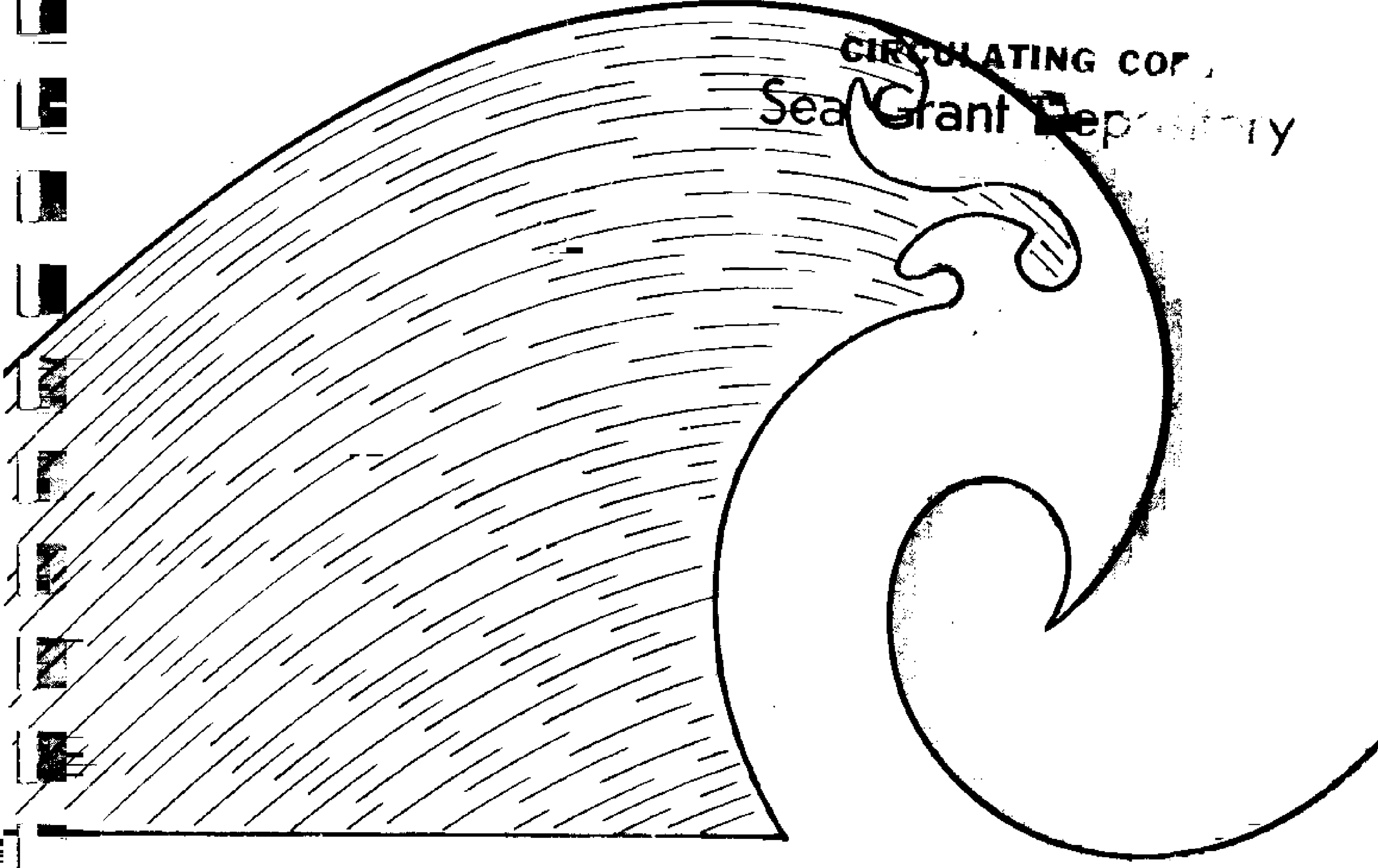

DEPARTMENT OF OCEAN ENGINEERING

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Report Number 4

NARRAGANSETT BAY;
AN EXAMPLE IN ESTUARY CLASSIFICATION

BY
KURT W. HESS
30 JUNE 1970

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by

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University of Rhode Island

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ACKNOWLEDGMENT

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NARRAGANSETT BAY: AN EXAMPLE OF ESTUARY CLASSIFICATION

1.0 Introduction

This report summarizes data collected by the author during the academic year 1969-1970 as a participant in the Bay Watch project. The information given within condenses an enormous amount of available data, and presents it in a form the author feels is instructive. This paper also serves as an introduction to the functioning of the bay system, and as a guide for and prerequisite to the model study.

2.0 Estuary Classification

The problem of estuary classification has been extensively studied. Its primary function is to identify the major processes, with emphasis on overall circulation and mixing. The work of Bowden, Pritchard, and Hansen and Rattray will be reviewed herein.

An excellent qualitative survey of the subject by Bowden (1) will serve as an introduction. The pattern for common estuaries is basically the upstream flow of more saline (and, therefore, denser) seawater, opposed by the flow of relatively "fresh" water (essentially zero salinity), which enters primarily as river discharge. Conservation of mass implies that some water must be leaving the estuary. This is usually accomplished by a two-layer flow at the estuary entrance, with the denser seawater entering at the bottom, and the lighter mixture leaving at the top. The strength of each flow, and the extent of mixing are indices for classification.

The ratio of tidal volume to freshwater volume is a typical parameter. As the relative tidal volume increases, the tidal mixing becomes important, and stratification decreases. Degree of vertical stratification is another important parameter. Three of Bowden's major types of estuaries appear in Figures 1 a, b, c, based on volume flows and stratification.

The most stratified type is the salt wedge, characterized by strong river flow. Mixing between water masses is slight, and occurs mainly by the effects of friction.

A second type is the two-layer flow with entrainment. Mixing is accomplished by the upward flow of seawater which occurs when internal waves break. There is no downward flux of freshwater.

The third type is a two-layer flow with vertical mixing. Here the strong tidal currents cause salt transport over the entire vertical column, although the upper flow is still less saline.

The last type is the vertically homogeneous estuary, with tidal currents so strong as to produce only horizontal salinity gradients. In real estuaries, however, vertical gradients must exist if the estuary is freshwater fed.

Pritchard's (2) work deals with the dynamics as well as the classification. He evolves the concepts of mixing, beginning with a frictionless, non-tidal model, and adding processes until the stratified estuary is described.

Assume there is no friction or tidal motion. Undiluted seawater would extend upstream to a point where the riverbed was approximately at sea level. The opposing riverflow would hug the nightward shore (looking downstream) due to coriolis effect. A two-layer system with no mixing would exist.

The next step is the non-tidal model with friction. Breaking internal waves would carry saline water upwards only, and a net motion in the lower layer would replace the water lost upward. Thus the volume of the upper layer would increase toward the sea, and salt would move by advection alone.

Introducing the tides causes a great amount of turbulence. Turbulent eddy diffusion is another mechanism of mixing, causing a two-way motion of salt in the vertical.

Other forces include coriolis effects and horizontal and vertical pressure gradients. These will be dealt with more quantatively in future papers by the author.

Pritchard has selected, as the dominant parameter for classification, the ratio of "the volume of water flowing up the estuary through a given section during the flood tide to the volume of freshwater flowing into the estuary above the section during a complete tidal cycle." (2)

The value of this ratio indicates the extent of mixing as follows:

r of order unity	negligable mixing
$10 < r < 100$	partially mixed
r of order 10^3	fully mixed

The latest and most quantatively precise work in classifications has been done by Hansen & Rattray (3). Their concepts and scheme will be used as a base for this paper and investigation, and as a format to introduce the relevant physical data on Narragansett Bay in a cohesive manner.

The classification of Hansen & Rattray is based on net flow and stratification, and contains seven types. Types I a, b, are net flow seaward at all levels, and corresponds to Bowden's well-mixed estuary. Types II a, b, III a, b, and IV show varying degrees of two-layered behavior, with Type IV being the salt wedge estuary. The extent of vertical stratification is the other parameter: subtype (a) is slight vertical stratification (well-mixed), and subtype (b) is appreciable stratification (unmixed or partially mixed). The scheme is summarized in Table 1.

ESTUARY TYPES (AFTER HANSEN & RATTRAY, 1966)

	NET FLOW	MIXING	REMARKS
I	NET FLOW SEAWARD AT ALL DEPTHS	a. WELL-MIXED; SLIGHT VERTICAL STRATIFICATION b. UNMIXED OR PARTIALLY-MIXED; APPRECIABLE STRATIFICATION	UPSTREAM SALT TRANFER BY DIFFUSION: PREDOMINANT TIDAL MIXING
II	NET FLOW REVERSES WITH DEPTH		ADVECTION AND DIFFUSION
III	NET FLOW REVERSES WITH DEPTH		ADVECTION ACCOUNTS FOR AT LEAST 99% OF SALT TRANSFER
IV	NET FLOW REVERSES WITH DEPTH	b. UNMIXED	NEGLIGABLE TIDAL EFFECTS

TABLE 1

Again, the two important factors are stratification and circulation. Two dimensionless parameters arise from the investigations of Hansen and Rattray, whose work has led to the use of similarity solutions (as in boundary-layer flows). (4) These parameters are:

1. (stratification) $\frac{S}{S_o}$
2. (circulation) U_s/U_f

where S is salinity (o/00), U_s is net surface current, and U_f is mean freshwater velocity, and

$$S = S_{bottom} - S_{top}$$

$$S_o = \tfrac{1}{2}\,(S_{bottom} + S_{top})$$

$$U_f = \frac{Q\ \text{freshwater}}{\text{Area}}$$

From the work on similarity comes another parameter, , the "diffusive fraction." Basically this is the fraction of salt transferred upstream by diffusion (as opposed to advection). It is interesting to note that is a function of both stratification and circulation.

Hansen and Rattray have plotted and estuary type as functions of $\frac{S}{S_o}$ and U_s/U_f. These appear as Figures 2 a, b.

In summary, we have seen that several oceanographic quantities are used to classify estuaries and identify important processes. The next topics for discussion are therefore:

(a) Geography:	the physical dimensions of the estuary are necessary to determine the importance of coriolis effect and the lateral variability; cross-sectional areas and volumes of the bay will also be useful.
(b) Freshwater Flow:	this provides one of the basic quantities for classification. Also, annual variations of river flow and precipitation will be examined.

(c) Tidal Conditions:	tidal heights, velocities and transports will be examined. Non-tidal circulation can be inferred from tidal records.
(d) Salinity Distribution:	vertical stratification is relevant for classification, as well as inferring the depth of no motion, and as a check on model predictions.

3.0 Geography

The first topic of consideration is geologic data, including bay geometry. A scale map of the Bay appears in Figure 3, and includes hydrographic stations and sections which will be referred to later. A summary of physical quantities appears in Table 2.

TABLE 2

AREA AT MEAN LOW TIDE (area above dotted lines, Fig. 3)	136 sq. mi.
AVG. DEPTH (at mean water level)	29 ft.
MAX. DEPTH	185 ft.
MEAN VOLUME	1.10×10^{11} cu. ft.
MEAN TIDAL PRISM	1.50×10^{10} cu. ft.
LENGTH: Fox Point (Providence) to Beavertail Point	25.1 mi.
WIDTH: Tiverton, due West to East Greenwich	9.9 mi.
AREA OF WATERSHED. (including Bay)	1700 sq. mi.
AREA OF ISLANDS	250 sq. mi.

The first item to consider is the coriolis effect. A comparison of width to depth (Table 2) indicates that coriolis forces will be important in the dynamics. The Rossby number,

$$R_o = (\tfrac{V}{L})/\Omega$$

is a useful indication of relative importance of the earth's rotation, and has a value of about 2.7 (taking V = 1 knot, L = 10 mi., the width of the bay).

The coriolis force is expected to have a discernable effect on the flow, and on the entering bottom water in particular. Figures 4 a, b show the relative proportions of channel cross-sections identified in Figure 3. The entering bottom water is forced to the right by the coriolis effect, and scouring causes the channels to be deeper there. Sections 2 and 4 (Figure 4a) show this most clearly, although it appears in many of the other sections (sections 13 and 14 have been dredged, and therefore are not natural channels).

Secondly, the relative shallowness of the Bay ought to contribute to the mixing process; this point will be explored further in the section dealing with salinity.

Lastly, the geometry can be used to predict how the flow divides around an obstruction, such as an island. Hicks (5) has studied this, and he has found that the geometry of the channel is of small importance compared to that of the channel entrance.

4.0 Fresh Water Flow

The primary sources of freshwater input to Narragansett Bay are river flow, city discharge, and direct precipitation. Typical values for each are summarized in Table 3. River and city inputs are included in Figure 5, which graphically demonstrates the upstream freshwater influx of typical estuarine behavior. The mean total input has been taken to be 2170 cfs (6), although other sources cite a figure of 2890 cfs (7). The lower number is probably accurate as a total flow from the six largest rivers (corrected for city discharge), while the higher probably includes other sources, such as direct precipitation, direct runoff, and smaller rivers. The quantity used is indicated in all charts and calculations.

