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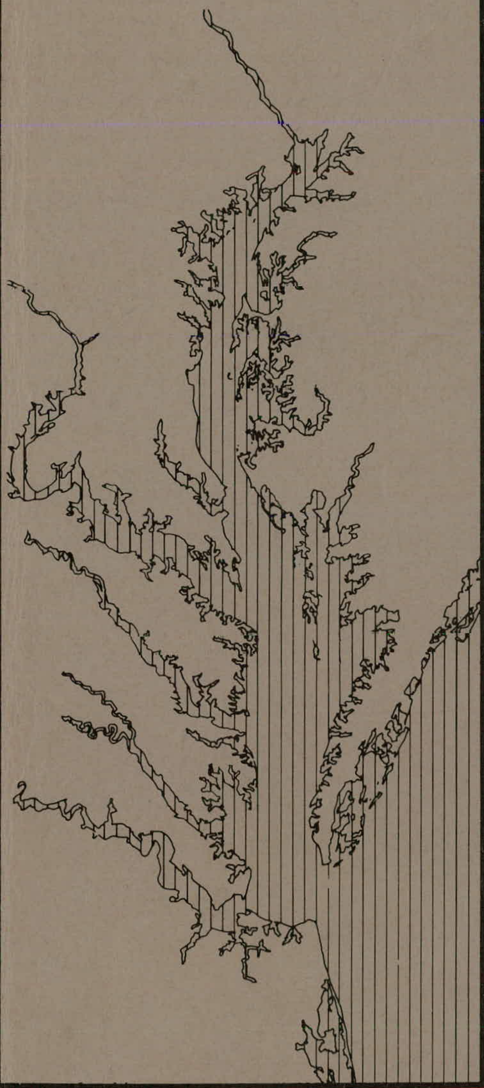

THE DISTRIBUTION OF EXCESS TEMPERATURE FROM THE MORGANTOWN GENERATING STATION ON THE POTOMAC ESTUARY

H. H. Carter

Reference 73-10 October 1973

Technical Report 84

DISCLAIMER

Please File in Master COO-3062-18

UNITED STATES
ATOMIC ENERGY COMMISSION
CHICAGO OPERATIONS OFFICE
9800 SOUTH CASS AVENUE
ARGONNE, ILLINOIS 60439

TELEPHONE
(312) 739-7711

January 28, 1974

Mr. Alfred P. Ashton, Director
Office of Sponsored Research Administration
228 Garland Hall
The Johns Hopkins University
34th and Charles Streets
Baltimore, Maryland 21218

Dear Mr. Ashton:

CONTRACT NO. AT(11-1)-3062, THE JOHNS HOPKINS UNIVERSITY CHESAPEAKE BAY INSTITUTE TECHNICAL REPORT NO. 84 (COO-3062-18)

This is in reply to Mrs. W. C. Hof's letter of January 10, 1974, setting forth the distribution accomplished for CBI Technical Report No. 84 (COO-3062-18).

Our letter of September 13, 1973, Miller to Ashton, delineated the distribution to be accomplished for all reports generated under the subject contract. A copy of that letter is being furnished to Mrs. Hof.

In accordance with the distribution instructions contained in the above referenced letter, the following distribution should have been accomplished for CBI Technical Report No. 84:

1. Two advance copies to the Director, Reactor Research Division.

2. One copy to the Assistant General Counsel for Patents, Office of the General Counsel, USAEC, Washington, D. C. 20545, with AEC Form 426. The Brookhaven Patent Office is no longer the cognizant activity for patent matters relating to Johns Hopkins University contracts.

3. One copy to Director, Contracts Management Office, USAEC, Chicago Operations Office with AEC Form 426.

4. Two-Hundred-Sixty-One (261) copies to TIC with AEC Form 426.

5. Copies to the Cooling Waters Study Group, the number of copies required to be determined by the Chesapeake Bay Institute.

As to the actual distribution made for the subject report, the only corrective action required is the submission of AEC Form 426 to the Technical Information Center in lieu of the previously submitted Form 427. The Brookhaven Patent office will forward the subject report to our Headquarters Patent Group. However, for all future reports, you are to adhere to the distribution instructions contained in our September 13, 1973, letter.

Sincerely yours,

Seymour Zirin
Senior Contract Administrator
Contracts Management Office

cc: W. C. Hof, Johns Hopkins University Chesapeake Bay Institute, with CMO letter dated September 13, 1973
L. Belkin, Chief, Brookhaven Patent Group, with Hof letter of January 10, 1974
✓Manager, TIC, with Hof letter of January 10, 1974

THE JOHNS HOPKINS UNIVERSITY • BALTIMORE, MARYLAND 21218

KVM

CHESAPEAKE BAY INSTITUTE

10 January 1974

Mr. Harold N. Miller, Director
Contracts Division
U.S. Atomic Energy Commission
Chicago Operations Office
9800 South Cass Avenue
Argonne, Illinois 60439

Dear Mr. Miller:

In accordance with requirements, work carried out for the U.S. Atomic Energy Commission under Contract AT (11-1)-3062, we are enclosing one (1) copy of

Chesapeake Bay Institute Technical Report No. 84,
Document No. COO-3062-18, with copy of Form AEC-427.

