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Characterizing Late Summer Water Quality in the Seekonk River, Providence River, and Upper Narragansett Bay (SQUIRT)

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Narragansett Bay Estuary Program

Characterizing Late Summer Water Quality in the Seekonk River, Providence River and Upper Narragansett Bay

Final Report

Submitted To

The Narragansett Bay Project

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by

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FOREWORD

The United States Congress created the National Estuary Program in 1984, citing its concern for the "health and ecological integrity" of the nation's estuaries and estuarine resources. Narragansett Bay was selected for inclusion in the National Estuary Program in 1984 and designated an "estuary of national significance" in 1988. The Narragansett Bay Project (NBP) was established in 1985. Under the joint sponsorship of the U.S. Environmental Protection Agency and the Rhode Island Department of Environmental Management, the NBP's mandate is to direct a five-year program of research and planning focussed on managing Narragansett Bay and its resources for future generations. The NBP will develop a comprehensive management plan by December, 1990, which will recommend actions to improve and protect the Bay and its natural resources.

The NBP has established the following seven priority issues for Narragansett Bay:

- management of fisheries
- nutrients and potential for eutrophication
- impacts of toxic contaminants
- health and abundance of living resources
- health risk to consumers of contaminated seafood
- land-based impacts on water quality
- recreational uses

The NBP is taking an ecosystem approach to address these problems and has funded research that will help to improve our understanding of various aspects of these priority problems. The Project is also working to expand and coordinate existing programs among state agencies, governmental institutions, and academic researchers in order to apply research findings to the practical needs of managing the Bay and improving the environmental quality of its watershed.

This report represents the technical results of an investigation performed for the Narragansett Bay Project. The information in this document has been funded wholly or in part by the Rhode Island Department of Environmental Management under account #8710-17100. It has been subject to the Agency's and the Narragansett Bay Project's peer and administrative review and has been accepted for publication by the Management Committee of the Narragansett Bay Project. The results and conclusions contained herein are those of the author(s), and do not necessarily represent the views or recommendations of the NBP. Final recommendations for management actions will be based upon the results of this and other investigations.

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Executive Summary

The purpose of the SQUIRT Cruise was to gather data on oxygen concentration and metabolism in the Seekonk - Providence River in order to better understand the underlying causes of the chronic hypoxic and anoxic conditions observed in bottom water during the summer. The cruise occurred on September 7, 1989 when freshwater discharge into the estuary was low. The cruise was a joint effort involving the EPA Laboratory at Narragansett, the Marine Science Department of the University of Connecticut and the Marine Ecosystems Research Laboratory of the University of Rhode Island.

Oxygen levels were depressed at the head of the Providence River relative to concentrations observed both to the north and south. This depression was centered in the Fox Point Reach of the river (stations 4,5). Cross channel depressions were also observed with surface water in the channel having lower oxygen concentrations than surface water on the shallow flanks. Steep near bottom gradients of decreasing concentration were not observed in the channel but were found at some stations on the shallow flanks. Mid water oxygen minima were also observed but these were ephemeral.

Bottom water oxygen concentration varies both seasonally and on shorter time scales (weeks, tidal). Seasonally, concentrations are highest in the winter - spring and lowest in summer. During a 17 day period preceding the cruise bottom water concentrations in the Fox Point Reach steadily increased from zero to about 3.5 mg/l. The small, statistically non-significant tidal increase in bottom water concentration observed on the SQUIRT cruise could account for this steady increase observed over 2 weeks. Tidally induced vertical transport of oxygen from the surface may play an important role in relieving bottom water anoxia.

The origins of biological oxygen demand present in the system during the SQUIRT Cruise were most likely internal and caused by high biological productivity. External loading could not account for observed levels of BOD in the system. The high biological production of organic matter was supported by nutrients present in the system as well as by external input from point sources. The concentration of nutrients in the Providence River is to a large degree controlled by this point source input. The recurrent hypoxic or anoxic conditions in bottom water during the summer may result from high biological production near the surface, warm temperatures and high respiration in the bottom layer coupled with insufficient transport of oxygen either vertically from the surface or horizontally from lower Narragansett Bay.

Introduction

On September 7, 1989 the Marine Ecosystem Research Laboratory (URI), in conjunction with the Department of Marine Sciences (UCONN) and the Environmental Research Laboratory (EPA), conducted the SQUIRT Cruise. The main purpose of this cruise was to gather data which might lead to a better understanding of the chronic low dissolved oxygen concentrations observed during the summer in the Providence River. Specifically, previous surveys lacked ancillary information on processes (biochemical oxygen demand, sediment oxygen demand, production and respiration) which might allow meaningful interpretation of observed concentrations.

The report first summarizes the distribution of oxygen in the system over space and time. A second part summarizes the various rate processes which were measured. Throughout, a number of calculations are presented. These calculations implicitly assume steady state conditions and in some instances no movement of water. We are not trying to present a definitive model of oxygen dynamics. Rather we are attempting to identify and illustrate the importance of various processes which might be included in such a model.

Sampling

Details of sampling strategy, and sample processing and analysis are given in Doering et al. (1989) and will not be entirely reiterated here.

In brief, 10 longitudinal stations, corresponding in location to those of the SPRAY Cruises (see Doering et al., in press) and a number of transect stations (Fig. 1) were occupied within ±1.5 hours of low and high tide. Low tide occurred at about 6:00 a.m. and high tide at about 1:30 p.m. EDT. Discrete water samples (1 meter below surface and 1 meter above bottom) were taken at all stations excepting transect stations adjacent to stations 3 and 9. These samples were analyzed for a number of parameters given in Table 1. Vertical profiles of at least salinity temperature and dissolved oxygen were obtained at all stations.

Vertical profiles were obtained at stations 3, 6 and 9 periodically throughout the day in order to quantify diel changes in dissolved oxygen. Phytoplankton production and dark respiration of oxygen were also measured at these stations by standard incubation techniques. Sediment for oxygen demand measurements was collected from several sites in the river during the week following the cruise.

Point sources (5 rivers, 3 waste water treatment facilities) were sampled for 3 days preceding the cruise (see Fig. 1, Table 1). Freshwater discharge rates from these sources were obtained from the U.S. Geological Survey and treatment plant operators.

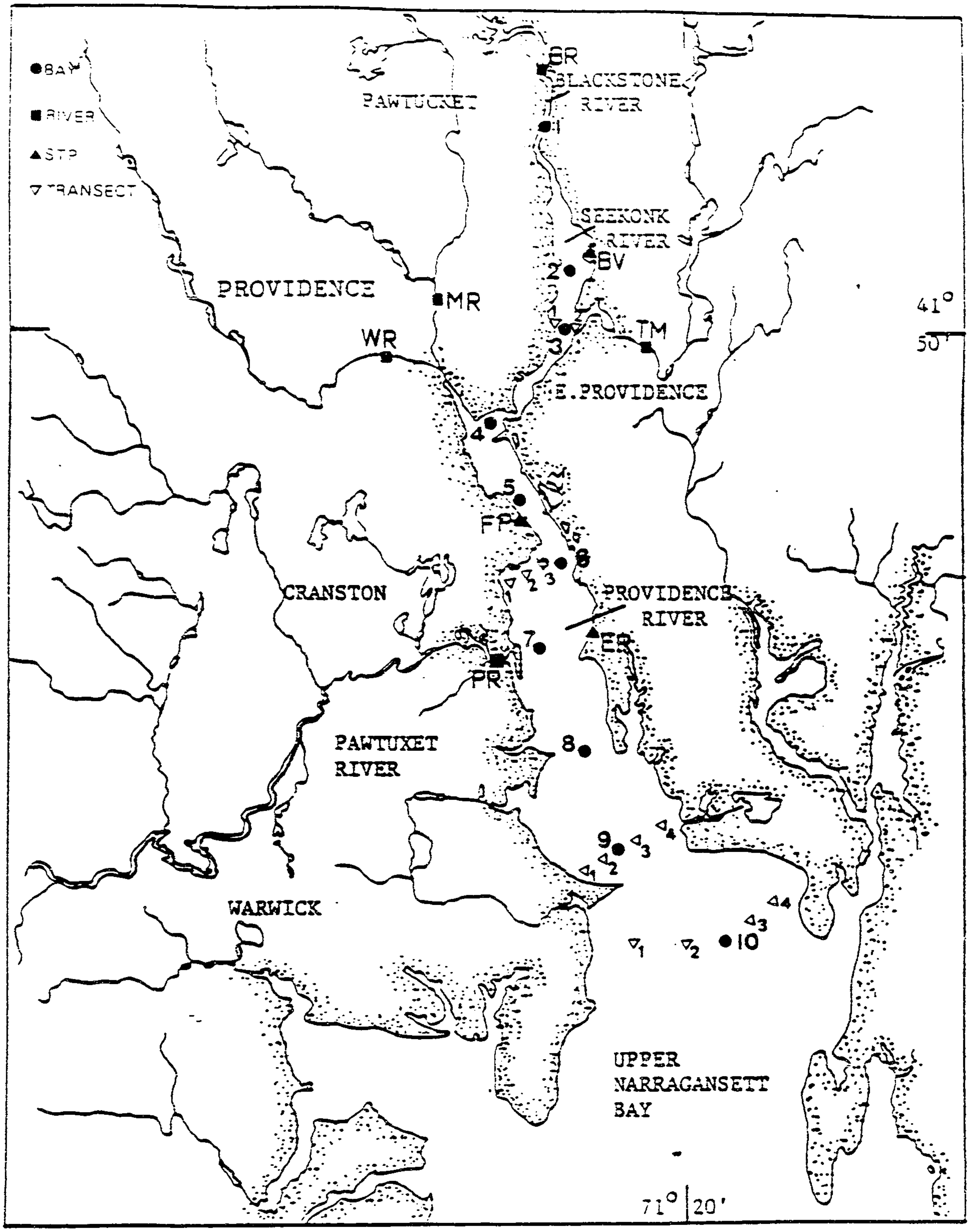

Figure 1. Station Locations For SQUIRT Cruise.
Rivers: BR=Blackstone, MR=Moshassuck, WR=Woonasquatucket, TM=Ten Mile PR=Pawtuxet. Sewage Treatment Plants: FP=Field's Point, BV=Blackstone Valley, EP=East Providence

Table 1. Water quality parameters measured on discrete water samples on the SQUIRT Cruise.

Providence and Seekonk River (stations 1-10, 6.1-6.3, 10.1-10.4)

- Chlorophyll a
- Particulate Carbon
- Total Nitrogen
- Total Phosphorus
- Dissolved Inorganic Nutrients (NH_3, NO_2+NO_3, PO_4, SiO_2)
- Salinity
- Dissolved Oxygen
- BOD
- Total Metals

Rivers

- Chlorophyll a
- Particulate Carbon
- Total Nitrogen
- Total Phosphorus
- Dissolved Inorganic Nutrients (as above)
- Total Metals
- BOD

Sewage Treatment Plants

- Particulate Carbon
- Total Nitrogen
- Total Phosphorus
- Total Metals
- Dissolved Inorganic Nutrients (as above)
- BOD

Results and Discussion

A Comparison with SPRAY

The purpose of this section is to demonstrate that conditions prevailing during the SQUIRT Cruise (Sept. 1989) did not appear abnormal based on the SPRAY Cruises conducted in 1986 and 1987.

The total freshwater discharge to the system averaged about 19 m^3/sec during the three days preceding the SQUIRT Cruise (Fig. 2). This discharge falls within the range of the October, June and August SPRAY cruises. Thus freshwater input to the system during SQUIRT was typical of late summer.

Total average (3 day) loadings of nutrients to the estuary during SPRAY and SQUIRT are compared either directly or as a function of freshwater inflow in Figures 3-7. Aside from ammonia loading which appears a bit lower than during the SPRAY Cruises all others are commensurate with previous observations.

Average total loadings for the SQUIRT Cruise are summarized in Figure 8 and have not been broken down by source because general patterns compared well with those observed during the SPRAY cruises. Rivers were the major source of dissolved silicon and nitrate + nitrite. Ammonia came mostly from sewage treatment plants with Field's Point being the largest single source. Rivers and sewage treatment plants both represented significant sources of dissolved phosphorus, particulate carbon, total nitrogen and total phosphorus.

In the estuary most constituents behaved as might be expected from SPRAY results as judged by correlations of concentration and salinity (Table 2). The correlations of dissolved silicon and ammonia with salinity were somewhat lower during SQUIRT than SPRAY but not drastically so.

In summary, the comparisons that can be made indicate that conditions prevailing during the SQUIRT Cruise did not represent a major departure from those during SPRAY.

Table 2. Linear correlation of salinity and concentration of various constituents measured during the SQUIRT and SPRAY Cruises. Data are for longitudinal stations 1-10 both tides, both surface and bottom sampling depths.

Constituent	SQUIRT	SPRAY Cruise Range	
		Low	High
Nitrate + Nitrate	-0.983	-0.970	-0.995
Dissolved Phosphorus	-0.464	-0.108*	-0.785
Dissolved Silicon	-0.847	-0.953	-0.998
Ammonia	-0.230	-0.340	-0.938
Total Nitrogen	-0.955	-	-
Total Phosphorus	-0.626	-	-
Particulate Carbon	-0.434	-0.081*	-0.851

* not statistically significant ($p > 0.05$)

Dissolved Oxygen Concentration

Seasonal Variation - Mean oxygen concentration in both surface and bottom waters tends to be high in the winter and spring and low in the summer (Fig. 9,10). This pattern appears related to both temperature and freshwater input (Doering et al. 1988a). Cool temperatures and high freshwater discharge in the winter - spring contrasted with warm temperatures and low freshwater input may at least in part drive seasonal fluctuations. These factors are unlikely to exert direct influence on oxygen concentration. Rather, they control processes such as respiration, solubility and water replacement time which proximately affect dissolved oxygen concentration.

Weekly Variation - Figure 11 depicts dissolved oxygen concentration at three depths over the two week period preceding the SQUIRT Cruise in the vicinity of the Field's Point sewage treatment plant. Bottom water shows a consistent increase in dissolved oxygen from zero to somewhat over 3 mg/l. Thus the September SQUIRT Cruise apparently occurred during a period in which bottom waters were recovering from anoxia.

Tidal Variation - The gross tidal changes in dissolved oxygen for the ten longitudinal stations were large in surface waters (~3 mg/l) and small (0.2 - 0.3 mg/l) in mid and bottom waters (Fig. 12). In general concentrations were higher at high tide, which occurred in the afternoon than at low tide which occurred early in the morning. The change in surface water was probably a function of production (see below). The process that acted to increase bottom water concentration is unknown but some sort of physical mixing seems a likely first candidate.

Although tidal changes in dissolved oxygen were small and not statistically discernable they may be important. Assuming a minimum tidal enhancement of 0.2 mg/l in bottom water, it would take 16.5 tidal transitions to raise the concentration from 0 to 3.3 mg/l, or the change observed in Figure 11 over a 17 day period. Assuming 2 tidal transitions per day, this slight tidal enhancement more than accounts for the observed change. Even assuming one transition per day, prediction (3.4 - 5.1 mg/l) and observation (3.3 mg/l) are in reasonable agreement.

The mechanisms which account for reoxygenation of bottom waters in the Providence River will remain a matter of debate despite the SQUIRT Cruise. Nevertheless, the above calculation suggests that some tidal process may fuel a slow, steady increase such as that depicted in Figure 11.

Spatial Variation at Low Tide - As examples of the vertical distribution of oxygen in the Providence River data from station 6 below Field's Point and from station 10 in upper Narragansett Bay are shown in Figures 13 and 14. At station 6 oxygen concentration was relatively high in the surface and declined rapidly to a constant value at depth. The oxycline in this profile corresponds to the pycnocline. The pattern at station 10 was more complex with high concentrations in the surface mixed layer and a potential oxygen minimum at about eight meters. The surface oxycline corresponds to a shallow pycnocline while the oxygen minimum is correlated with a deep, small change in density.

Cross channel variations in density at station 6 were slight (Fig. 15). Water of a particular density was found at comparable depth in the channel and on the shallow flanks. Oxygen concentrations (Fig. 16) showed a generally similar pattern except at the most shoreward stations (6.1), where oxygen concentrations were higher than at comparable depths in the channel. Oxygen concentrations near the surface were everywhere higher on the flanks than in the channel. The reason for this is unknown. The other point worth noting is that this section shows no evidence of a near bottom zone of water depleted in oxygen.

With the exception of a couple of patches of relatively light water near the surface at station 10, cross channel variation in density in upper Narragansett Bay was not great (Fig. 17). There may be more water of sigma-t 20-21 on the eastern side of the channel. Water near the surface was relatively depleted in oxygen in mid channel relative to the flanks (Fig. 18). The two stations on the western side of the channel (10.1, 10.2) exhibited steep gradients in oxygen concentration near the bottom. This near bottom zone of oxygen depleted water suggests that benthic respiration may play an important role in oxygen consumption at least in some places in the shallow flanks.

The longitudinal distribution of sigma-t and dissolved oxygen at low tide are shown in Figures 19 and 20. The section of sigma-t suggests a strong stratification in the Seekonk River which becomes progressively weaker with distance from station 1. Much of the mixing of fresh and salt water occurs in the Seekonk. Water apparently flowing down estuary in the top 2 meters has already achieved a density of at least 16 when it reaches the upper Providence River at station 4.

The longitudinal oxygen section (Fig. 20) shows a sag in suface (<4m) oxygen concentration at stations 4 and 5 in the upper Providence River. This pattern is frequently found during the summer (Doering et al. 1988a).

On this occasion oxygen concentration in the sag did not exceed 5 mg/l in the top 2 to 3 meters of the water column.

Spatial Variation at High Tide - The vertical distribution of dissolved oxygen at stations 6 and 10 was similar to that observed at low tide (Fig. 21, 22). The surface oxycline at both stations was steeper and oxygen concentrations in the mixed layer greater than at low tide. Mid-water oxygen minima below the pycnocline were not apparent at either station.

Cross channel variation did not change dramatically with the tide (Fig. 23-26). The potential effect of sediment oxygen demand is apparent on the flanks adjacent to both stations: steep, near-bottom gradients at station 10.1 and a pool of oxygen-depleted water at station 6.2. Although less pronounced at the station 10 transect, surface water in mid channel tended to be less oxygenated than comparable water over the flanks. The cross channel distributions of sigma-t suggest that both the near bottom gradients and differences in surface water oxygen concentration were not a function of water mass variation.

The longitudinal distribution of sigma-t at high tide is shown in Figure 27. In comparison with low tide denser water has moved further up into the Seekonk River. The lens of relatively light, fresher water is still evident in the Seekonk. At depth there appears to have been an influx of water with sigma-t 21-22.

The pattern of dissolved oxygen distribution did not change substantially with tide (Fig. 28). The sag in surface concentration in the vicinity of stations 4 and 5 at the head of the Providence River is still present. What has changed is the concentration in the surface layer. Concentrations on either side of the sag are higher than at low tide especially in the lower Providence River. Concentrations within the sag have increased by about 1 mg/l.

