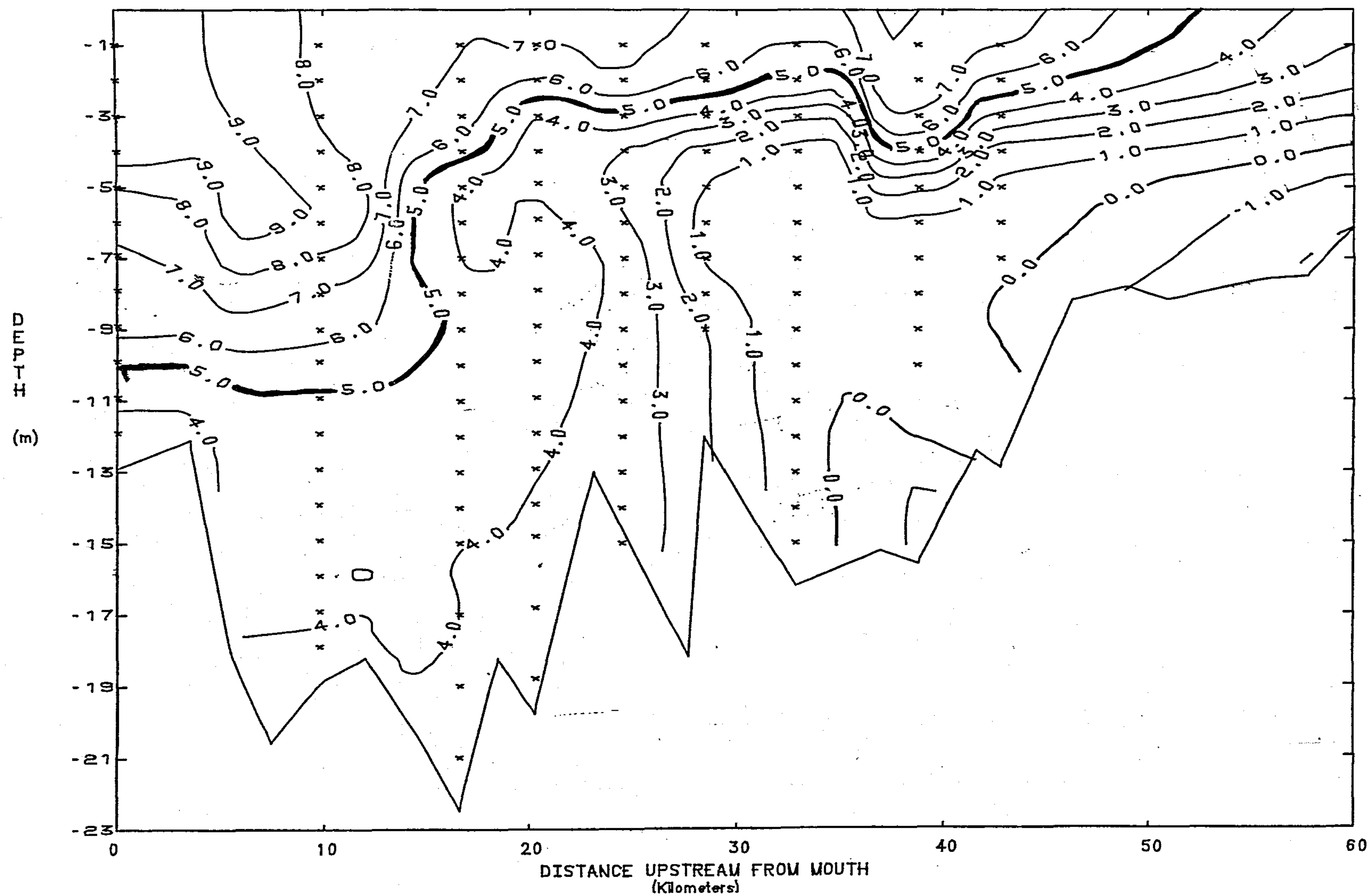


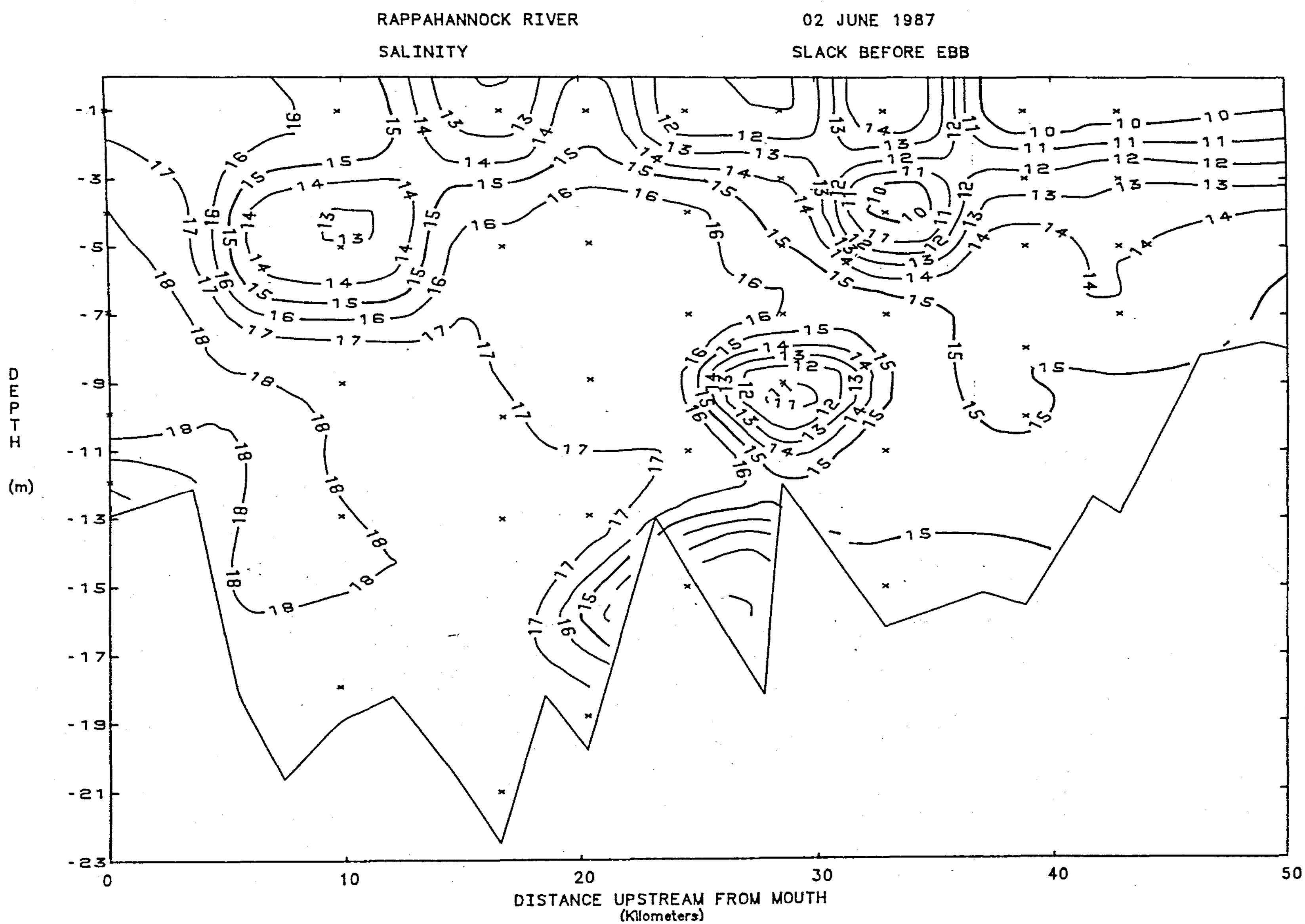
Figure 25. Percentage of water column with DO below 5 and 2 mg/l (S designates date of stronger spring tide).

APPENDIX

Contours of Constant Dissolved Oxygen, Salinity and Temperature Constructed from Slackwater Survey Data

RAPPAHANNOCK RIVER 02 JUNE 1987
DISSOLVED OXYGEN SLACK BEFORE EBB

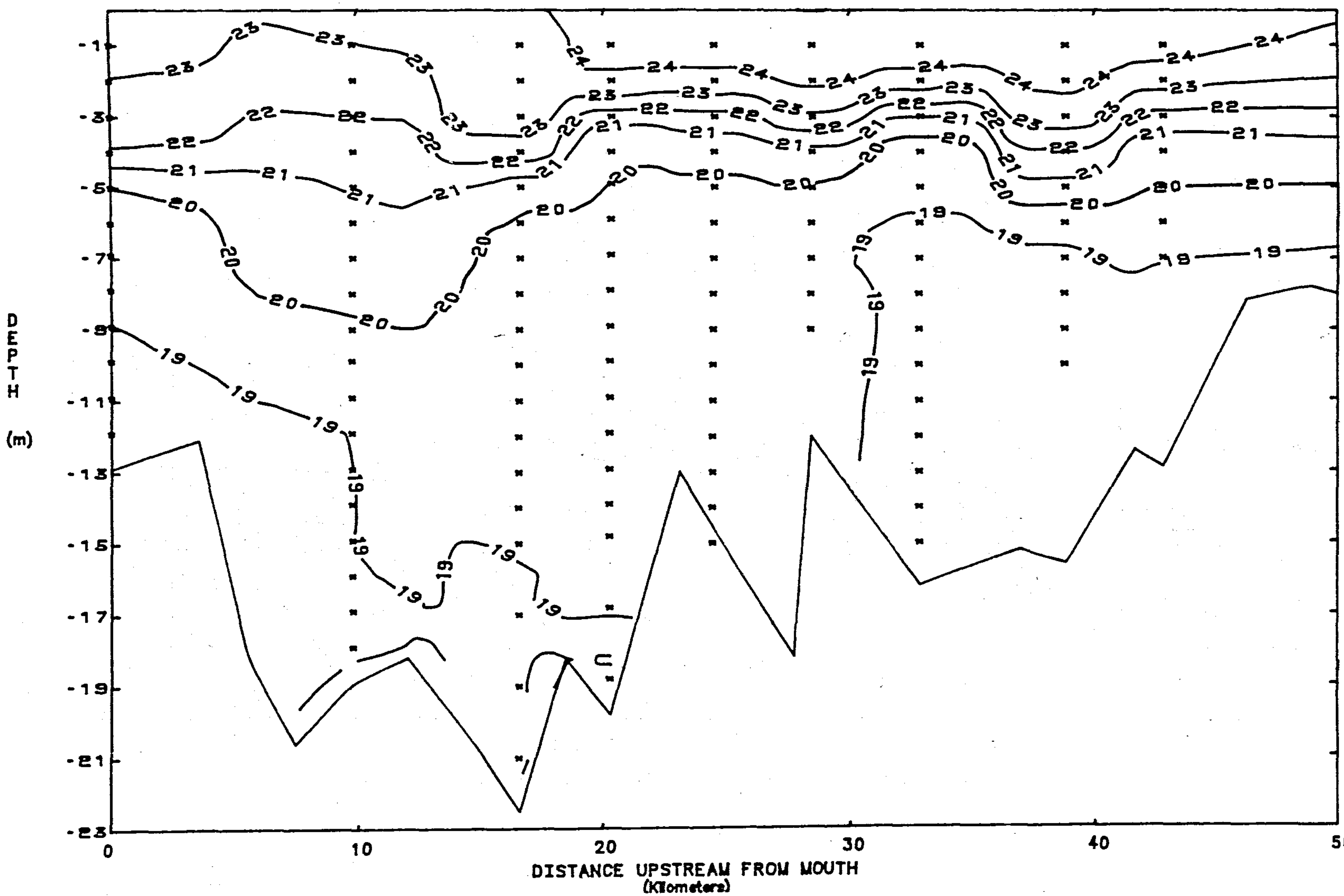


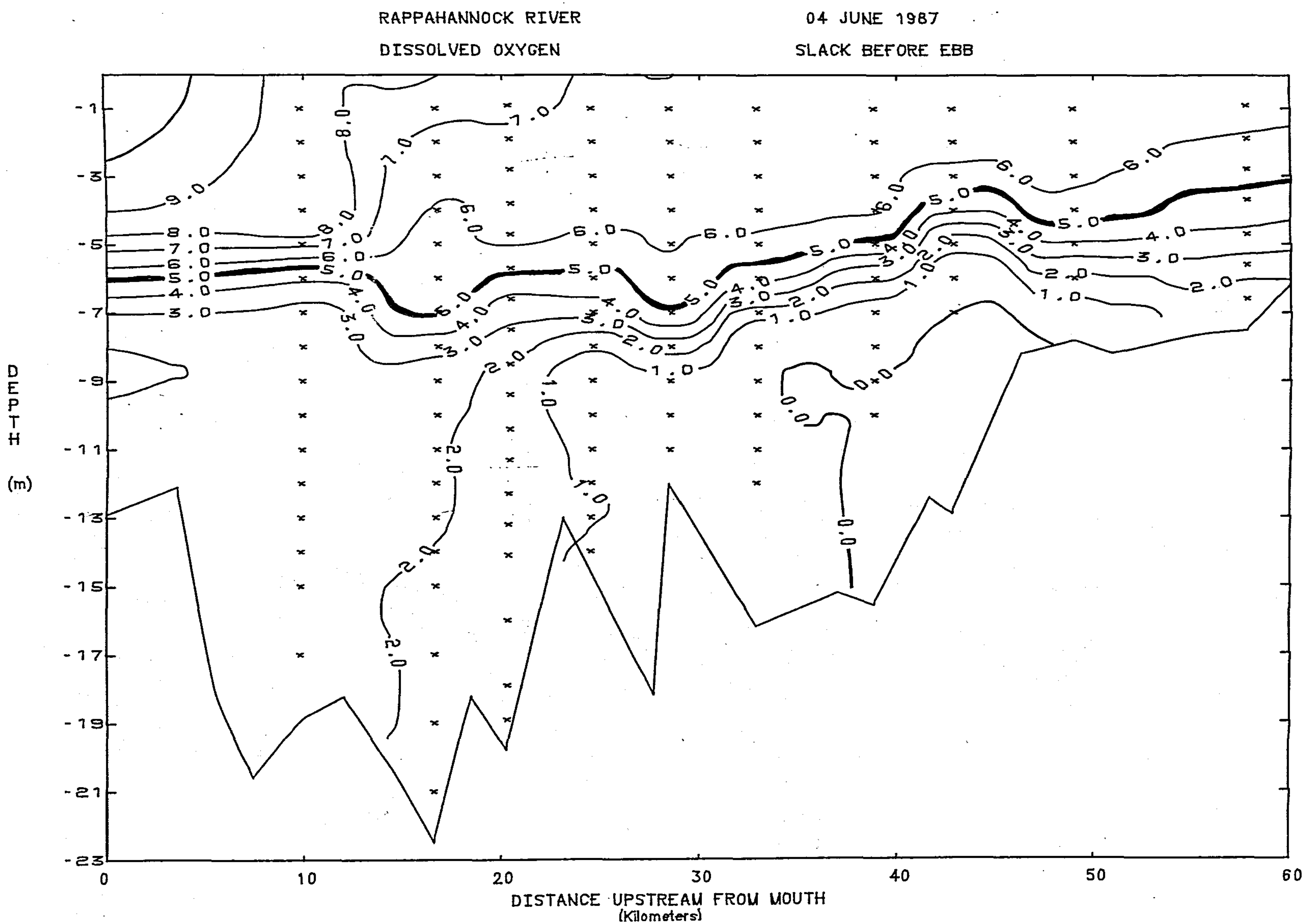


RAPPAHANNOCK RIVER
SALINITY
02 JUNE 1987
SLACK BEFORE EBB
DEPTH (m)
DISTANCE UPSTREAM FROM MOUTH
(Kilometers)