FRESH-WATER INPUTS

TABLE 3

RIVER FLOW

Blackstone Ri	707 cfs
Providence Ri	118
Pawtuxet Ri	392
Potowomut Ri	42
Palmer Ri	10
Taunton Ri	659

CITY DISCHARGE

Providence (1968)	80
Fall River (est.)	12
Newport	--

DIRECT PRECIPITATION

on Bay ($39^{in}/yr$)	320

DIRECT RUNOFF

OTHER

Watuppa & Staford Pond	150

TOTAL

Adding to the complexity of this problem is the fact that the river discharge varies widely throughout the year. Seasonal changes may account for differences of 50 to 100% from the mean value. Figure 6a, shows the annual flow of the Blackstone River and the Pawtuxet River. The spring thaw, releasing the frozen moisture locked in the ground during the winter months, swells the rivers to nearly double their average volumes. The summer sun and vegatation take excess moisture from the ground, so that the dry soil takes in rain water through the fall, preventing it from reaching the rivers.

Although spring rains may be expected to influence the river discharge, Figure 6b shows that precipitation is nearly constant over the year. In fact, the maximum rainfall (for 1941-1950) occurs in November, when river flow is approximately two-thirds its mean value.

An approximation of total riverflow can be made using the total precipitation and the area of the drainage basin. Comparison of runoff records for the Blackstone and Pawtuxet Rivers indicates that fifty percent of the rainfall reaches the bay thru the rivers. Thus, the mean runoff can be predicted approximately from precipitation. Figure 7 shows the watershed area for the entire Narragansett Bay. Data on individual river basins can be obtained from (6).

5.0 Tidal Conditions

The mean tidal variation for the bay (difference between high and low tide) is shown in Figure 8 (8). The characteristic standing wave of cosine shape (5) is evident. The amplification factor has a mean value of 1.31, indicating an estuary tidal wavelength of approximately 225 miles.

From the given data, the tidal prism (volume of water stored in the bay from low to high tide can be computed to be approximately 1.50×10^{10}

cu. ft. This is on the order of one-tenth the volume of the bay. Flushing times (1) can be calculated for various sections using the formula:

$$T_i = \frac{V_i + P_i}{P_i}$$

where T_i is the flushing time at section i (in tidal cycles), V_i is the mean volume above section i, and P_i the tidal prism above i. The flushing time for several sections has been computed and summarized below in Table 4.

TABLE 4

Section	V_i (10^8 cuft)	P_i (10^8 cuft)	T(# of cycles)
1-2	980	123	8.9
5-6-8	470	85	6.5
9-11	120	31	4.9
12	78	21	4.7
13	36.7	11.5	4.2
14	17.9	5.7	4.1

The tidal currents, which account for a great deal of the mixing, are produced by the ebb and flood and reach maximum values at about 3 hours after high and low tides. Surface tidal currents have been summarized by Haight (9).

The irregularity of these currents is evidenced by the following quote (10):

> The currents of Narragansett Bay have a pronounced irregularity which is evidenced at times during the month by a long period of approximate slack water preceeding the flood, and at other times by a double flood of two distinct maximums of velocity separated by a period of lesser velocity. These peculiarities appear to be somewhat unstable, consequently, flood currents differing from those predicted should be expected.

The surface currents for each hour after high tide at Newport for three stations along section #1 (Figure 3) are shown in Figure 9. The double flood (positive velocity) can be distinctly seen in the curve labeled #I, and to a lesser extent in #III.

9 years [illegible]

The non-tidal surface currents can be obtained from the hourly values, and the results are shown in Figure 10. Note that the flow is generally downstream toward the sea, as expected in the two-layer estuary. Of special interest is the upstream component occuring on the western side of several of the channels. Whether this is a dominant feature, or an error or transient effect must be determined in future studies.

Hicks (5) has calculated non-tidal transports based on non-tidal surface velocities and salinity gradients. Mean river flow and bottom water transports are shown in Figures 11 a, b, using updated figures by Hicks' methods.

6.0 Salinity Distribution

Since river water of essentially zero salinity must mix with seawater, a longitudinal salinity variation must be expected. It is the lateral and vertical variation which give added information about the flow and mixing in the estuary, and add complexity to any mathematical model of the system. In Figures 13 a-e the longitudinal and vertical variations of salinity (and temperature) are evident (11). Note the bottom intrusion of saline water near the mouth, most evident in the spring. It is obvious that the bay is vertically stratified; salinity-depth profiles are shown in Figure 12.

The longitudinal variations are shown in Figure 14. The salinity increases toward the sea. Note that the more shallow West Passage shows greater mixing (bottom water less saline due to greater mixing with surface water), an effect predicted from the geometry alone.

The lateral variation is indicated in the plots of bottom and surface salinity (Figures 15, 16). As expected from geometry and coriolis forces, the water remains more saline in the East Passage. However, notice the variation in Figure 16 of the same surface and bottom salinity (12), one year earlier than the conditions for Figure 15.

7.0 Classification of Narragansett Bay

The above data indicates that the bay has a rather complex and ever-changing character. For this reason, the parameters used in classification will be computed at several cross-sections, rather than for the whole bay.

A. Pritchard: the parameter, $r = \frac{\text{Vol tidal}}{\text{Vol river}}$ has been calculated at most of the sections shown in Figure 3. At the mouth of the bay, the value of r is 158 (E. Passage) and 610 (W. Passage). These values approach those for well-mixed estuaries, exactly as the salinity profiles indicate. In the mid-bay, the values range from 60 to 100, indicating the partially-mixed condition. Up around Providence, r is calculated to be around 30, or approaching the salt wedge. Nothing can be concluded about relative mixing in each passage. Results are given in Table 5.

B. Hansen and Rattray: Proceeding through the calculations, we find a similar distinction between upper and lower bay as in Pritchard's interpretation. From the plot (Figure 2a), we see that the lower bay and East Passage have low diffusive fractions, ($\nu < 0.10$), while the upper bay has somewhat higher fractions, ($\nu < 0.50$). From Figure 2b we see that the lower bay and East Passage are Type III, and other parts are Type II.

8.0 Conclusions

The preceeding analysis shows that the bay does not have uniform mixing qualities, but rather a systematized distribution of relevant processes (advection, diffusion). The lower bay is well-mixed (slight vertical stratification), while the upper bay is not. More importantly, the primary method of salt transfer upstream in the lower bay and East Passage is advection. This means that bottom water moves relatively undiluted up into

	SECTION	AREA (SQFT)	S‰		Q_f (CFS)	u_o (F/SEC)	Q_T (10^3 CFS)	$\frac{Q_T}{Q_f}$	u_f (FT/SEC)	[illegible]	[illegible]
			TOP	BOTTOM							
EAST PASSAGE	2	8.5% 354,000	31.5	32.5	1584	.625	165.2	107	.00185	3.13×10^{-2}	3.88×10^{-2}
	4	342,300	30.6	31.9	1584	—	—	—	.00247	4.5×10^{-2}	—
	(6)	231,000	28.0	30.8	372	1.86 .186	7.3	20	.00128	5.3×10^{-2}	1.17×10^{-1}
	8	301,000	26.5	31.7	1212	.135	—	—	.00165	1.12×10^{-1}	5.33×10^{-1}
	11	213,000	25.75	30.25	622	.085	7.5	12	.00785	1.61×10^{-1}	2.34×10^{-1}
	12	360,000	25.5	29.75	1307	—	—	—	[illegible]	1.54×10^{-1}	—
	13	71,000	26.5	28.75	1297	.371	3.0	7	.01815	1.08×10^{-2}	2.05×10^{-1}
	14	64,000	28.0	26.75	505	—	—	—	.01336	2.85×10^{-1}	—
WEST PASSAGE	1	304,000	31.0	32.5	345	.405	35.5	173	.00113	4.17×10^{-2}	3.38×10^{-2}
	3	151,200	30.6	31.0	345	—	—	—	.00214	1.39×10^{-2}	—
	5	264,000	30.0	30.25	345	.135	10.7	31	.00131	8.5×10^{-3}	1.03×10^{-2}
	7	405,000	27.5	29.5	717	—	—	—	.00145	6.16×10^{-2}	—
	9	39,800	26.4	28.6	675	.017	—	—	.00152	[illegible]	2.26×10^{-2}

ALL DATA SPRING, 1957

TABLE 5

the bay through the East Passage to the Mount Hope Bay entrance. The West Passage carries less seawater, but allows more vertical mixing with upper water to occur in its broad and shallow channels.

The distribution of volume transports can be determined by elementary hydraulic principles, using only the areas of channel entrances. Further verification is advisable, but the principle seems to be quite sound and important.

Lateral variation over the whole bay is considerable, but is probably not too great in individual channels (except entrances). Thus a possible model approach to consider is that of the bay as a network of cross-connected shallow channels, with little (or well-known) lateral variation, and a two-layer flow field.

Another possibility is to incorporate the similarity approach to the present two-dimensional (in the horizontal) model. Having calculated average velocity over the depth, possible inferences as to vertical velocity distribution (as functions of tidal exchange and river flow, for example) can be made.

A third point to consider is whether the mathematical model should calculate velocity or salinity as the primary variable. When velocity is known at each model station, the salinity profile could be predicted using similarity techniques, and the velocity computed from that.

Lastly, it should be noted that all the necessary parameters for calculating flushing times (river discharge, salinity distributions, bay geometry, and tidal volumes) are included in this report, and at least two methods may be used for such calculations (1).

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TABLES AND FIGURES

Tables

Figures

ESTUARY TYPES

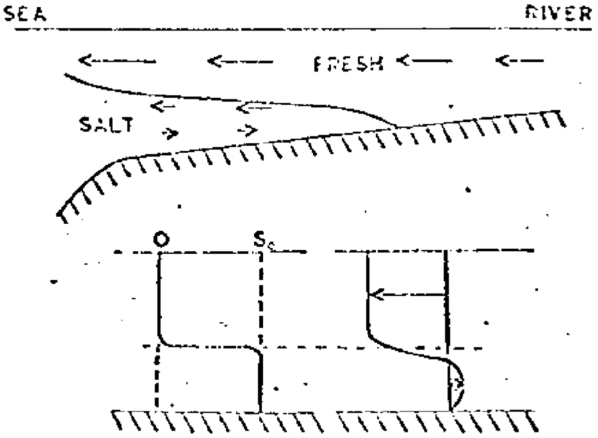


Fig. a. Salt wedge estuary: above—section along estuary; below—typical salinity and velocity profiles.

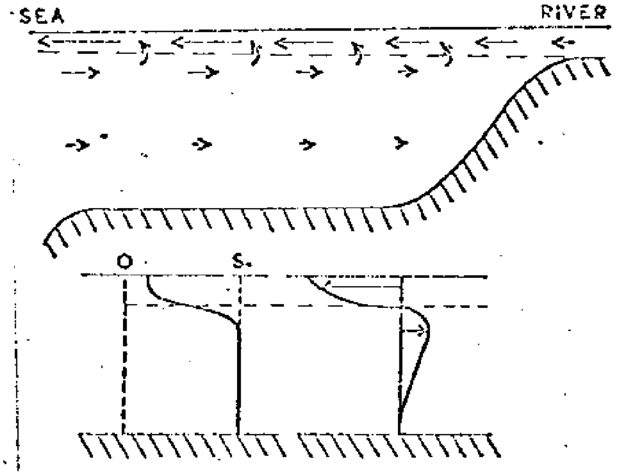


Fig. b Two-layer flow with entrainment: above—section along estuary; below—typical salinity and velocity profiles.

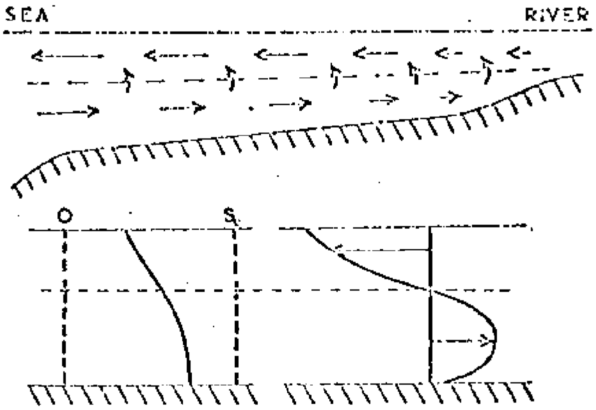


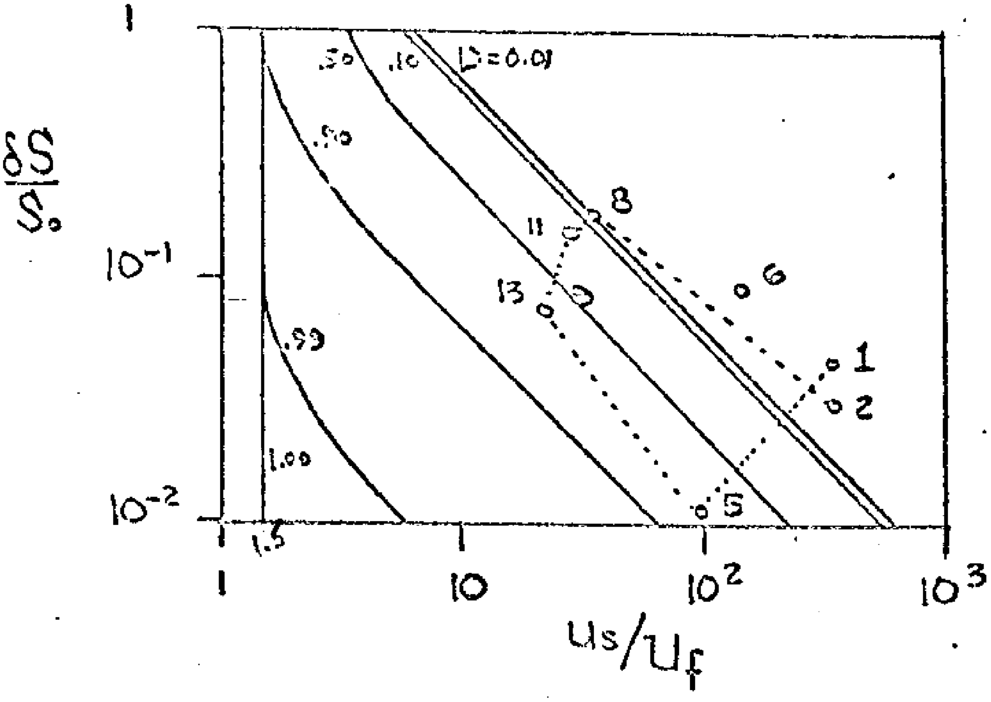
Fig. c. Partially mixed estuary with entrainment and mixing: above—section along estuary; below—typical salinity and velocity profiles.