Hourly Variation in Oxygen Concentration - As an example of daily variation in oxygen concentration in the Providence River data from station 9 are depicted in Figures 29 and 30. The section of sigma-t (Fig. 29) essentially shows the tide flowing in as indicated by the decreasing depth of lines of equal density and subsequently flowing out, with lighter water becoming more evident at the surface. Dissolved oxygen (Fig. 30) shows the same pattern. There is a rapid build-up of oxygen in the surface layer in the afternoon which corresponds to the ebbing tide. The section shows no evidence of this highly oxygenated water having been advected into the system on the flood tide: most of the highly oxygenated water (>12 mg/l) appears on the ebbing tide.

The oxygen section (Fig. 30) also shows evidence of oxygen minima in the early morning around slack low tide. These occur both near the surface centered at 1 meter and at depth centered at 4.5 meters. Whether these develop in situ or represent water advected horizontally from the flanks is unknown. Nevertheless these minima appear to be ephemeral.

Oxygen concentration in the Seekonk - Providence River varies both spatially and temporally. Concentrations near the surface tend to be higher than those at depth. In the summer time oxygen levels are depressed at the head of the Providence River (sta. 4,5) relative to the Seekonk River to the north and the lower Providence River to the south. On the SQUIRT Cruise surface water concentrations also appeared lower in mid channel than over the shallower flanks on either side. Steep gradients of decreasing oxygen concentration did not occur near the bottom of the channel but such gradients were found at some stations on the flanks. This indicates that benthic oxygen consumption may be important, at least locally.

On the SQUIRT Cruise oxygen concentration increased between low tide which occurred early in the morning and high tide in the afternoon. Increases near the surface were most dramatic but small increases also occurred in bottom water. These small statistically non-significant changes in bottom water concentrations were large enough however to account for the increasing bottom water concentrations observed over a 17 day period preceding the cruise. Thus, some sort of tidal mixing process may play a part in the reoxygenation of bottom waters in the Providence River. Although precipitous events such as turnover brought on by wind driven mixing cannot be discounted, the recovery of bottom water from anoxia may be a slow process resulting from disequilibrium between a number of opposing forces. Intuition suggests that the concentration of oxygen in the surface water, the strength of mixing across the pycnocline, the rate of oxygen consumption in bottom water and the residence time of water would be important. The former two factors would tend to relieve anoxia while increases in the latter two would exacerbate it.

Dissolved Oxygen Metabolism

Since excessive oxygen demand may exhaust the supply thus producing anoxia, a consideration of the sources of oxygen demand within a system represents an initial step toward understanding and alleviating the problem. This section of the report summarizes data collected during the SQUIRT Cruise with the purpose of determining whether oxygen demand within the system derives from external or internal sources.

Biochemical Oxygen Demand (BOD) - BOD (5-day) loading from rivers and sewage treatment plants totalled about 85.6 grams/sec (Fig. 31). Two rivers, the Pawtuxet and Blackstone, and two sewage treatment plants, Field's Point and the Blackstone Valley District Commission accounted for most of the loading (Fig. 31).

In the Seekonk - Providence River, the BOD of surface water was higher than that of bottom water (Fig. 32). There was no demonstrable tidal effect so only low tide data are depicted. The peaks in surface water BOD at stations 2 and 5 may reflect input from sewage treatment plants, but the limited data do not allow a firm conclusion.

The total BOD present in the Seekonk - Providence River was calculated as follows. Distinct estimates for the Seekonk and Providence Rivers were made by first separately averaging surface and bottom values. These were then averaged and multiplied by the appropriate volume after Chinman and Nixon (1985). Estimates for the Seekonk and Providence River were then added to arrive at a total. This total amounted to 1.99×10^8 grams BOD or 8.25 grams BOD/m^2.

Sediment Oxygen Demand (SOD) - An areally weighted estimate of SOD was calculated by distributing measurements among three regions: the Seekonk River, Fox Point Reach and the remainder of the Providence River. Measurements were averaged by regions and these multiplied by the appropriate area after Chinman and Nixon (1985). The total SOD for the system was 6.35×10^6 grams O_2/day or 0.26 grams O_2/m^2/day.

Production and Respiration - The net production of oxygen declined with depth at all three (3, 6, 9) stations (Table 3). Except at station 3, dark respiration showed a similar pattern. Total net production and dark respiration for the system were calculated as follows. Integrated totals were calculated over the depth of measurement at each station. Station 3 was assumed to be representative of the Seekonk River. Since incubation depths exceeded the average depth of the Seekonk River an average production per liter was calculated and total production for this part of the system was estimated through multiplication by total volume. Areal production was calculated by dividing by the total area. This procedure gave the most conservative estimate.

Table 3. Productivity data for the SQUIRT Cruise. Units are oxygen mg/l/incubation.

Station	Time	Depth(m)	Production Gross	Production Net	Dark Respiration
3	4.0 hrs	0.5	1.56	1.49	-0.07
		1.0	0.51	0.51	0.0
		2.0	0.32	0.08	-0.24
6	3.85 hrs	1.0	2.88	2.35	-0.53
		2.0	0.83	0.55	-0.28
		3.0	0.61	0.33	-0.28
9	4.0 hrs	0.5	3.93	3.05	-0.87
		1.0	2.46	1.88	-0.58
		2.0	1.19	0.63	-0.57

Stations 6 and 9 were assumed to be representative of the Providence River. Since incubation depths did not exceed average depth of the system, production under 1 m^2 of surface was calculated directly by integrating over the depth of incubations. Estimates from the two stations were averaged and this was taken to represent production in the Providence River.

Daily areal production for the entire system was calculated by weighting estimates for the Seekonk and Providence Rivers by relative area and assuming that 55% (Vollenweider, 1965) of the total production occurred during the incubation. Estimates for dark respiration were similarly derived.

Sources of BOD - Metabolism data are summarized in Table 4. A comparison of dark respiration and sediment oxygen demand indicates that most (96%) of the respiration in the system occurred in the water column. This conclusion is commensurate with the oxygen profile data which suggests that benthic oxygen consumption was only locally important.

The two potential sources of material which fuel water column respiration are input from rivers and sewage treatment plants and in situ production. A third unevaluated source may be up-estuary transport from Narragansett Bay. The standing stock of BOD in the Seekonk - Providence River may be taken to represent the amount of material available for aerobic oxidation. One way to judge the relative importance of a given source of BOD is to calculate the time required for that process to create the observed standing stock of BOD. In situ net production could produce the observed BOD in 1.2 days (Table 5) while nearly 27 days of loading from rivers and sewage treatment plants would be required to accumulate the observed BOD. This comparison alone suggests that internal processes dominated BOD production during the SQUIRT Cruise. Since the system flushes within 3 to 10 days, it is unlikely that external input could ever account for observed BOD under the conditions prevailing during SQUIRT.

An alternative way to assess the sources of oxygen demand is to examine sources of organic matter. A production of 7 g O_2/m^2/day is equivalent to 2.63 g C/m^2/day. Assuming that 20 to 50% of this production is dissolved about 1.3 - 2.1 g C/m^2 is particulate. This production is 5.5 - 8.8 times the external particulate carbon loading (0.24 g C/m^2/day). Thus on the SQUIRT cruise the largest source of organic matter was internal to the system.

Table 4. Summary of oxygen metabolism data gathered during the SQUIRT Cruise.

	Hourly Rate	Daily Rate
Net Production	0.96 g $O_2/m^2/hr$	7.00 g $O_2/m^2/day$
Dark Respiration	0.30 g $O_2/m^2/hr$	-
Sediment Oxygen Demand	0.011 g/$O_2/m^2/hr$	0.26 g/$O_2/m^2/day$
BOD Loading (5 day)	85.62 g O_2/sec	0.31 g $O_2/m^2/day$
Particulate Carbon Loading	67.29 g C/sec	0.24 g $C/m^2/day$
Average BOD (5 day) in System	-	8.25 g O_2/m^2

Table 5. Time (days) required for a given process to create the standing stock of BOD observed on the SQUIRT cruise.

Production Processes

Net Production: 8.25/7.00 = 1.20 days

BOD Loading: 8.25/0.31 = 26.6 days

Daily Fluctuations in Oxygen Concentration - Since low tide occurred early in the morning and high tide in the afternoon the potential influences of tidal exchange and biological production on oxygen concentration were confounded on the SQUIRT Cruise. Oxygen concentration was substantially higher in surface waters at high tide than at low tide (Fig. 12). The purpose of this section is to determine whether this change was tidal or mediated by internal processes.

If the change in surface water oxygen concentration were purely a function of tidal advection of oxygenated, more saline water from lower Narragansett Bay then the slopes of oxygen vs. salinity relationships should not vary with tide. In the Providence River (Sta. 4-10), they do (Table 6). Further more, the data from station 9 (Fig. 30) suggest the appearance of highly oxygenated water on the out-going tide. Lastly, bottle incubations indicate a high net production of oxygen (7.0 g O_2/m2/day), over twice the annual daily average (~3.1 g O_2/m^2/day, see Oviatt et al. 1981). Taken together these observations argue for in situ production of oxygen during the day.

A Potential Link Between Nutrients, Production and BOD - The summary of metabolic oxygen measurements taken during the SQUIRT Cruise suggest that the BOD and organic matter present in the Seekonk - Providence River arose from in situ biological production rather than external loading. Thus factors which affect biological production such as nutrient availability; light, etc. may be important determinants of oxygen dynamics in the system.

First we consider two proximate controls of phytoplankton production which have demonstrable import in other systems (Cole and Cloern, 1984). These are light and phytoplankton biomass. Then we consider the role of nutrients in fueling production.

Production of oxygen was measured at 3 stations and at three depths per station by the light-dark bottle oxygen technique. Chlorphyll a (phytoplankton biomass) was estimated from in vivo fluorescence profiles taken by EPA (3-4, 6-3, 9-3 in the data report for this cruise). High tide (afternoon) profiles of downwelling light were available for 2 of the 3 stations (6 and 9). The fraction of light at the surface which remained at each incubation depth was calculated from extinction coefficients derived from these profiles. The net production of oxygen during each incubation was significantly correlated with phytoplankton biomass ($R^2=0.515$ $p<0.05$ $n=8$) and the fraction of surface insolation remaining at depth ($R^2=0.835$

$p<0.05$ $n=6$). A multiple regression of net mg O_2/incubation on both independent variables explained 95% of the variance at the 90% level of confidence ($n=5$). Despite the paucity of data, these results are encouraging and suggest that light and biomass largely control short term rates of phytoplankton production in the Seekonk-Providence River. Before such relationships could be used for predictive purposes far more data, under a variety of light and biomass combinations would be required.

With respect to nutrients, the important question is whether these are causing cultural eutrophication. In order to answer this question with some confidence it is helpful to know whether 1) dissolved nutrient concentrations in the Seekonk - Providence River are at least in part controlled by anthropogenic input and 2) dissolved nutrients are in fact utilized to a large extent in the river itself. Since the limiting nutrient in salty waters is generally thought to be nitrogen (Howarth, 1988), the behavior of this nutrient in the estuary is critical.

Previous analysis of the SPRAY Cruise data has shown that in general nutrient concentrations including the dissolved forms of nitrogen, are largely a function of point source input (Doering et al. 1988b, Doering et al., in press).

Table 6. Regressions of oxygen on salinity at high and low tide in surface water of the Providence River. Data are for station 4-10 from the UCONN Profiles.

High tide:

O_2 mg/l = -57.24 + 2.53 * Salinity ‰
r = 0.926 n = 7 $p<0.05$

Low tide:

O_2 mg/l = -15.90 + 0.91 * Salinity ‰
r = 0.789 n = 7 $p<0.05$

F-test for equality of slopes:

F = 8.25 d,f = 1,10 p = 0.0166

In order to assess whether nitrogen is in fact utilized in the river, an expected mean concentration has been calculated by the freshwater fraction method and compared to an observed concentration in Table 7. The difference is taken as potential utilization. The expected concentration is derived from a flow weighted concentration of freshwater input and the concentration in bottom water in upper Narragansett Bay (station 10). These are then weighted according to the mean salinity in the estuary itself to calculate the expected concentrations. Simple averages over tides, stations and surface and bottom samples were used to calculate both mean salinity and observed concentrations in the estuary. The calculations (Table 7) show that potential utilization can be significant especially during the summer (cruises 5 and 6). Interestingly, the highest potential utilization occurred when lowest oxygen concentrations were observed (cruise 5).

This analysis can be taken further to determine which form of DIN is being used in the estuary. Plots of expected versus observed ammonia and nitrate + nitrite suggest that ammonia is the form of nitrogen being utilized in the estuary (Fig. 33). Whereas predicted and observed nitrate + nitrite are clustered around the 1:1 line, several data for ammonia fall above the line, suggesting loss within the estuary.

The SQUIRT Cruise occurred during low freshwater discharge conditions in the summer. Thus significant nitrogen utilization is expected. A rough calculation supports this conclusion. Given a net day time production of 7 g O_2/m^2/day a nitrogen demand of 0.033 moles N/m^2/day can be calculated assuming an O:N ration of 13.25. The total dissolved nitrogen loading was 5.14 moles/sec or 0.0092 moles/m^2 over a 12 hour period. The demand of production is at least 3.5 times greater than the input. Thus a decline in dissolved nitrogen concentration should have occurred during the SQUIRT Cruise.

An examination of ammonia concentrations in surface waters at low tide (early morning) and high tide (afternoon) support this prediction (Fig. 34). Concentrations were higher at low tide than high tide. Chlorophyll a, a measure of phytoplankton biomass shows an opposite pattern, suggesting accumulation during the day (Fig. 35). The possibility that these changes were in fact due to tidal advection cannot be easily dismissed owing to the rather poor correspondence between changes in either ammonia or chlorophyll a and changes in salinity. Nevertheless, if biologically mediated, the ratio of change in nitrogen, phosphorus and production should approach the Redfield (Redfield, 1958) Ratio of 106 C:16 N:1P.

Table 7. Potential nitrogen utilization during the SPRAY cruises. Potential utilization may be inferred from the difference between expected and observed concentrations. Dissolved Inorganic Nitrogen (DIN) = $NH_3+NO_2+NO_3$ concentrations in µmole/l.

Cruise	Freshwater m^3/sec	Expected DIN	Observed DIN	Observed Minus Expected
1	15.66	80.61	69.10	-11.51
2	68.98	54.35	51.65	-2.70
3	90.22	42.79	32.55	-10.24
4	121.34	32.15	29.77	-2.38
5	16.81	97.48	58.83	-38.65
6	14.02	59.50	40.87	-18.63

Table 8 summarizes the net consumption of nutrients (DIN and DIP) and the net production of oxygen between samplings in a 1 meter deep, 1 meter wide water body extending about 10.7 Km between stations 4 and 9 in the Providence River. It is over this region that the greatest tidal changes occurred (Fig. 34, 35). Net oxygen production has been estimated in two ways. Net production estimates from incubations in the top 1 meter at stations 6 and 9 were averaged, prorated to 7 hrs (time between samplings) and assumed to apply to the whole water body. Secondly, the change in mass of oxygen in the water body was estimated by horizontal integration of discrete surface water samples (z=1.0 m) taken at each sampling. Changes in the mass of nutrients were estimated similarly. Changes in nutrient concentration were in turn adjusted for point source input (see Table 8).

The results in Table 8 are interesting for several reasons. First the two estimates of net oxygen production differ by only 170 moles or about 12% of their average. On average high tide concentrations are thus about 0.5 mg/l lower than production incubations would suggest. Secondly, the calculated Redfield Ratio is very close to the accepted value if production incubations are used and nutrient changes are adjusted for input. These calculations suggest that the organic production observed during the SQUIRT Cruise was fueled not only by nutrients present in the system but by external input as well. Lastly it can be calculated that the areally weighted nutrient input could replace the mass of dissolved nitrogen in 0.9-1.8 days and the mass of P in 2-3 days. Assuming a 2.5 meter deep surface layer, replacement times for nitrogen range from 2-4.5 days and for phosphorus from 5.7-7.5 days. If external input is to the surface layer, the supply of nutrient in the river could be replaced relatively quickly by point sources.

Analysis of SQUIRT and SPRAY data therefore suggest that the origins of BOD in the Providence River are internal at least during low freshwater discharge in the summertime. Biological production appears to be the source of BOD. This production is supported by inorganic nutrients, whose concentration is to a large degree determined by point source input. The recurrent hypoxic or anoxic conditions in bottom water during the summer may result from high biological production near the surface, warm temperatures and high respiration in the bottom layer coupled with insufficient transport of oxygen either vertically from the surface or horizontally from lower Narragansett Bay.

Table 8. Net apparent consumption of dissolved inorganic nutrients and production of oxygen in a hypothetical 1 meter deep, 1 meter wide water body extending from Station 4 to Station 9 in the Providence River, units are moles.

	O_2 Concentration	DIN	DIP	Net Production O_2
Low Tide:	2259	355	41.5	-
High Tide:	3587	174	31.5	-
Net Change:	1328	181	10	1498
Area Based[1] Input:	-	58	4	-
Total Change:	1328	239	14	1498
	C[2]	N	P	C[2]
Redfield Ratio:	106	16	1	106
Observed Ratio:	94.9	17.1	1	107

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[1] Area Based Input: The total input to the system was divided by the total area to estimate input/m^2/7 hrs. This figure was multiplied by area of the water body (10.72×10^3 m^2).

[2] Oxygen production converted to carbon fixation assuming PQ of 1.0.

Acknowledgements

The following persons participated in the SQUIRT Cruise in one capacity or another. Depending on one's point of view we left the dock very late at night or very early in the morning. The good nature and cooperativeness exhibited by everyone is much appreciated and made an otherwise long and difficult day seem particularly enjoyable. Thank you all: Eric Klos, Edwin Requintina, Scott Metzger, Nancy Craig, Mark Gustafson, James Allan, Craig Eller, John McCleoud, Laura Weber, Carin Asjian, Aimee Keller, Ken Hinga, Lynn Beatty, Jack Seites, Fred Godshall, Greg Tracey, David Drapeau, Cindy Heil, James McKenna, Edward Dettmann, Jenny Martin. We also thank Cindy Lima, Paul Kinney, and Russ Houde for providing samples from the treatment plants and Lance Ramsbey from the USGS for the river discharge data.