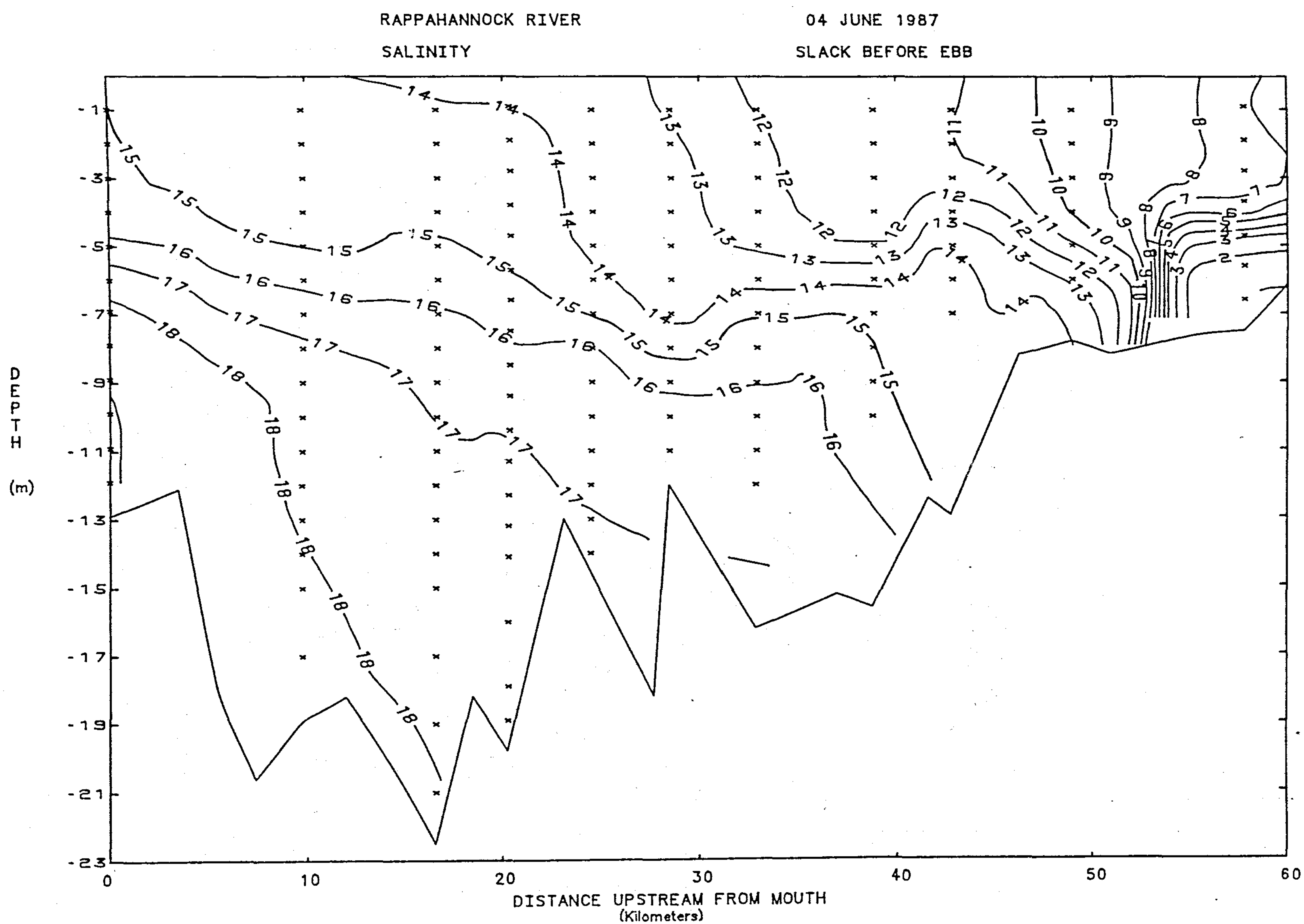
RAPPAHANNOCK RIVER 02 JUNE 1987

TEMPERATURE SLACK BEFORE EBB



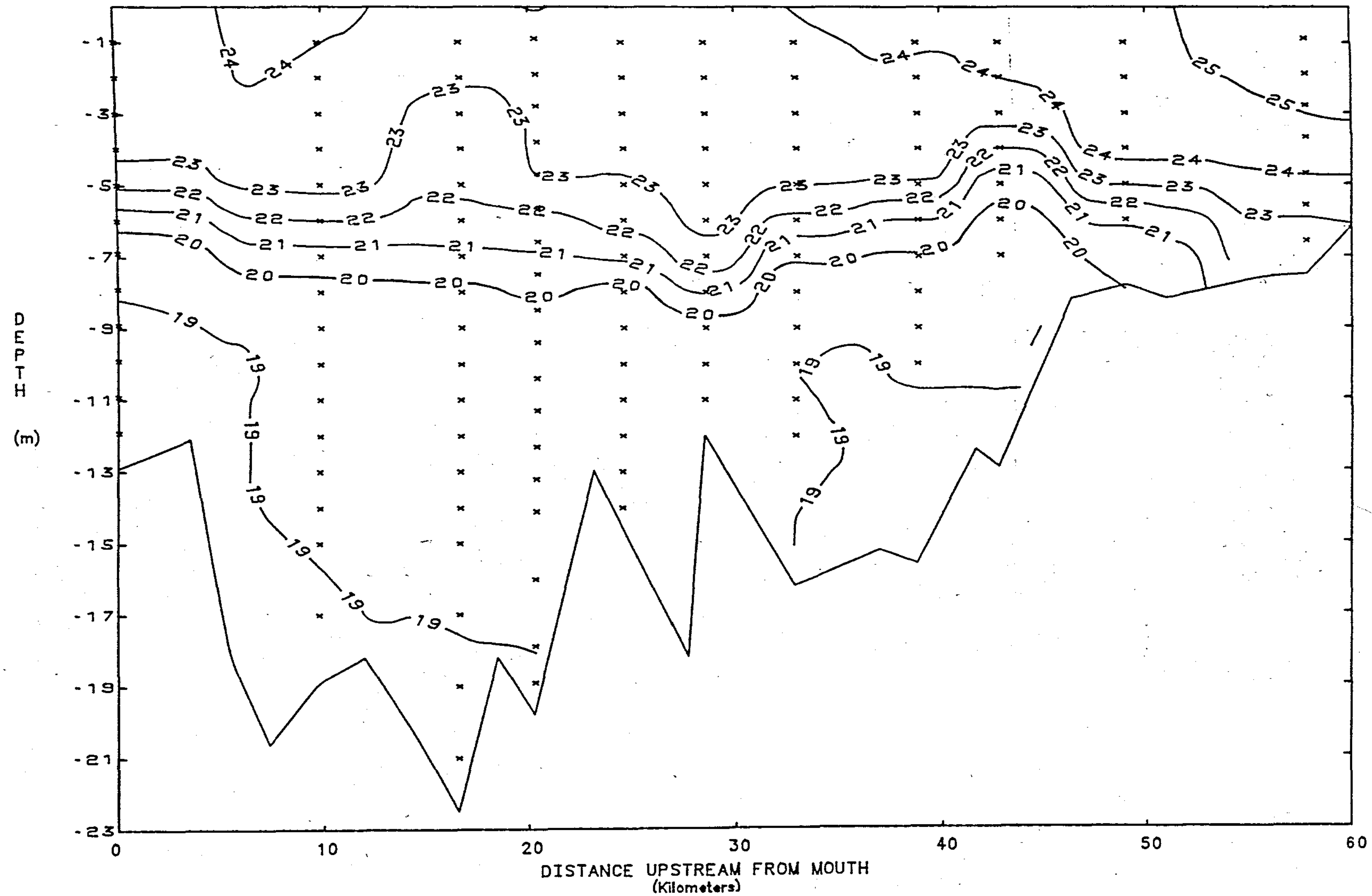


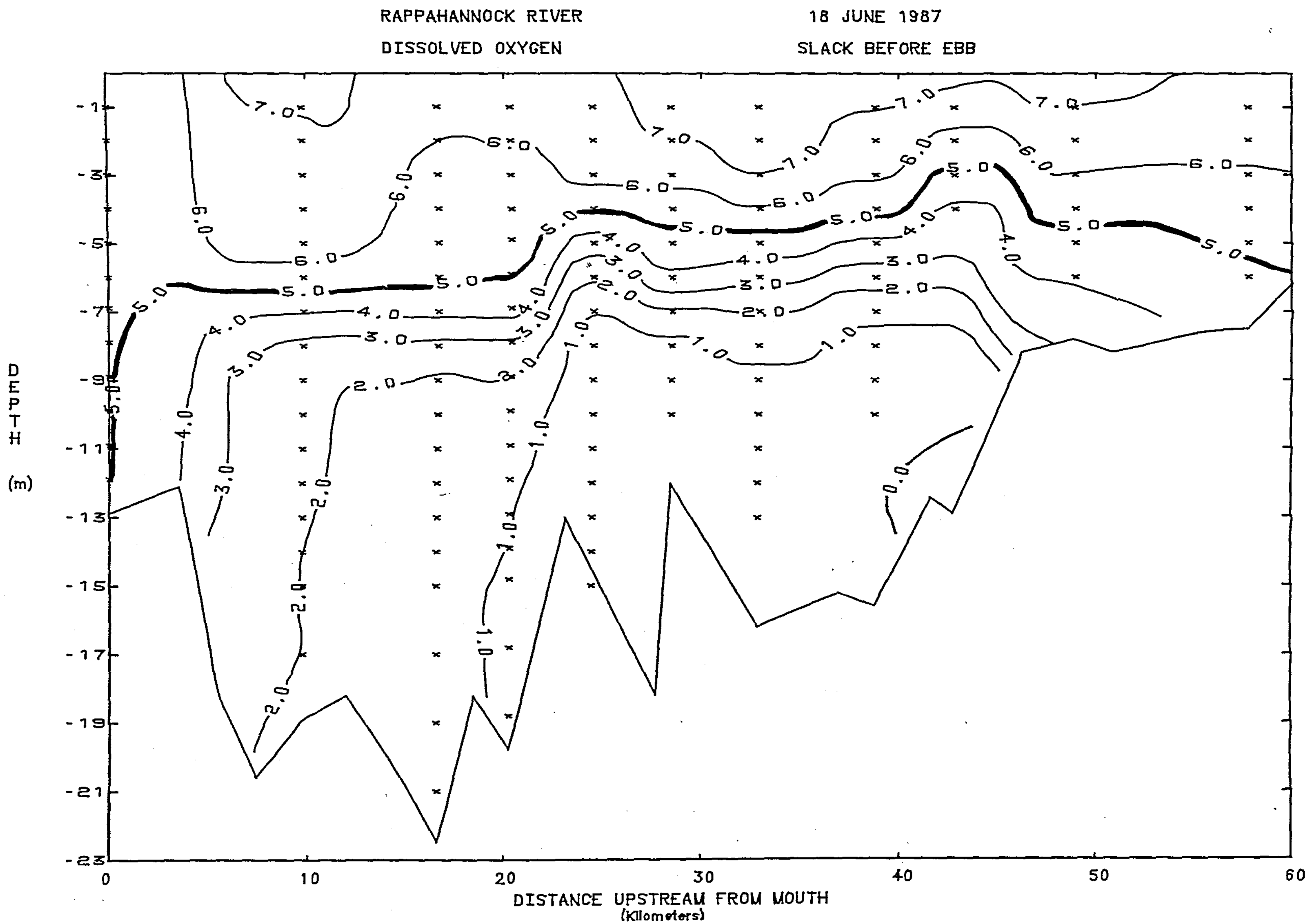
RAPPAHANNOCK RIVER
04 JUNE 1987
DISSOLVED OXYGEN
SLACK BEFORE EBB
DEPTH
(m)
-1
-3
-5
-7
-9
-11
-13
-15
-17
-19
-21
-23
0
10
20
30
40
50
60
DISTANCE UPSTREAM FROM MOUTH
(Kilometers)
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0

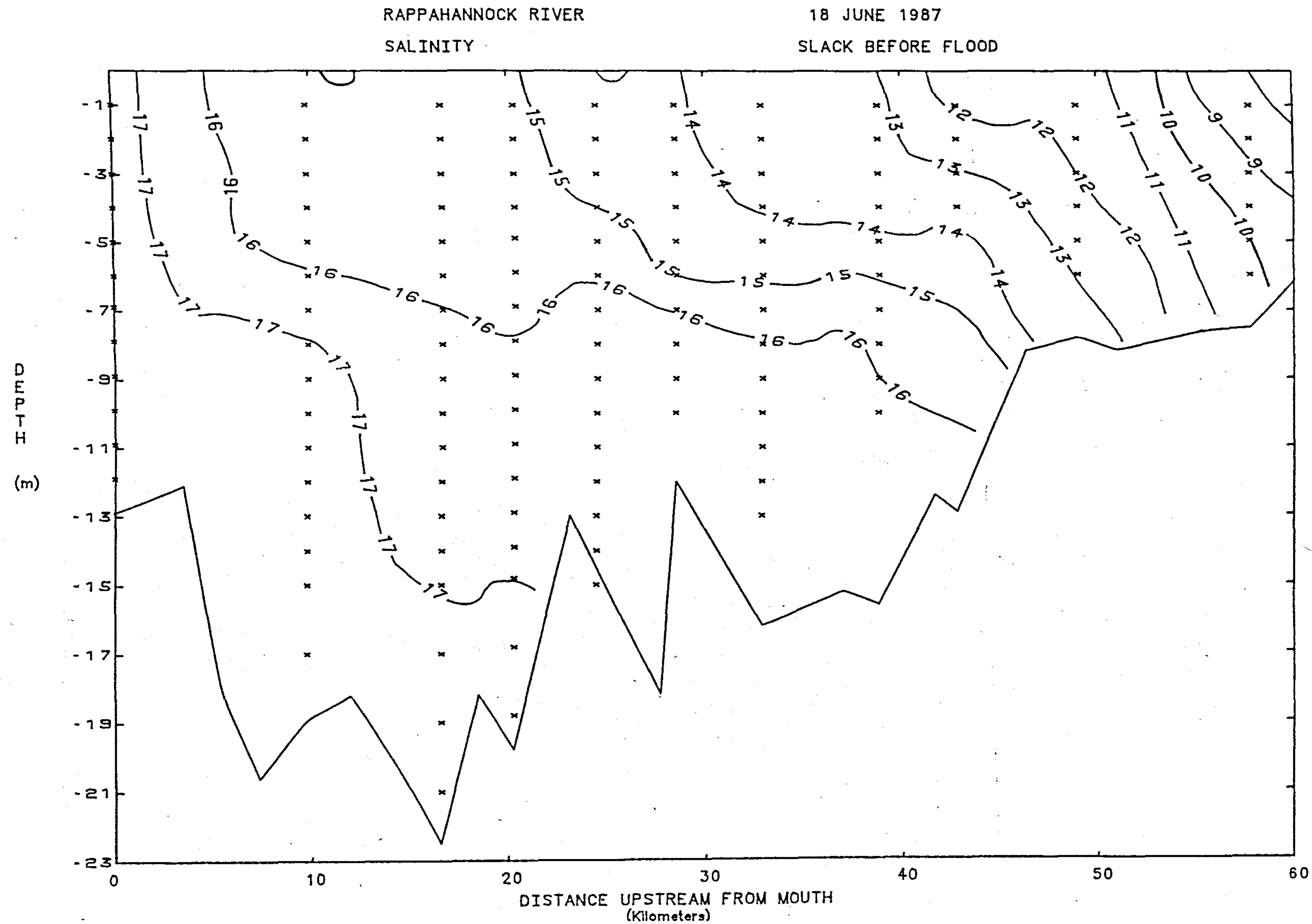

RAPPAHANNOCK RIVER
SALINITY
04 JUNE 1987
SLACK BEFORE EBB
DEPTH (m)
DISTANCE UPSTREAM FROM MOUTH
(Kilometers)

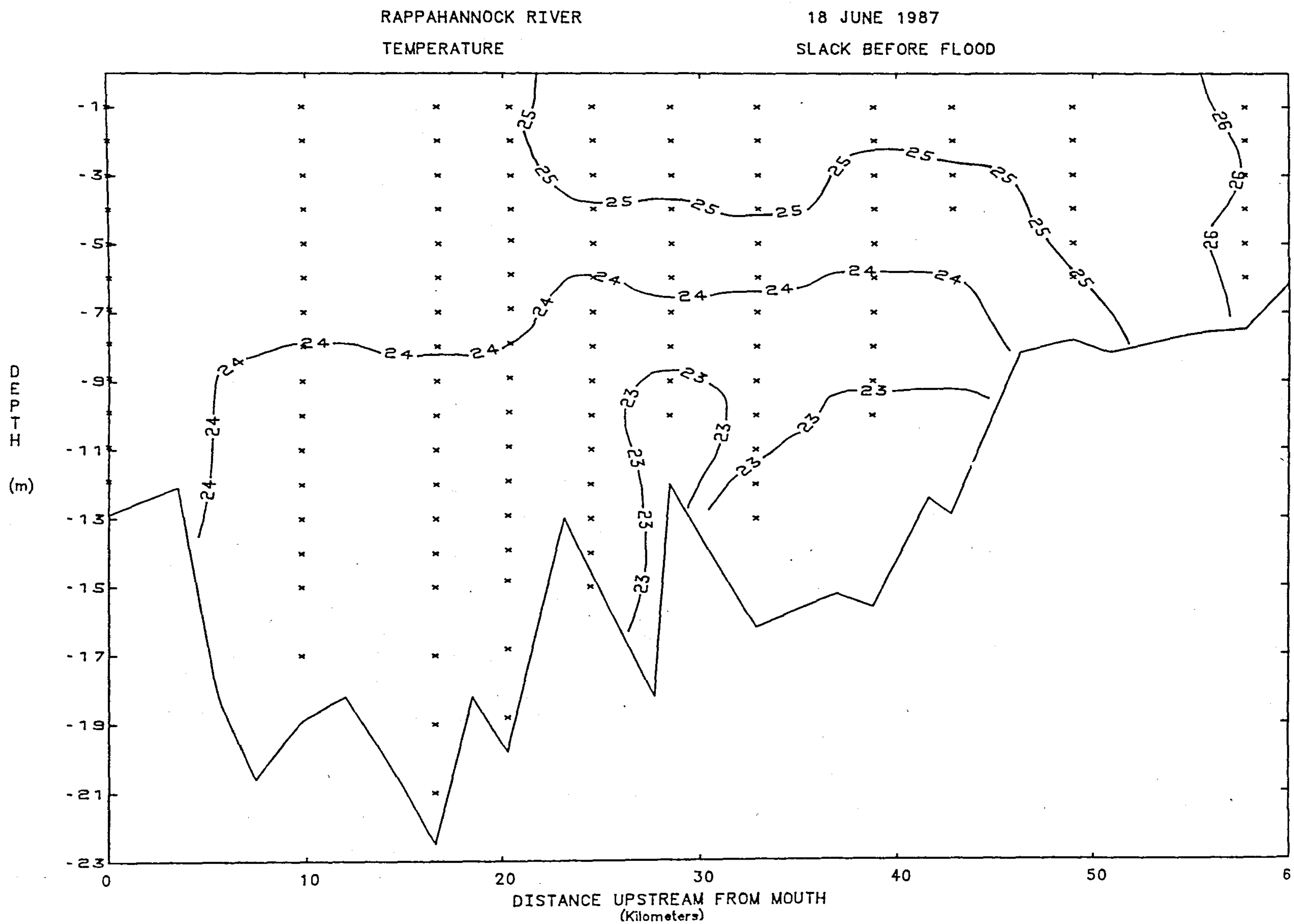
RAPPAHANNOCK RIVER 04 JUNE 1987

TEMPERATURE SLACK BEFORE EBB

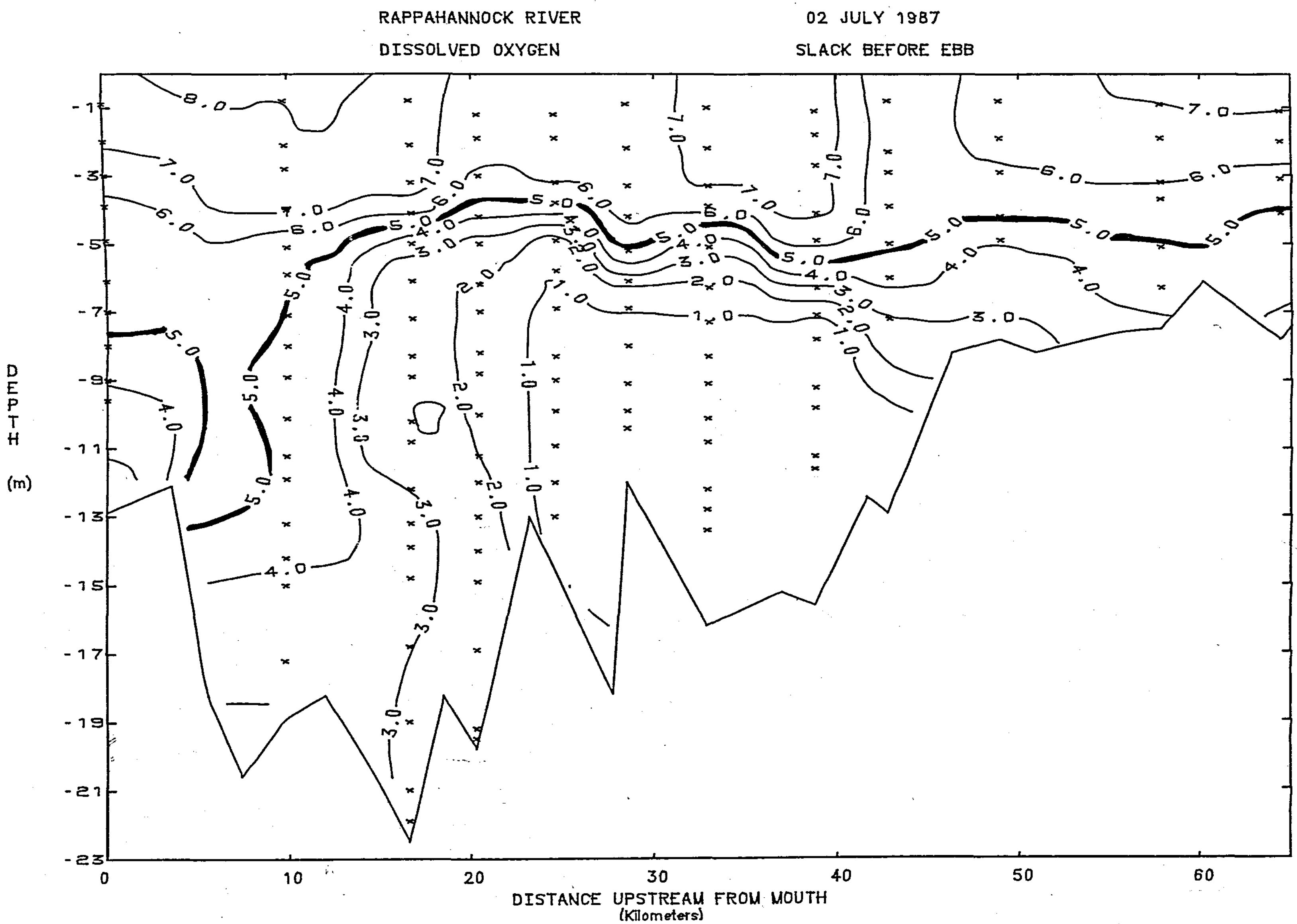



RAPPAHANNOCK RIVER
DISSOLVED OXYGEN
18 JUNE 1987
SLACK BEFORE EBB
DEPTH
(m)
-1
-3
-5
-7
-9
-11
-13
-15
-17
-19
-21
-23
0
10
20
30
40
50
60
DISTANCE UPSTREAM FROM MOUTH
(Kilometers)
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0

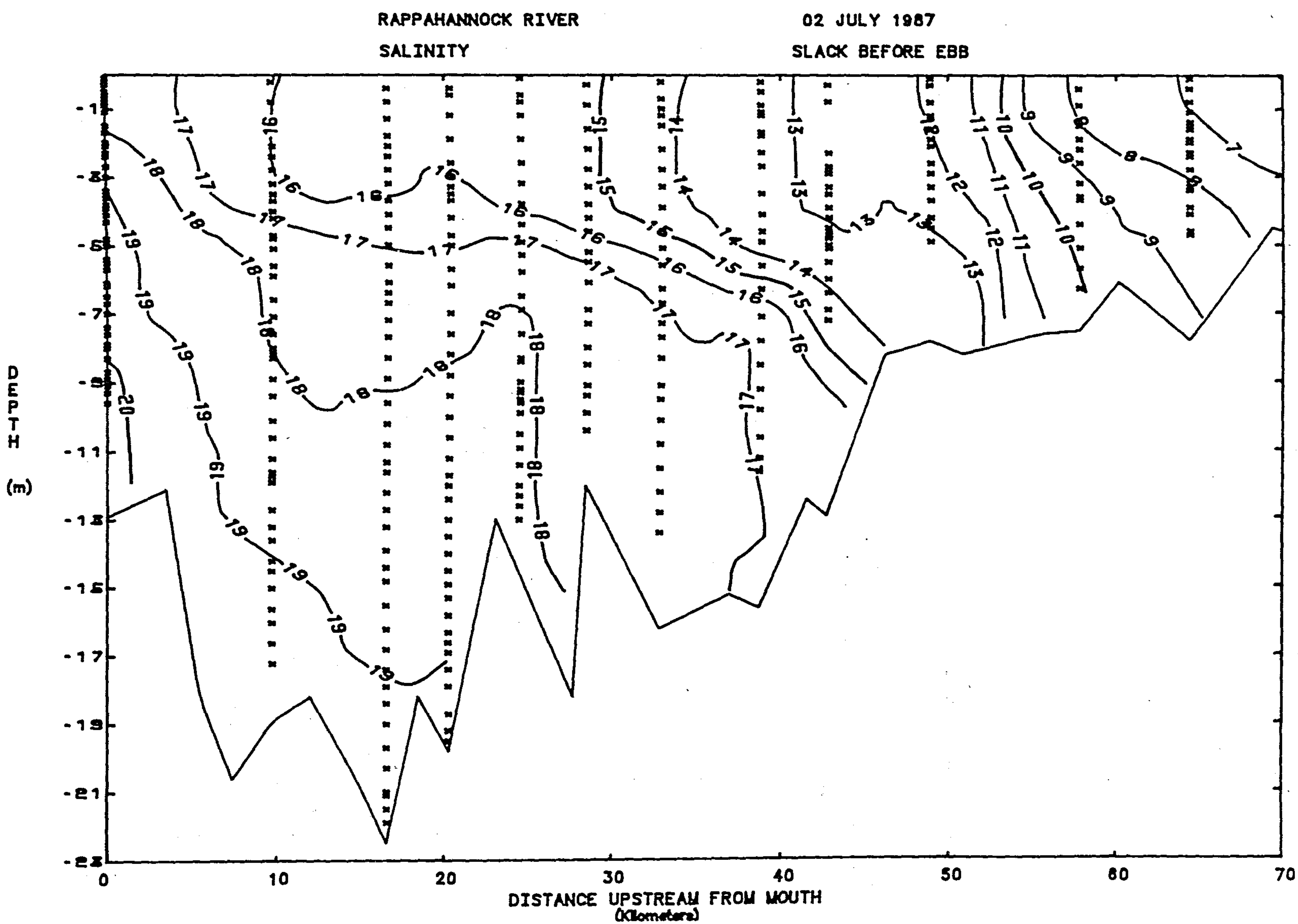

RAPPAHANNOCK RIVER
18 JUNE 1987
SALINITY
SLACK BEFORE FLOOD
DEPTH
(m)
-1
-3
-5
-7
-9
-11
-13
-15
-17
-19
-21
-23
0
10
20
30
40
50
60
DISTANCE UPSTREAM FROM MOUTH
(Kilometers)