(FROM BOWDEN, 1967)

FIGURE 1

PARAMETER PLOTS
(HANSEN & RATTRAY, 1966)

a. DIFFUSIVE FRACTION



b. ESTUARY TYPES

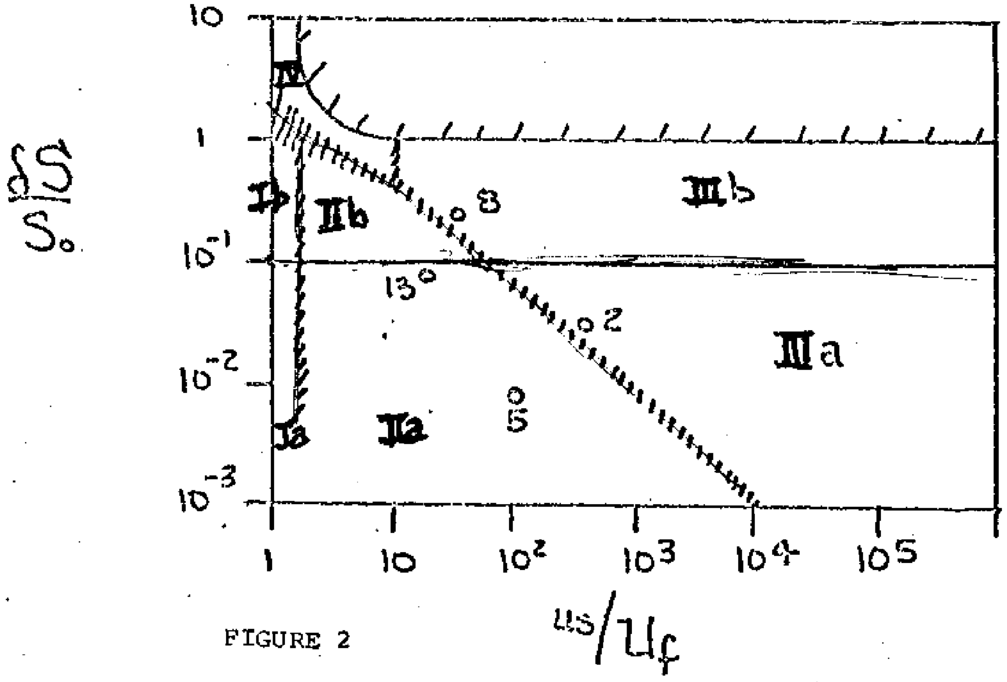


FIGURE 2

RHODE ISLAND

NARRAGANSETT BAY

STATIONS AND SECTIONS

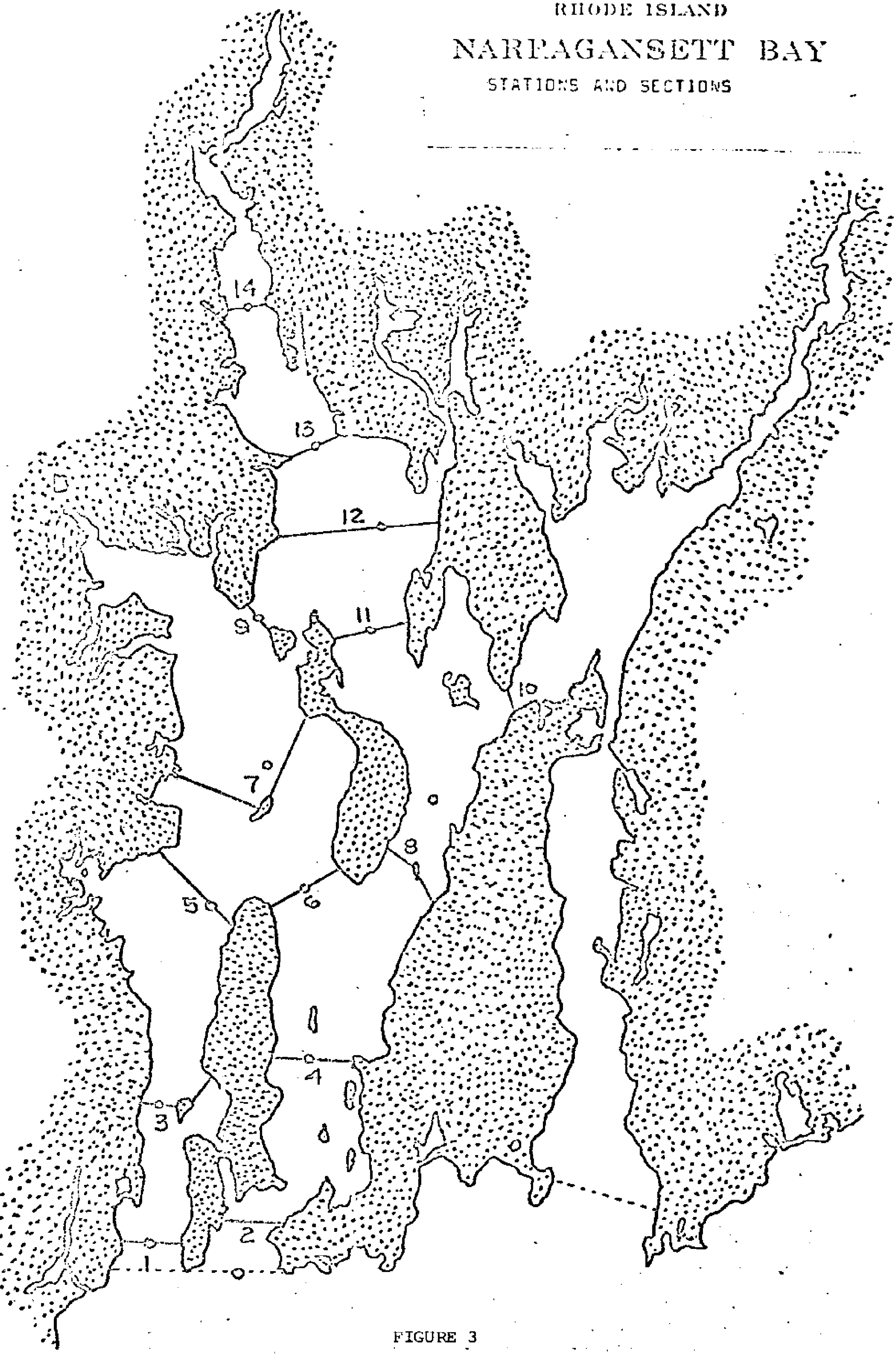


FIGURE 3

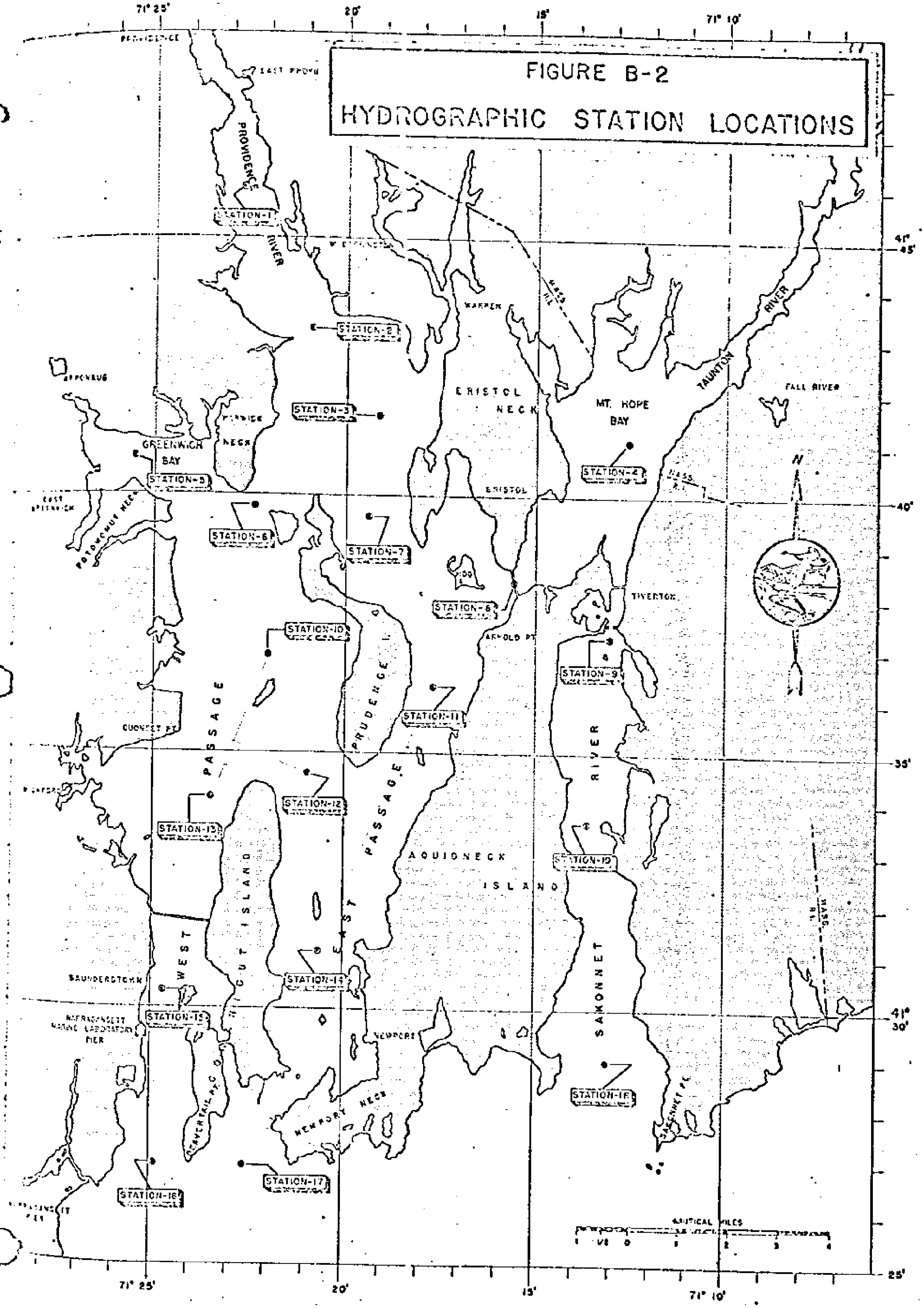


FIGURE B-2
HYDROGRAPHIC STATION LOCATIONS

FIGURE 3 (Cont.)

SCALE: HORIZ 1" = 3,375'
VERT. 1" = 80'

CROSS-SECTIONS
(LOOKING NORTH)