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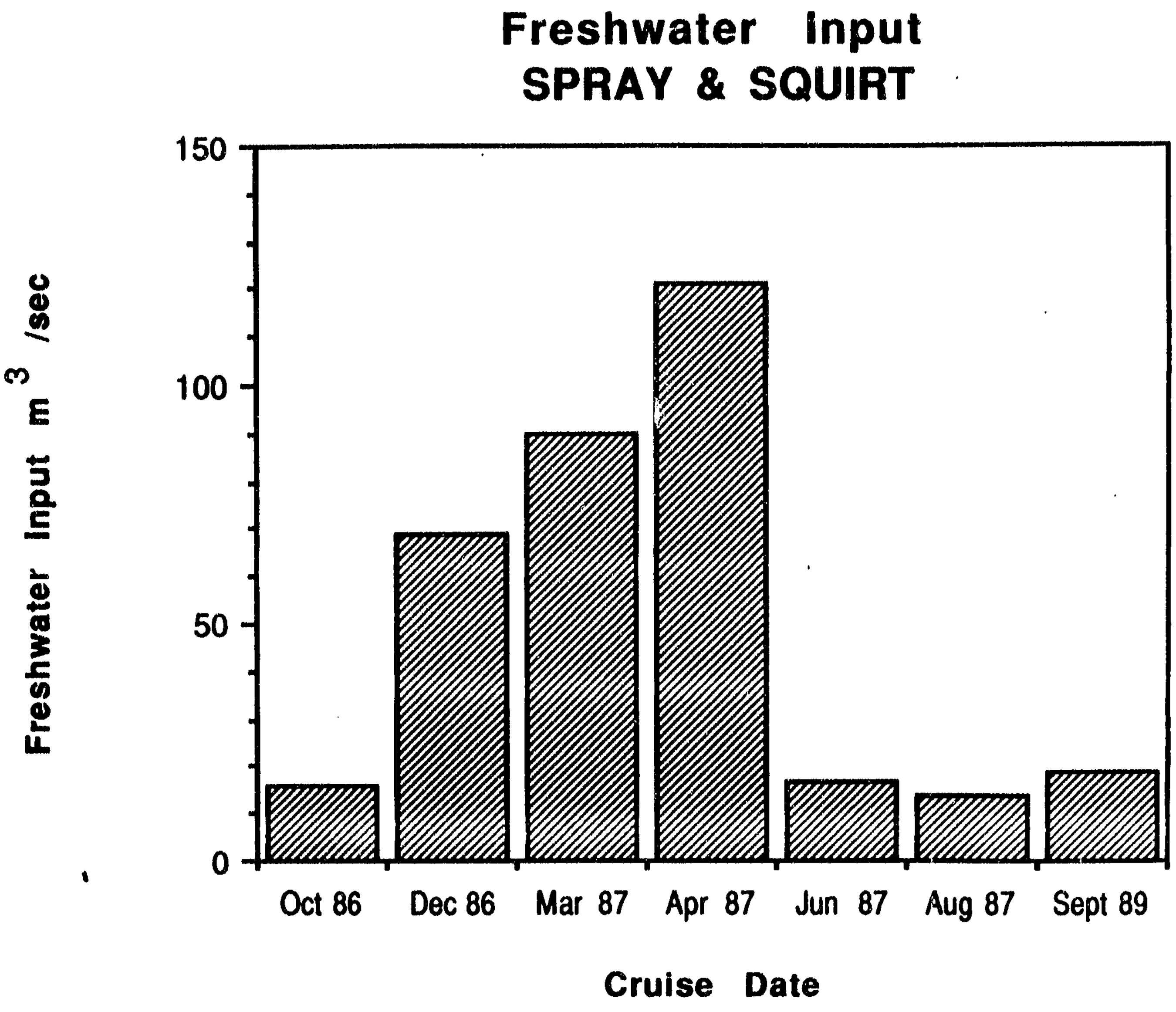


Figure 2. Total freshwater input during the SPRAY and SQUIRT Cruises.

Figure 3. Total input of ammonia (3 day average) to the Providence and Seekonk Rivers during the SPRAY and SQUIRT Cruises.

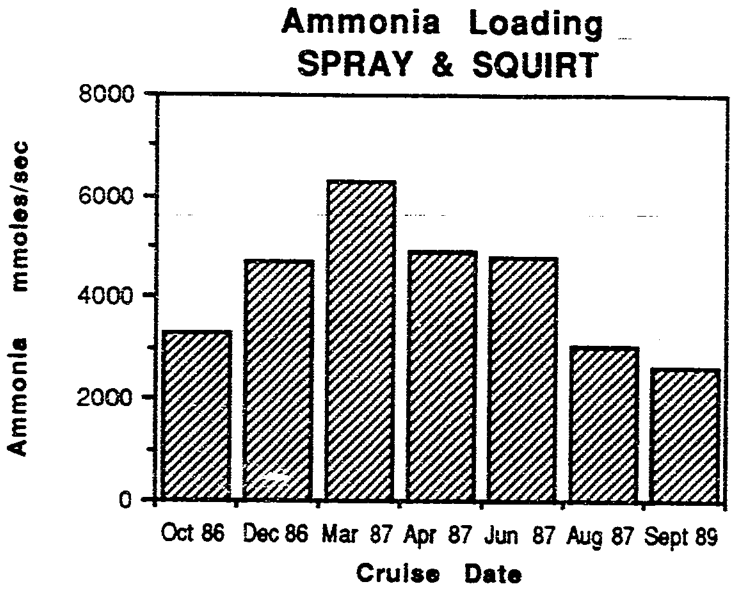


Figure 4. Total input of dissolved phosphorus (3 day average) to the Seekonk and Providence Rivers during the SPRAY and SQUIRT Cruises.

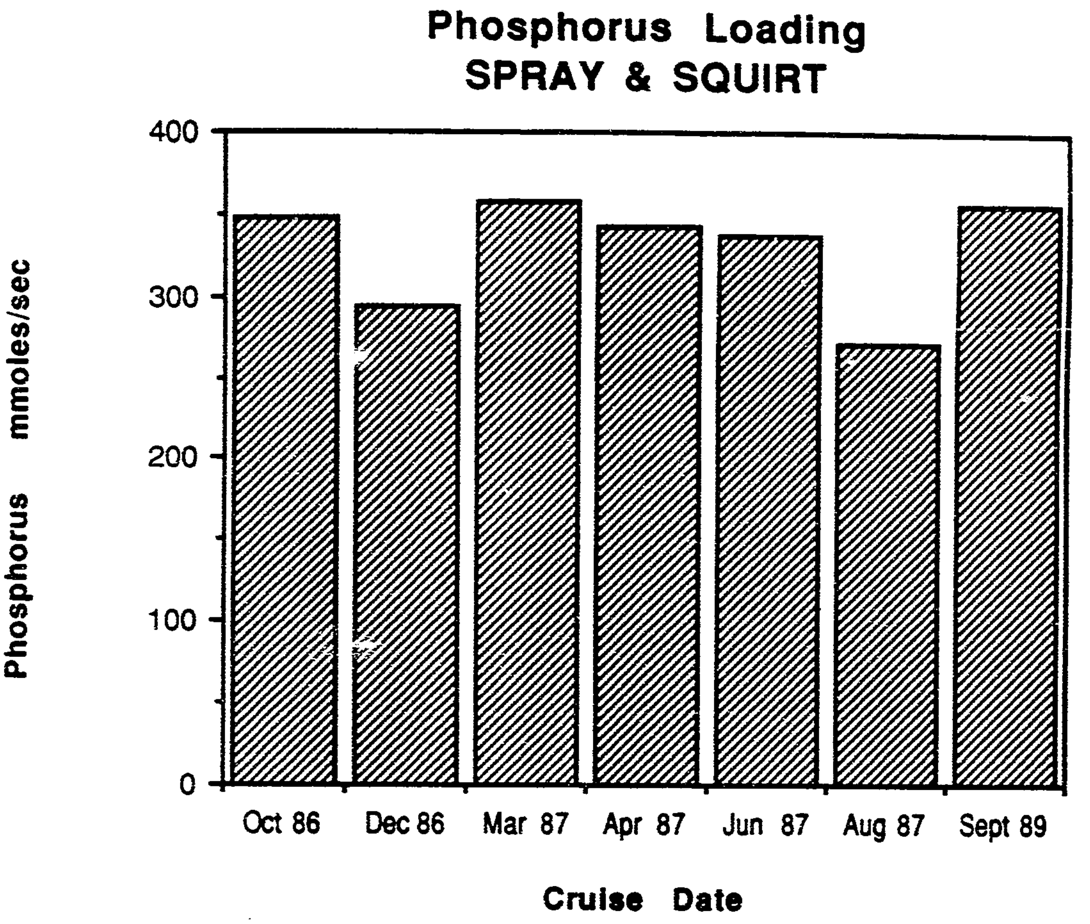


Figure 5. Loading of Nitrate + Nitrite to the Seekonk and Providence Rivers as a function of freshwater input. Arrow indicates SQUIRT Cruise other data for SPRAY Cruises.

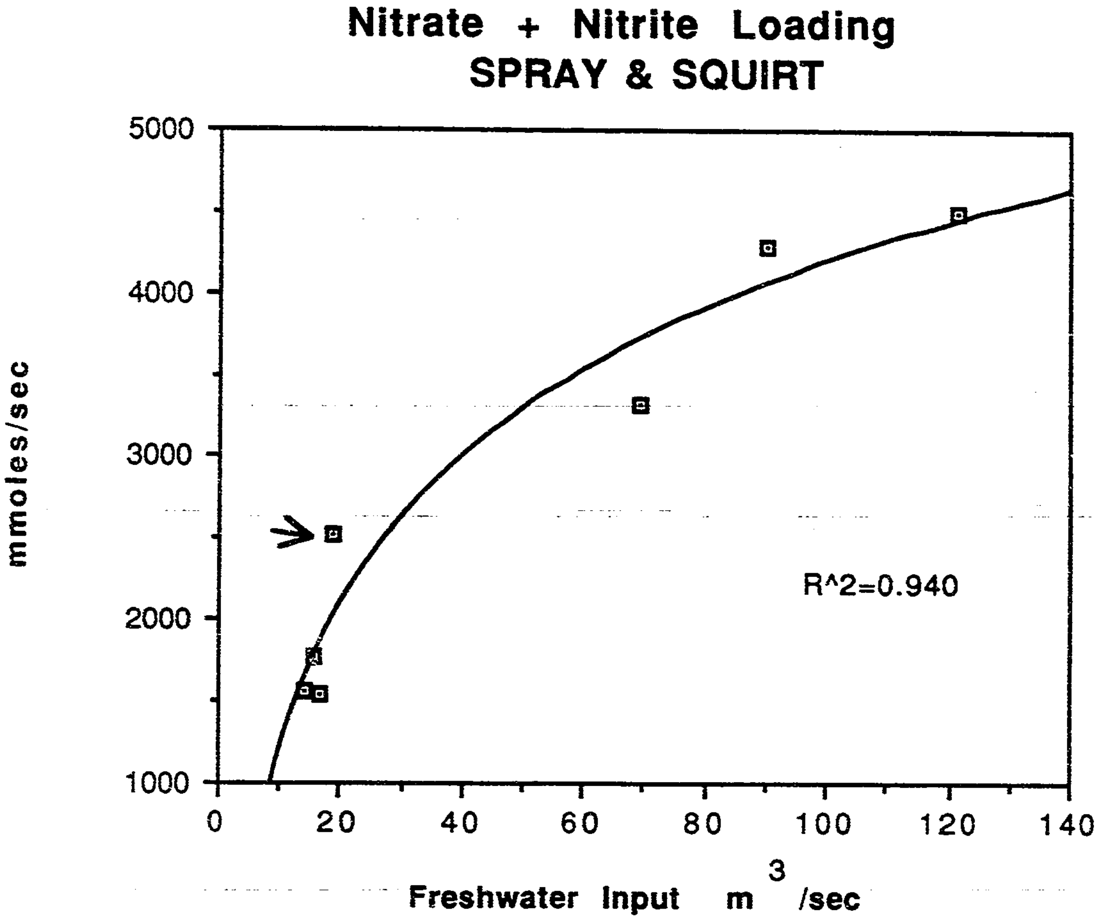
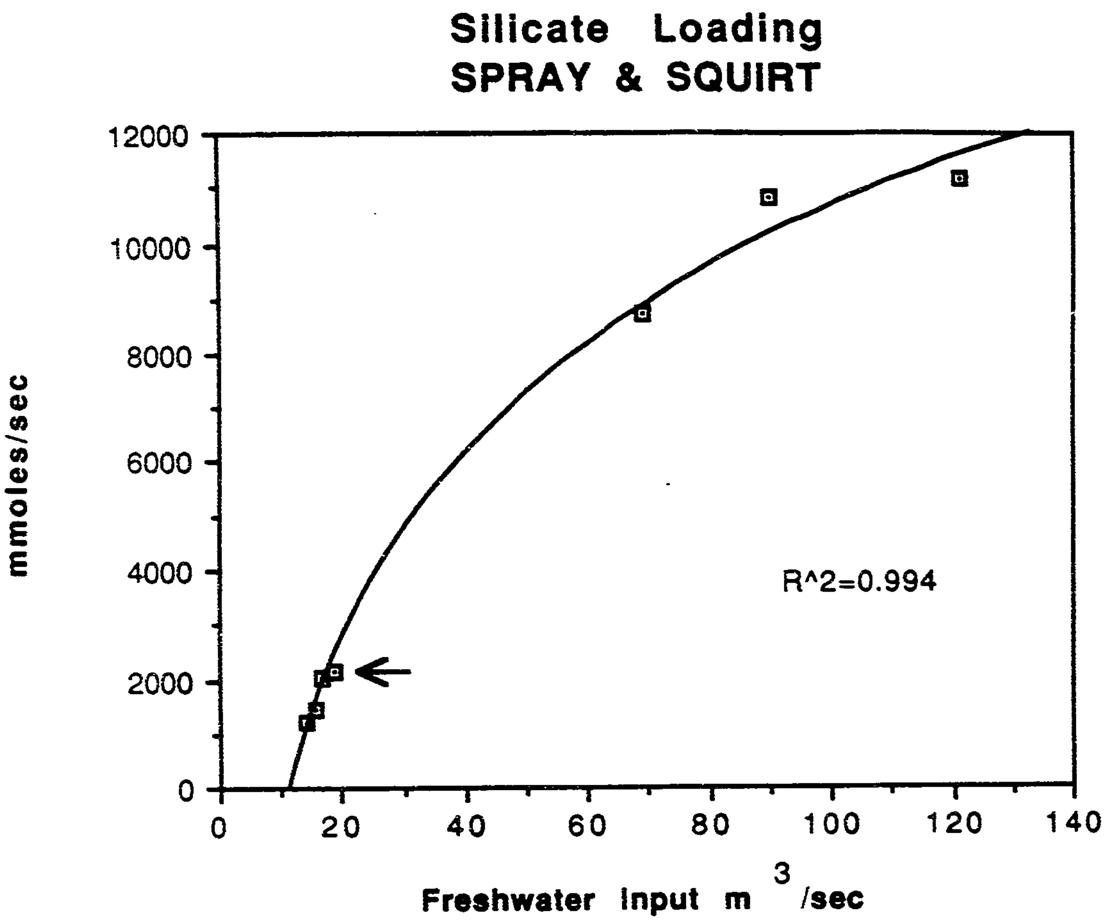


Figure 6. Loading of dissolved silicon as a function of freshwater input. For details see legend for Figure 5.



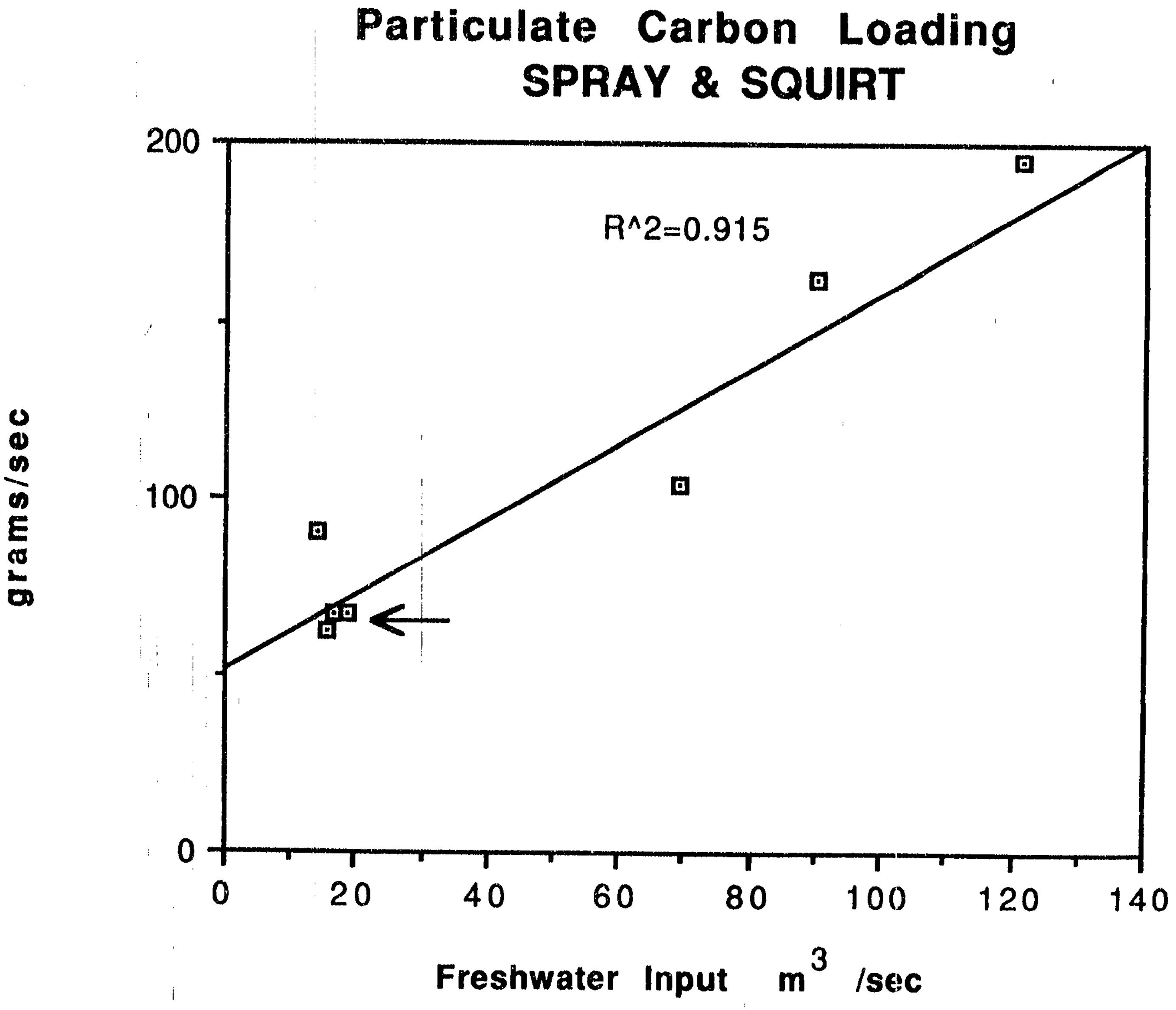


Figure 7. Loading of Particulate Carbon as a function of freshwater input. For details see legend of Figure 5.

Figure 8. Average (3 day total) loadings measured during the SQUIRT Cruise.