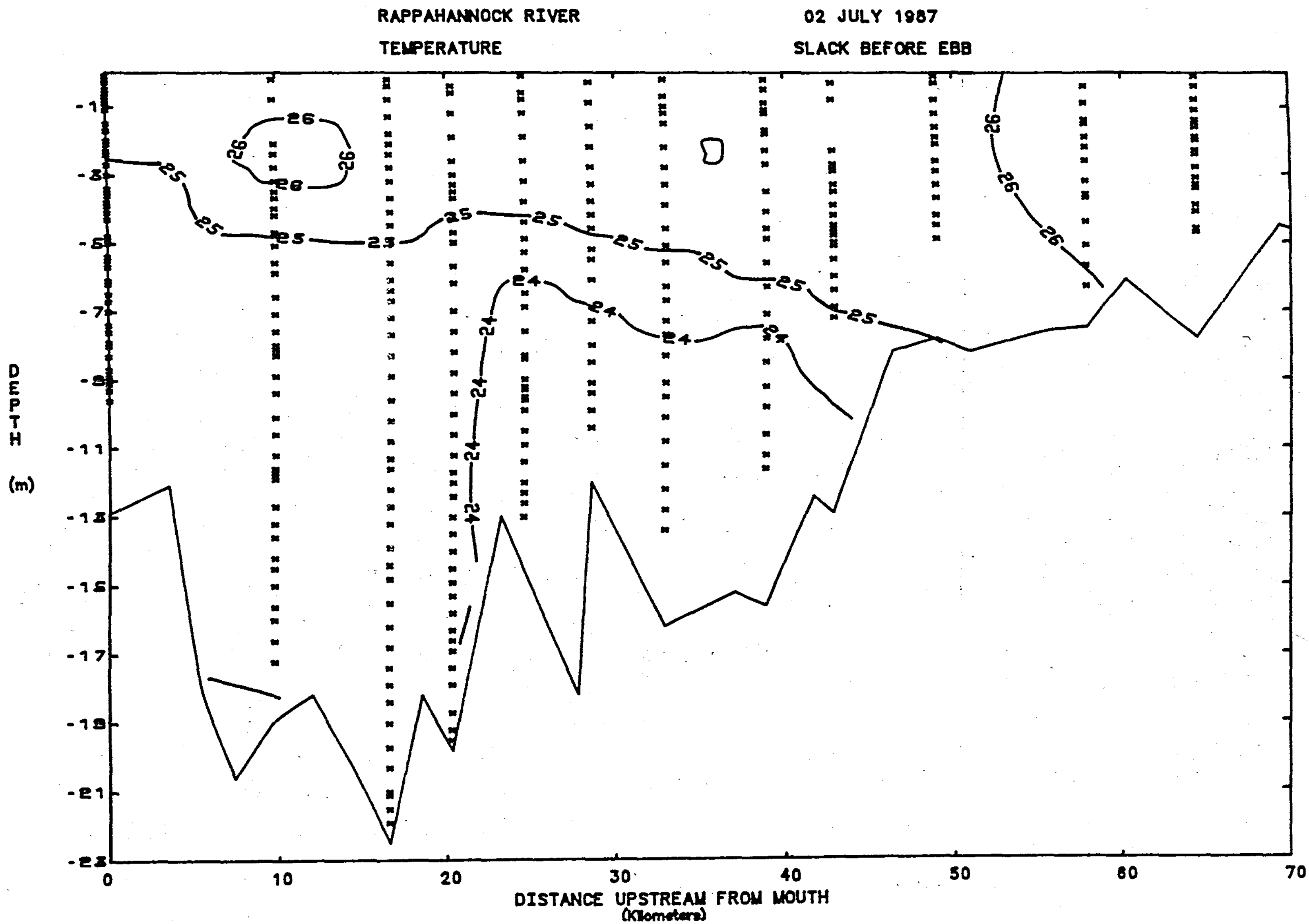


RAPPAHANNOCK RIVER
18 JUNE 1987
TEMPERATURE
SLACK BEFORE FLOOD
DEPTH
(m)
DISTANCE UPSTREAM FROM MOUTH
(Kilometers)

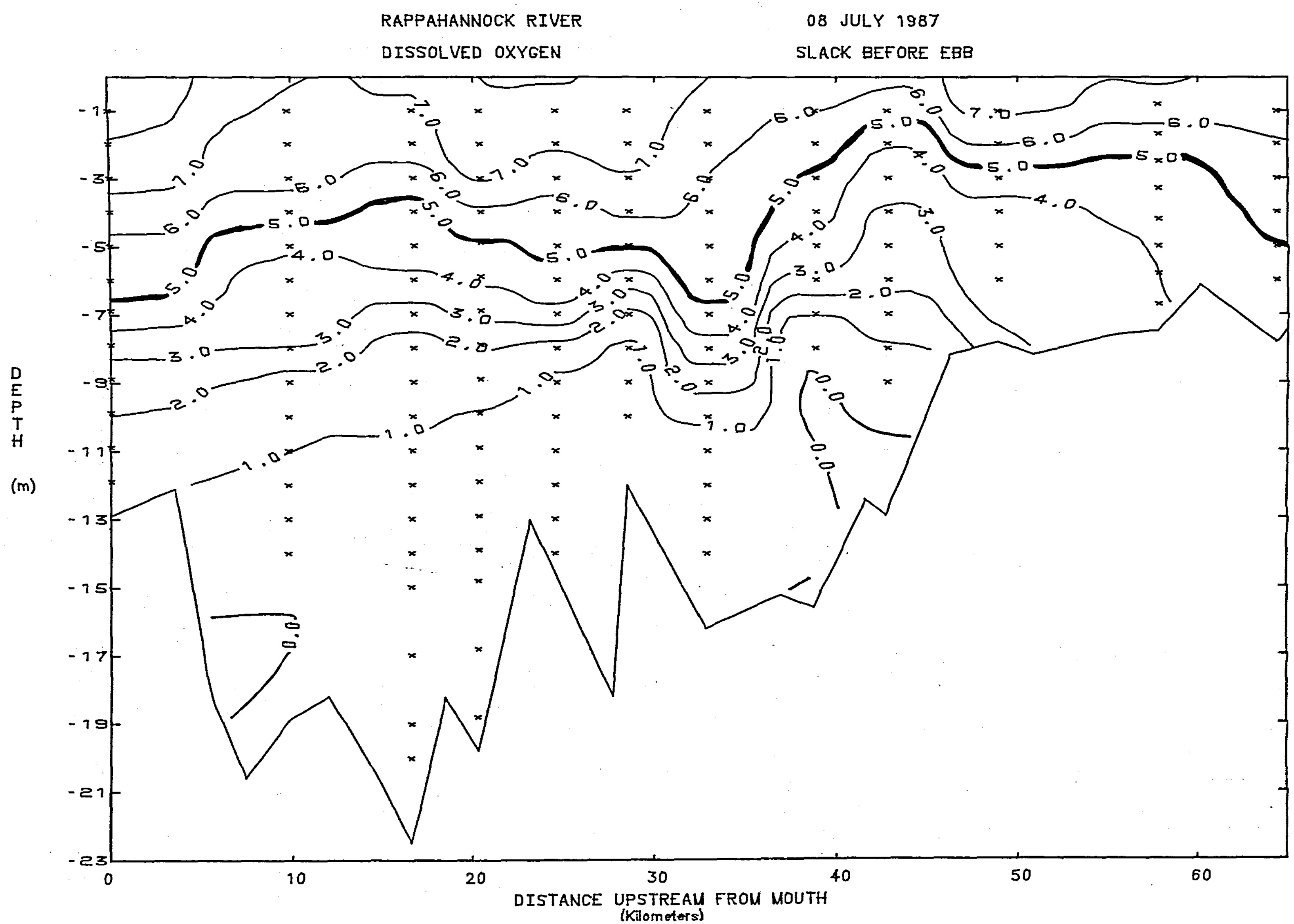


RAPPAHANNOCK RIVER
02 JULY 1987
DISSOLVED OXYGEN
SLACK BEFORE EBB
DEPTH
(m)
DISTANCE UPSTREAM FROM MOUTH
(Kilometers)

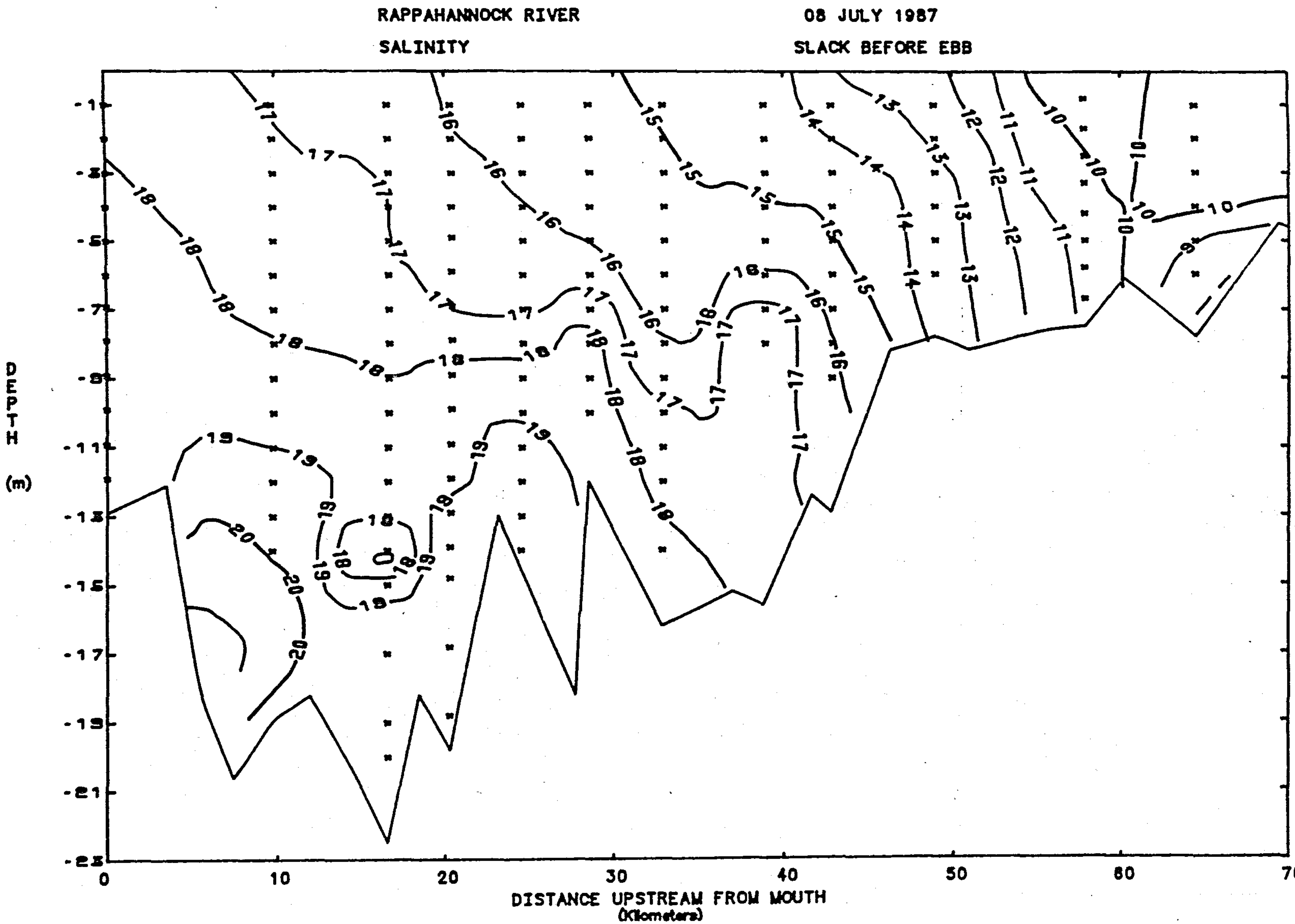

RAPPAHANNOCK RIVER
SALINITY
02 JULY 1987
SLACK BEFORE EBB
DEPTH (m)
DISTANCE UPSTREAM FROM MOUTH (Kilometers)
0
10
20
30
40
50
60
70



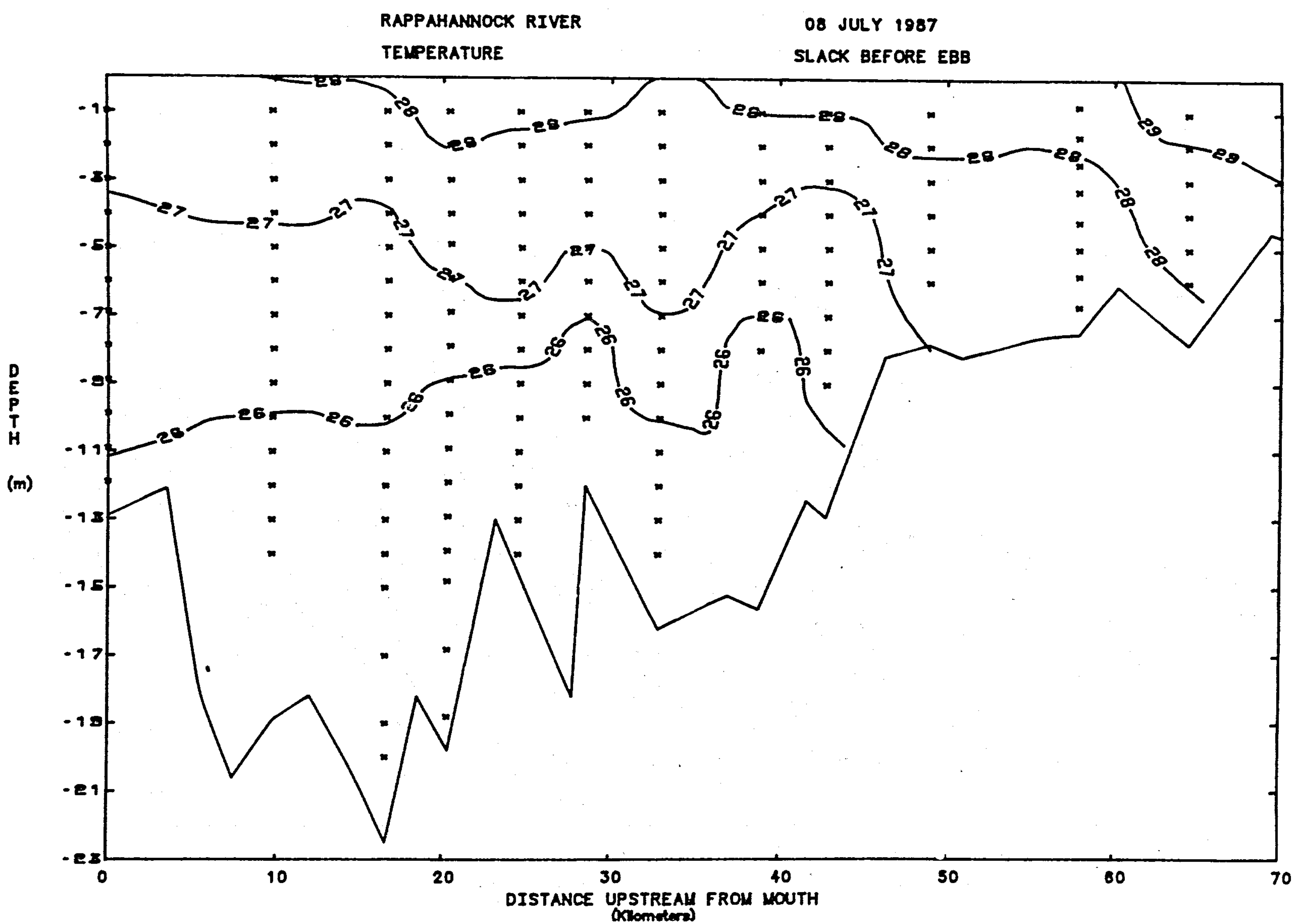
RAPPAHANNOCK RIVER
02 JULY 1987
TEMPERATURE
SLACK BEFORE EBB
DEPTH
(m)
DISTANCE UPSTREAM FROM MOUTH
(Kilometers)

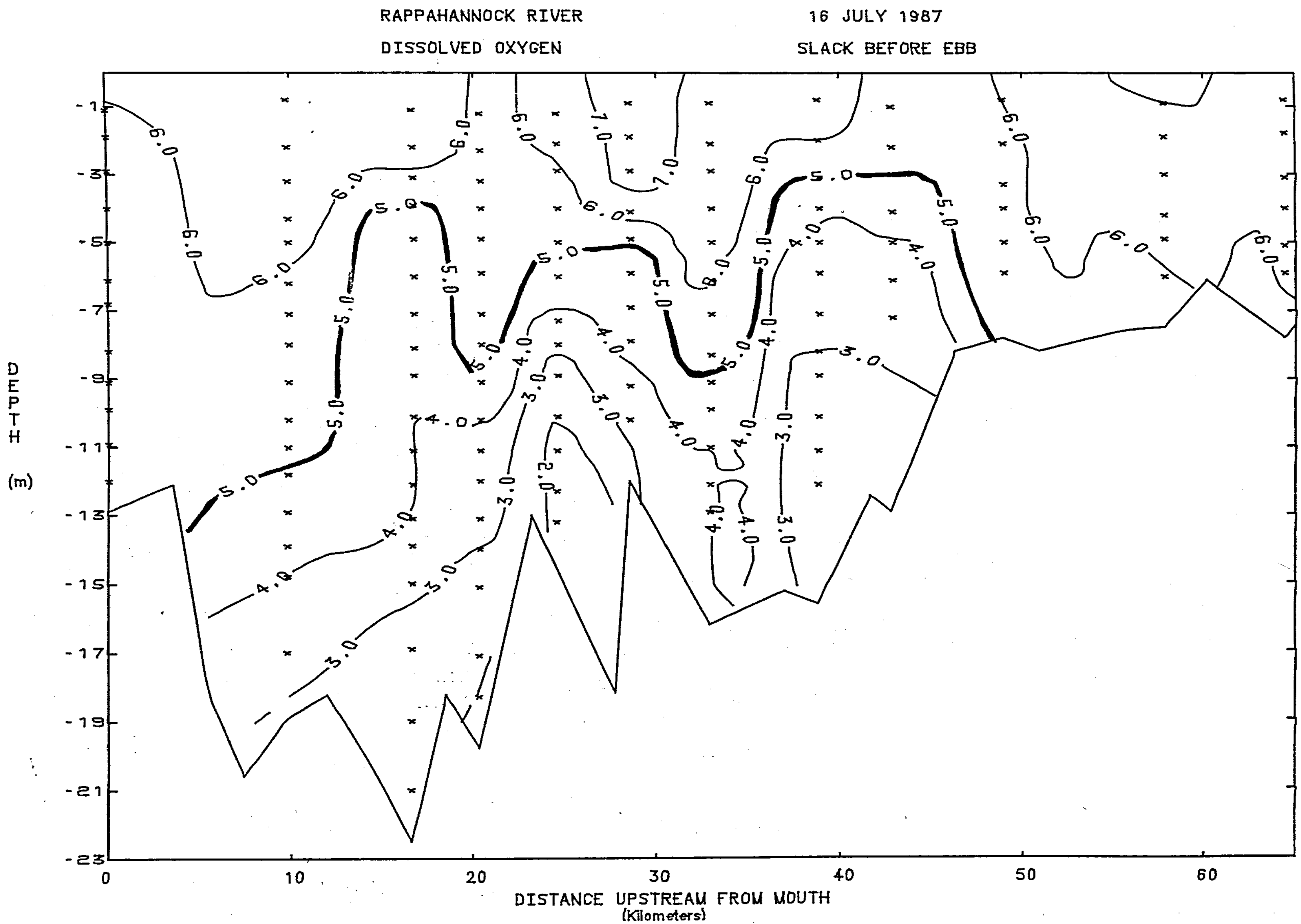


RAPPAHANNOCK RIVER
08 JULY 1987
DISSOLVED OXYGEN
SLACK BEFORE EBB
DEPTH
(m)
-1
-3
-5
-7
-9
-11
-13
-15
-17
-19
-21
-23
0
10
20
30
40
50
60
DISTANCE UPSTREAM FROM MOUTH
(Kilometers)
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0