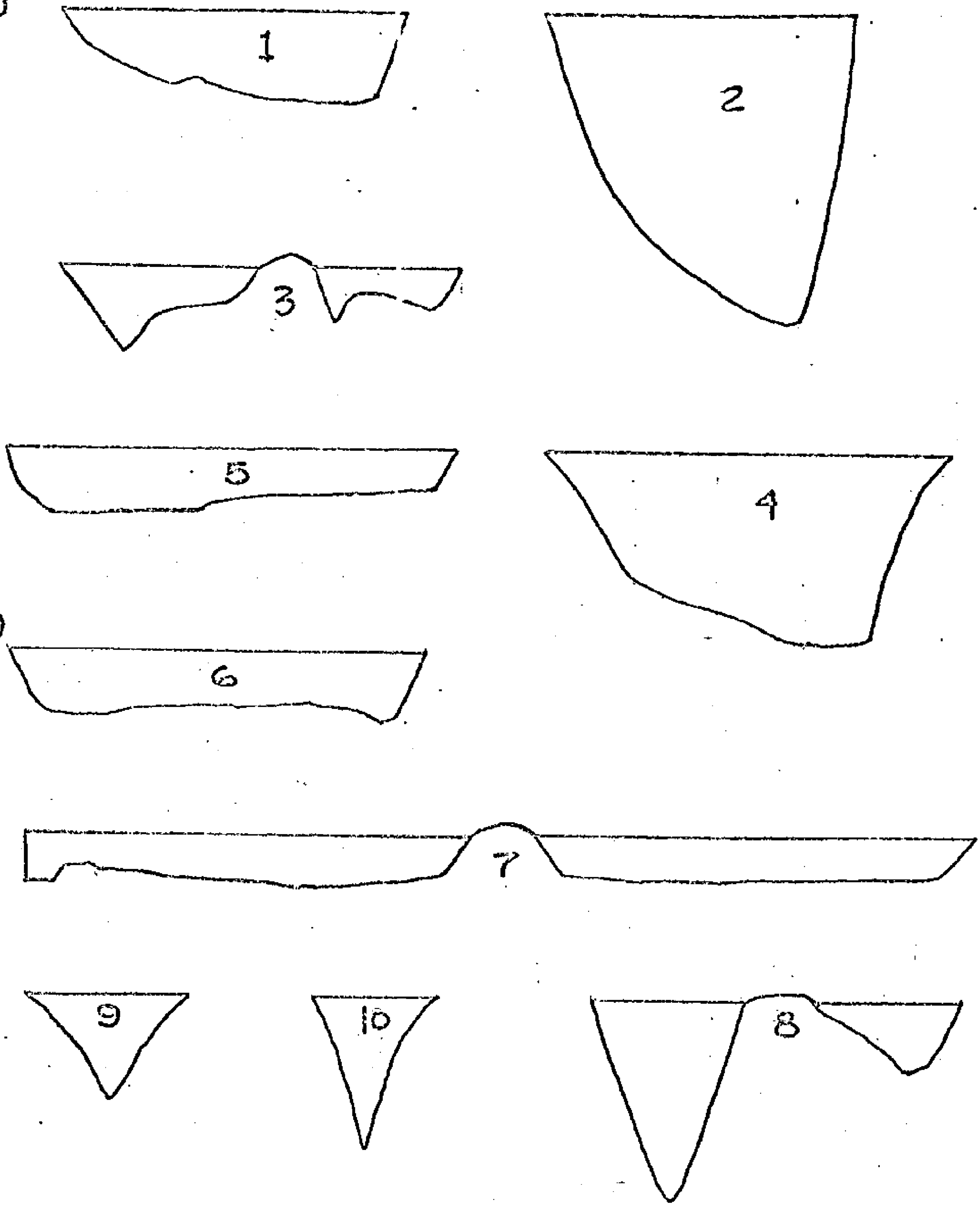
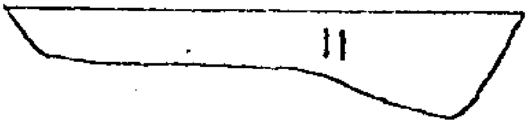
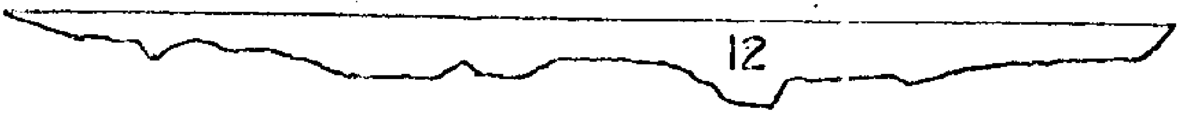


FIGURE 4

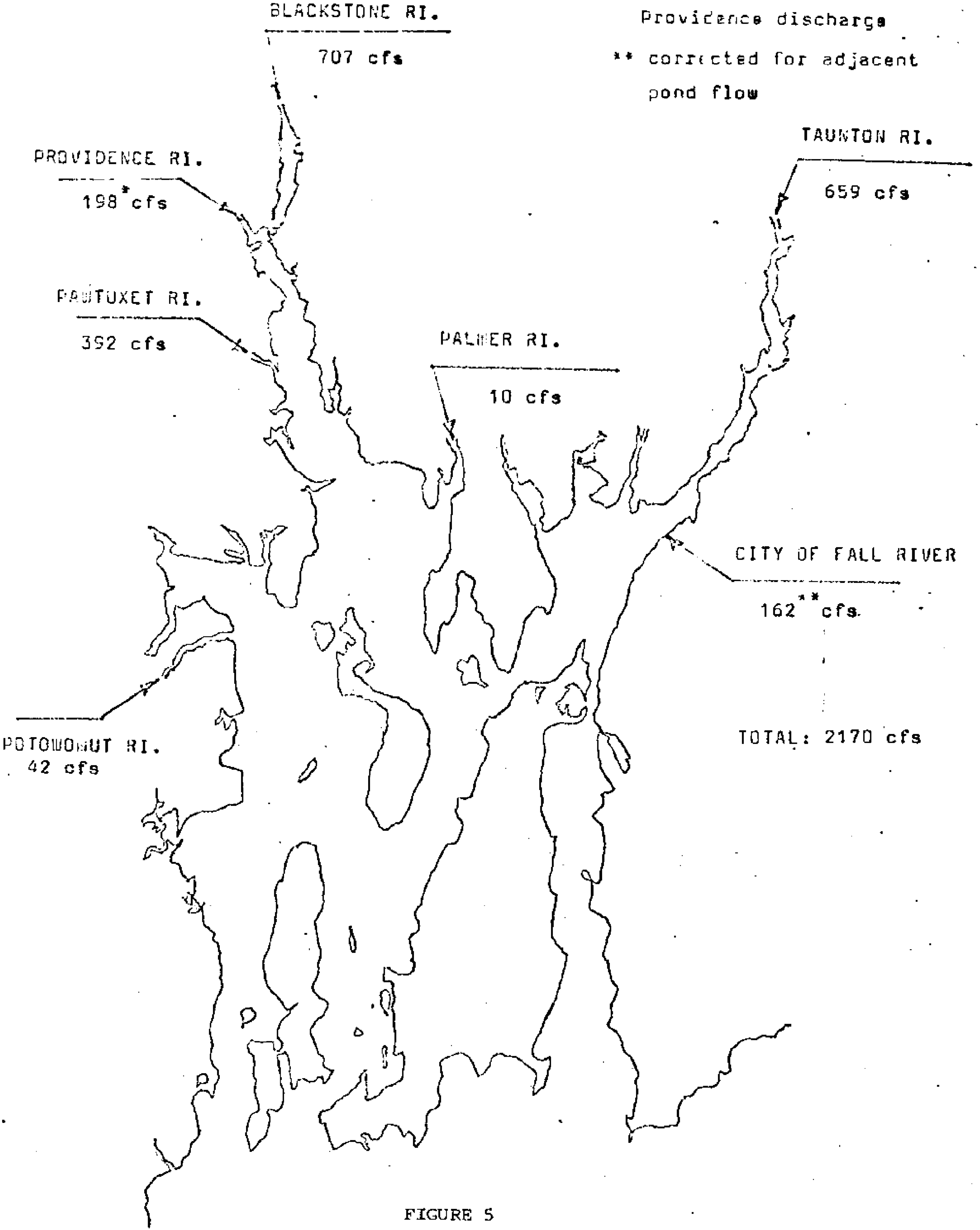
CROSS SECTIONS
(CONT'D)





SECTION	WIDTH	AVG DEPTH	AREA	
1	8,030'	37.9'	304,000 □'	
2	7,230	117.2	856,000	
3	7,830	20.6	161,200	
4	9,400	68.4	642,500	
5	9,700	27.2	264,000	38
6	9,600	30.3	291,000	96
7	20,500	24.1	495,000	
8	6,970	43.2	301,000	
9	3,680	24.4	89,800	
10	2,900	32.3	93,800	
11	8,810	24.4	215,000	
12	20,100	17.9	360,000	
13	5,390	13.5	71,700	
14	4,210	15.4	64,900	

FIGURE 4 (Cont.)



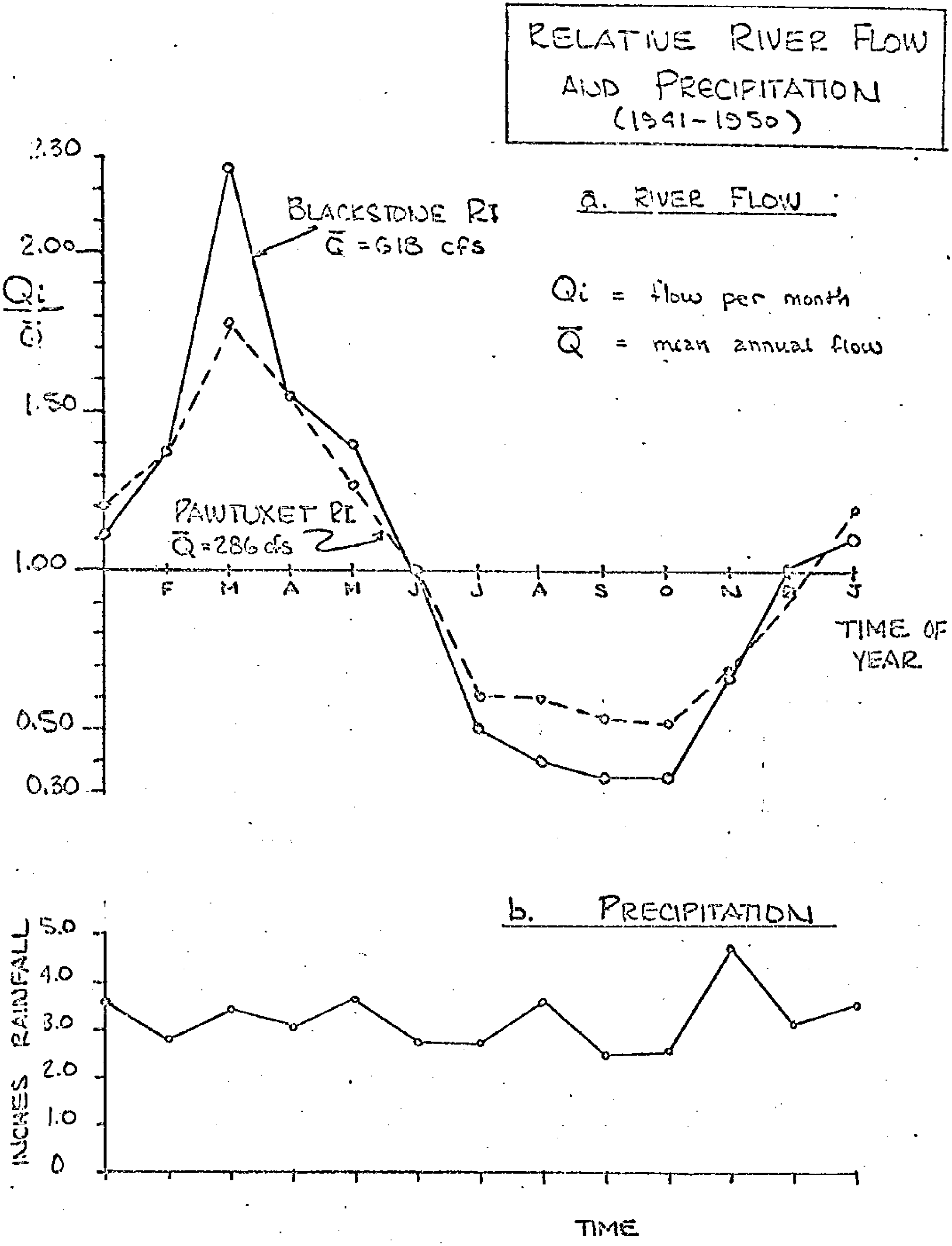
NARRAGANSETT BAY

MEAN RIVER FLOW

* corrected for City of Providence discharge

** corrected for adjacent pond flow

FIGURE 5



RELATIVE RIVER FLOW AND PRECIPITATION (1941-1950)