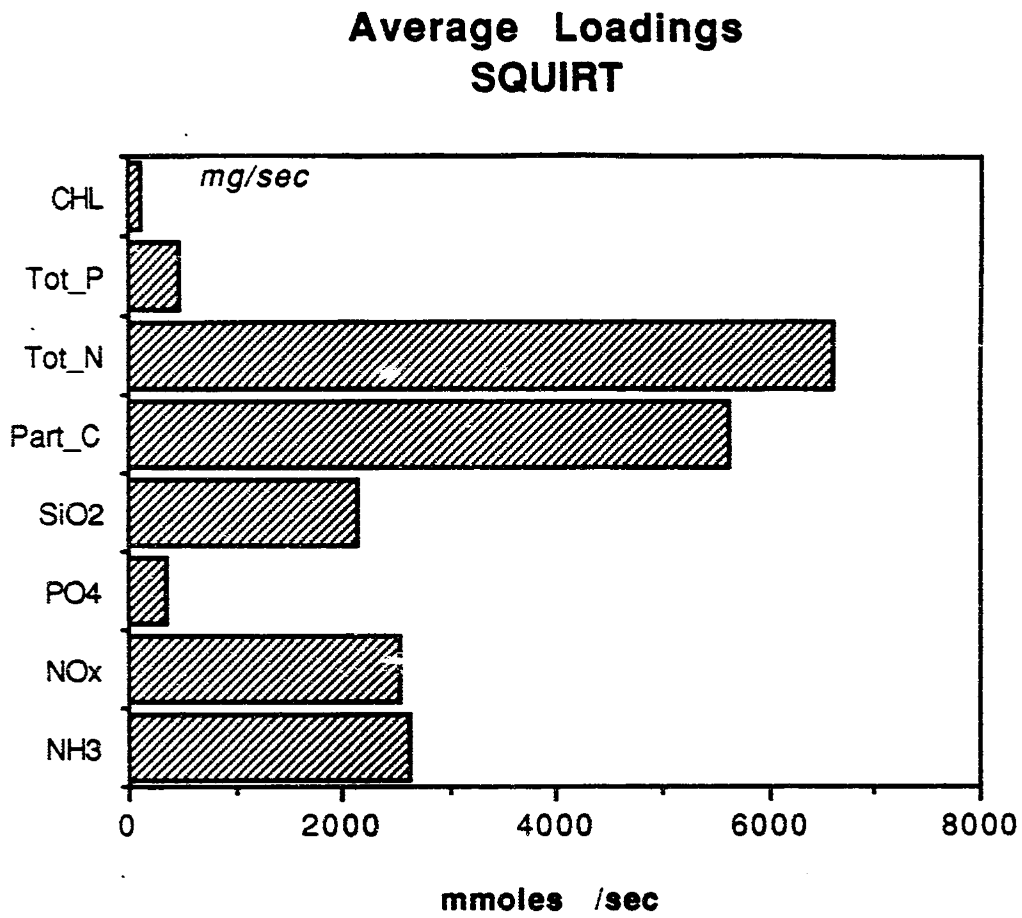


Figure 9. Mean concentration of oxygen in the Seekonk and Providence Rivers. Mean derived from 10 longitudinal stations. SQ = SQUIRT, other data from SPRAY.

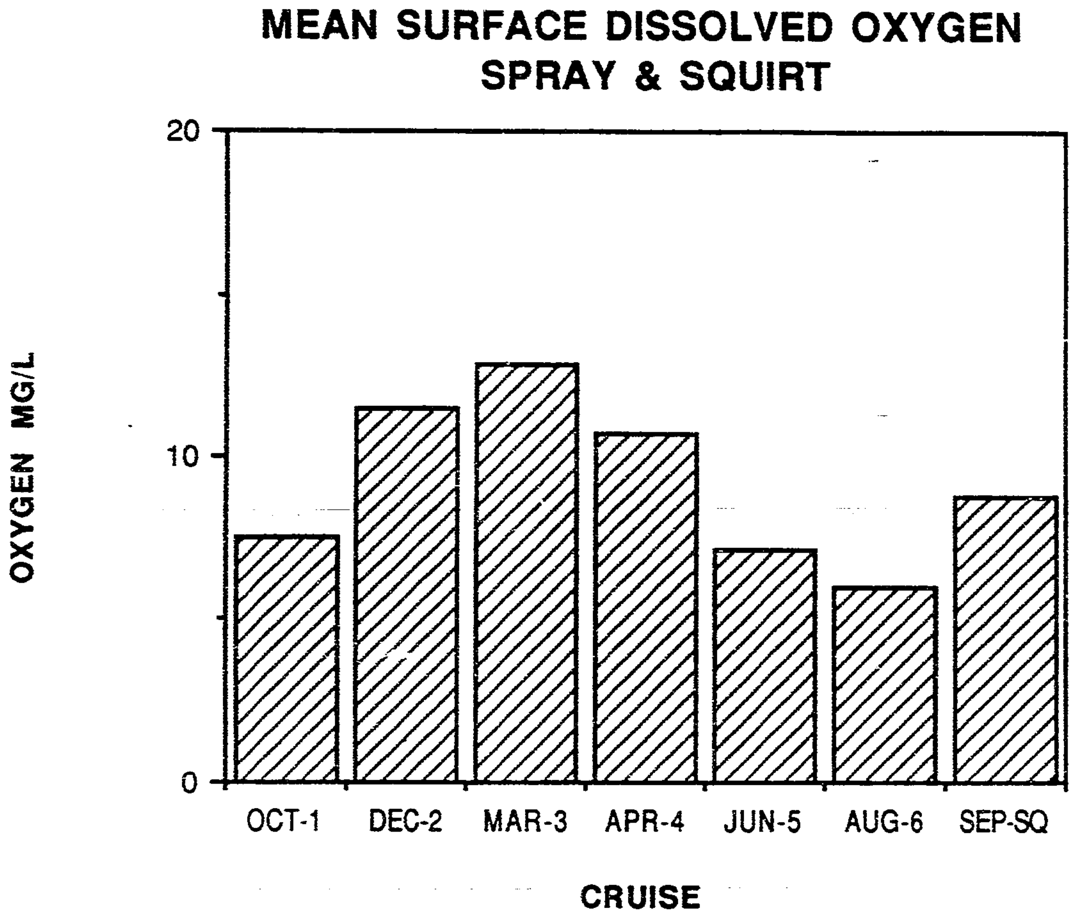


Figure 10. Mean oxygen concentration in bottom water. For details see legend for Figure 9.

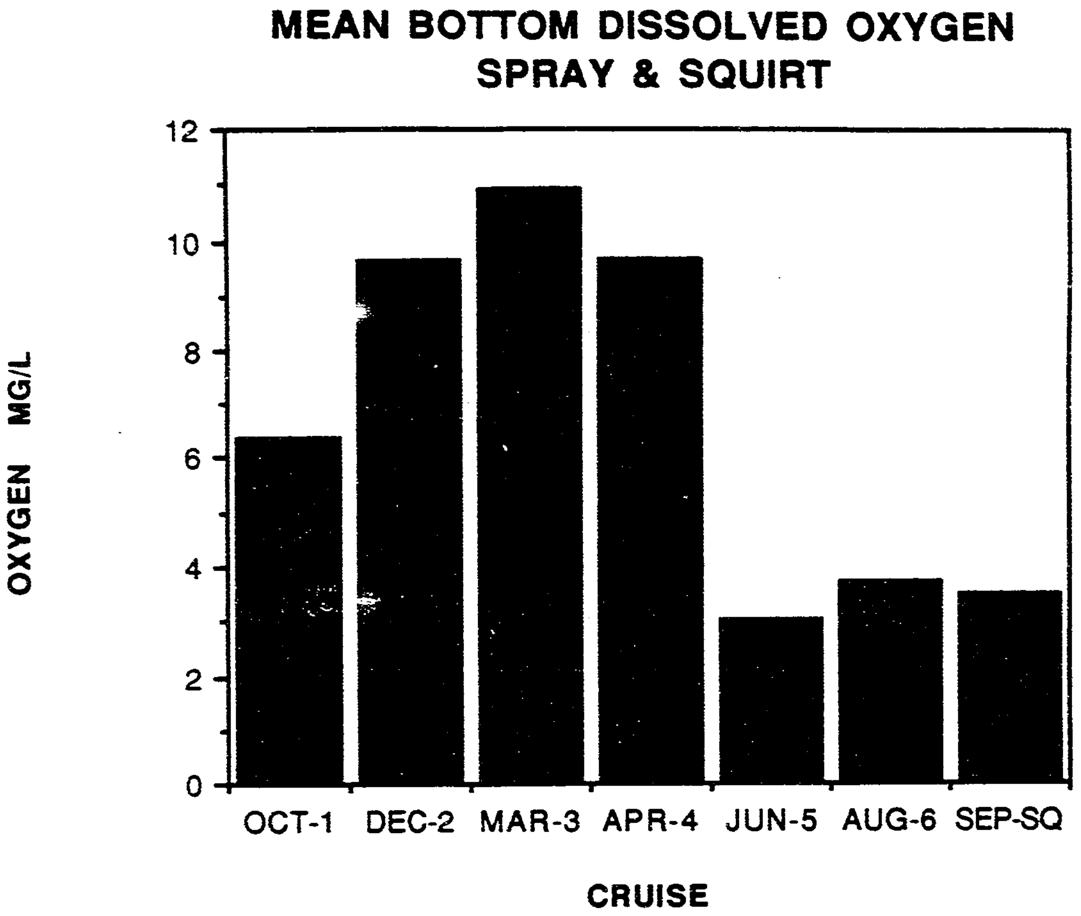


Figure 11. Dissolved oxygen concentration in the vicinity of Field's Point in the Providence River over a 17 day period culminating in the SQUIRT Cruise.

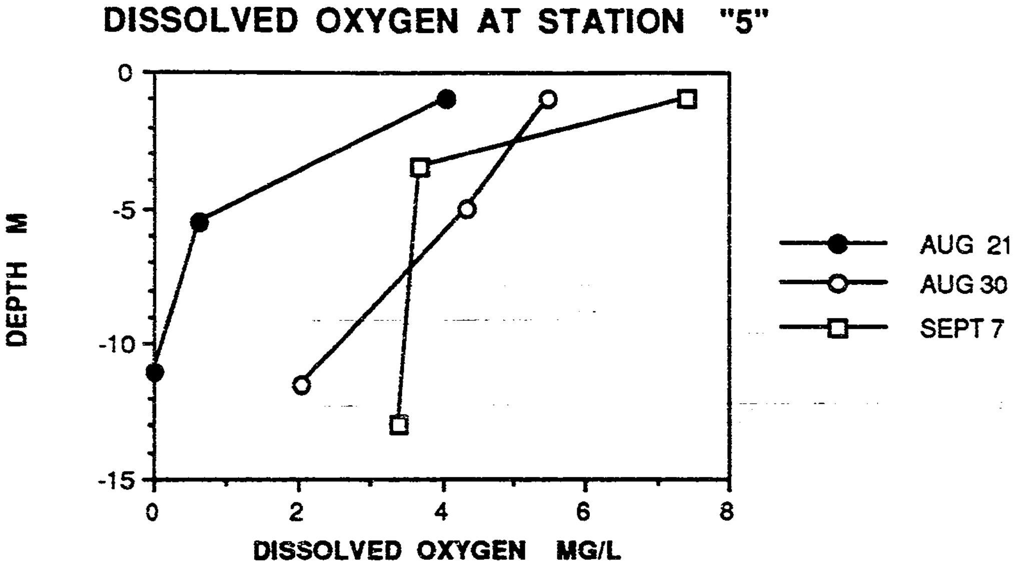
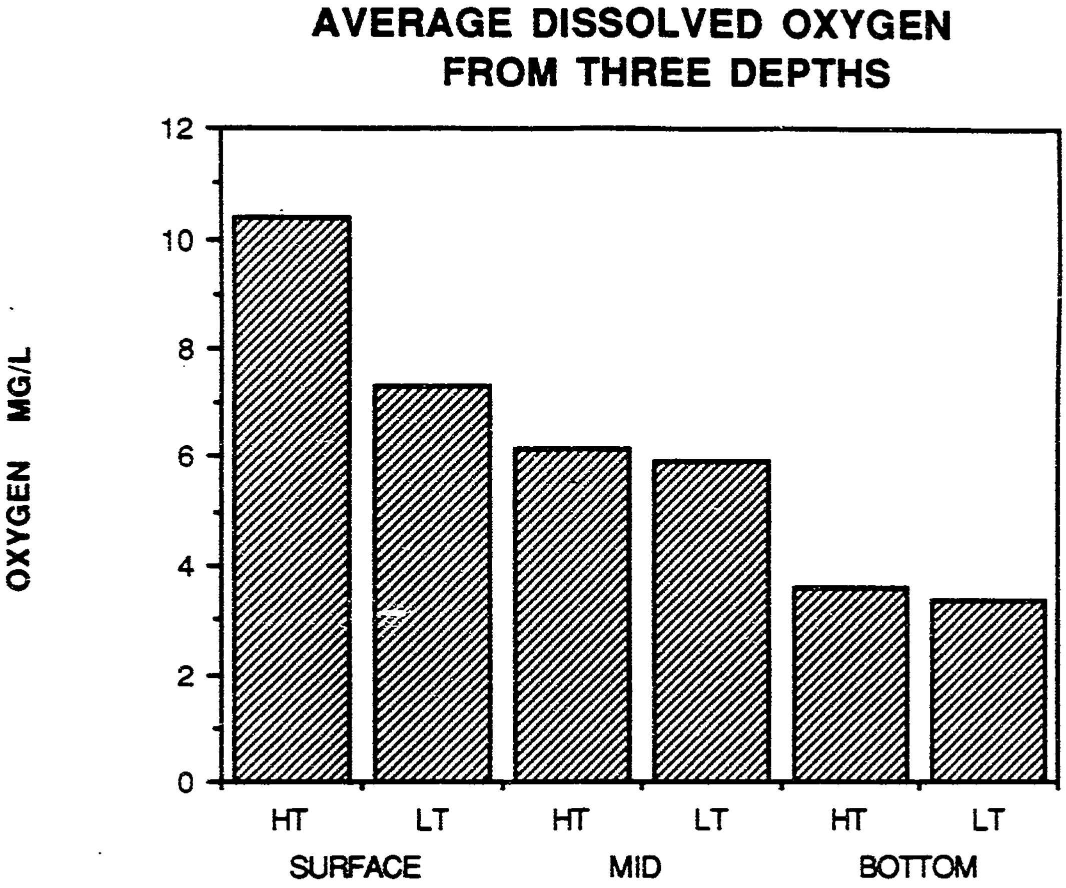


Figure 12. Average oxygen concentration in the Providence River at High and Low Tide at three depths: 1m below surface, at the pyconocline, and 1m from the bottom. Averages are for stations 1-10.



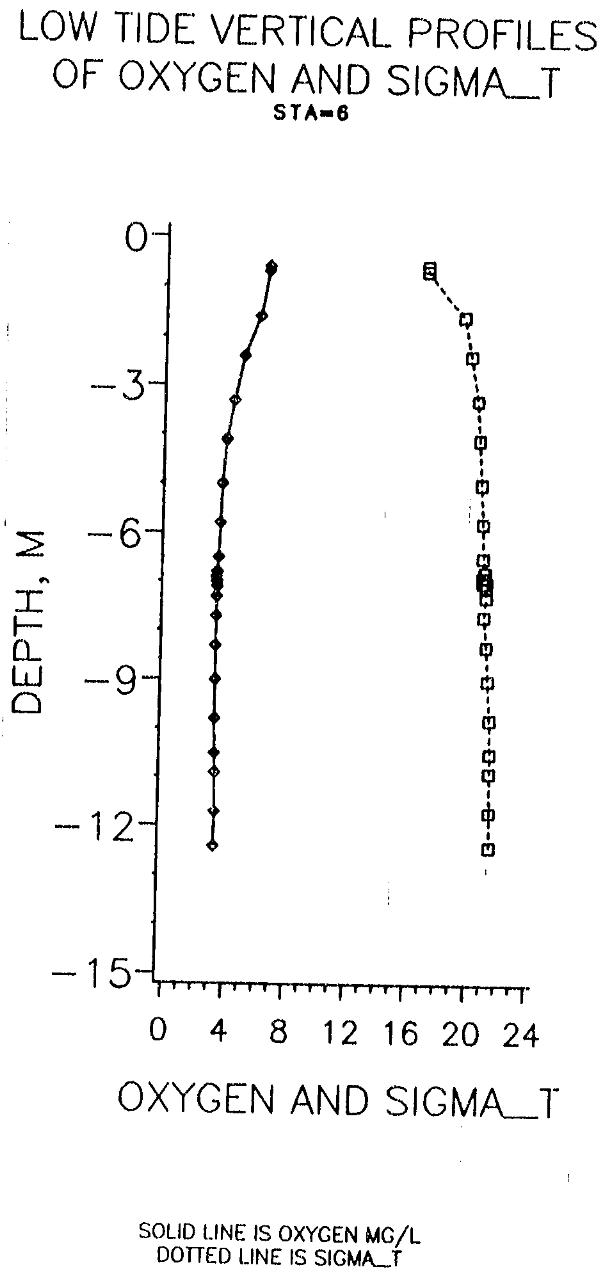


Figure 13. Oxygen and density as a function of depth.

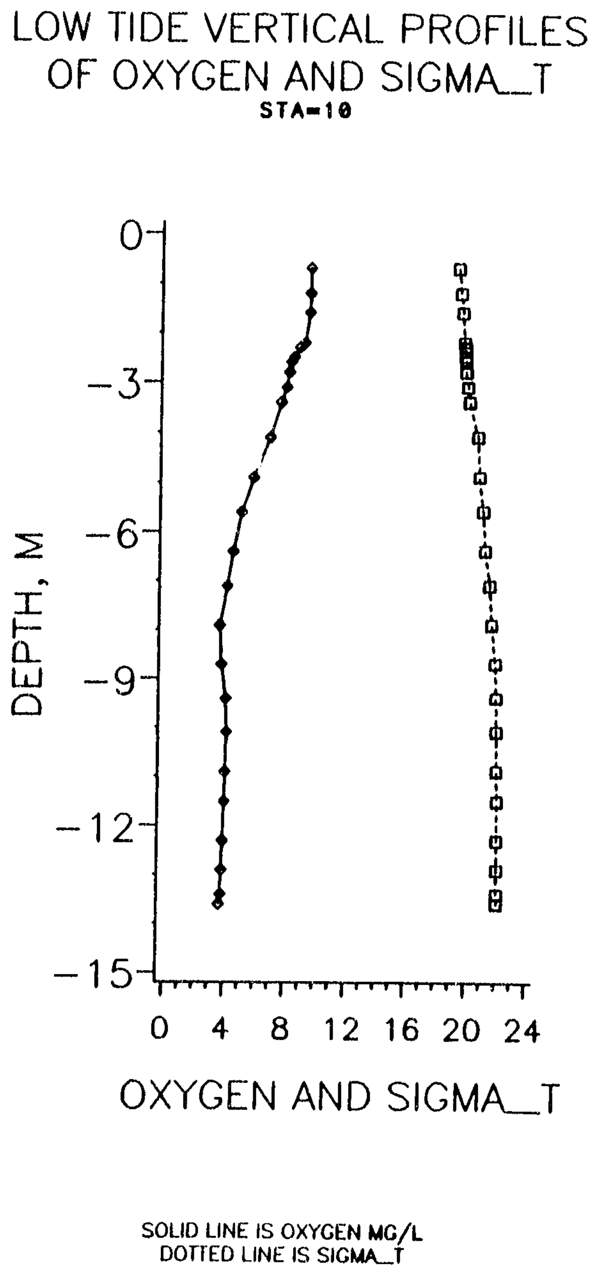


Figure 14. Oxygen and density as a function of depth.