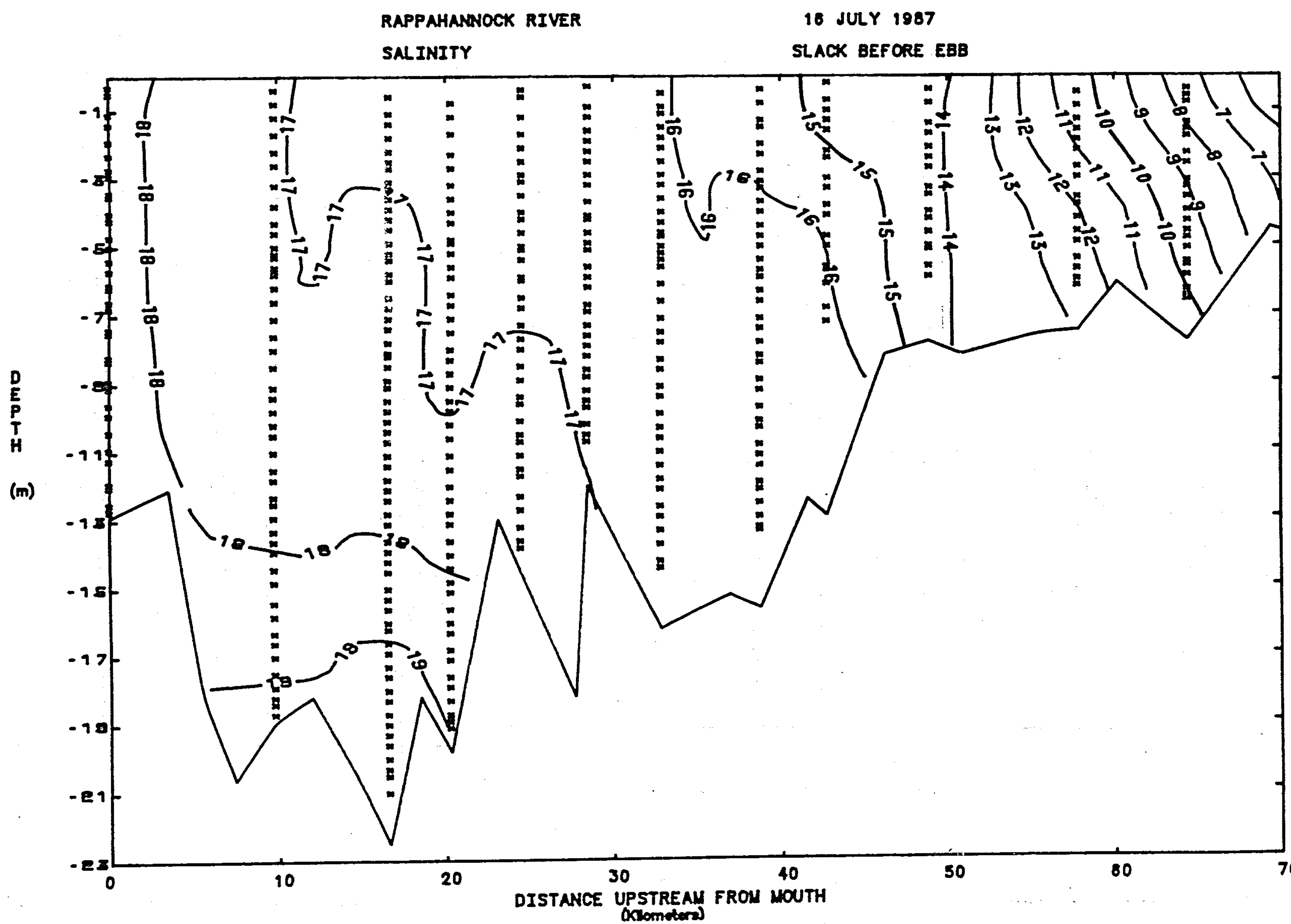


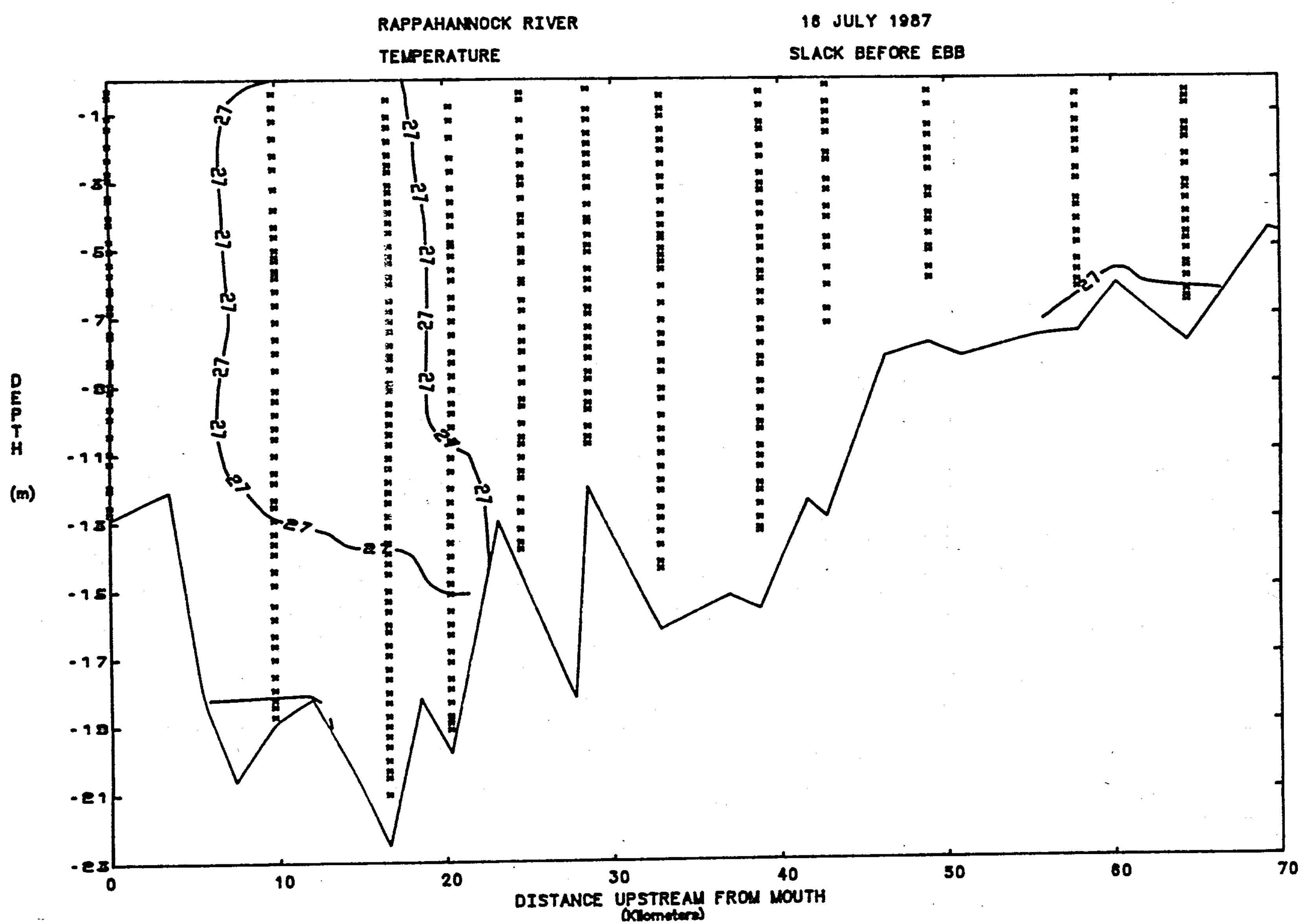
RAPPAHANNOCK RIVER
SALINITY
08 JULY 1987
SLACK BEFORE EBB
DEPTH (m)
DISTANCE UPSTREAM FROM MOUTH
(Kilometers)


RAPPAHANNOCK RIVER
TEMPERATURE
08 JULY 1987
SLACK BEFORE EBB
DEPTH
(m)
DISTANCE UPSTREAM FROM MOUTH
(Kilometers)

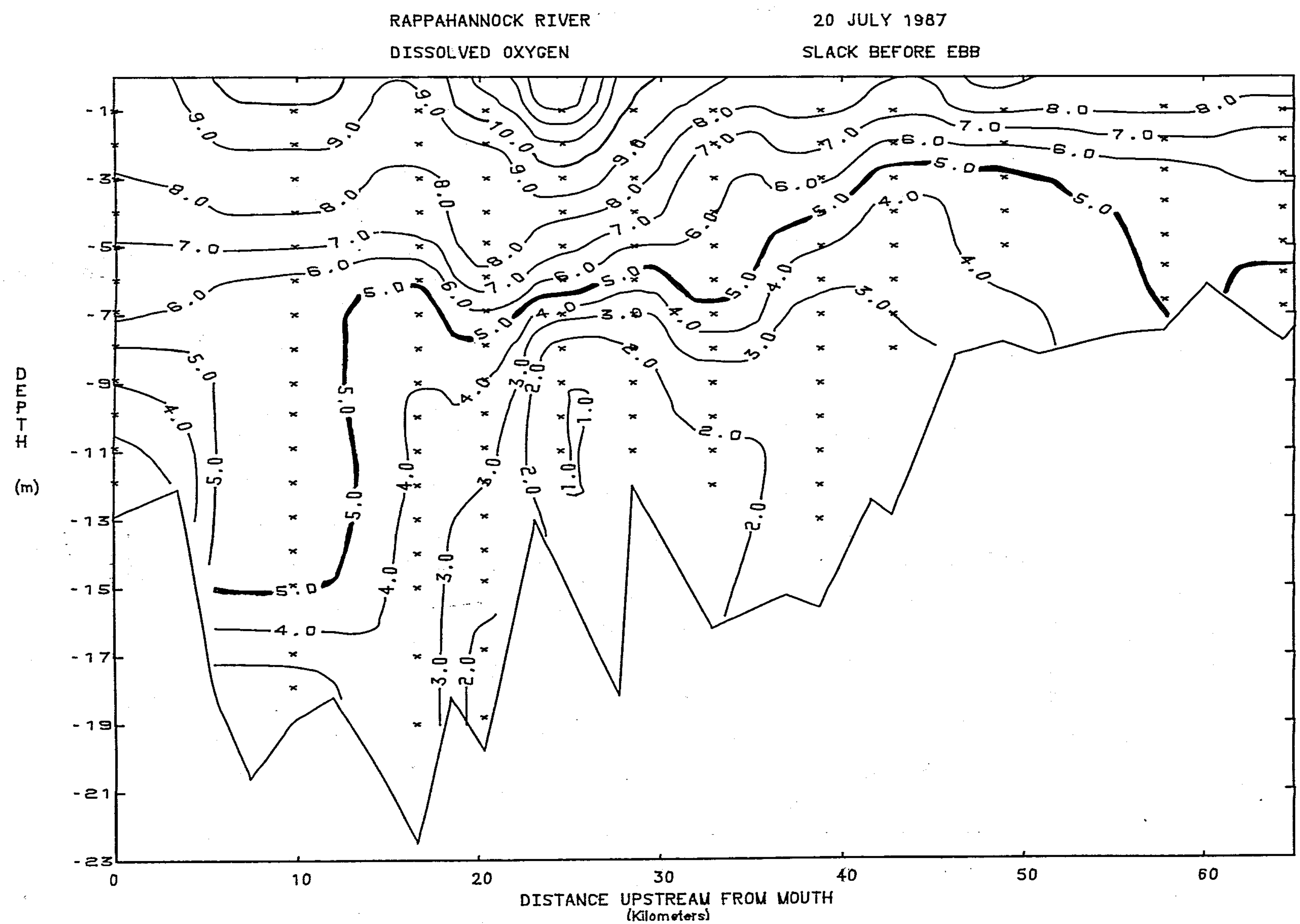


RAPPAHANNOCK RIVER
16 JULY 1987
DISSOLVED OXYGEN
SLACK BEFORE EBB
DEPTH (m)
-1
-3
-5
-7
-9
-11
-13
-15
-17
-19
-21
-23
0
10
20
30
40
50
60
DISTANCE UPSTREAM FROM MOUTH
(Kilometers)
7.0
6.0
5.0
4.0
3.0
2.0

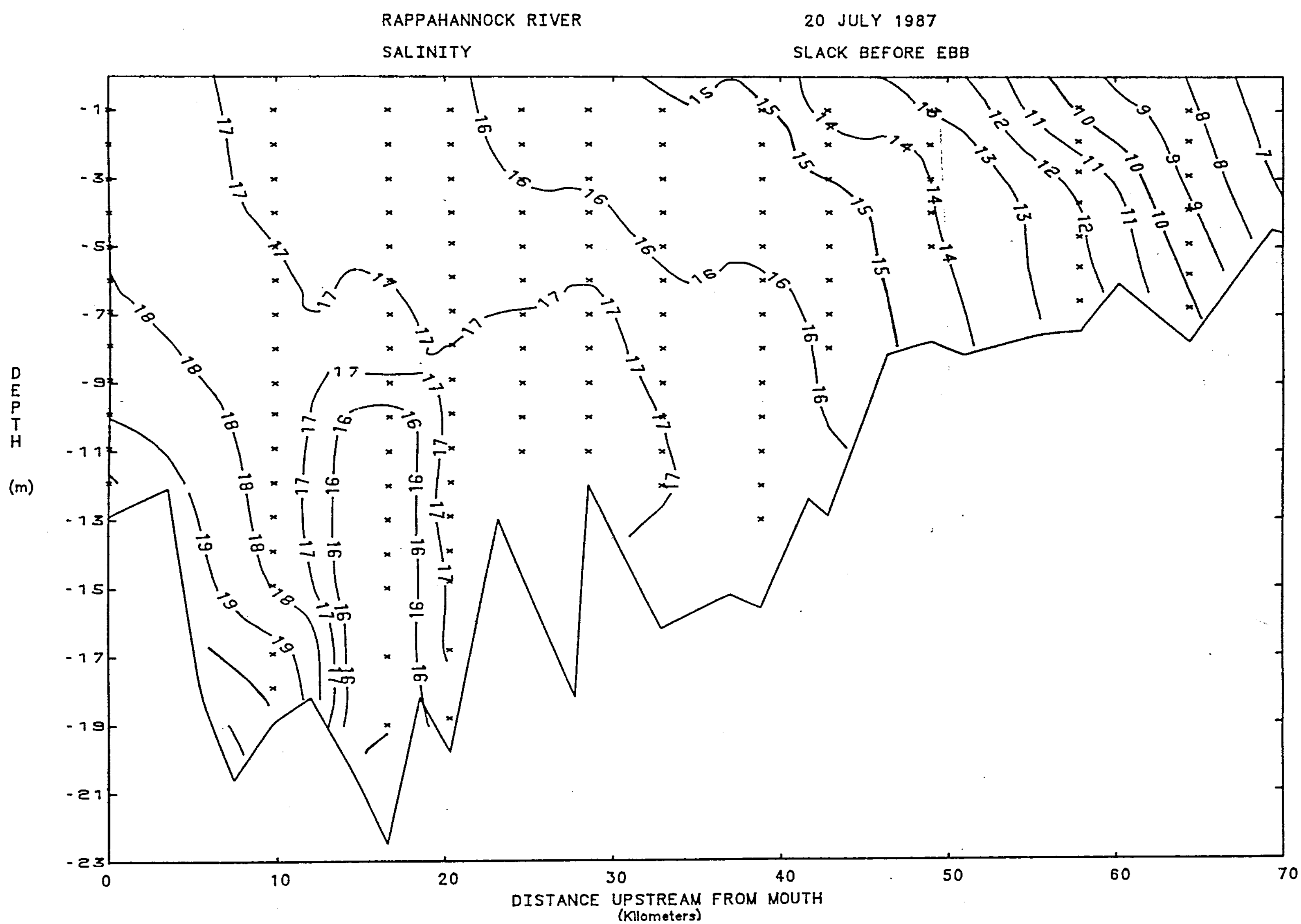

RAPPAHANNOCK RIVER
SALINITY
16 JULY 1987
SLACK BEFORE EBB
DEPTH (m)
DISTANCE UPSTREAM FROM MOUTH
(Kilometers)

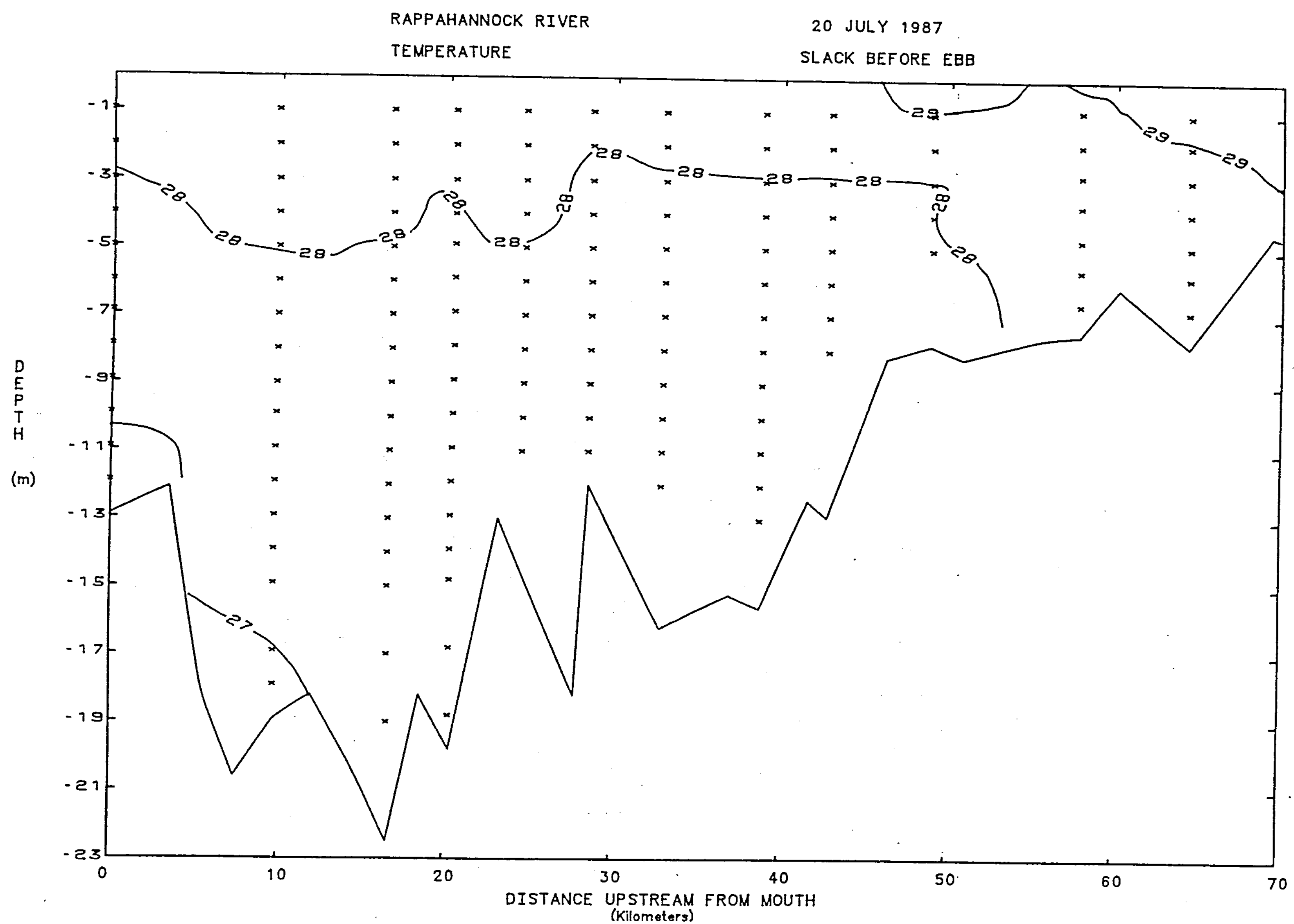


RAPPAHANNOCK RIVER
TEMPERATURE
16 JULY 1987
SLACK BEFORE EBB
DEPTH
(m)
-1
-3
-5
-7
-9
-11
-13
-15
-17
-19
-21
-23
27
0
10
20
30
40
50
60
70
DISTANCE UPSTREAM FROM MOUTH
(Kilometers)



RAPPAHANNOCK RIVER
DISSOLVED OXYGEN
20 JULY 1987
SLACK BEFORE EBB
DEPTH
(m)
DISTANCE UPSTREAM FROM MOUTH
(Kilometers)