a. RIVER FLOW

b. PRECIPITATION

FIGURE 6

NARRAGANSETT BAY DRAINAGE BASIN

FIGURE 7

1 in = 8.3 mi
6 cm = 20 mi

NARRAGANSETT BAY

THE STANDING TIDAL WAVE

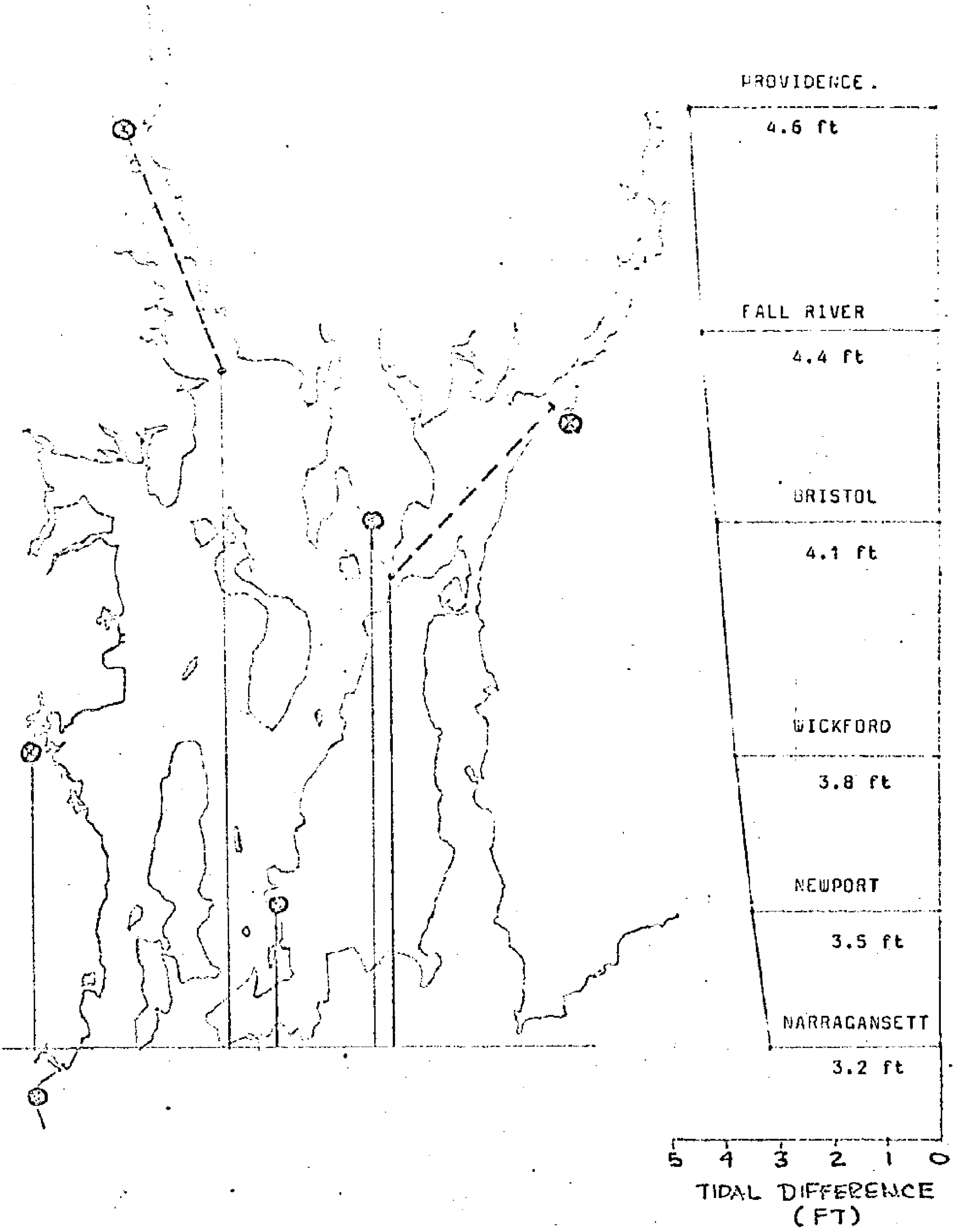


FIGURE 8

HALF-DAY CURRENT CYCLE - LOWER WEST PASSAGE

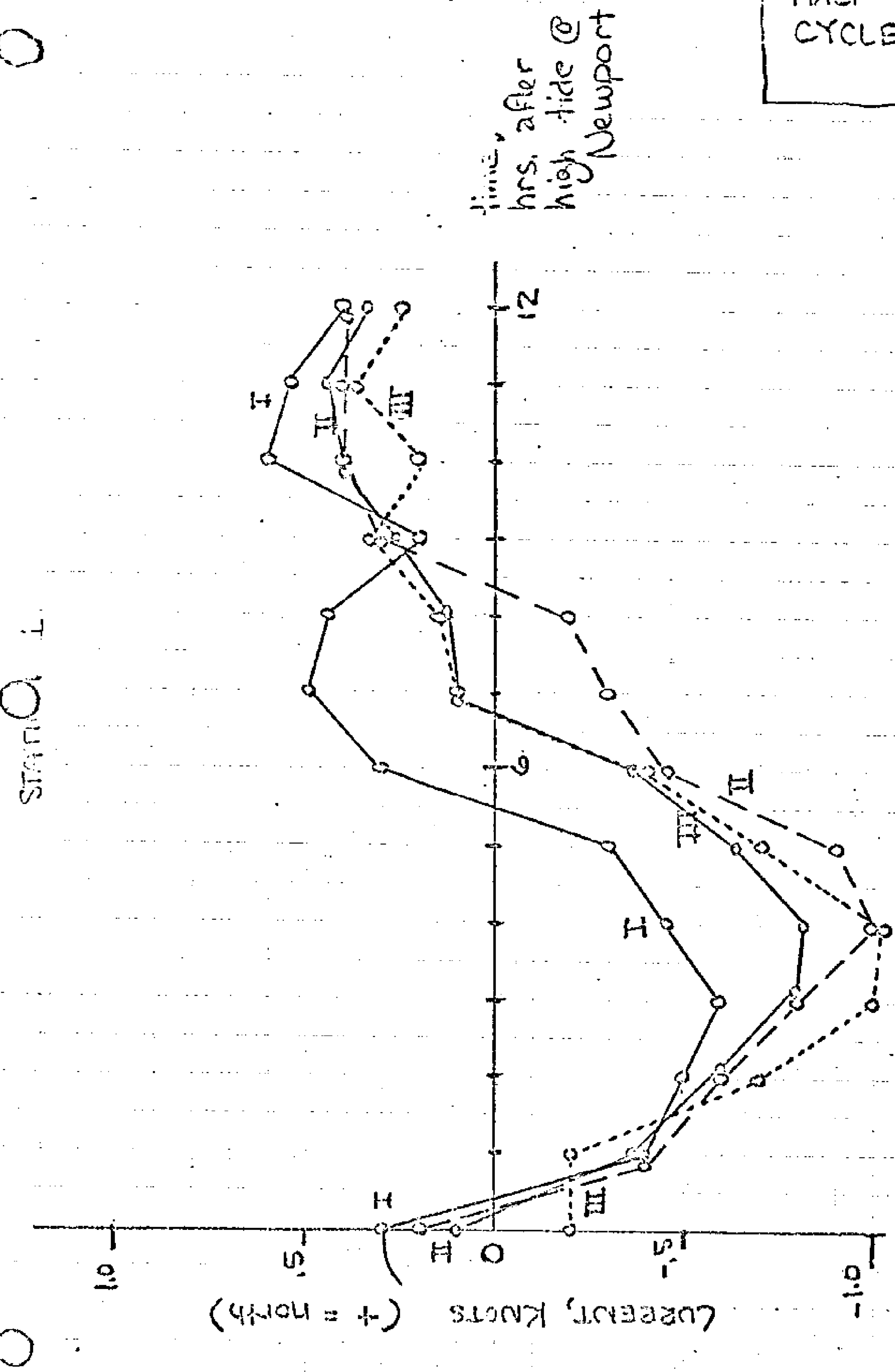
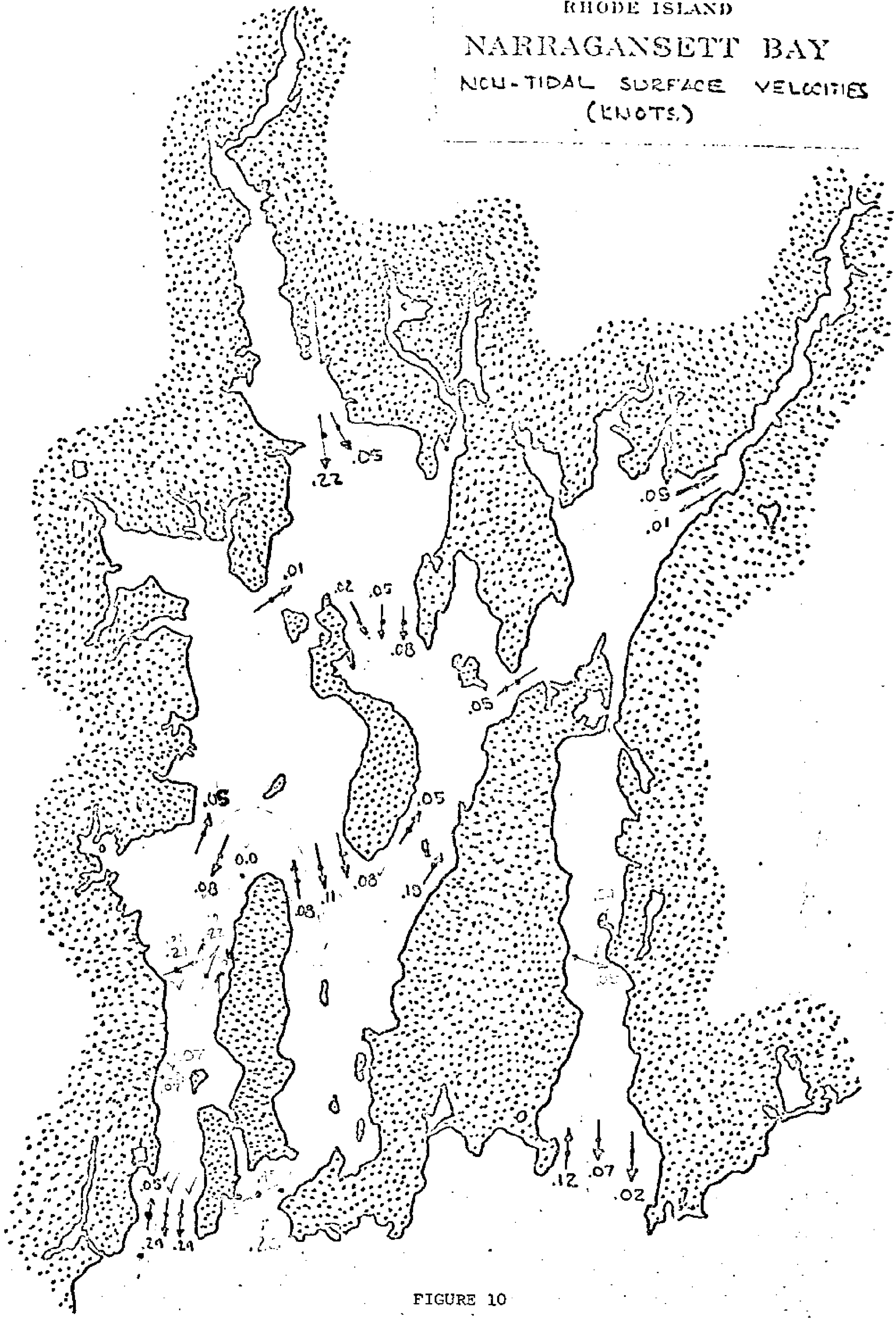


FIGURE 9



RHODE ISLAND

NARRAGANSETT BAY

NON-TIDAL SURFACE VELOCITIES (KNOTS)

FIGURE 10

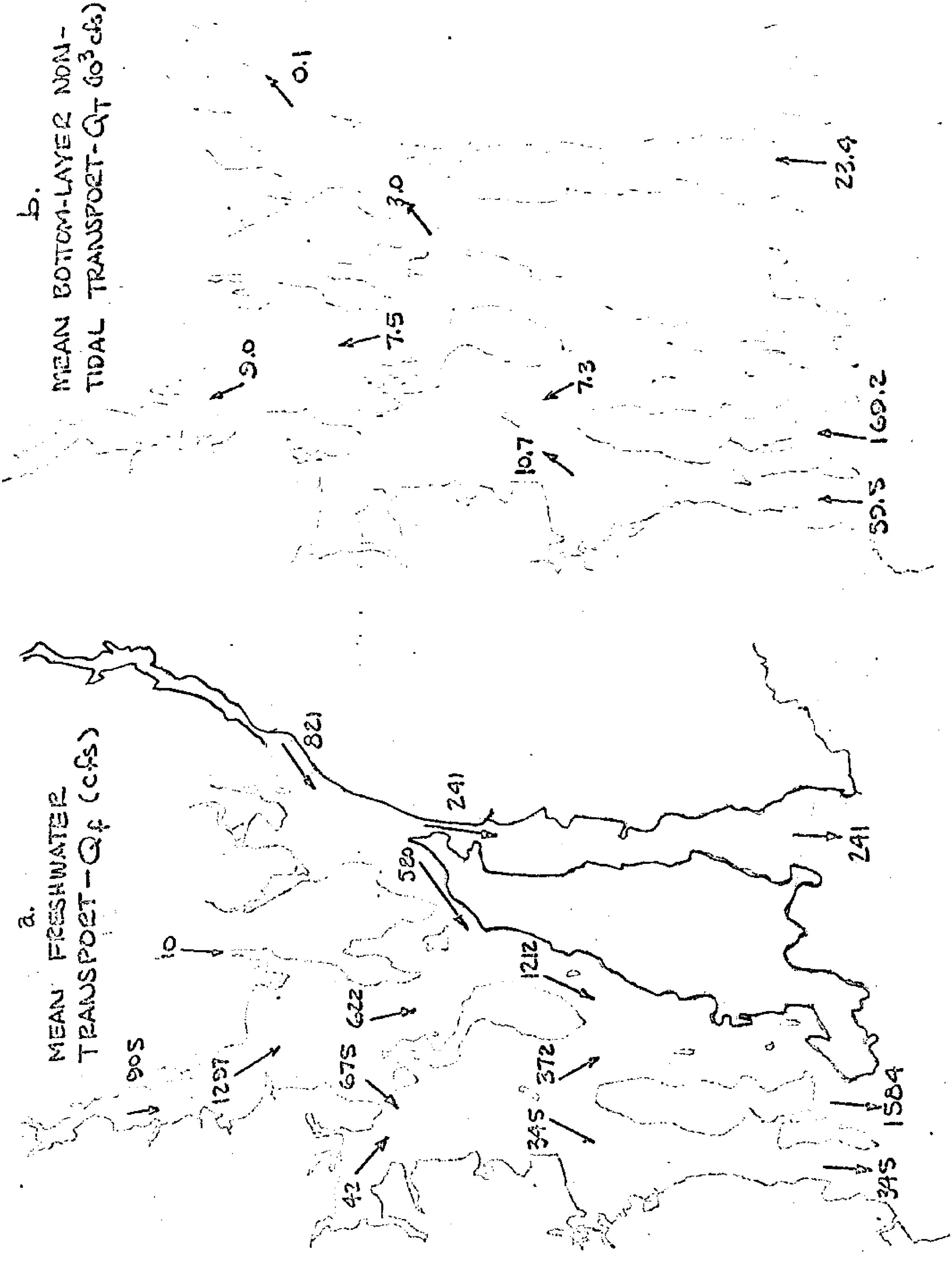

b.
MEAN BOTTOM-LAYER NON-TIDAL TRANSPORT - Q_T (10^3 cfs)
0.1
3.0
23.4
9.0
7.5
7.3
10.7
169.2
59.5
a.
MEAN FRESHWATER TRANSPORT - Q_f (cfs)
821
241
580
241
10
1212
622
905
1297
675
372
345
42
1584
345