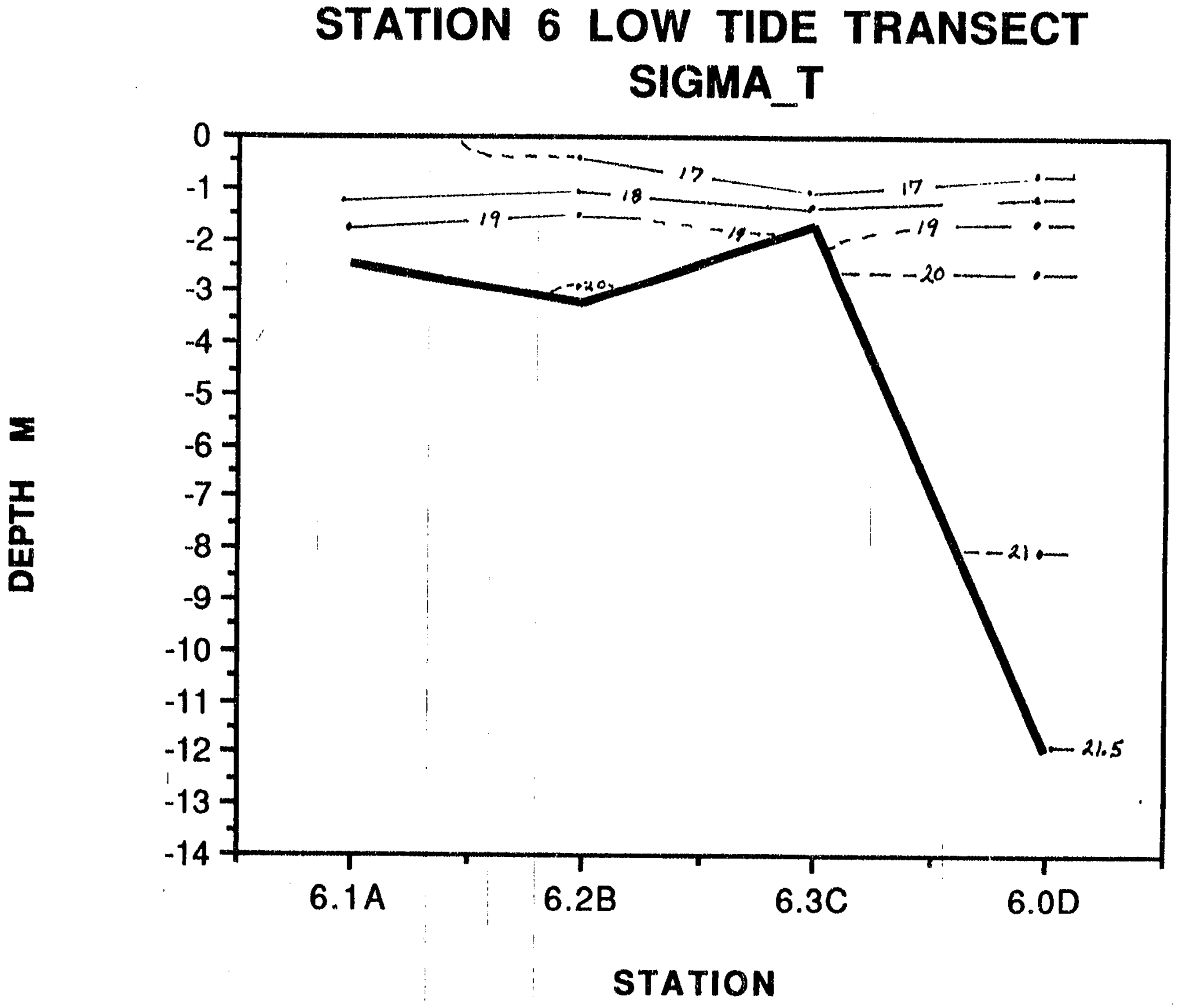


Figure 15. Cross channel transect of density. Thick line represents station depth not true bathymetry.

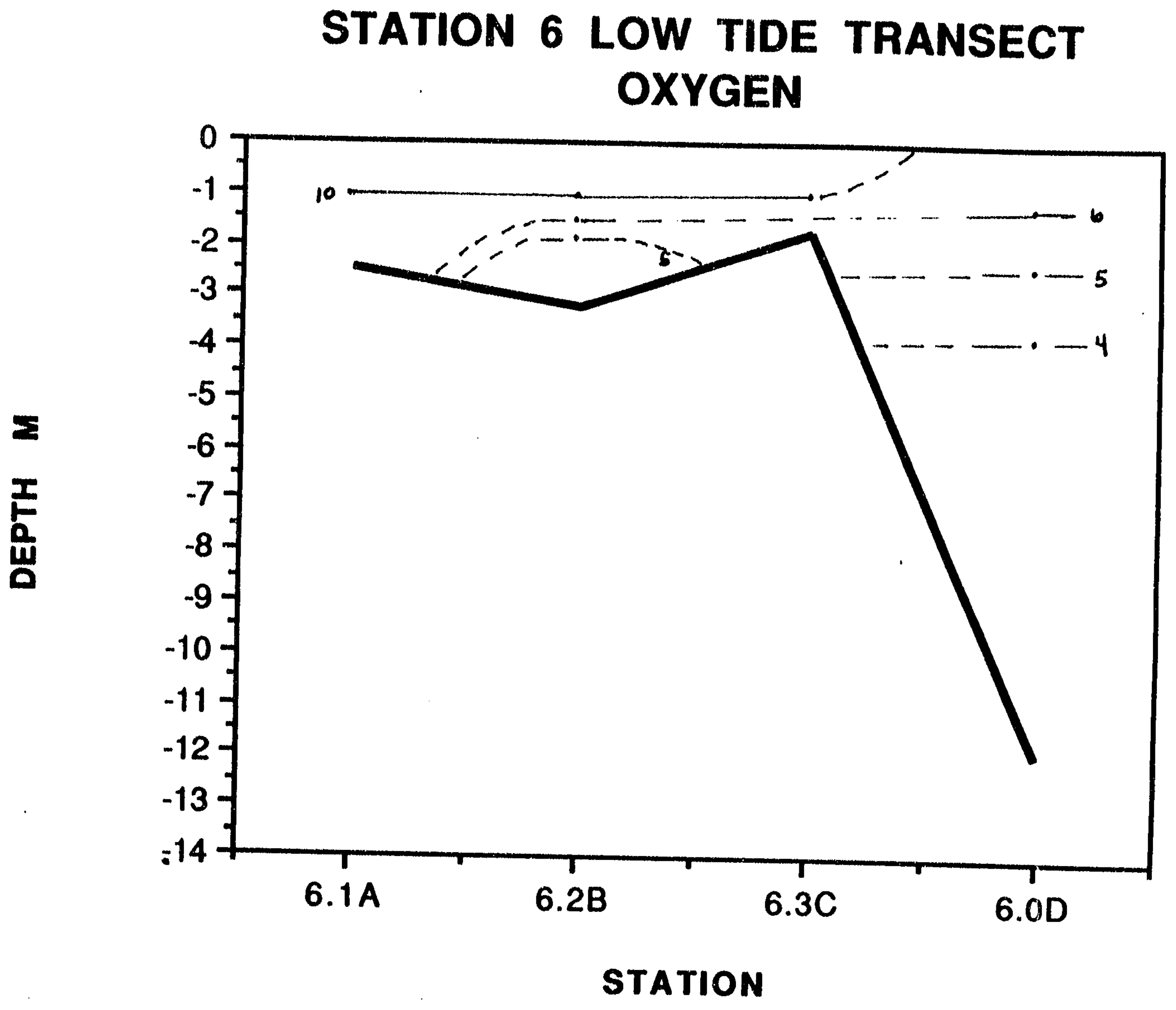


Figure 16. Cross channel transect of oxygen. Thick line represents station depth not true bathymetry.

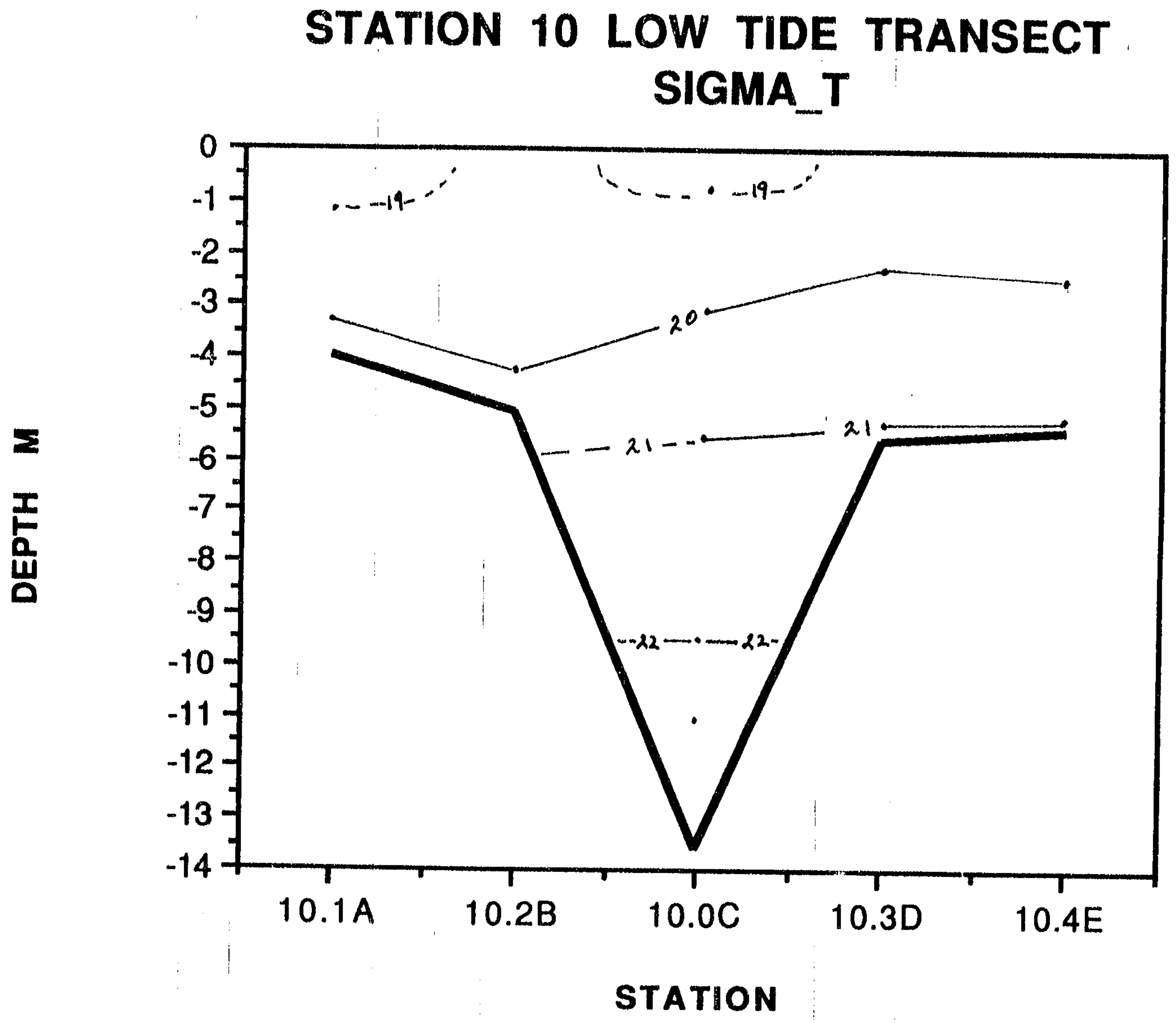


Figure 17. Cross channel transect of density. Thick line represents station depth not true bathymetry.

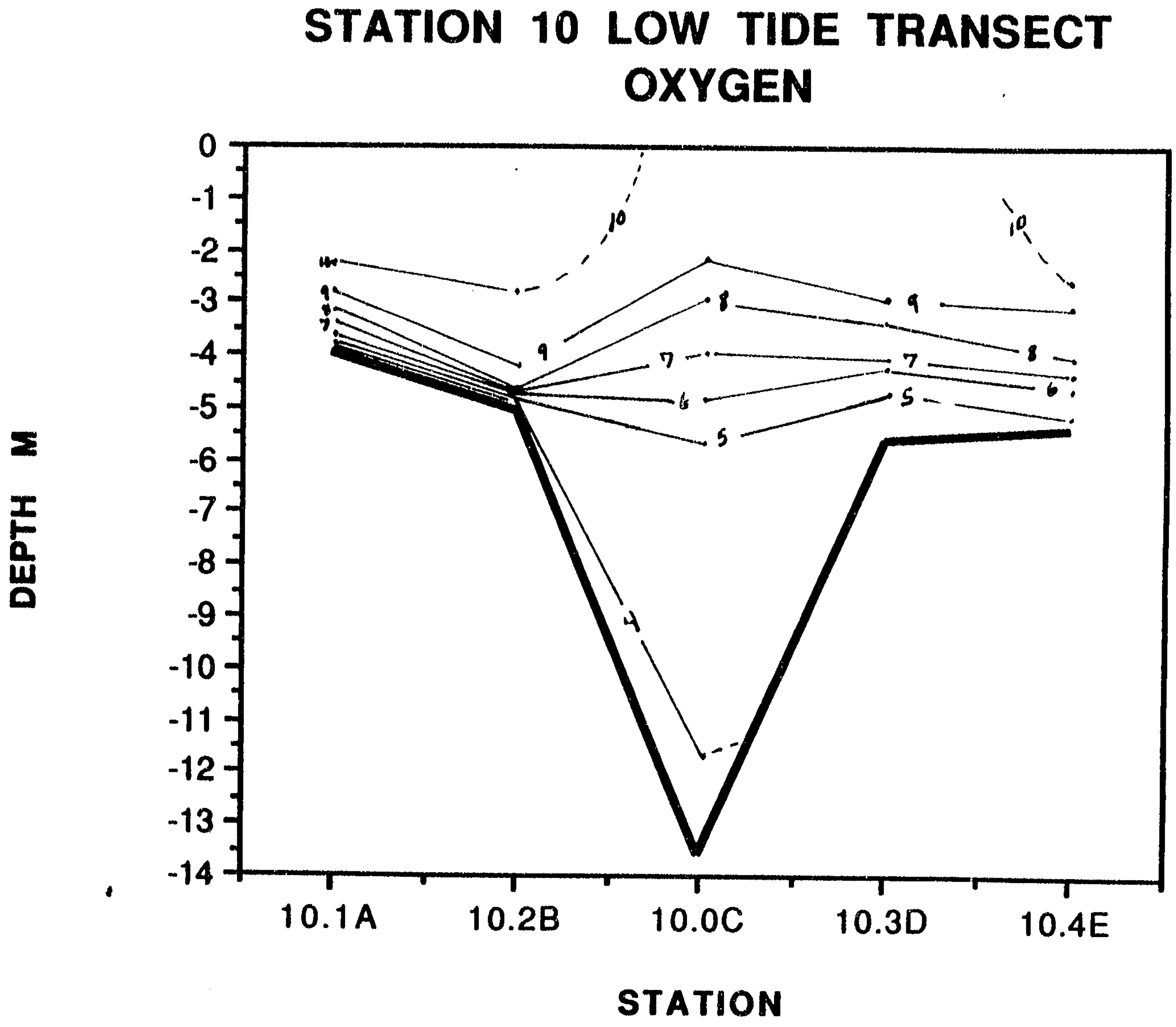


Figure 18. Cross channel transect of oxygen. Thick line represents station depth not the true bathymetry.

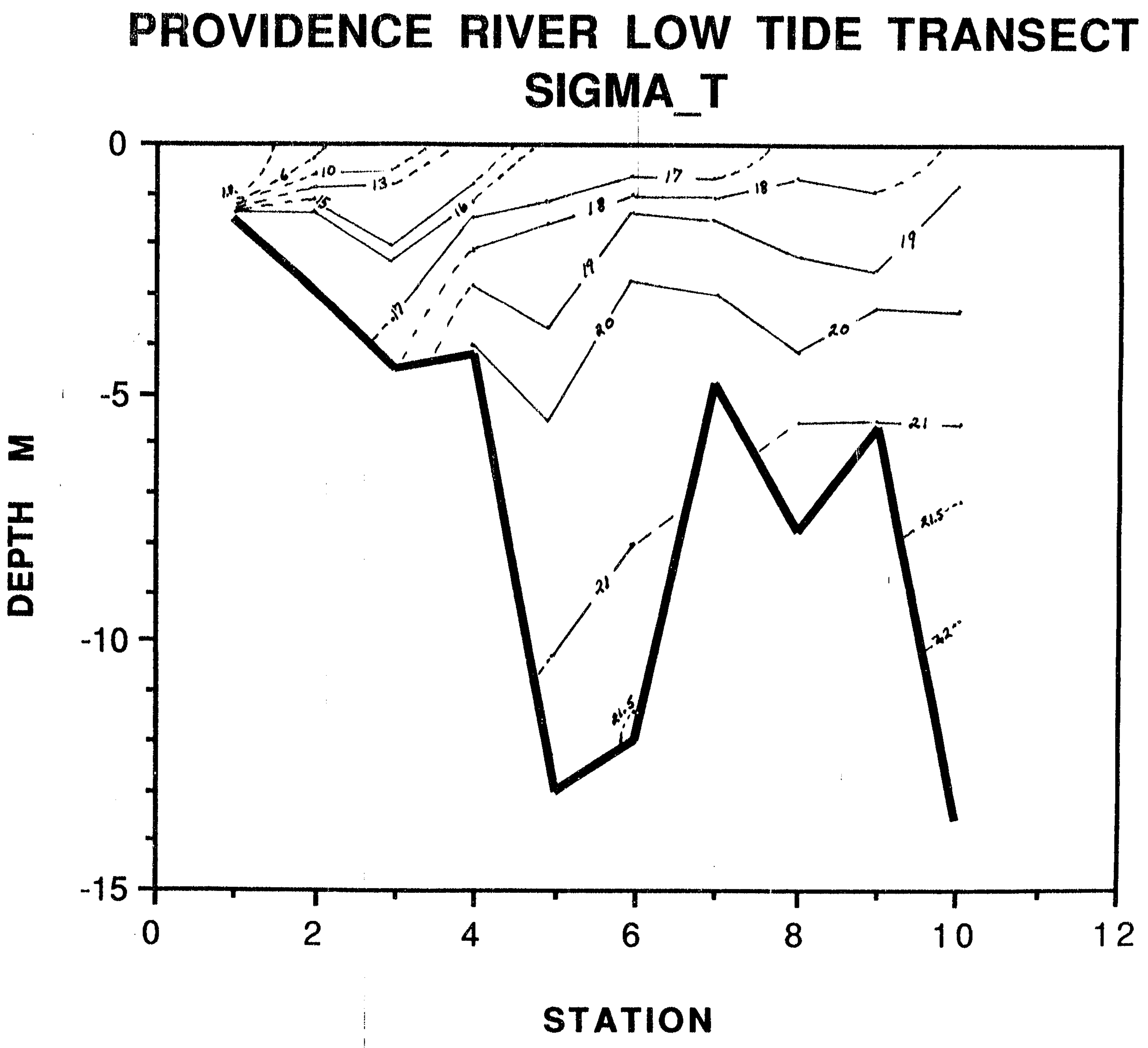


Figure 19. Longitudinal transect of density. Thick line represents station depth not the true bathymetry.