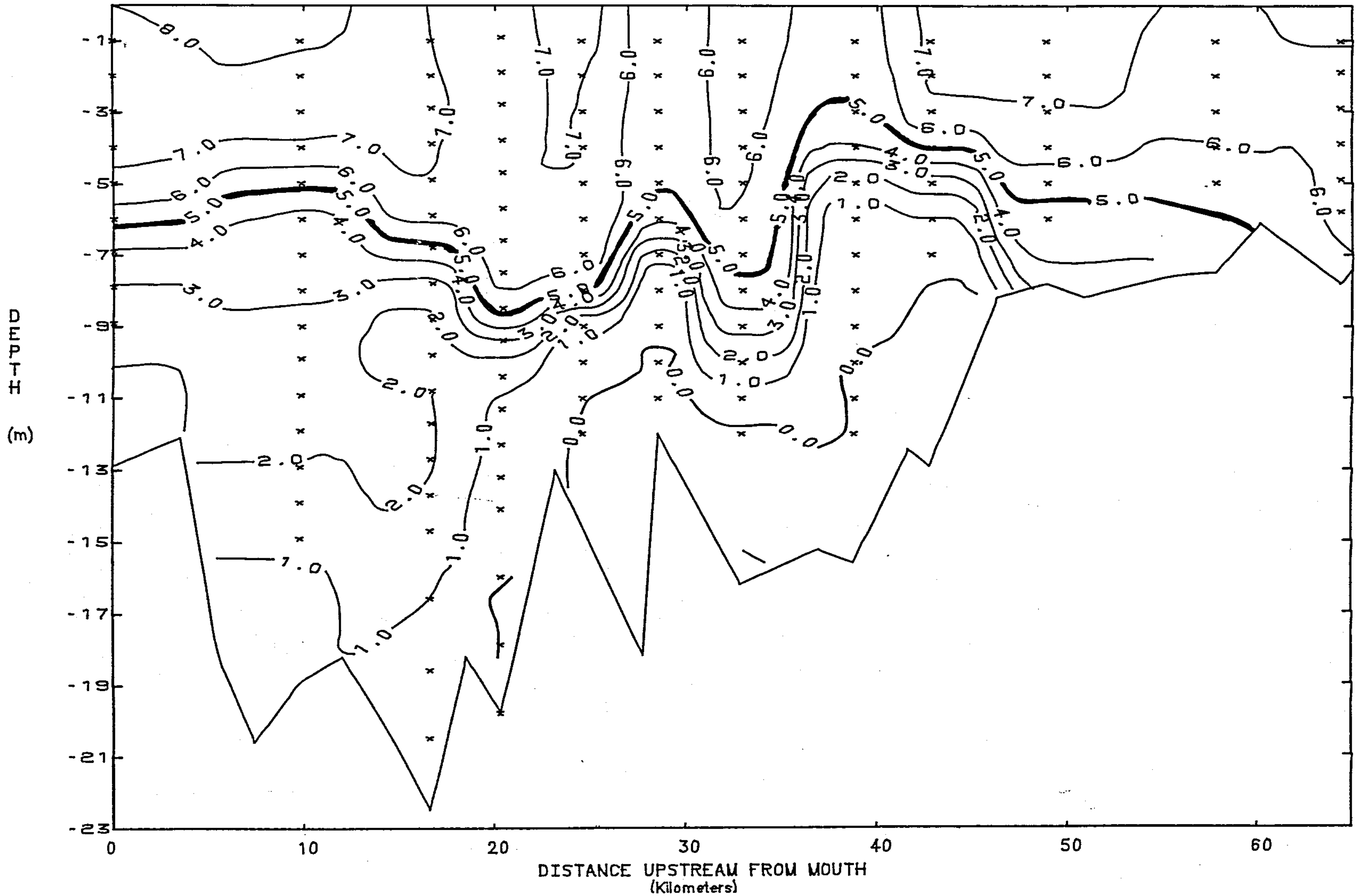

RAPPAHANNOCK RIVER
SALINITY
20 JULY 1987
SLACK BEFORE EBB
DEPTH
(m)
-1
-3
-5
-7
-9
-11
-13
-15
-17
-19
-21
-23
0
10
20
30
40
50
60
70
DISTANCE UPSTREAM FROM MOUTH
(Kilometers)

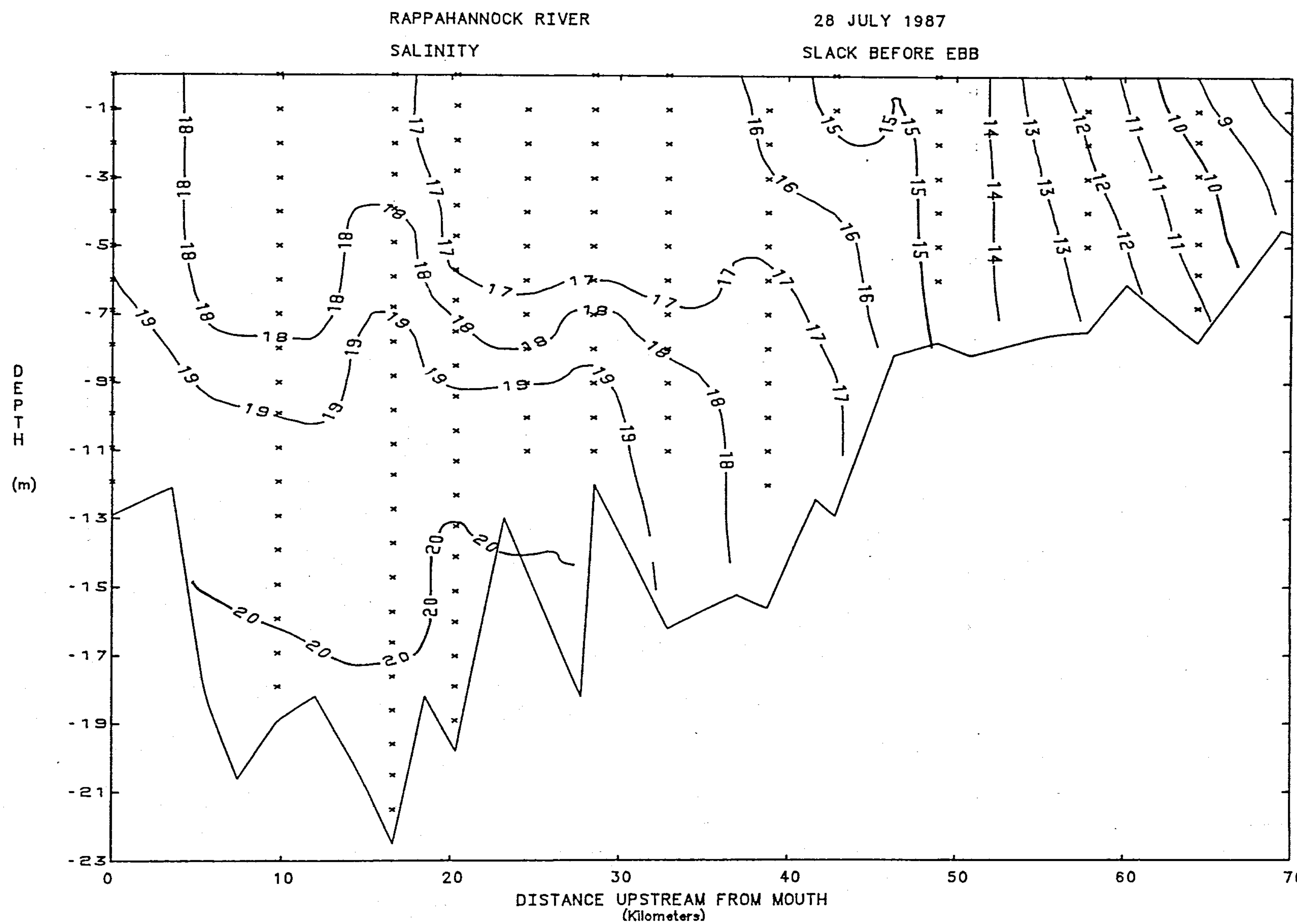


RAPPAHANNOCK RIVER
TEMPERATURE
20 JULY 1987
SLACK BEFORE EBB
DEPTH (m)
-1
-3
-5
-7
-9
-11
-13
-15
-17
-19
-21
-23
0
10
20
30
40
50
60
70
DISTANCE UPSTREAM FROM MOUTH
(Kilometers)
27
28
29

RAPPAHANNOCK RIVER 28 JULY 1987

DISSOLVED OXYGEN SLACK BEFORE EBB

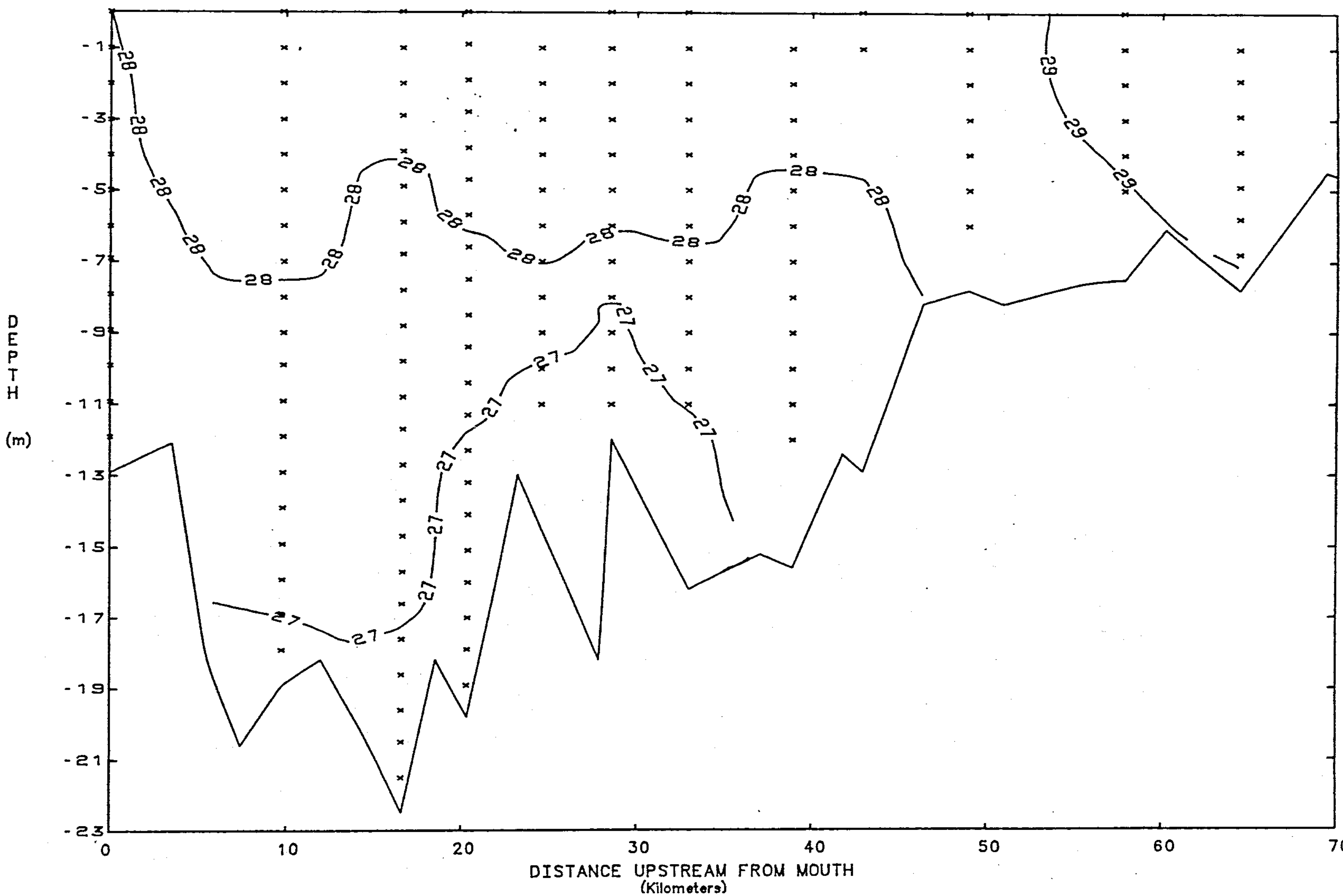


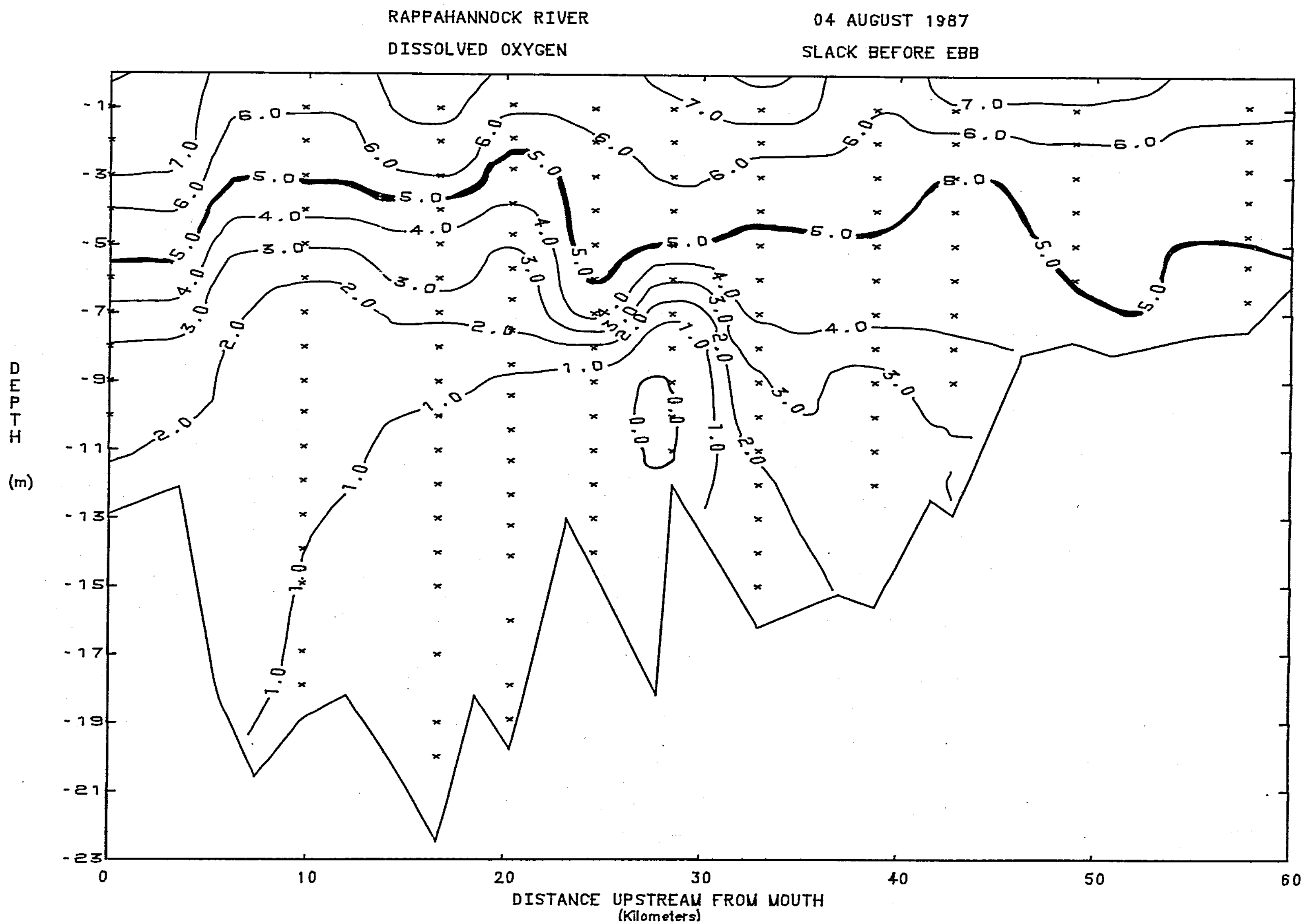


RAPPAHANNOCK RIVER
SALINITY
28 JULY 1987
SLACK BEFORE EBB
DEPTH (m)
DISTANCE UPSTREAM FROM MOUTH (Kilometers)

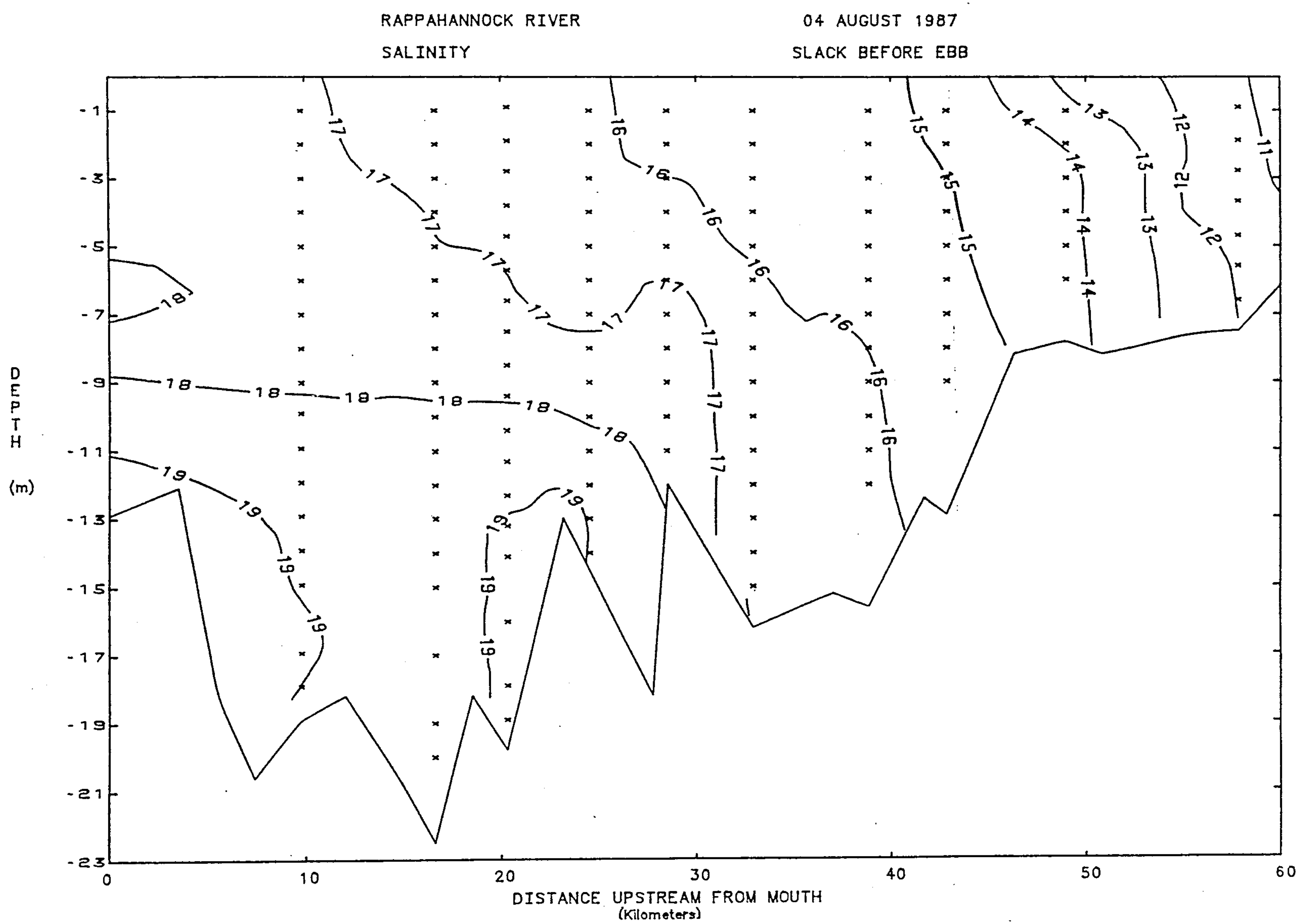
RAPPAHANNOCK RIVER 28 JULY 1987

TEMPERATURE SLACK BEFORE EBB





RAPPAHANNOCK RIVER
DISSOLVED OXYGEN
04 AUGUST 1987
SLACK BEFORE EBB
DEPTH (m)
DISTANCE UPSTREAM FROM MOUTH (Kilometers)
-1
-3
-5
-7
-9
-11
-13
-15
-17
-19
-21
-23
0
10
20
30
40
50
60

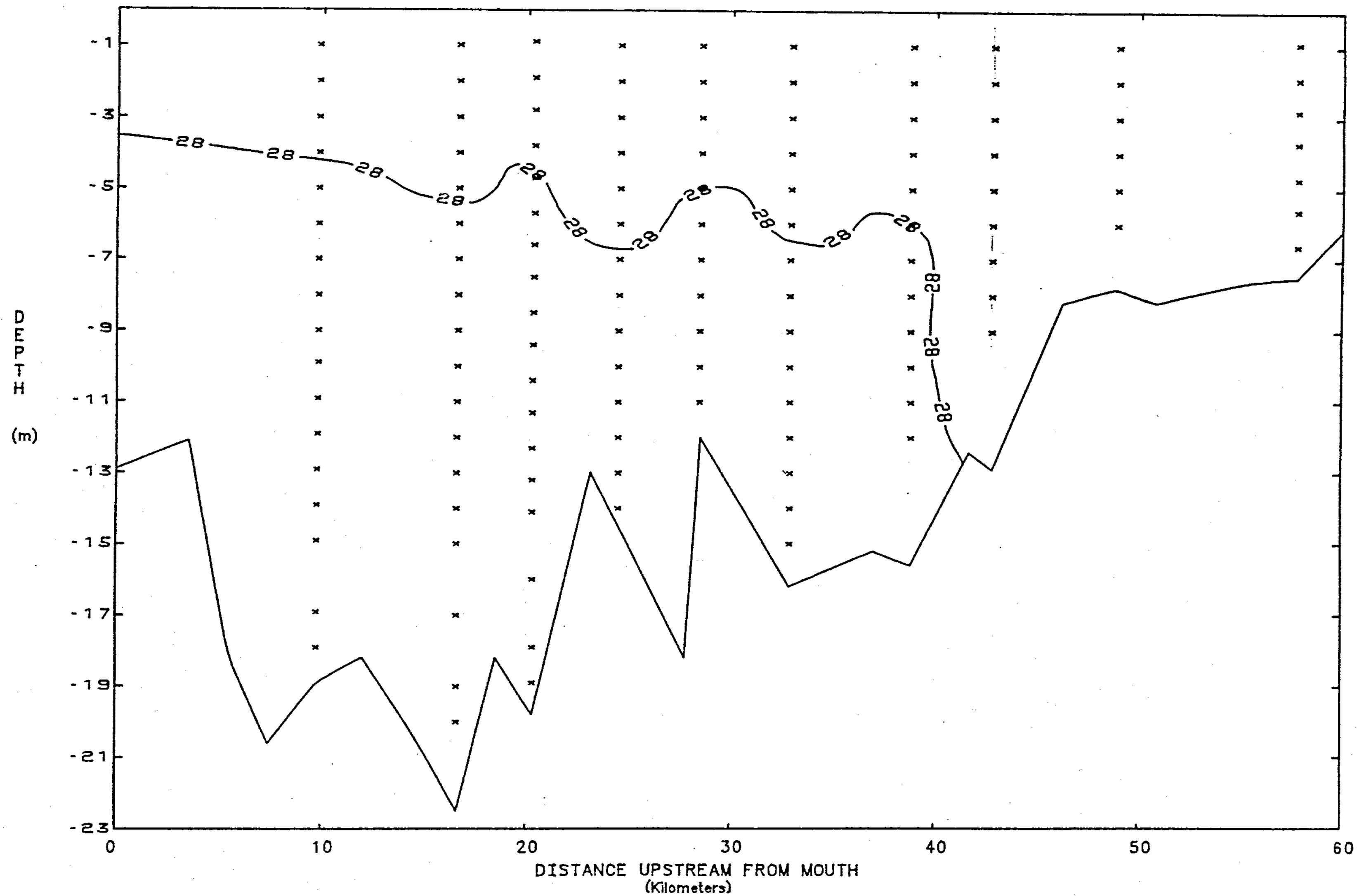

RAPPAHANNOCK RIVER
SALINITY
04 AUGUST 1987
SLACK BEFORE EBB
DEPTH (m)
DISTANCE UPSTREAM FROM MOUTH
(Kilometers)