FIGURE 11

SALINITY PROFILES
(SECTIONS REFER TO STATION
OF HURRICANE BARRIER
STUDIES)

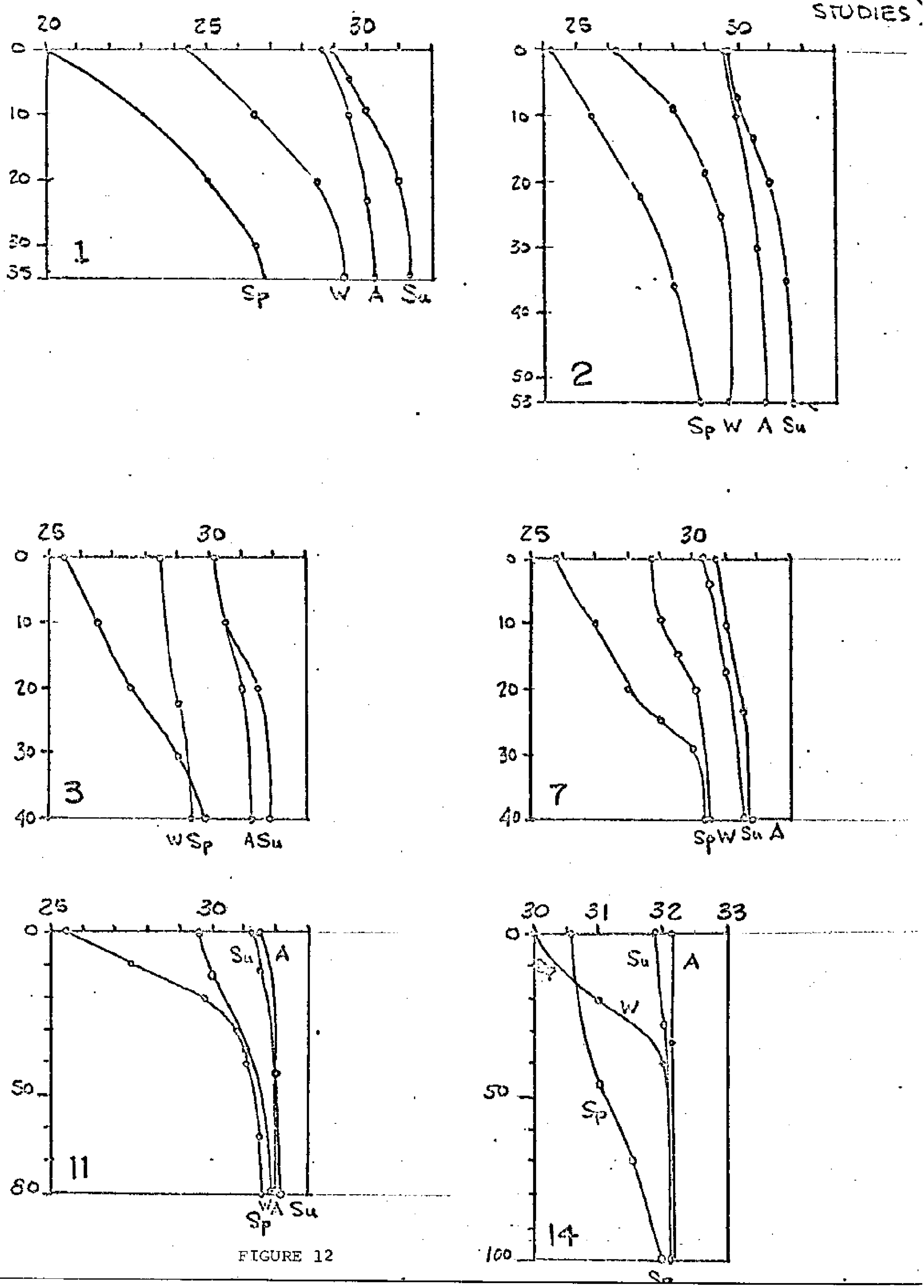


FIGURE 12

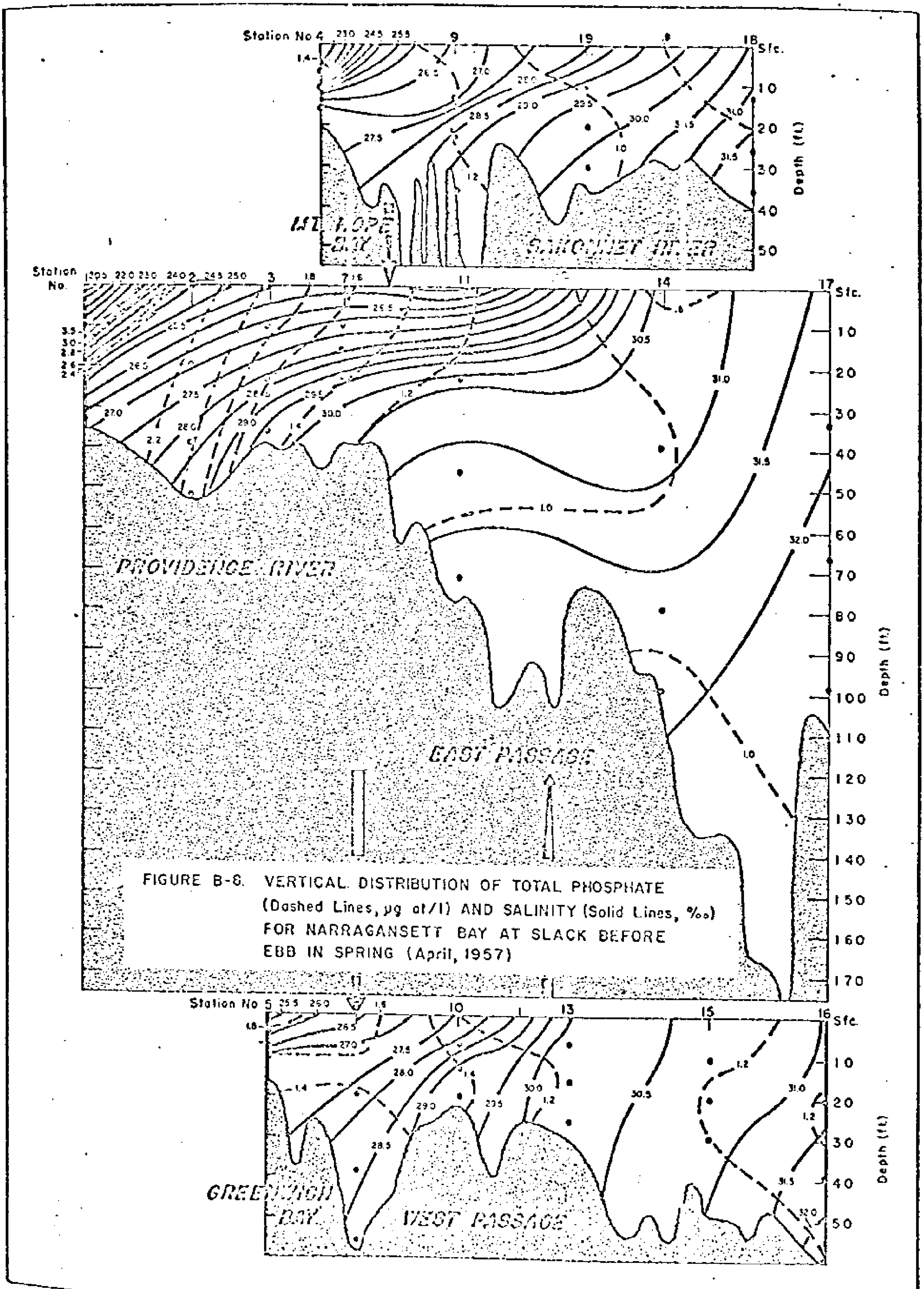


FIGURE B-8. VERTICAL DISTRIBUTION OF TOTAL PHOSPHATE (Dashed Lines, µg at/l) AND SALINITY (Solid Lines, ‰) FOR NARRAGANSETT BAY AT SLACK BEFORE EBB IN SPRING (April, 1957)

FIGURE 13

U.S. Dept. of Interior (1964)
Hurricane Damage Control
Narragansett Bay

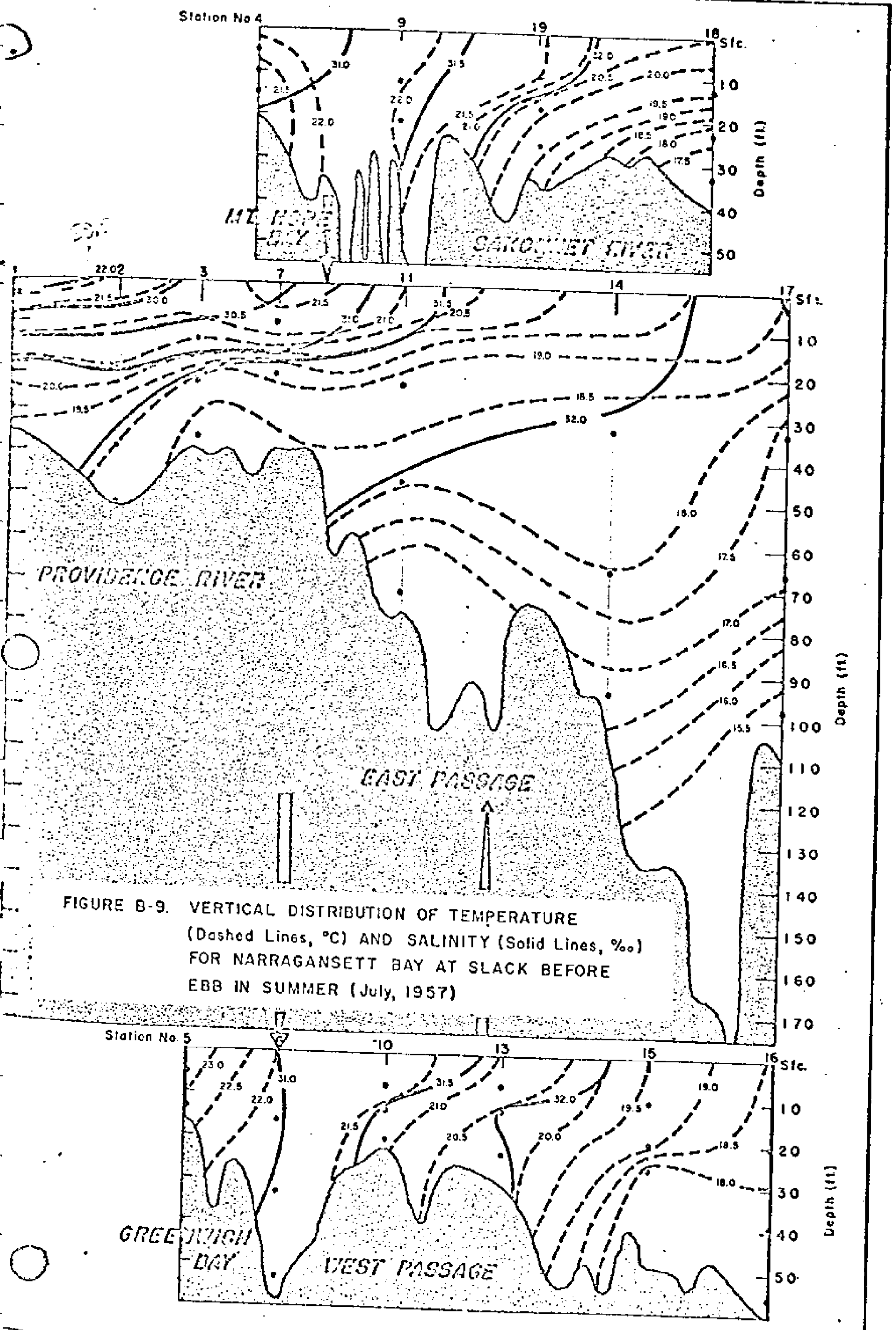


FIGURE B-9. VERTICAL DISTRIBUTION OF TEMPERATURE (Dashed Lines, °C) AND SALINITY (Solid Lines, ‰) FOR NARRAGANSETT BAY AT SLACK BEFORE EBB IN SUMMER (July, 1957)

FIGURE 13 (Cont.)