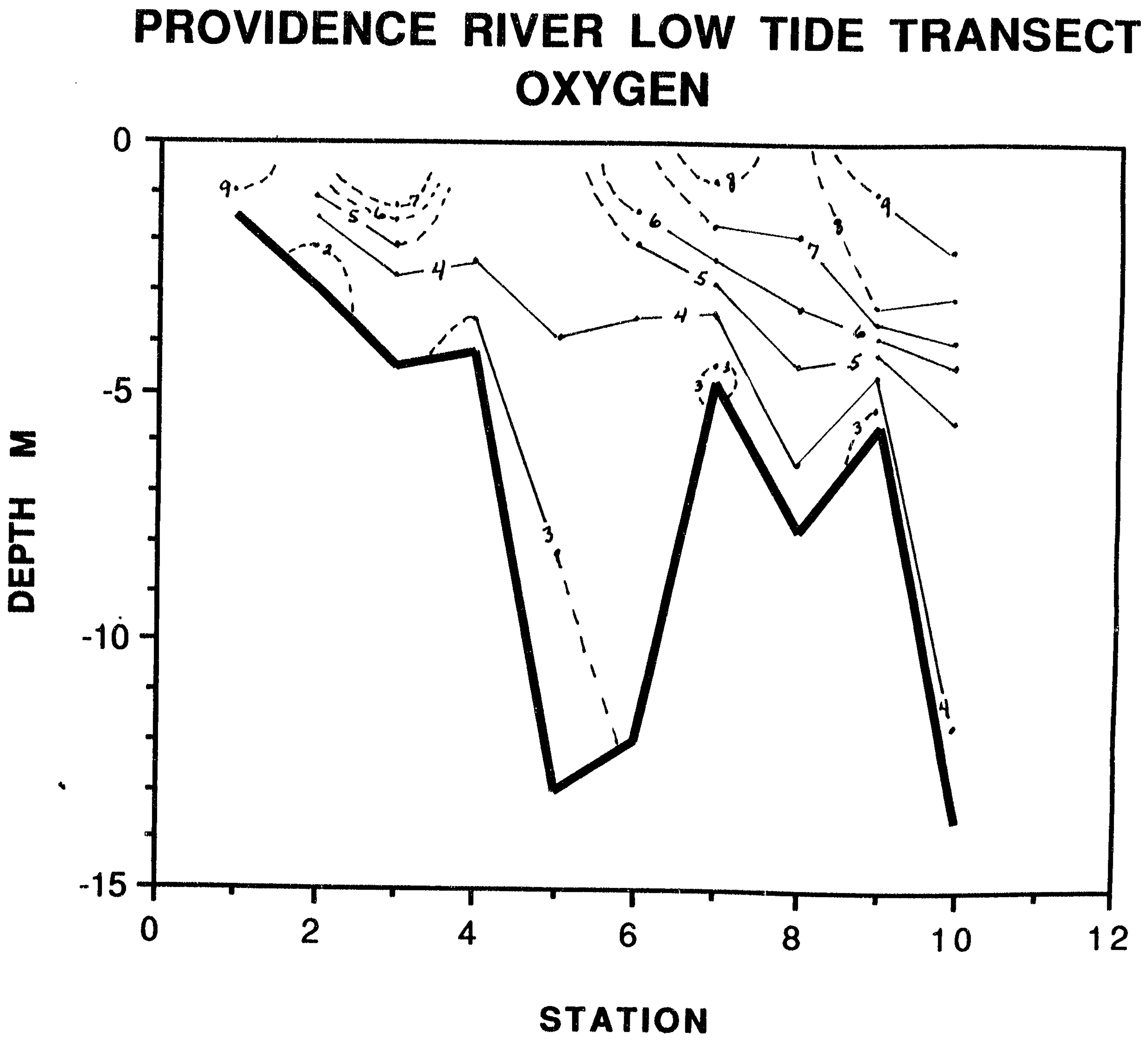


Figure 20. Longitudinal transect of oxygen. Thick line represents station depth not the true bathymetry.

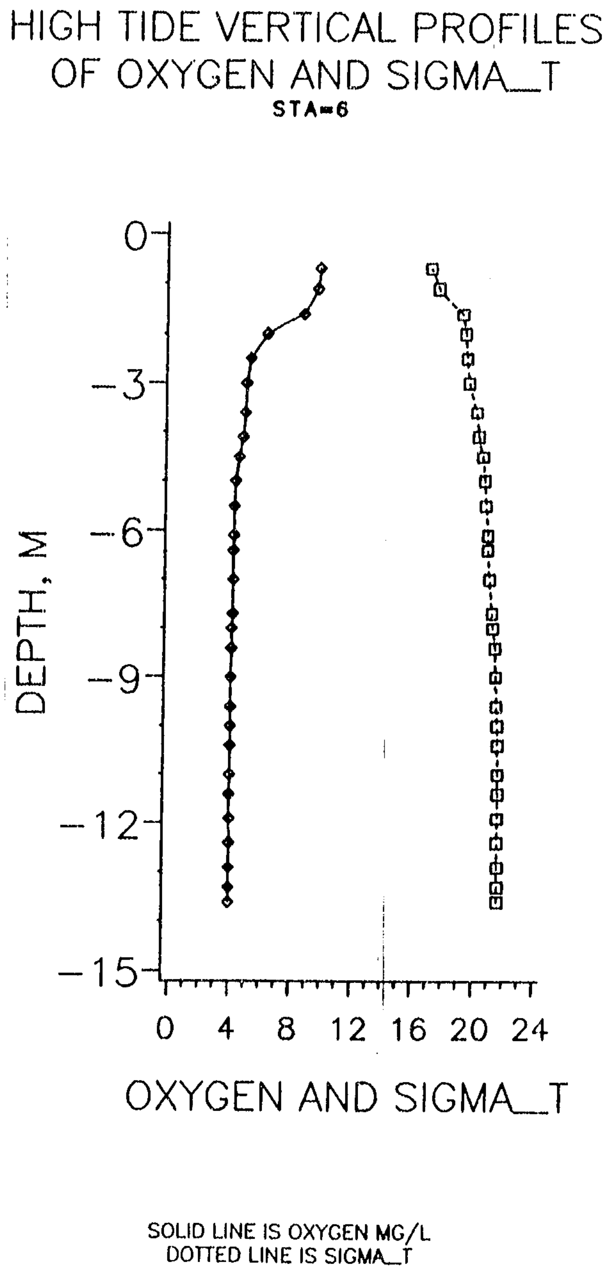


Figure 21. Oxygen and density as a function of depth.

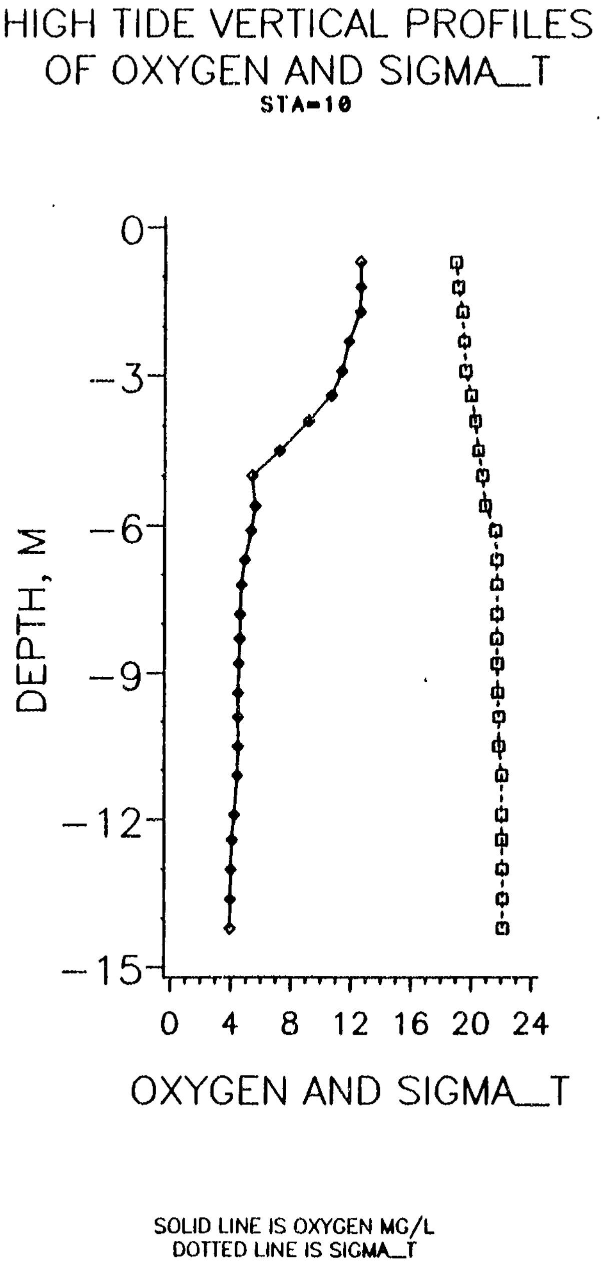


Figure 22. Oxygen and density as a function of depth.

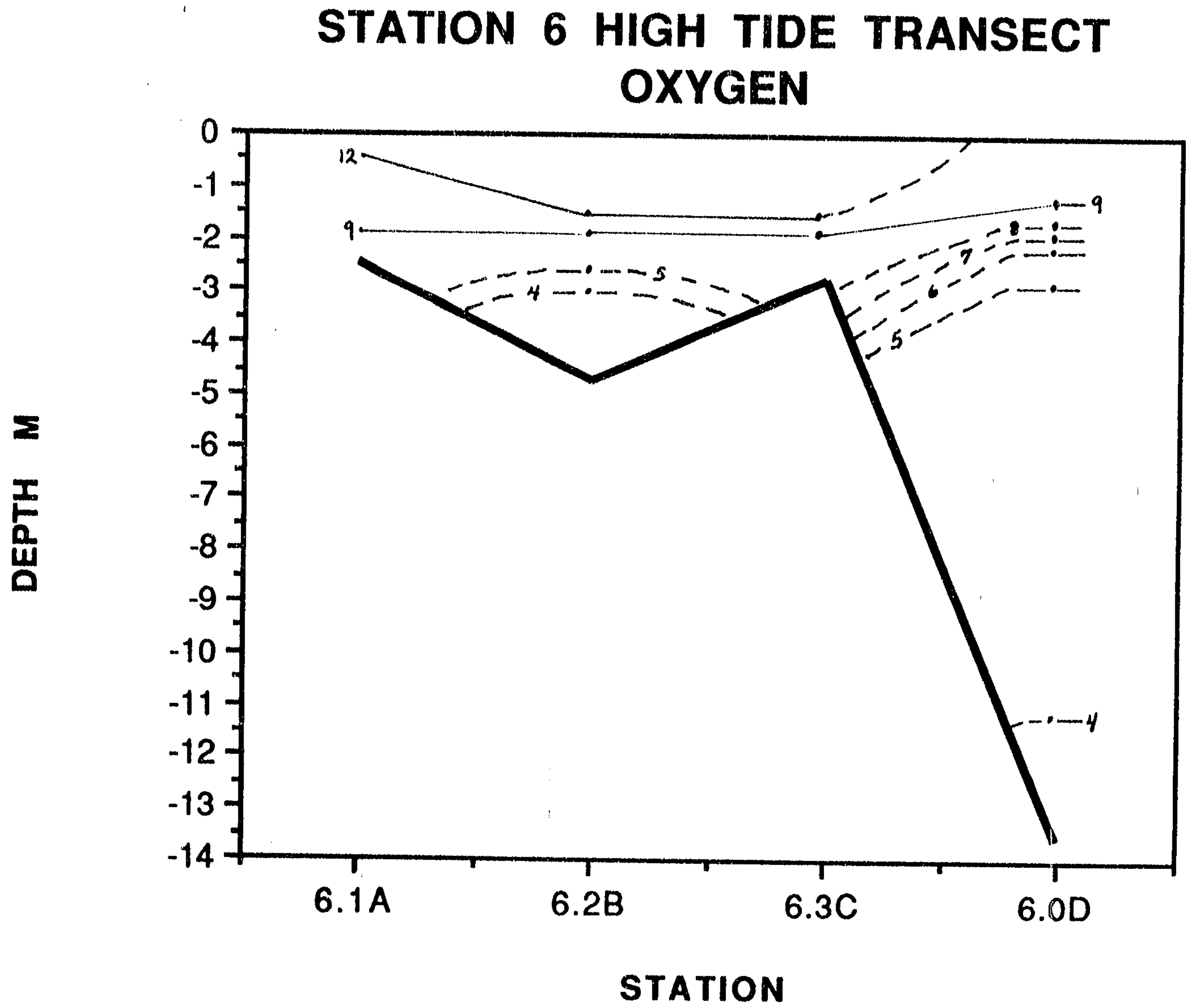


Figure 23. Cross channel transect of oxygen. Thick line represents station depth not the true bathymetry.

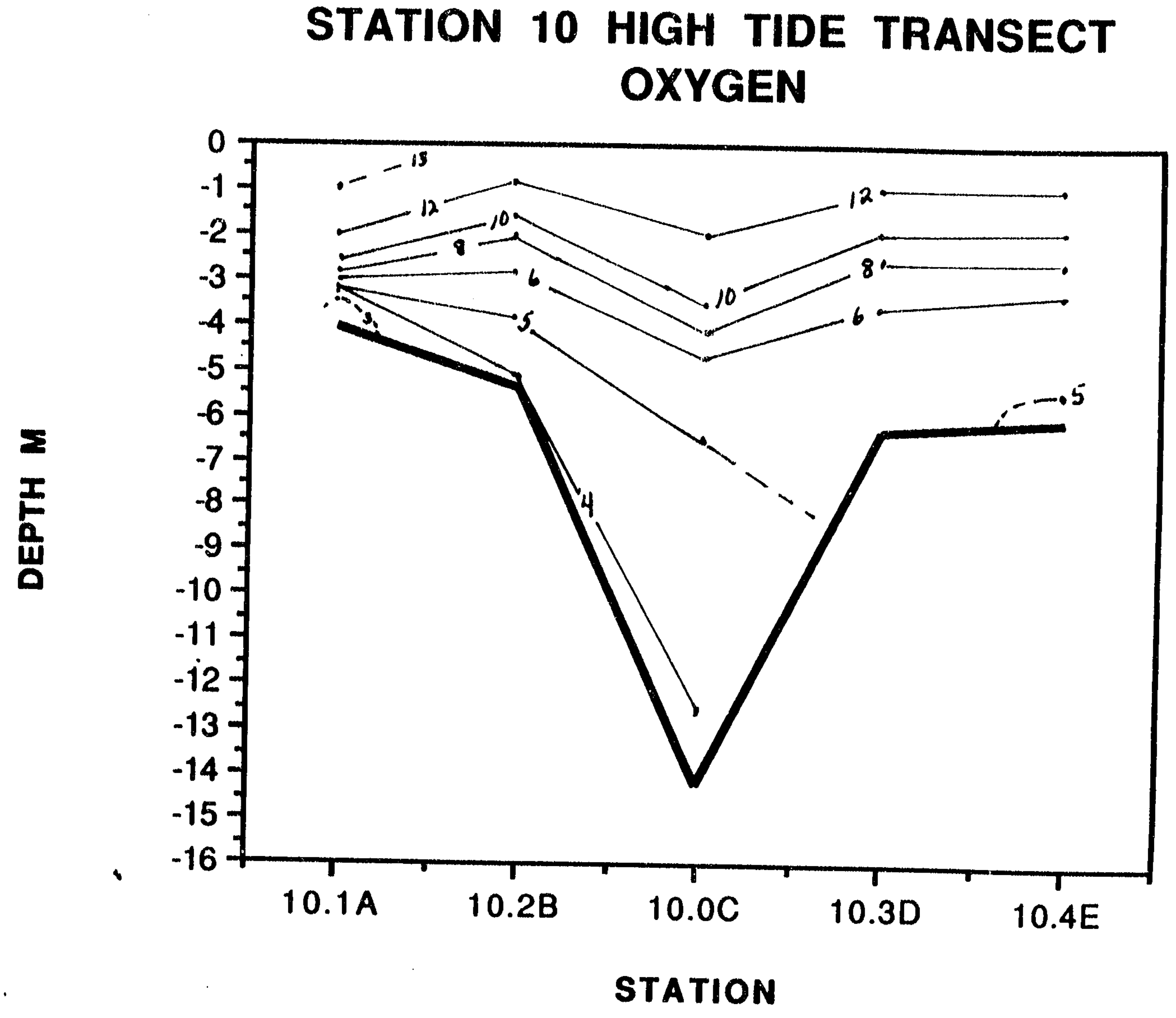


Figure 24. Cross channel transect of oxygen. Thick line represents station depth not the true bathymetry.

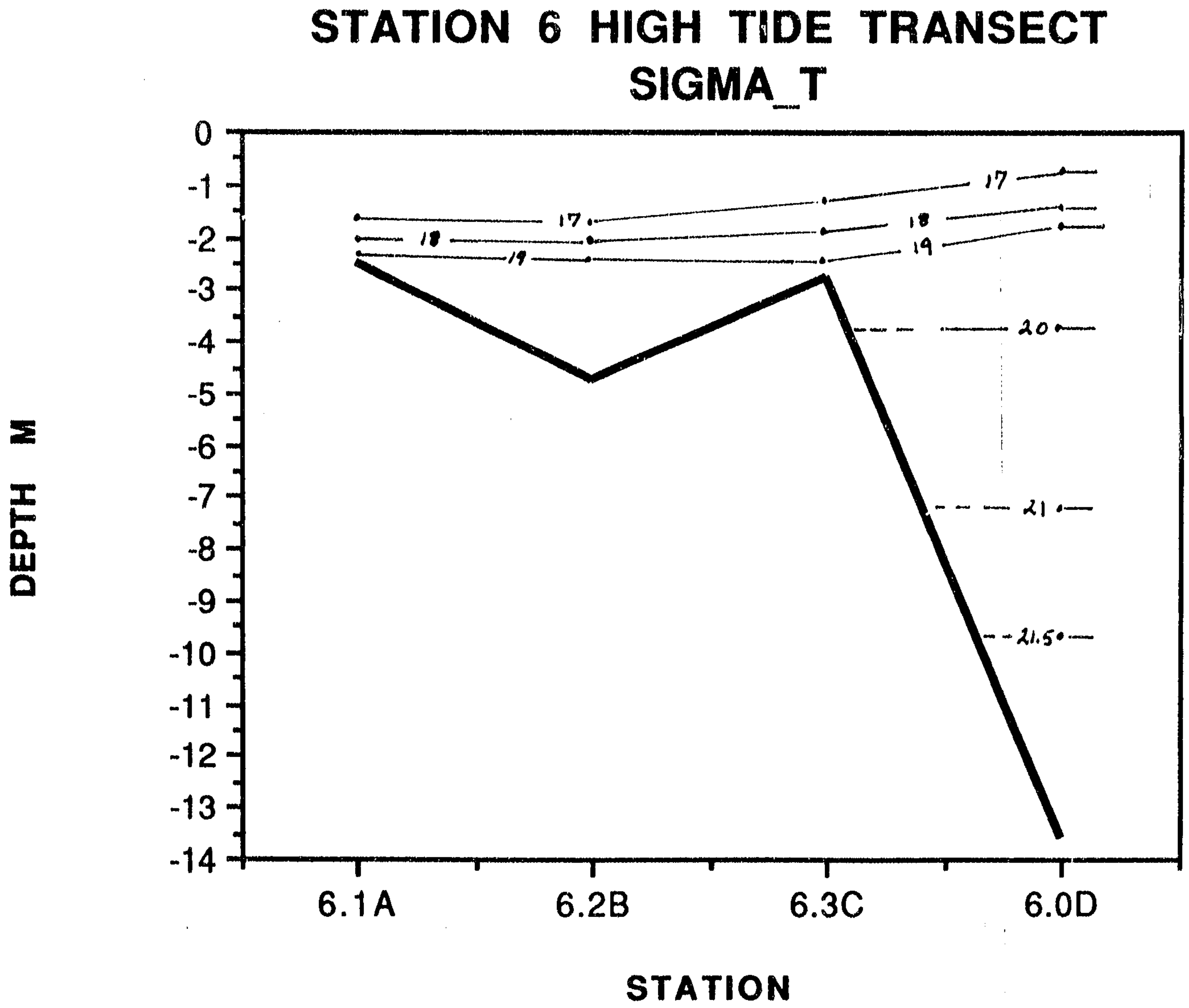


Figure 25. Cross channel transect of density. Thick line represents station depth not the true bathymetry.