RAPPAHANNOCK RIVER

TEMPERATURE

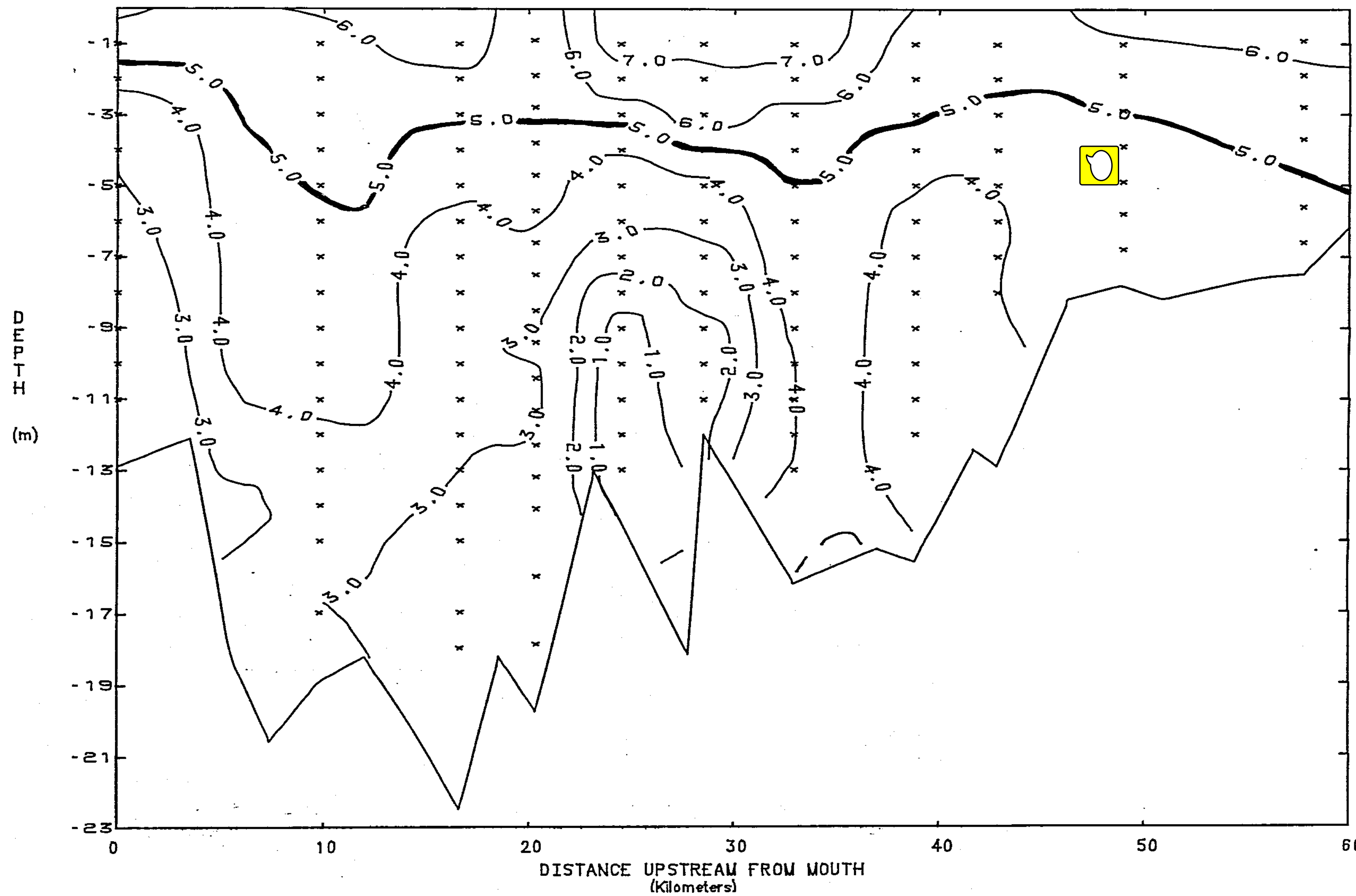
04 AUGUST 1987

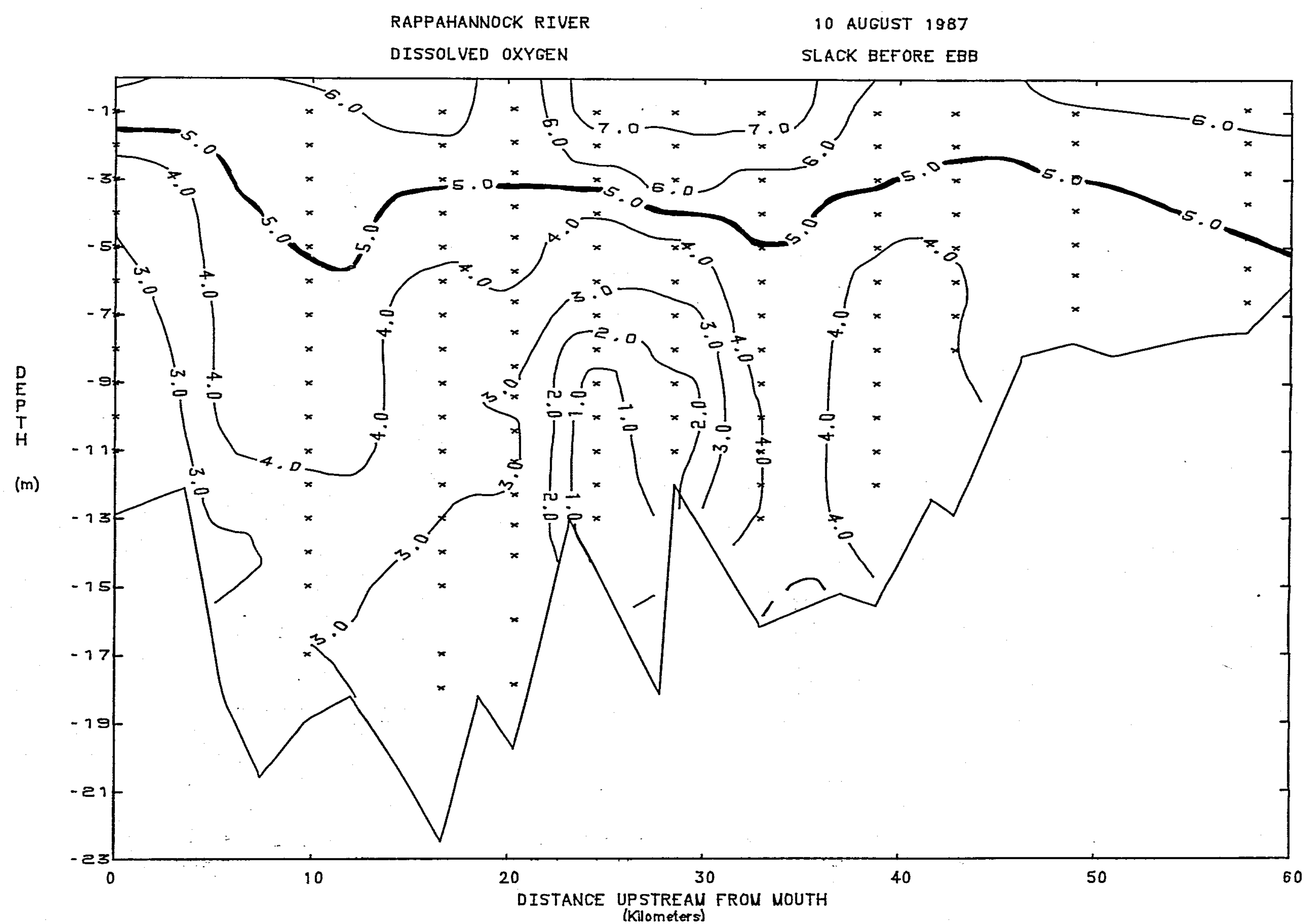
SLACK BEFORE EBB



RAPPAHANNOCK RIVER — DISSOLVED OXYGEN

10 AUGUST 1987 — SLACK BEFORE EBB



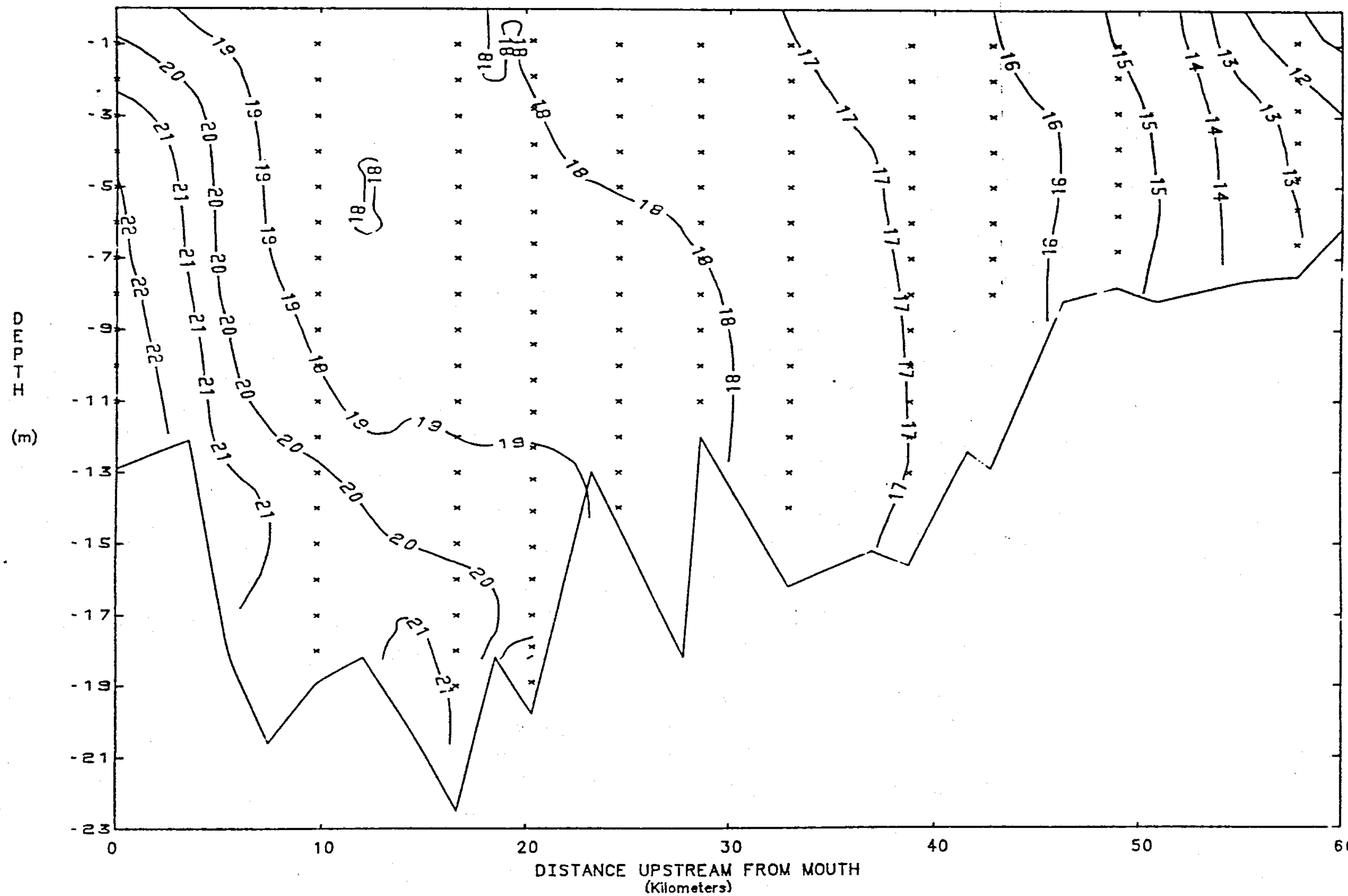

RAPPAHANNOCK RIVER
DISSOLVED OXYGEN
10 AUGUST 1987
SLACK BEFORE EBB
DEPTH (m)
DISTANCE UPSTREAM FROM MOUTH (Kilometers)
-1
-3
-5
-7
-9
-11
-13
-15
-17
-19
-21
-23
0
10
20
30
40
50
60
1.0
2.0
3.0
4.0
5.0
6.0
7.0

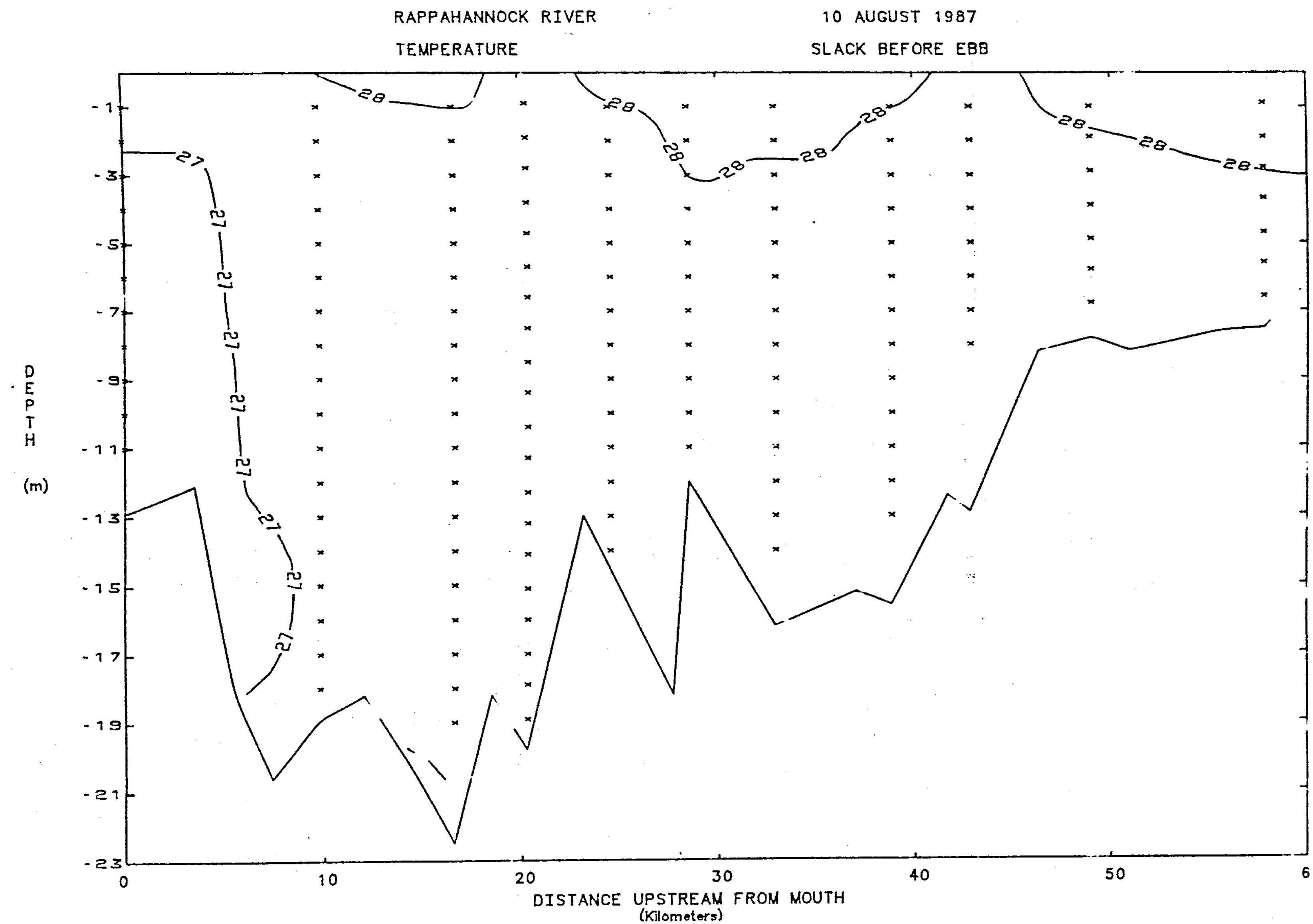
RAPPAHANNOCK RIVER

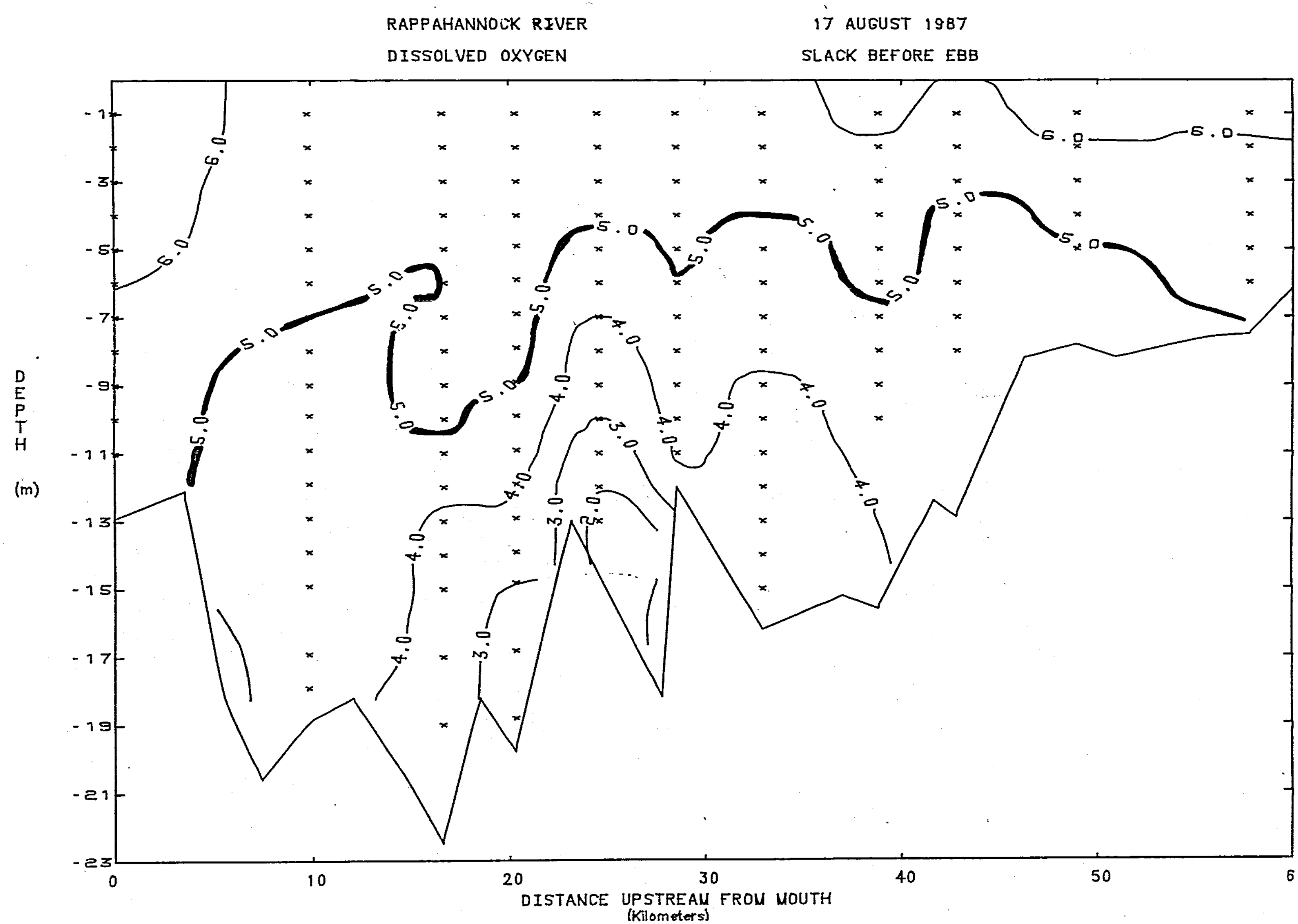
SALINITY

10 AUGUST 1987

SLACK BEFORE EBB




RAPPAHANNOCK RIVER
TEMPERATURE
10 AUGUST 1987
SLACK BEFORE EBB
DEPTH (m)
-1
-3
-5
-7
-9
-11
-13
-15
-17
-19
-21
-23
0
10
20
30
40
50
60
DISTANCE UPSTREAM FROM MOUTH
(Kilometers)
27
28