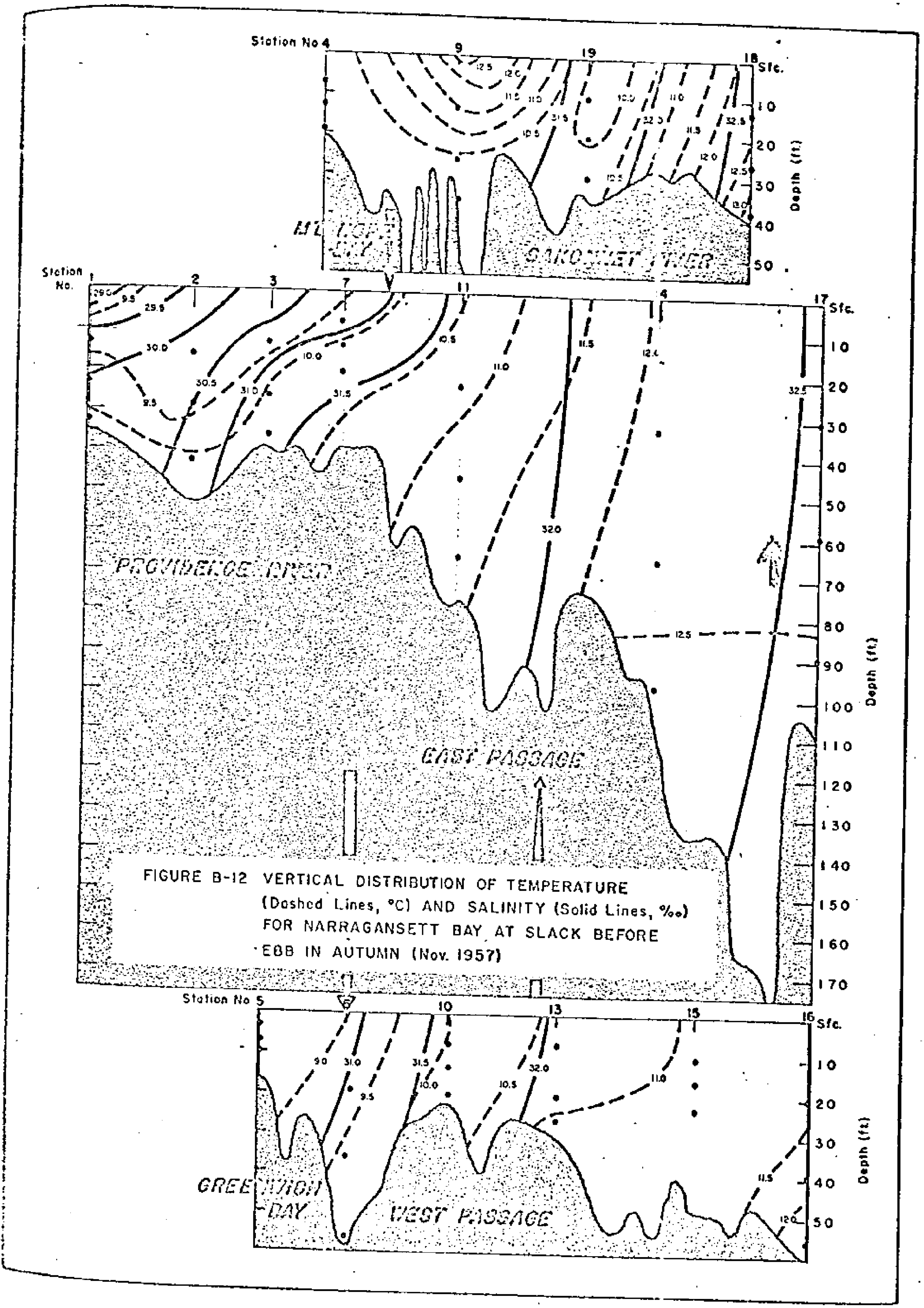


FIGURE B-12 VERTICAL DISTRIBUTION OF TEMPERATURE (Dashed Lines, °C) AND SALINITY (Solid Lines, ‰) FOR NARRAGANSETT BAY AT SLACK BEFORE EBB IN AUTUMN (Nov. 1957)

FIGURE 13 (Cont.)

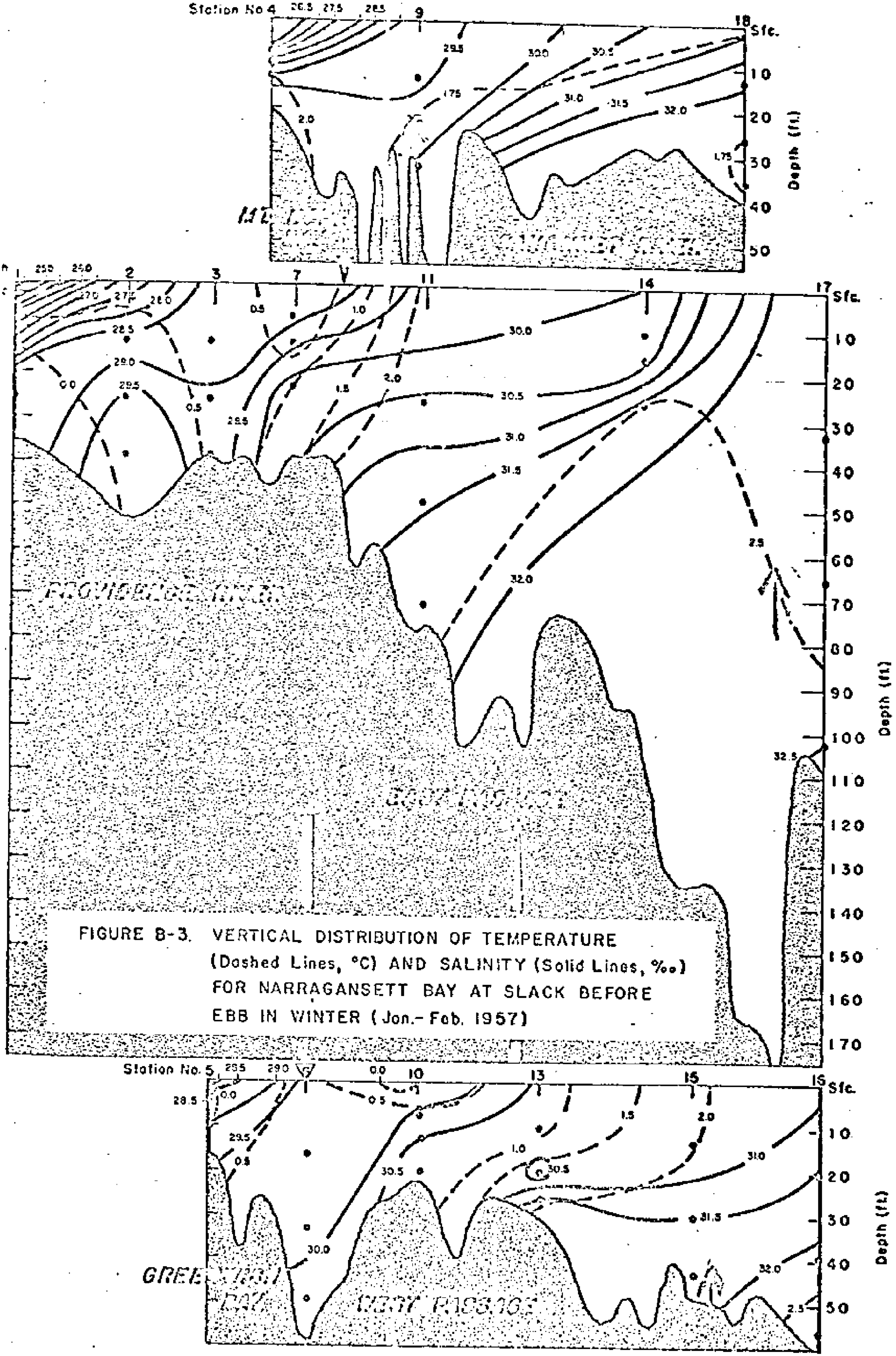
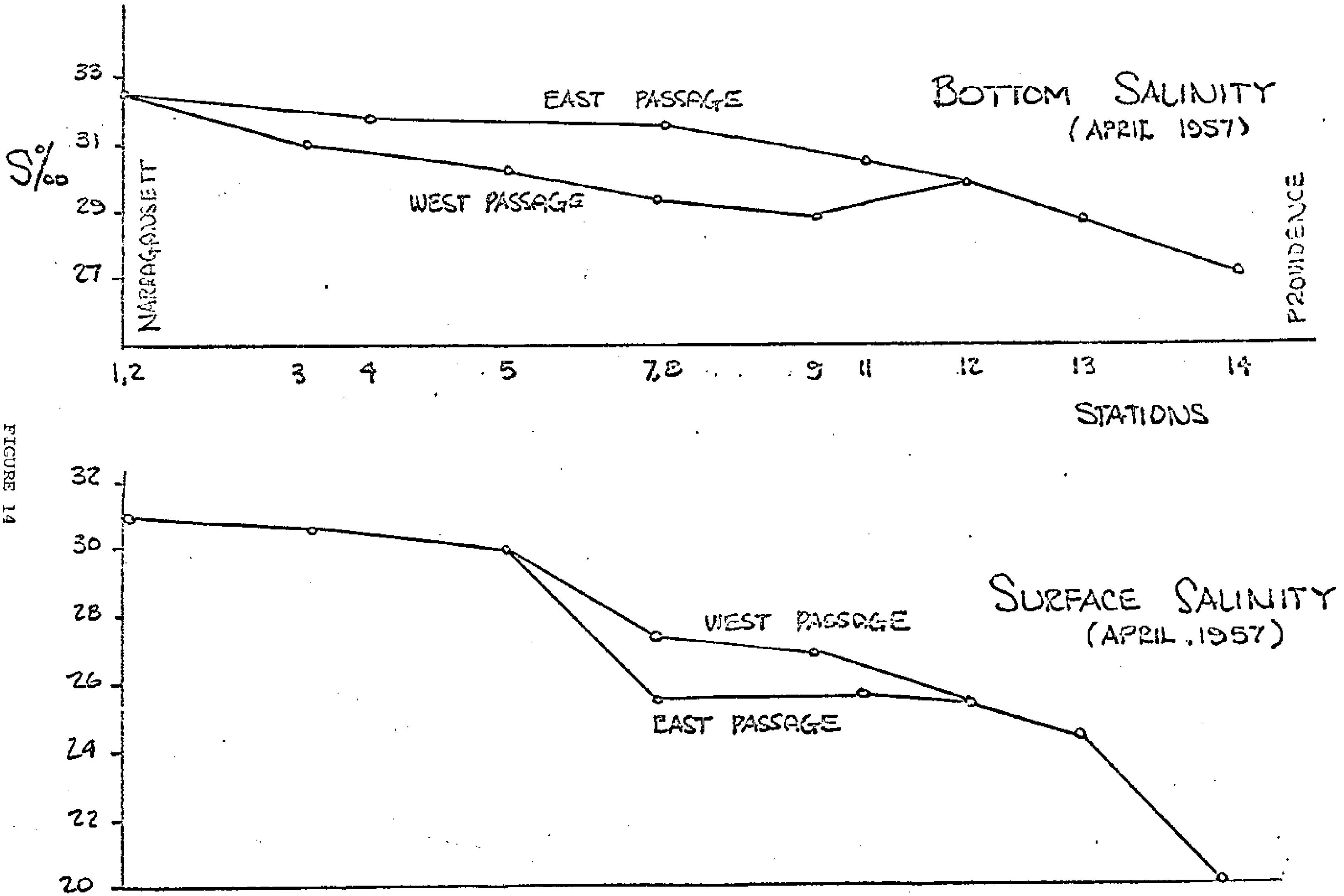


FIGURE 8-3. VERTICAL DISTRIBUTION OF TEMPERATURE (Dashed Lines, °C) AND SALINITY (Solid Lines, ‰) FOR NARRAGANSETT BAY AT SLACK BEFORE EBB IN WINTER (Jan.-Feb. 1957)

FIGURE 13 (Cont.)



LONGITUDINAL
SALINITY VARIATION

FIGURE 14

RHODE ISLAND

NARRAGANSETT BAY

SURFACE SALINITY - SPRING (April 1957)

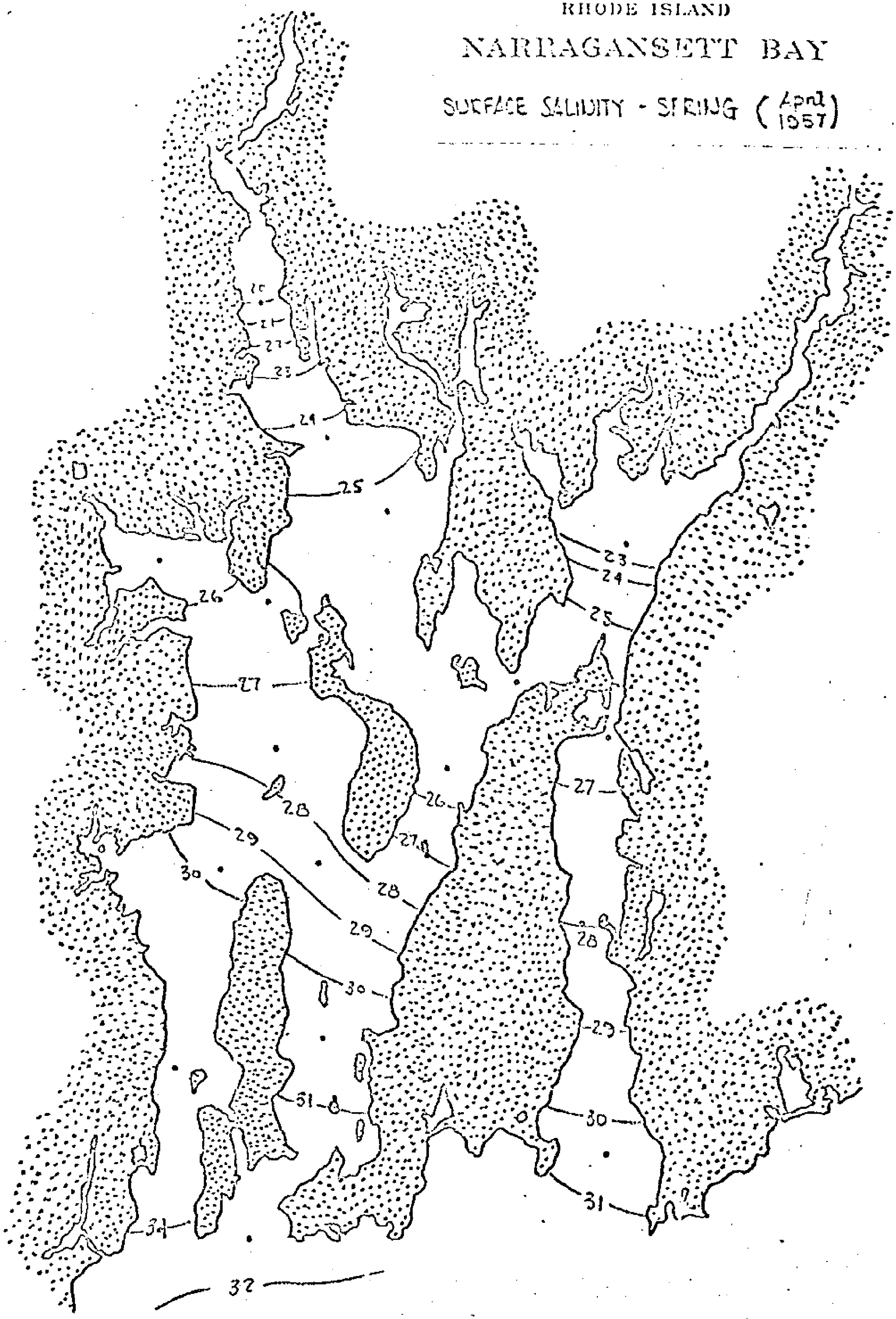


FIGURE 15

RHODE ISLAND

NARRAGANSETT BAY

BOTTOM SALINITY - SPRING (April 1957)