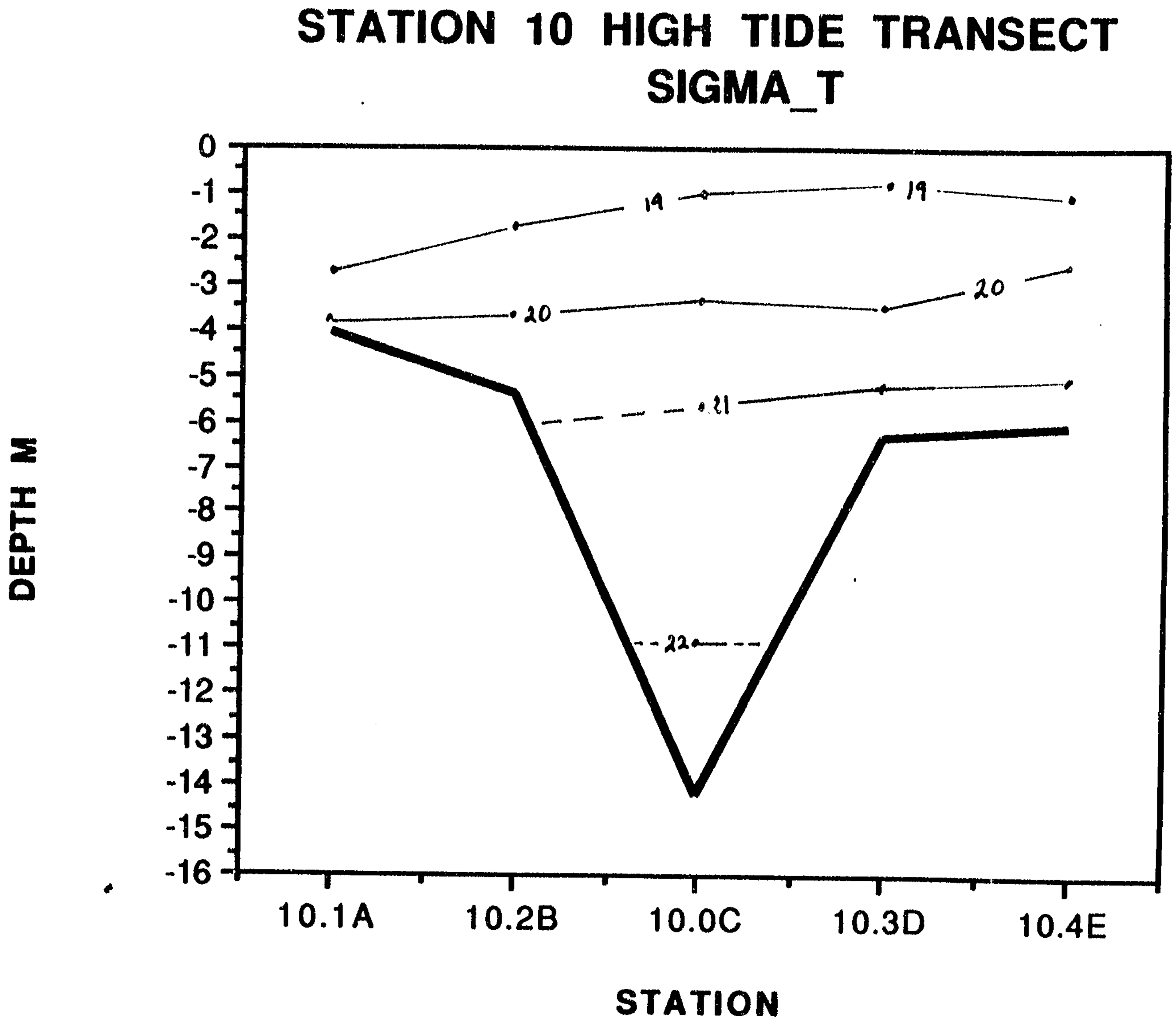


Figure 26. Cross channel transect of density. Thick lines represents station depth not the true bathymetry.

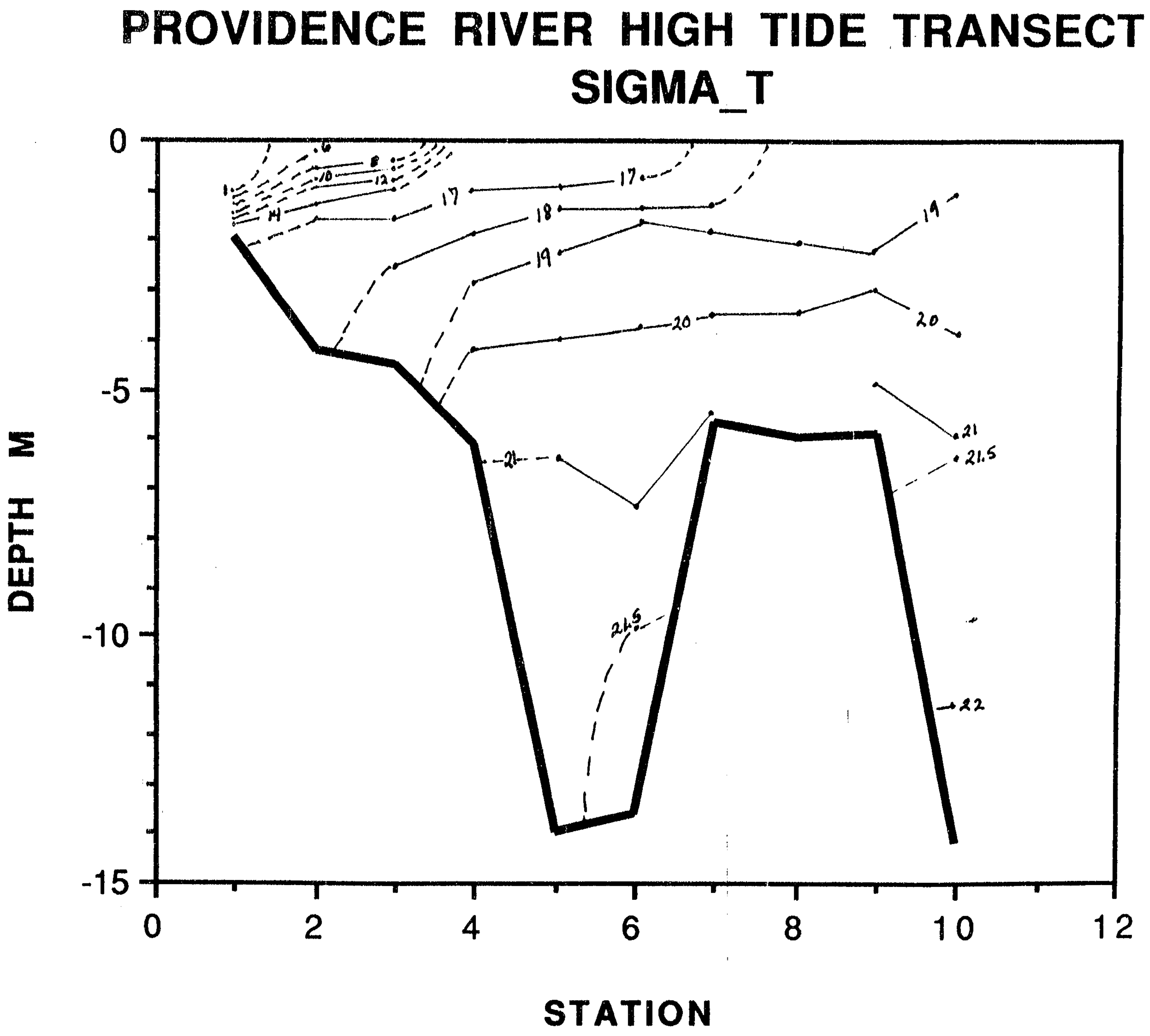


Figure 27. Longitudinal transect of density.

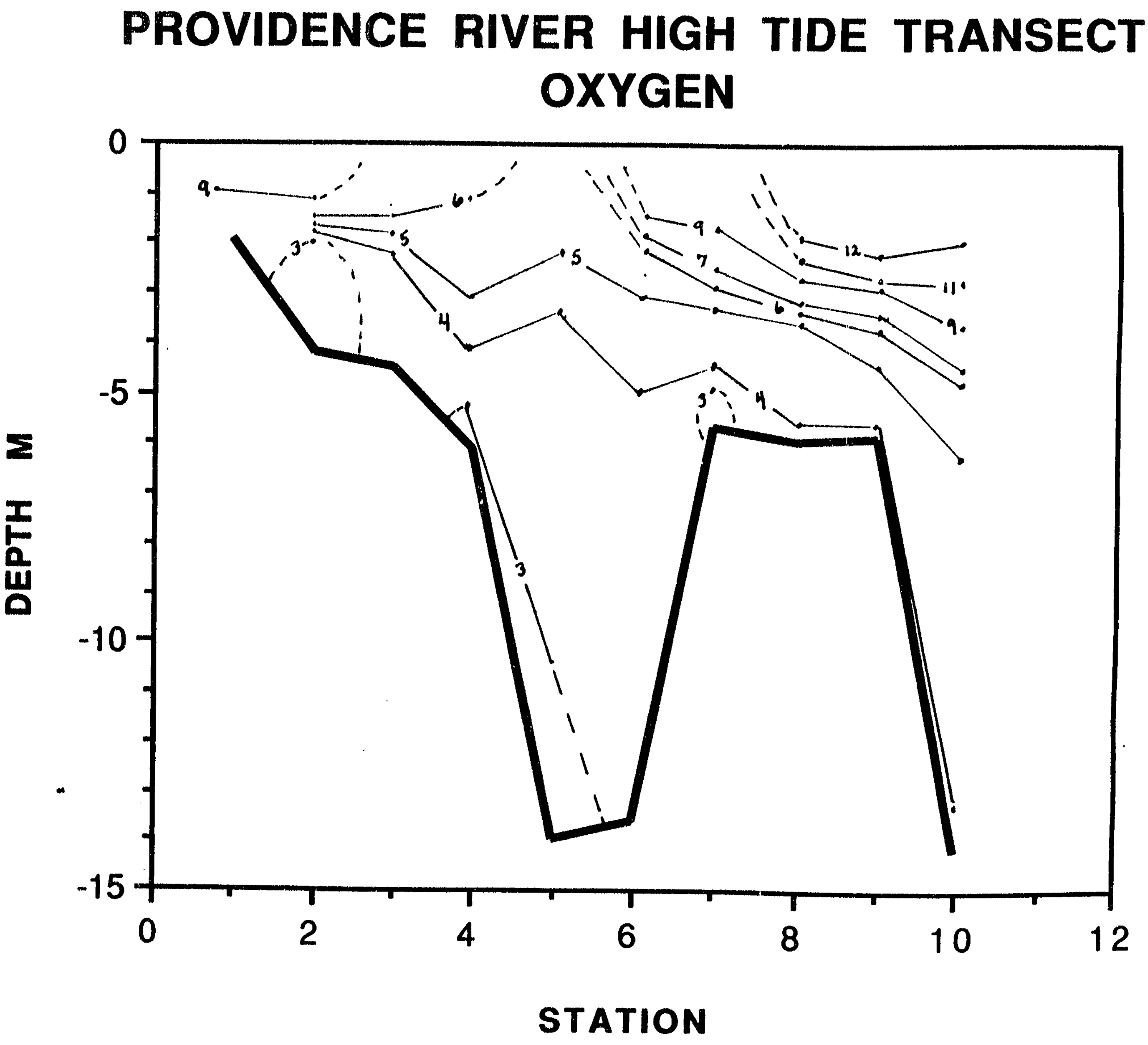


Figure 28. Longitudinal transect of oxygen. Thick lin represents station depth not the true bathymetry.

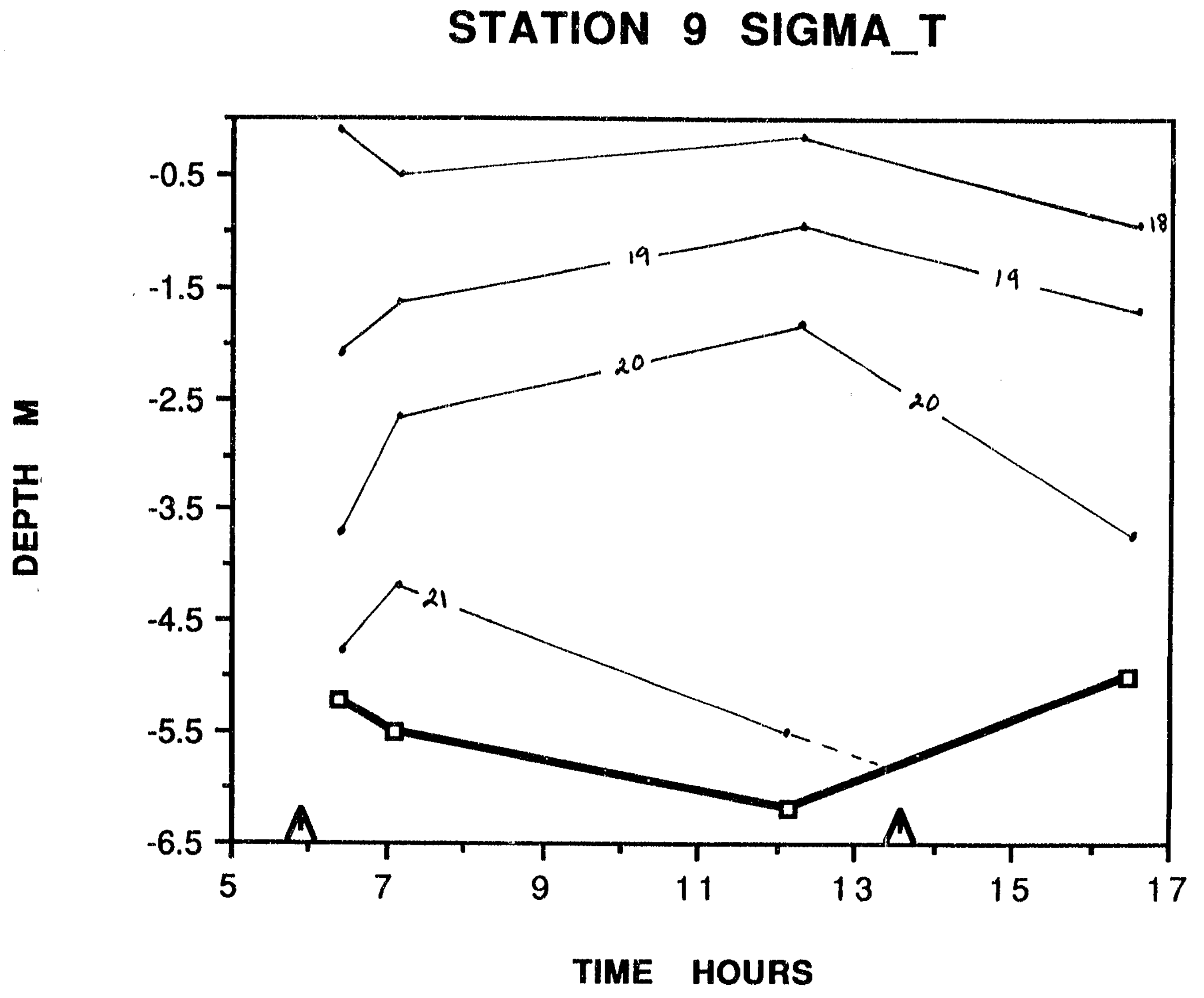


Figure 29. Temporal variation of density at station 9 in the lower Providence River.