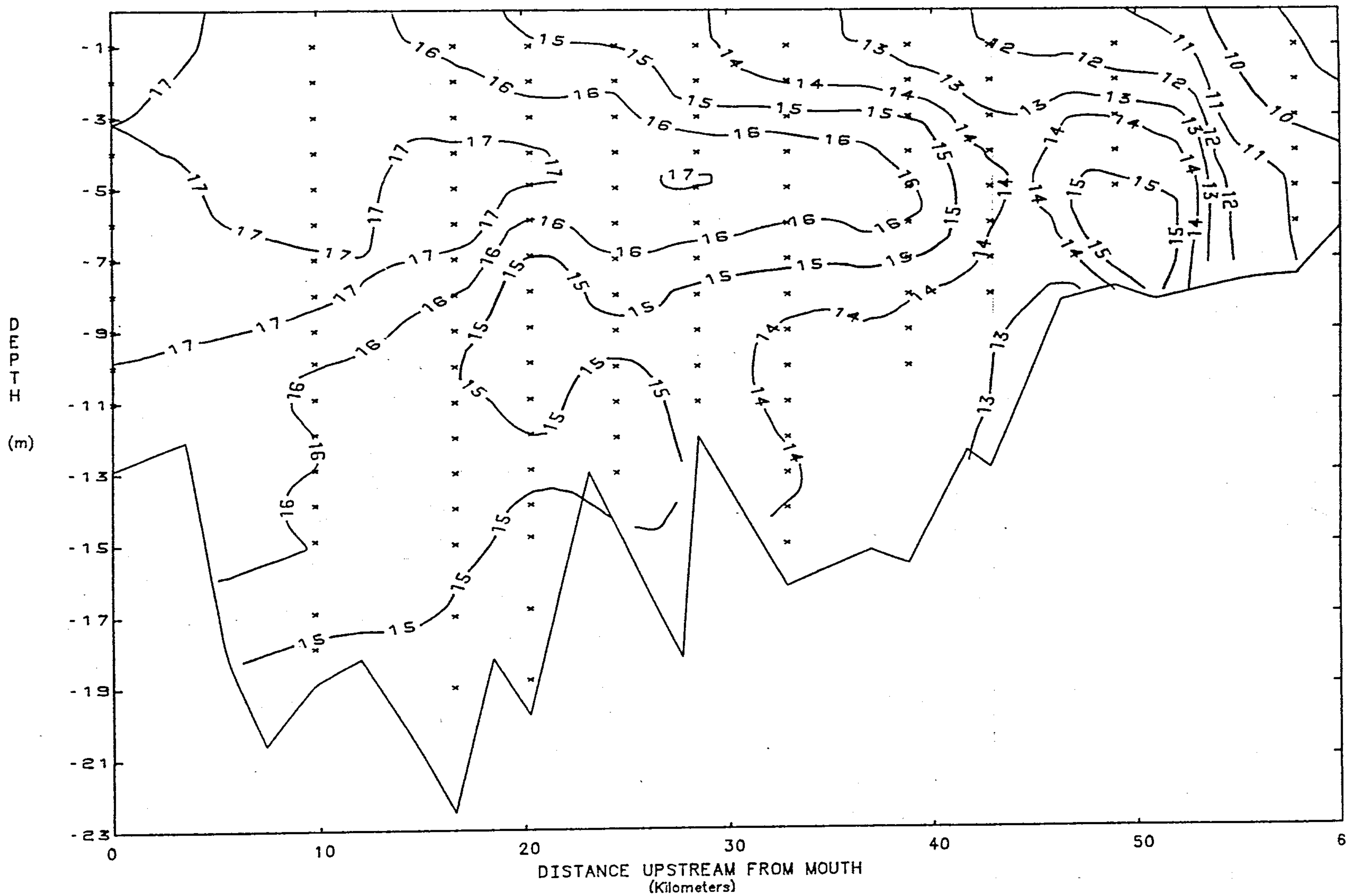
RAPPAHANNOCK RIVER
DISSOLVED OXYGEN
17 AUGUST 1987
SLACK BEFORE EBB
DEPTH (m)
DISTANCE UPSTREAM FROM MOUTH (Kilometers)
-1
-3
-5
-7
-9
-11
-13
-15
-17
-19
-21
-23
0
10
20
30
40
50
60
6.0
5.0
4.0
3.0
2.0

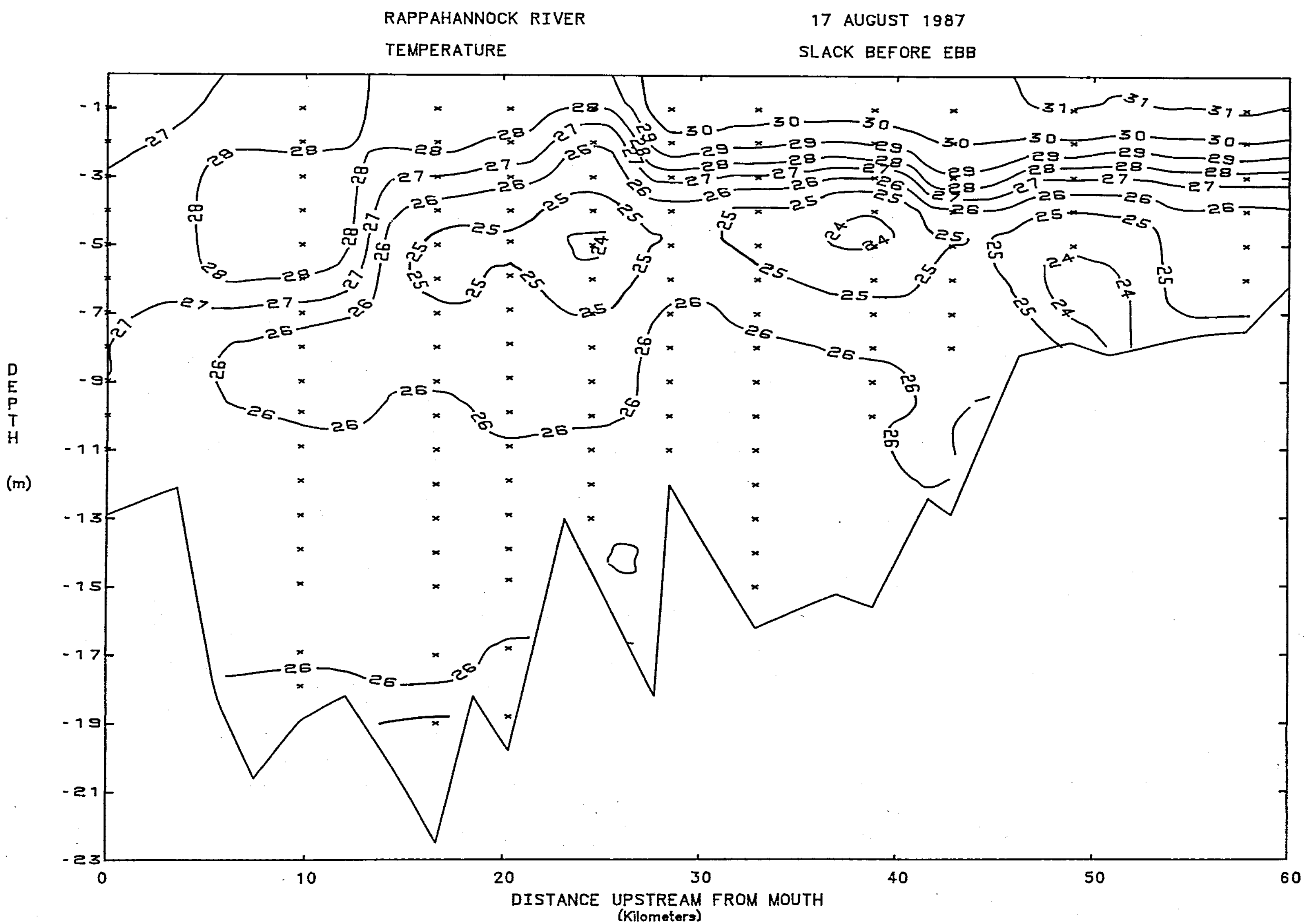
RAPPAHANNOCK RIVER

SALINITY

17 AUGUST 1987

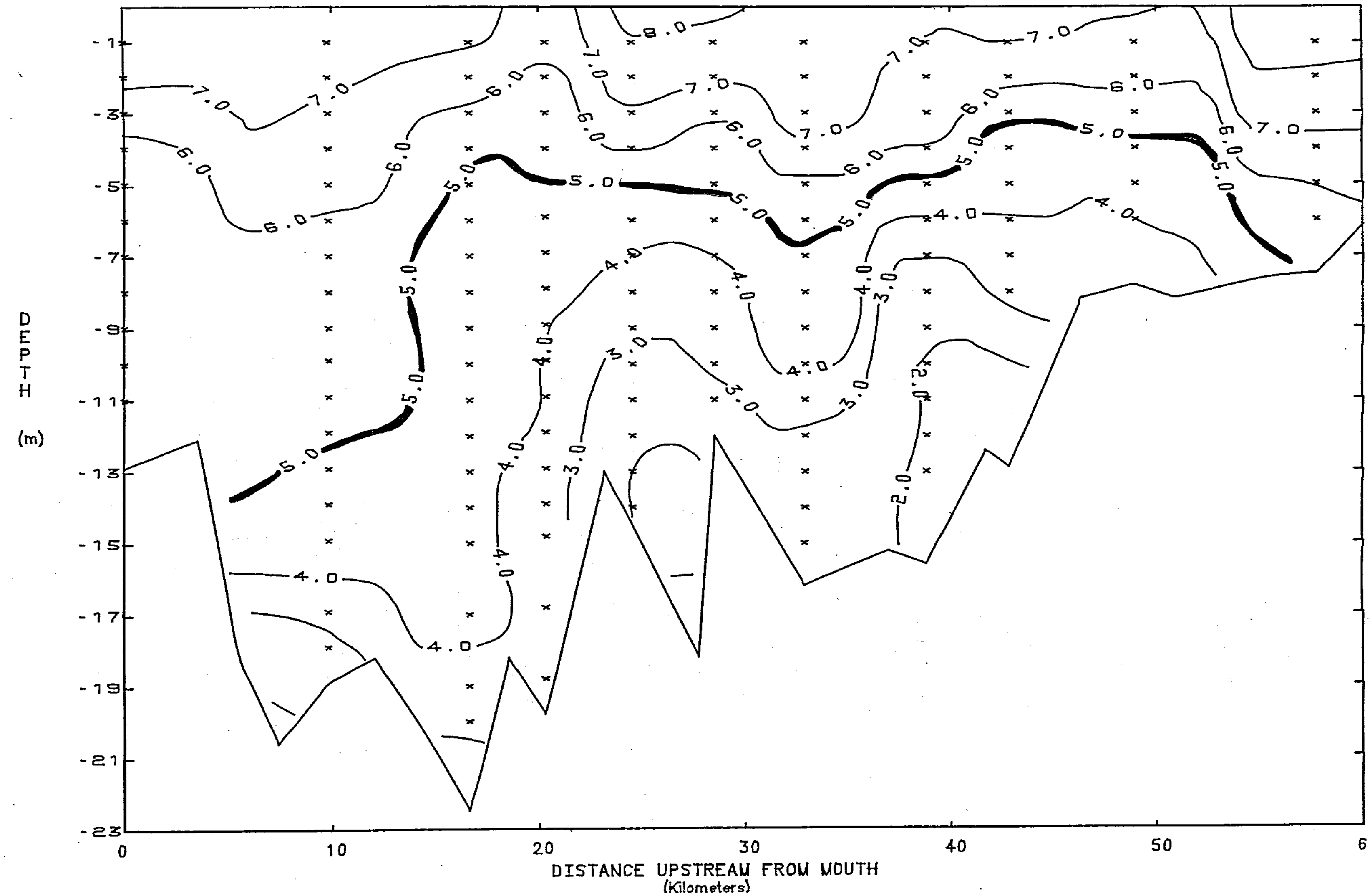
SLACK BEFORE EBB

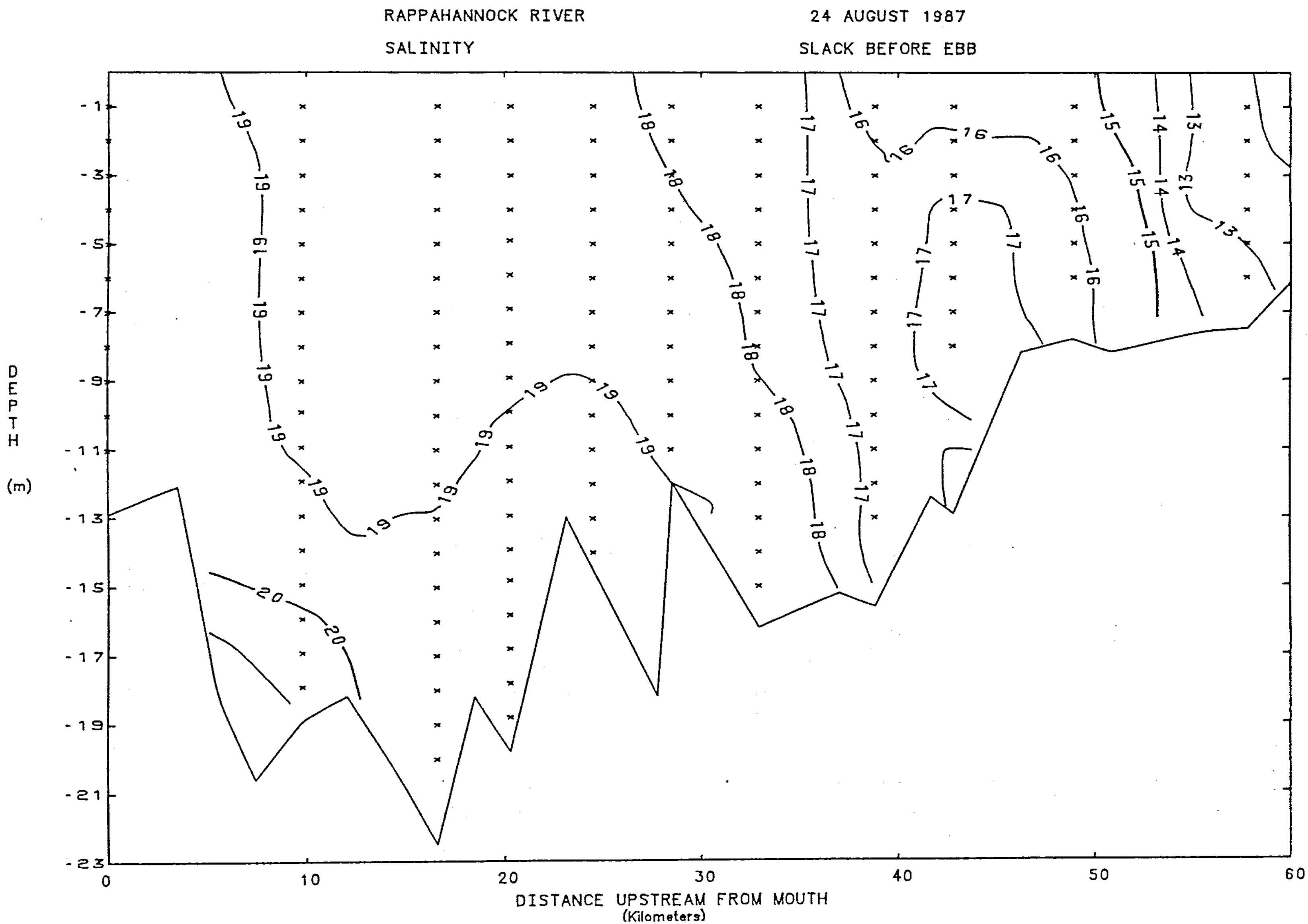



RAPPAHANNOCK RIVER
TEMPERATURE
17 AUGUST 1987
SLACK BEFORE EBB
DEPTH (m)
DISTANCE UPSTREAM FROM MOUTH
(Kilometers)