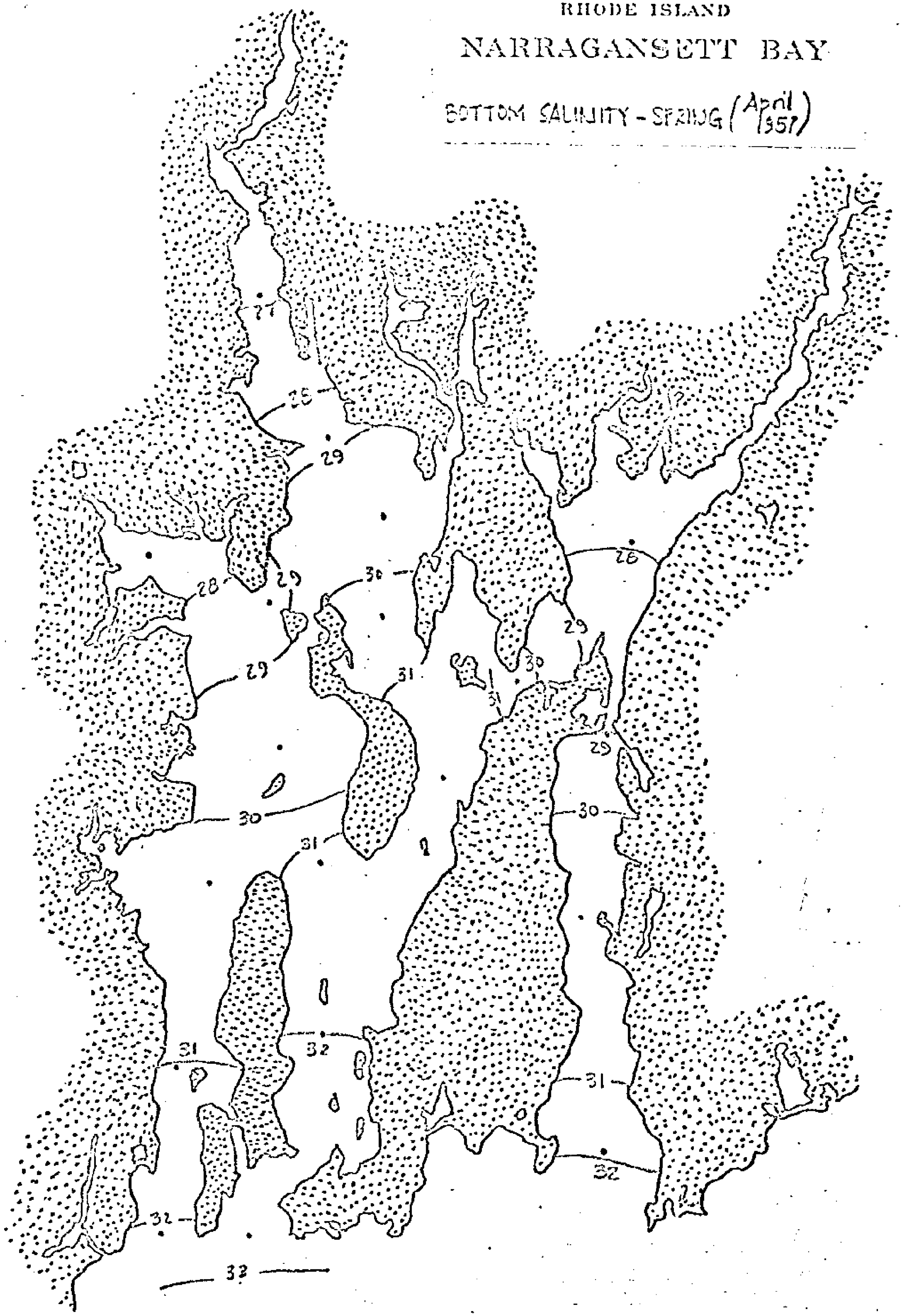


FIGURE 15 (Cont.)

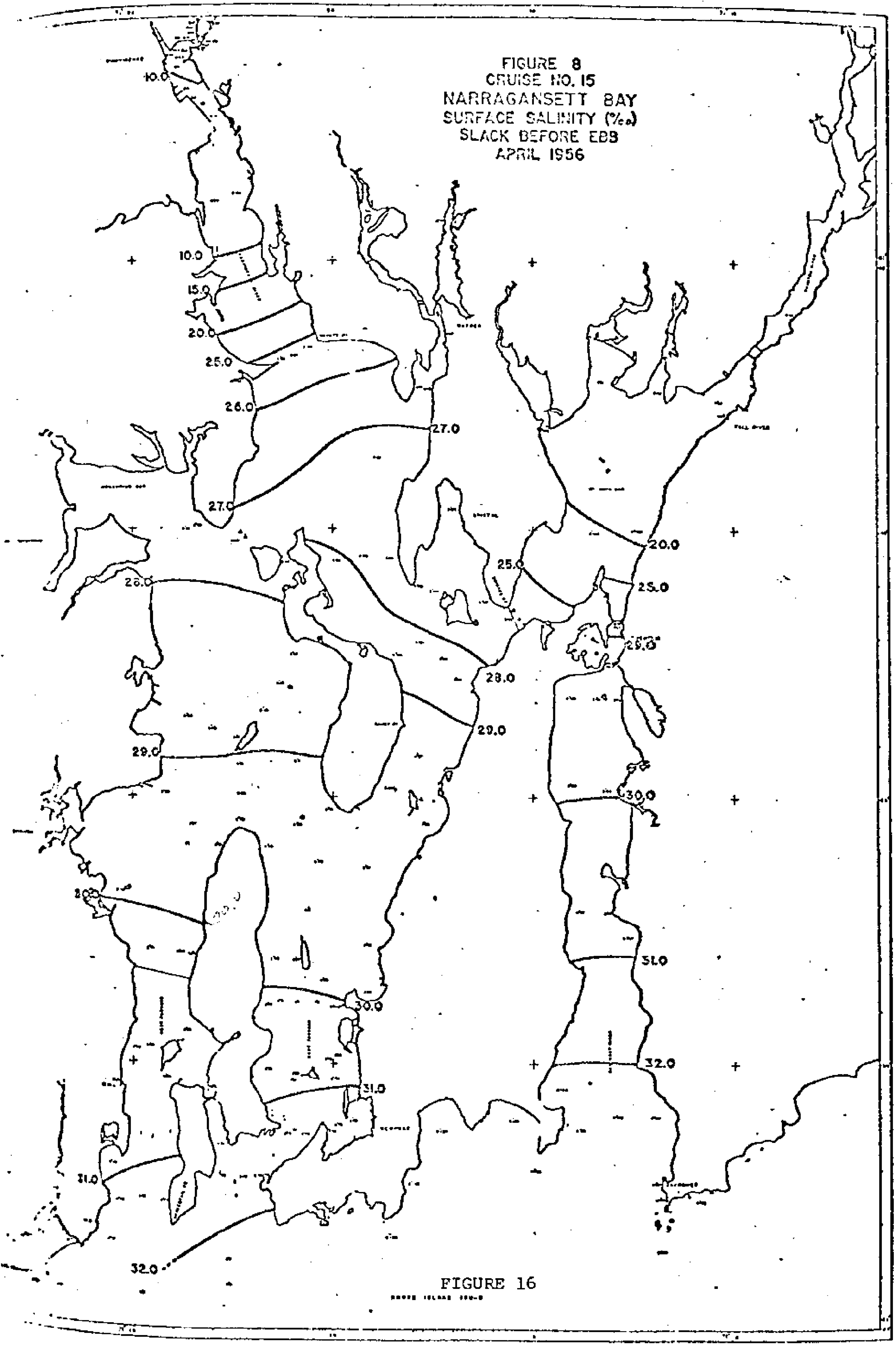


FIGURE 8
CRUISE NO. 15
NARRAGANSETT BAY
SURFACE SALINITY (‰)
SLACK BEFORE EBB
APRIL 1956
10.0
10.0
15.0
20.0
25.0
26.0
27.0
27.0
26.0
20.0
25.0
25.0
29.0
28.0
29.0
29.0
30.0
31.0
30.0
31.0
32.0
31.0
32.0

FIGURE 16

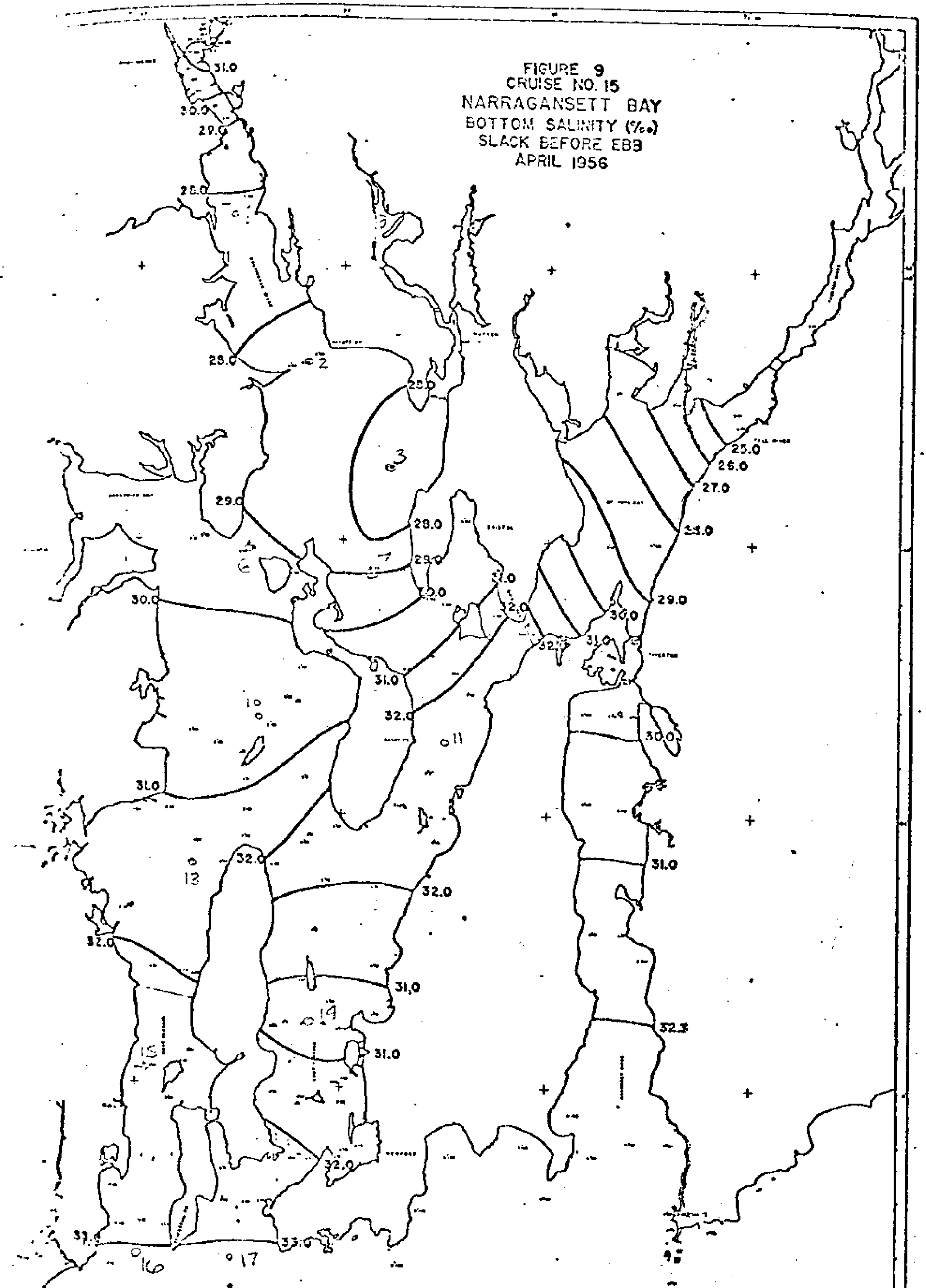


FIGURE 9
CRUISE NO. 15
NARRAGANSETT BAY
BOTTOM SALINITY (‰)
SLACK BEFORE EBB
APRIL 1956

FIGURE 16 (Cont.)