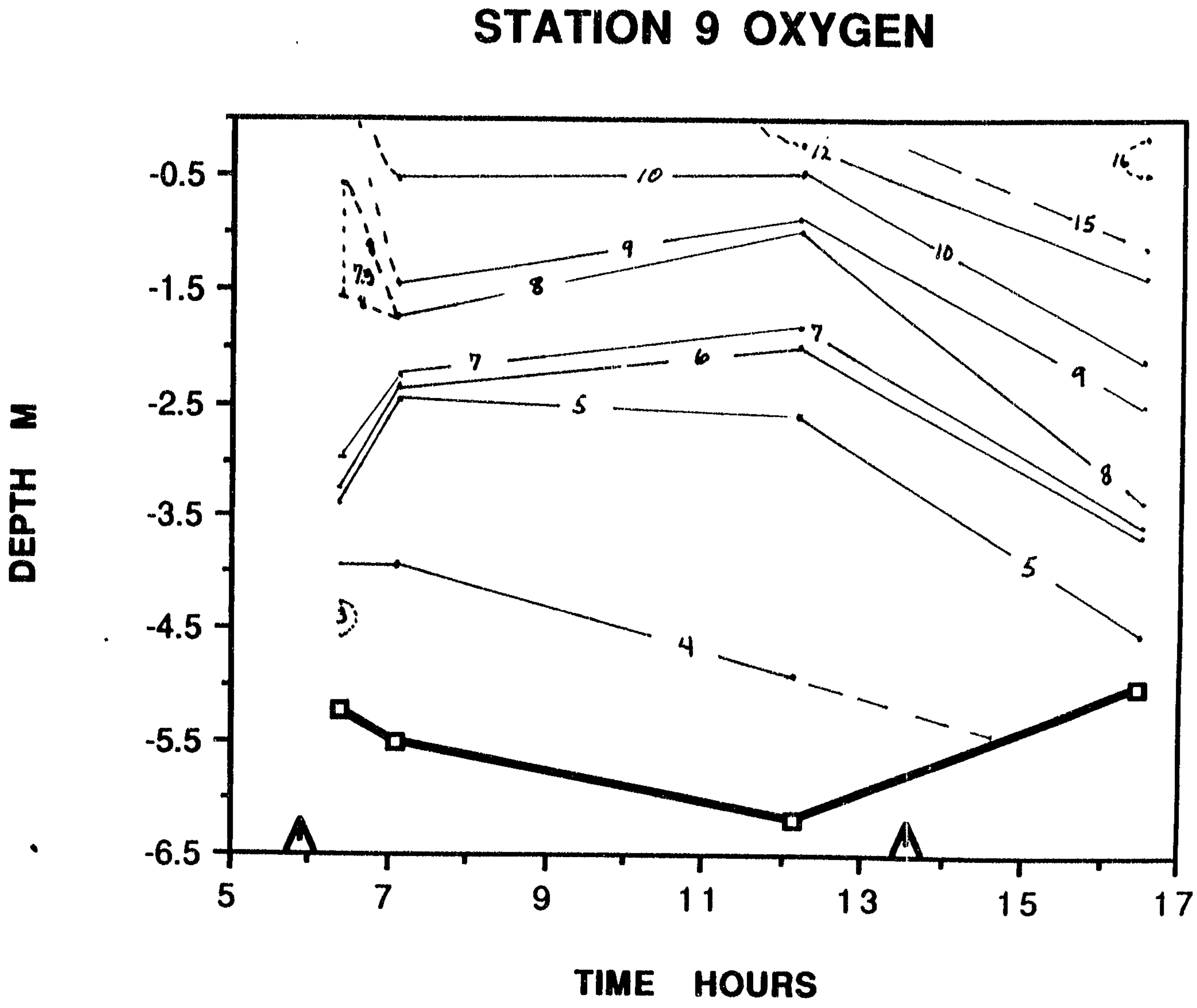


Figure 30. Temporal variation of oxygen at station 9 in the lower Providence River.

Figure 31. Average (3-day) BOD(Biochemical Oxygen Demand) by source for the SQUIRT Cruise. Abbreviations as in **Figure 1.** BOD is 5-day BOD.

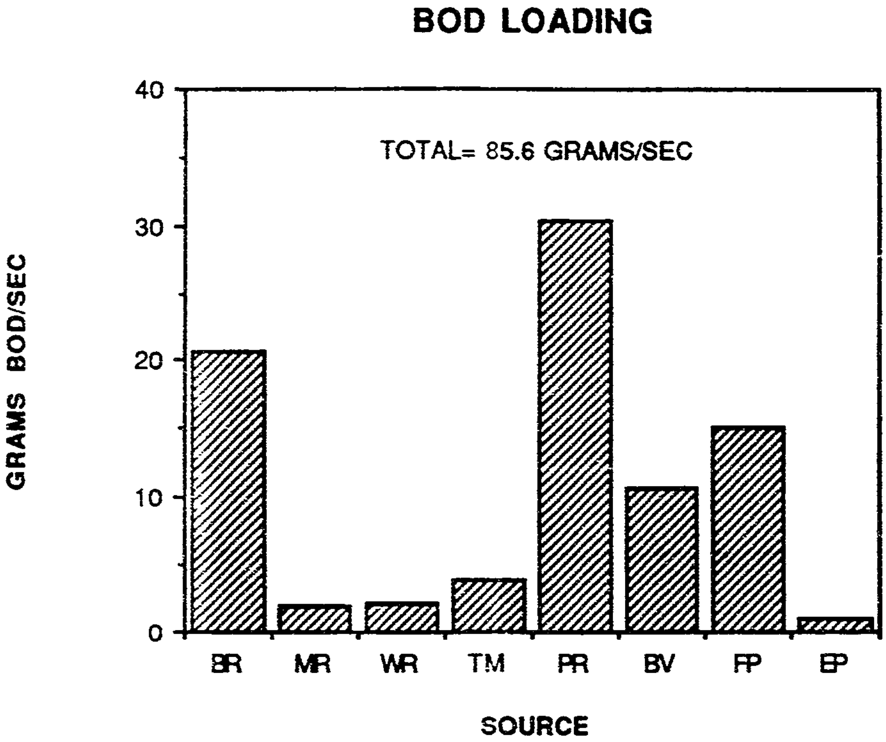
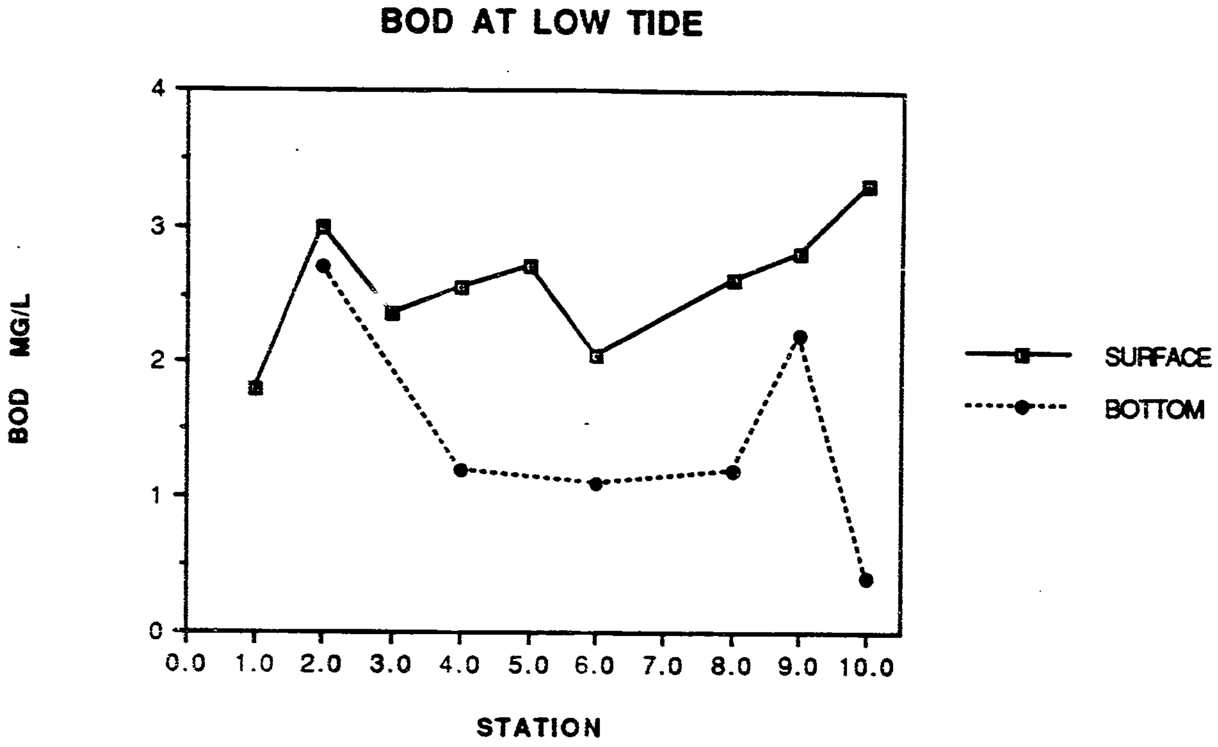


Figure 32. Biochemical Oxygen Demand (BOD) at low tide in the Seekonk and Providence RIvers. BOD is 5-day BOD.



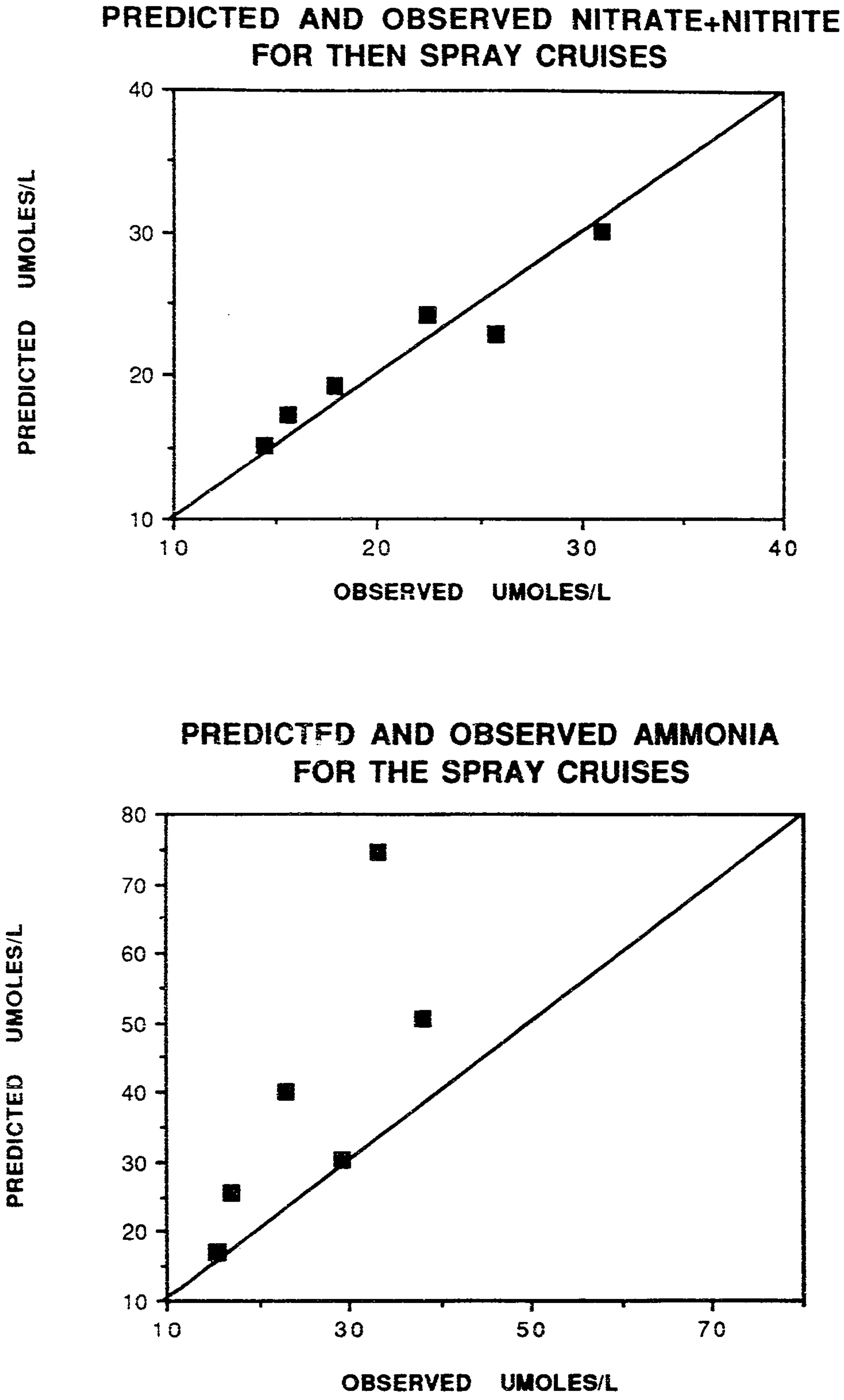


Figure 33. Expected and observed ammonia and nitrate + nitrite concentrations in the Seekonk and Providence Rivers during the SPRAY Cruises.

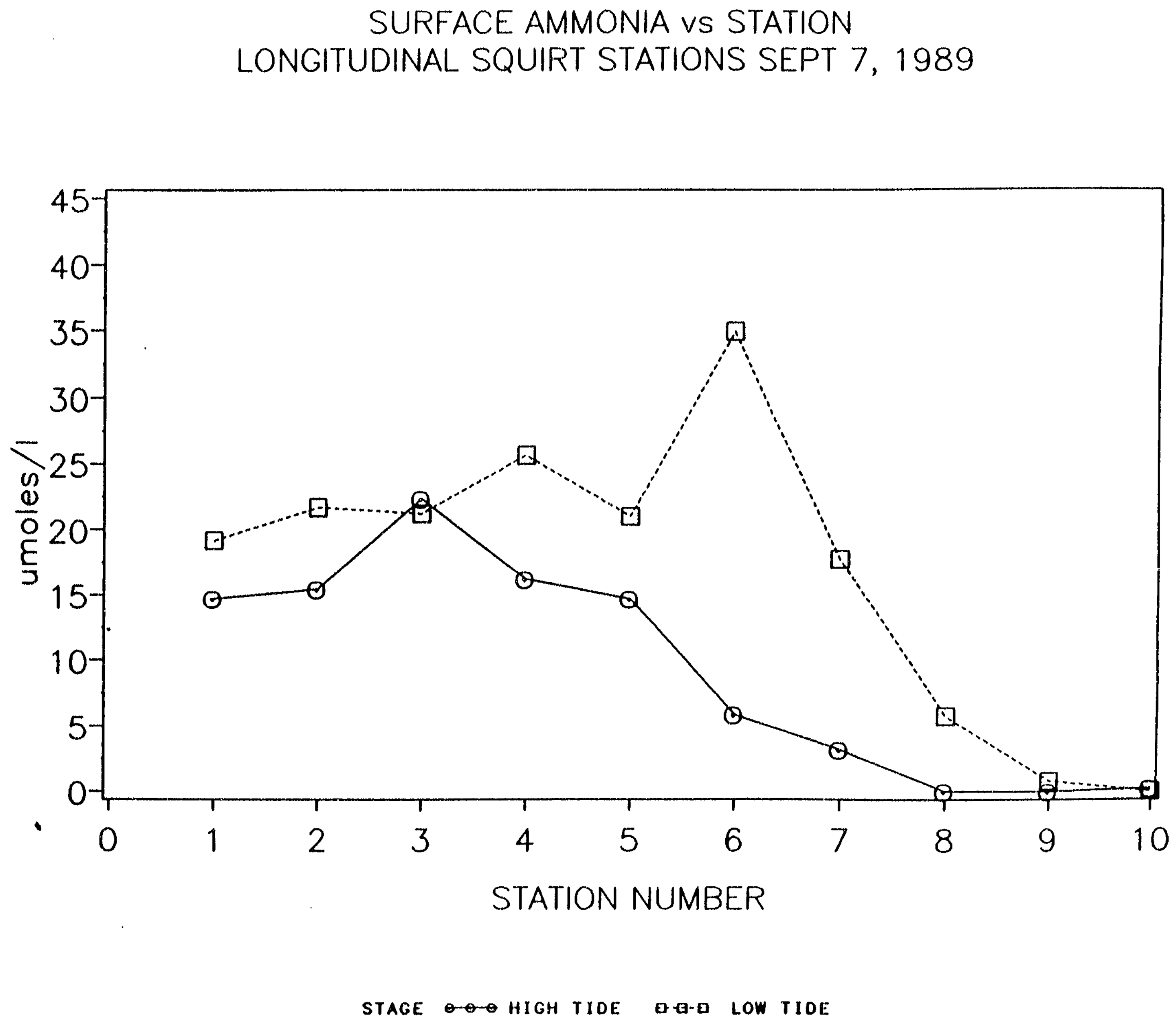


Figure 34. Longitudinal distribution of ammonia in surface waters at high and low tide during the SQUIRT Cruise.

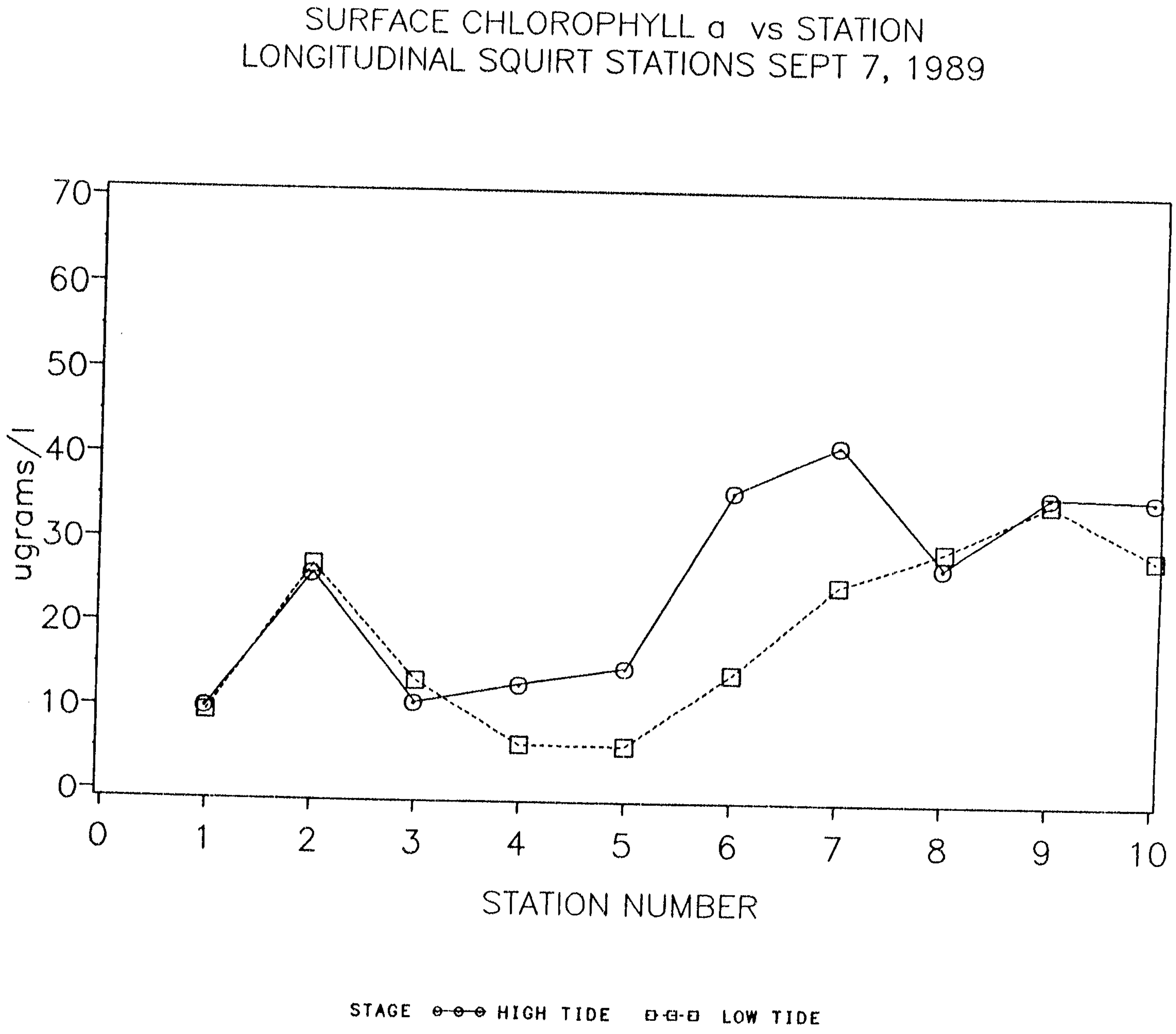


Figure 35. Longitudinal distribution of chlorophyll a at high and low tide during the SQUIRT Cruise.