RAPPAHANNOCK RIVER 24 AUGUST 1987

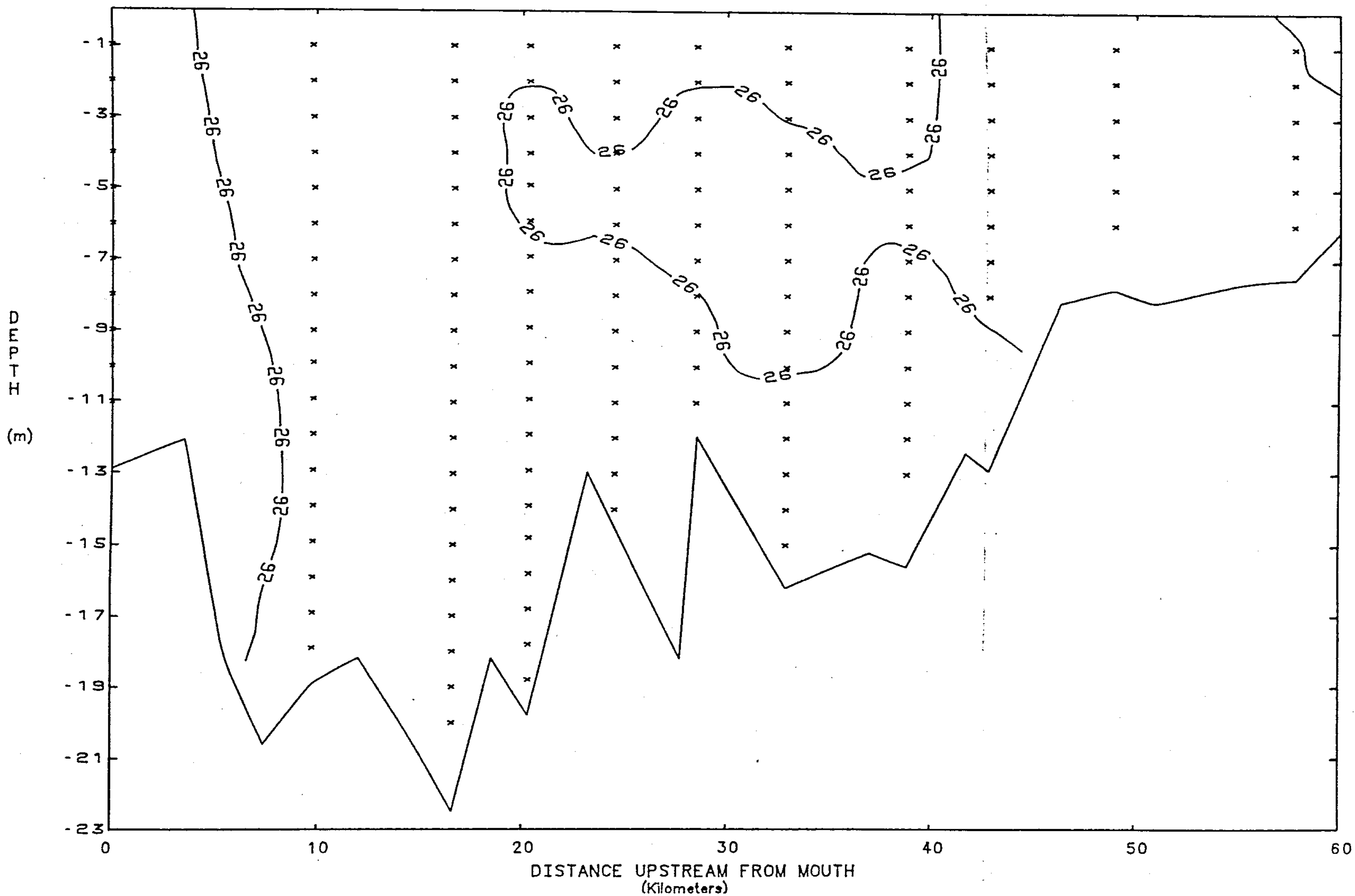
DISSOLVED OXYGEN SLACK BEFORE EBB

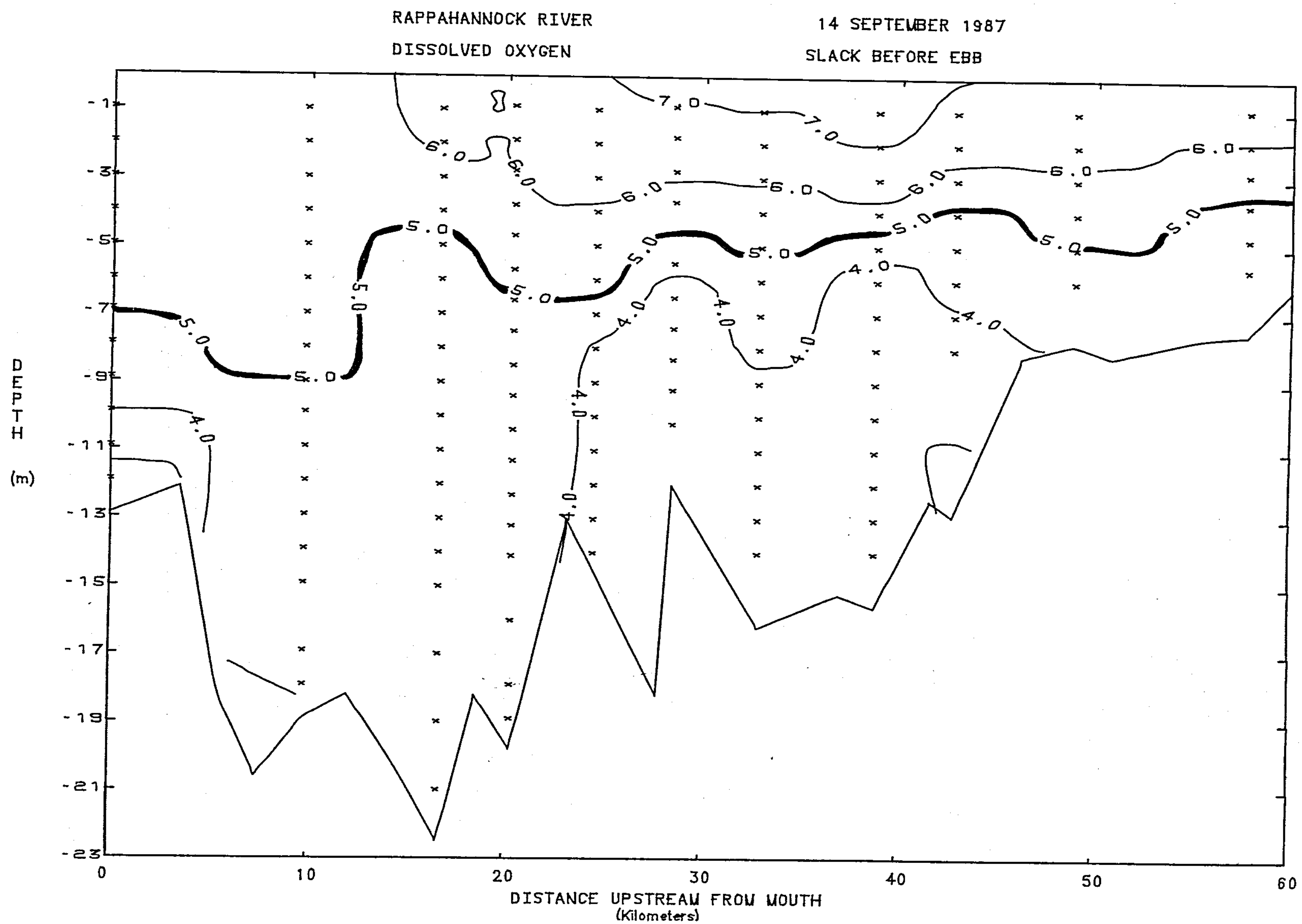


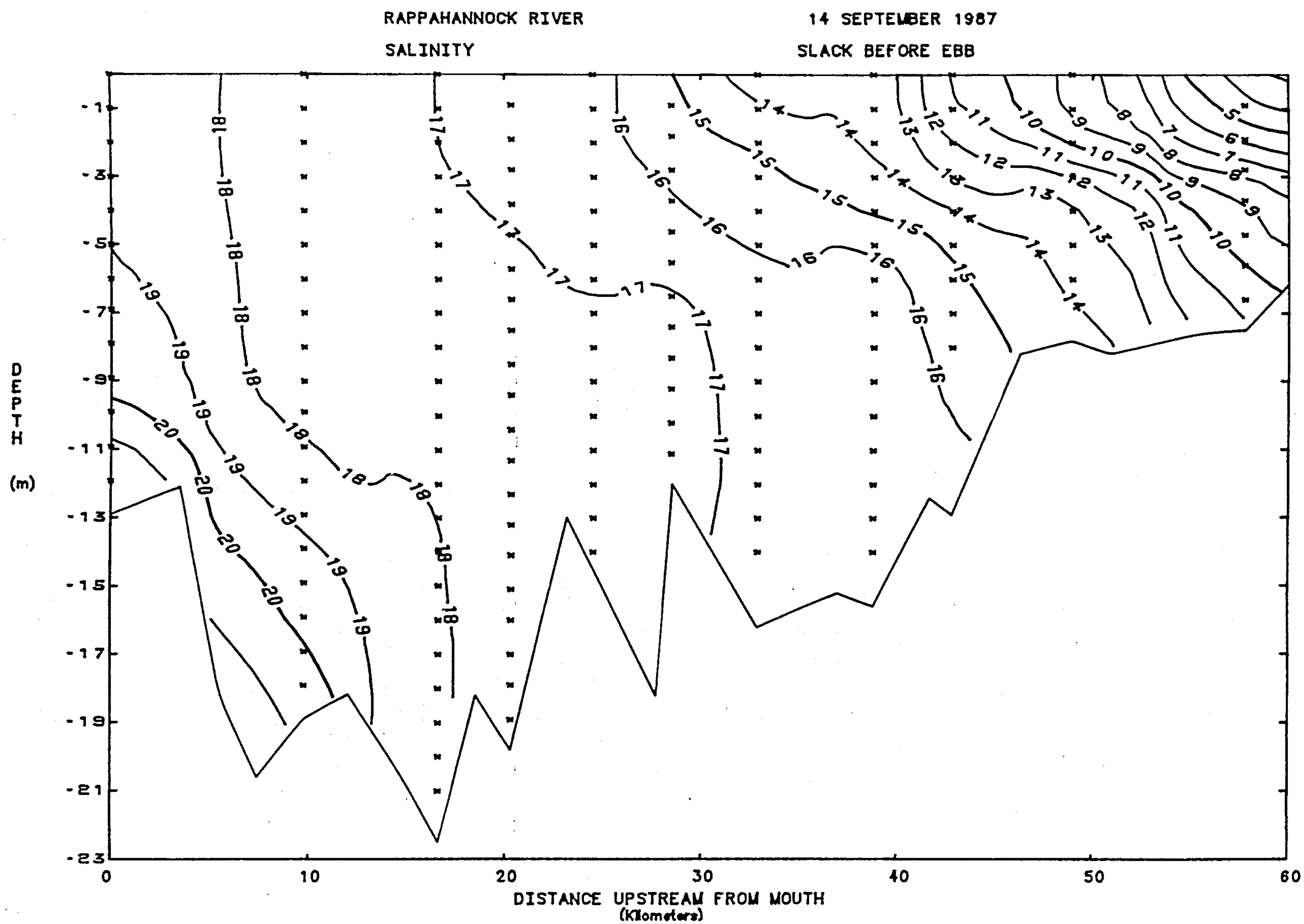

RAPPAHANNOCK RIVER
SALINITY
24 AUGUST 1987
SLACK BEFORE EBB
DEPTH (m)
-1
-3
-5
-7
-9
-11
-13
-15
-17
-19
-21
-23
0
10
20
30
40
50
60
DISTANCE UPSTREAM FROM MOUTH
(Kilometers)
13
14
15
16
17
18
19
20

RAPPAHANNOCK RIVER
TEMPERATURE

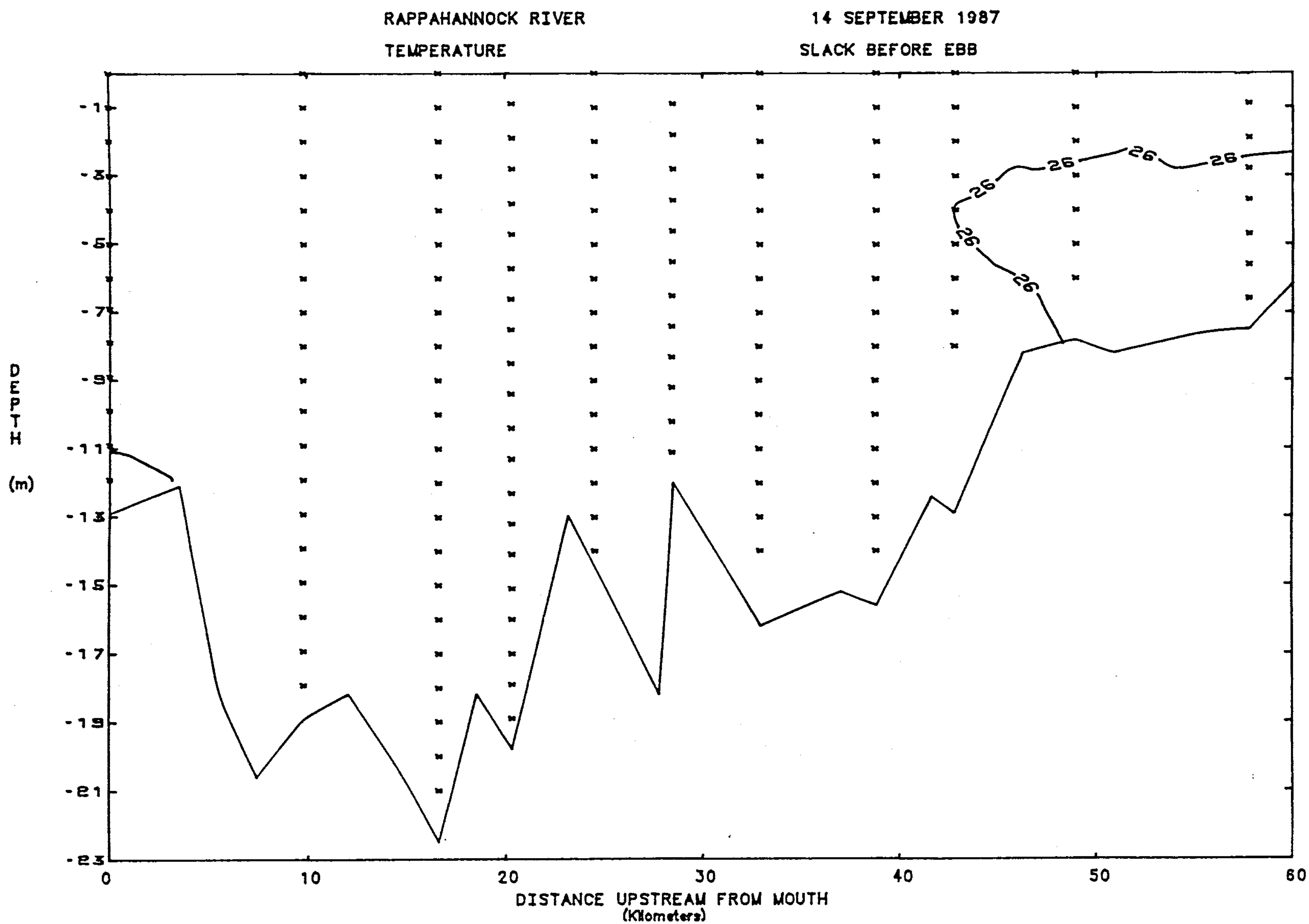
24 AUGUST 1987
SLACK BEFORE EBB




RAPPAHANNOCK RIVER
DISSOLVED OXYGEN
14 SEPTEMBER 1987
SLACK BEFORE EBB
DEPTH (m)
DISTANCE UPSTREAM FROM MOUTH
(Kilometers)
-1
-3
-5
-7
-9
-11
-13
-15
-17
-19
-21
-23
0
10
20
30
40
50
60
7.0
6.0
5.0
4.0



RAPPAHANNOCK RIVER
SALINITY
14 SEPTEMBER 1987
SLACK BEFORE EBB
DEPTH (m)
DISTANCE UPSTREAM FROM MOUTH
(Kilometers)


RAPPAHANNOCK RIVER
TEMPERATURE
14 SEPTEMBER 1987
SLACK BEFORE EBB
DEPTH
(m)
-1
-3
-5
-7
-9
-11
-13
-15
-17
-19
-21
-23
0
10
20
30
40
50
60
26
DISTANCE UPSTREAM FROM MOUTH
(Kilometers)

Dissolved oxygen, salinity and temperature
data at station CB6.1 in Chesapeake Bay.

DEPTH (METERS)	TEMPERATURE (^{o}C)	SALINITY	DISSOLVED OXYGEN (mg/l)
APR 06	Flood Tide		
1.00	8.68	16.75	12.39
2.00	8.68	16.87	12.29
3.00	8.37	17.19	11.88
4.00	8.37	17.29	11.42
5.00	8.52	17.58	11.33
6.00	8.40	17.76	11.30
7.00	8.42	18.43	10.89
8.00	8.28	18.72	10.16
9.00	8.60	19.14	10.15
10.00	8.68	19.63	10.12
11.00	8.68	20.07	9.91
12.00	8.68	20.29	9.72
13.00	8.68	20.29	9.72
APR 22	Flood Tide		
1.00	13.92	15.88	13.03
2.00	12.84	15.97	12.90
3.00	12.63	16.17	12.70
4.00	12.62	16.16	12.16
5.00	12.62	16.16	11.88
6.00	12.52	16.23	10.70
7.00	12.41	16.30	10.71
8.00	12.24	21.15	9.69
9.00	12.30	22.24	9.45
10.00	12.20	22.54	9.43
11.00	12.20	22.56	9.43
12.00	12.20	22.58	9.42
MAY 06	Flood Tide		
1.00	16.42	12.05	12.35
2.00	14.82	12.58	12.07
3.00	14.30	13.73	11.82
4.00	14.21	14.16	10.22
5.00	14.17	15.20	9.88
6.00	13.90	15.96	9.29
7.00	13.49	17.05	6.86
8.00	13.17	19.21	6.58
9.00	13.04	20.36	6.00
10.00	12.89	20.91	5.98
11.00	12.86	20.96	5.80
12.00	12.87	20.98	5.80

DEPTH (METERS)	TEMPERATURE (°C)	SALINITY	DISSOLVED OXYGEN (mg/1)
MAY 18	Ebb Tide		
1.00	19.04	13.57	10.39
2.00	18.85	14.08	10.72
3.00	17.37	15.68	11.35
4.00	16.49	16.83	10.74
5.00	16.01	18.73	7.74
6.00	15.38	19.86	6.38
7.00	15.22	20.00	6.02
8.00	15.18	20.08	5.84
9.00	15.16	20.11	5.84
10.00	15.15	20.12	5.84
11.00	15.15	20.12	
12.00	15.15	20.12	5.84
13.00	15.15	20.13	5.84
JUN 02	Flood Tide		
1.00	24.11	14.56	9.80
2.00	23.12	15.05	10.29
3.00	19.50	16.90	8.18
4.00	18.86	17.21	6.54
5.00	18.24	18.67	4.87
6.00	17.90	20.48	3.21
7.00	17.93	22.77	1.94
8.00	18.02	23.25	2.46
9.00	18.04	23.39	2.46
10.00	18.05	23.41	2.46
11.00	18.05	23.44	2.37
12.00	18.06	23.43	2.54
JUN 04	Slack Before Ebb		
1.00	22.78	18.94	7.72
2.00	22.77	16.11	8.49
3.00	22.77	16.11	8.49
4.00	22.77	16.11	8.49
5.00	22.76	16.12	8.31
6.00	22.71	16.53	7.92
7.00	18.87	18.03	5.42

DEPTH (METERS)	TEMPERATURE (°C)	SALINITY	DISSOLVED OXYGEN (mg/1)
JUN 04			
8.00	18.49	20.90	2.40
9.00	18.49	22.78	1.94
10.00	18.50	22.83	1.67
11.00	18.50	22.83	1.67
12.00	18.49	22.82	1.67
JUN 18	Flood Tide		
1.00	25.11	16.46	6.81
2.00	23.70	16.98	6.20
3.00	23.51	17.21	6.01
4.00	23.37	17.39	5.80
5.00	23.30	17.56	5.70
6.00	23.26	17.62	5.43
7.00	22.68	18.46	2.52
8.00	22.41	18.88	2.25
9.00	22.35	19.00	2.25
10.00	22.35	19.03	2.16
11.00	22.35	19.05	2.07
12.00	22.35	19.06	2.07
JUL 02	Slack Before Ebb		
1.00	25.15	18.55	6.00
2.00	25.11	18.58	6.00
3.00	25.09	18.60	6.00
4.00	25.06	18.62	5.91
5.00	24.95	18.69	5.82
6.00	24.90	18.73	5.73
7.00	24.86	18.77	5.64
8.00	24.38	19.74	5.38
9.00	23.58	21.19	3.38
10.00	23.58	21.19	2.58
11.00	23.58	17.27	
JUL 07	Flood Tide		
1.00	26.31	18.13	10.91
2.00	26.03	18.10	9.83
3.00	25.53	18.11	8.03
4.00	25.48	18.13	7.19

DEPTH (METERS)	TEMPERATURE (°C)	SALINITY	DISSOLVED OXYGEN (mg/l)
JUL 07			
5.00	25.40	18.27	6.55
6.00	25.67	18.96	6.10
7.00	25.56	19.10	5.83
8.00	24.79	19.61	3.65
9.00	23.90	22.00	1.24
10.00	23.82	22.17	1.24
11.00	23.81	22.21	1.24
12.00	23.81	22.21	1.24
JUL 08	Slack Before Ebb		
1.00	27.41	17.95	7.39
2.00	26.92	18.01	7.03
3.00	26.85	18.02	6.85
4.00	26.88	18.37	6.39
5.00	26.97	18.75	6.28
6.00	27.11	19.80	5.97
7.00	26.99	20.21	5.34
8.00	26.20	20.89	3.55
9.00	25.26	21.71	1.32
10.00	25.19	21.79	1.14
11.00	25.19	21.79	1.14
12.00	25.19	21.79	1.14
JUL 16	Slack Before Ebb		
1.00	25.90	18.36	5.77
2.00	25.91	18.38	5.67
3.00	25.94	18.42	5.67
4.00	25.94	18.41	5.58
5.00	25.94	18.47	5.58
6.00	25.86	19.81	5.36
7.00	25.46	21.10	4.94
8.00	25.19	21.98	3.59
9.00	25.10	22.21	3.06
10.00	25.04	22.33	2.97
11.00	25.03	22.38	2.97
12.00	25.00	22.47	

DEPTH (METERS)	TEMPERATURE (°C)	SALINITY	DISSOLVED OXYGEN (mg/l)
JUL 20	Flood Tide		
1.00	29.30	15.54	9.85
2.00	27.80	16.17	10.16
3.00	27.54	16.35	9.23
4.00	27.00	16.63	7.64
5.00	26.78	17.50	5.11
6.00	26.69	18.05	4.42
7.00	26.37	20.30	3.87
8.00	26.02	21.60	.66
9.00	25.97	21.88	.53
10.00	25.97	21.90	.53
11.00	25.97	21.93	.53
12.00	25.97	21.94	.53
13.00	25.96	21.94	.53
AUG 03	Flood Tide		
1.00	29.49	17.52	8.10
2.00	28.55	17.74	8.32
3.00	28.27	17.87	7.57
4.00	28.12	17.97	6.88
5.00	27.96	18.34	6.51
6.00	27.91	18.72	6.67
7.00	27.71	20.85	6.68
8.00	27.37	21.96	4.75
9.00	26.97	22.34	.44
10.00	26.97	22.35	.35
11.00	26.96	22.35	.35
12.00	26.96	22.36	.35
13.00	26.96	22.36	.35
AUG 10	Slack Before Ebb		
1.00	27.56	20.87	6.50
2.00	27.09	20.98	6.02
3.00	26.96	21.00	5.31
4.00	26.85	21.24	4.68
5.00	26.81	21.36	4.33
6.00	26.73	21.47	4.32
7.00	26.62	21.79	4.23
8.00	26.53	22.13	3.87
9.00	26.35	23.18	3.32
10.00	25.89	24.18	2.35
11.00	25.82	24.32	1.74

DEPTH (METERS)	TEMPERATURE (°C)	SALINITY	DISSOLVED OXYGEN (mg/1)
AUG 10			
12.00	25.79	24.38	1.74
13.00	25.79	24.38	
AUG 17	Flood Tide		
1.00	28.47	18.41	7.50
2.00	28.48	18.40	7.41
3.00	28.40	18.45	7.40
4.00	28.01	18.60	7.31
5.00	27.50	18.97	6.75
6.00	27.39	19.07	5.91
7.00	27.25	19.27	5.55
8.00	26.89	21.11	5.40
9.00	26.79	22.20	4.74
10.00	26.57	23.56	4.70
11.00	26.56	23.58	3.31
12.00	26.57	23.60	3.22
13.00	26.56	23.60	3.22
AUG 24	Slack Before Ebb		
1.00	25.40	20.42	6.55
2.00	25.42	20.40	6.55
3.00	25.42	20.39	6.55
4.00	25.33	20.39	6.47
5.00	25.31	20.38	6.29
6.00	25.28	20.37	6.29
7.00	25.26	20.37	6.20
8.00	25.27	20.37	6.11
9.00	25.26	20.38	6.02
10.00	25.27	20.45	5.49
11.00	25.47	23.94	2.94
12.00	25.48	24.15	2.77
13.00	25.48	24.15	
SEP 02	Ebb Tide		
1.00	25.23	19.41	6.86
2.00	25.23	19.41	6.86
3.00	25.23	19.41	6.86
4.00	25.24	19.41	6.77

DEPTH (METERS)	TEMPERATURE (°C)	SALINITY	DISSOLVED OXYGEN (mg/l)
SEP 02			
5.00	25.23	19.41	6.68
6.00	25.23	19.41	6.51
7.00	25.37	19.64	6.23
8.00	25.49	19.86	6.13
9.00	25.55	20.25	5.43
10.00	25.62	22.40	3.60
11.00	25.63	22.53	3.16
12.00	25.64	22.58	3.16
SEP 14	Ebb Tide		
1.00	25.13	19.34	7.49
2.00	25.13	19.35	7.49
3.00	25.14	19.35	7.44
4.00	25.15	19.45	7.48
5.00	25.11	20.55	7.43
6.00	25.19	21.86	6.49
7.00	25.18	23.24	6.26
8.00	24.91	23.98	4.59
9.00	24.87	24.39	3.45
10.00	24.80	24.61	3.62
11.00	24.80	24.68	3.62
12.00	24.80	24.69	3.62