We are also sending one (1) copy of CBI Technical Report 84 with AEC Form 427 to Leonard Belkin, Chief, Brookhaven Patent Group, Upton, N.Y. 11973; 261 copies of CBI T.R. 84 with AEC Form 427 to: Manager, Technical Information Center, U.S. AEC, Office of Information Services, Oak Ridge, Tennessee 37830. In addition we are sending 40 copies of CBI Technical Report 84 to Joseph A. Gerath, Jr., Research Coordinator, Maryland Academy of Sciences (Cooling Water Studies Group). Please advise whether our distribution meets your requirements.

Sincerely yours,

Waltraud C. Hof

(Mrs.) Waltraud C. Hof
Secretary for Publications
Chesapeake Bay Institute

1-25-74
Called Mrs Hof
In future AEC Form
426 should be
used. KVM

cc's to: L. Belkin, Chief,
Brookhaven Patent Group

Manager, Tech. Info. Ctr.,
Oak Ridge, Tenn.

J. A. Gerath, Jr., Research
Coordinator, Md. Acad. of Sciences
Baltimore, Md.

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CHESAPEAKE BAY INSTITUTE

THE JOHNS HOPKINS UNIVERSITY

TECHNICAL REPORT 84

THE DISTRIBUTION OF EXCESS TEMPERATURE FROM THE MORGANTOWN GENERATING STATION ON THE POTOMAC ESTUARY

by

H.H. Carter

This report contains results of work carried out for the U.S. Atomic Energy Commission under Contract AT(11-1) - 3062. Doc. No. COO-3062-18.

This report does not necessarily constitute final publication of the material presented.

Reference 73-10
October 1973

Erratum Sheet for: CBI TR 84 The distribution of excess temperature from the Morgantown Generating Station on the Potomac Estuary. H.H. Carter, Ref 73-10 Oct 73.

Addition to References

Schubel, J.R. 1973. Effects of exposure to time-excess temperature histories typically experienced at power plants on the hatching rates of fish eggs. Chesapeake Bay Institute, The Johns Hopkins University, Special Rept. 32, Ref. 73-11, 36 pp.

Acknowledgements

Scientists who make measurements in natural systems know and appreciate the value of efficient and knowledgeable research vessel crews. For these people, the hours are long and the pay is low. Even in the relatively well-sheltered waters of an estuary, field experiments are plagued by bad weather, vessel and equipment failures, groundings, etc. Accordingly, the assistance of the crews of the R/V MAURY and R/V LYDIA LOUISE II in carrying out the field experiments described herein, particularly Captains Charles V. Wessels and Wallace J. Gilbert, are gratefully acknowledged.

With respect to the report, the author wishes to acknowledge a number of helpful suggestions made by J.R. Schubel. The figures were drawn by Mrs. Dean Pendleton, and the manuscript typed by Ms. A. Sullivan.

Personnel of the Potomac Electric Power Company cooperated fully in the studies, providing both assistance and operating records on request; their cooperation is gratefully acknowledged.

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I. Introduction.

The research described in this report is an integral part of a multi-institutional, multi-agency study of power plant siting on Chesapeake Bay. Overall coordination of the program is carried out by the Steering Committee of the Chesapeake Bay Cooling Water Studies Group . Personnel of the Division of Reactor Development and Technology and the Division of Biomedical and Environmental Research, U.S. Atomic Energy Commission, are members of this Committee as well as representatives of the research institutions engaged in pertinent studies of the Chesapeake Bay; of state agencies responsible for resource management; and of the several electric utilities servicing the Chesapeake Bay area. Our overall research goals are to develop improved analytical and numerical models having general applicability for the prediction of the temperature distribution in the thermal plume from a condenser cooling water discharge; to develop design criteria for siting power plants on estuarine waters; and to develop field techniques for quantitating the distribution of excess heat [1] from an operating generating station.

The specific goals of the research described herein were three-fold. First of all, we wished to provide information regarding the actual distribution of excess heat from the Morgantown Generating Station to investigators working on other aspects of the joint study; secondly, to provide implicit quantification of the physical processes of advection and turbulent diffusion for tuning and/or constructing numerical models of

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[1] Here excess heat means the difference between the heat that a given parcel of water would contain under conditions of a heated discharge and the heat it would contain under "natural" conditions.

this portion of the Potomac Estuary[2] and thirdly to conduct both a preoperational and postoperational study for purposes of prediction of the probable distribution of excess heat (preoperational) and subsequent verification (postoperational). The first two objectives were achieved. The third objective was not achieved because of our inability to adequately simulate the postoperational effluent characteristics at the point of discharge during the preoperational study. That is, cooling water for the plant is withdrawn from the Potomac River through a deep intake channel (- 50.0 feet) with the intake channel and intake cove being separated by a curtain or skimmer wall which penetrates to - 30.0 feet. From the condensers the water is returned to the river through a discharge canal as a surface jet. This arrangement is illustrated schematically in Figures 2 and 3. The discharge velocity is maintained at between 8 and 9 feet sec^{-1} and independent of the plant's output by increasing or decreasing the orifice width 2 feet for every circulating water pump (167,000 gpm) that is put in service or removed. A significant vertical gradient in salinity results in a plume that is heavier than the surface waters into which it is being discharged. That is, even though its temperature is raised approximately 10°F as a result of passing through the condensers, its density will be greater than the density of the surface waters if its salinity is greater than the salinity of the surface water by an amount ΔS, which depends on the intake temperature. This is shown in Figure 4. In Figure 4, the dashed line connects points (ΔS, T_i) such that the salinity increase ΔS produces a density increase that exactly offsets the density decrease due to the temperature rise across the condensers for a given initial or intake temperature, T_i. Points to the right of the dashed line represent discharged parcels that

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[2] See Figure 1.

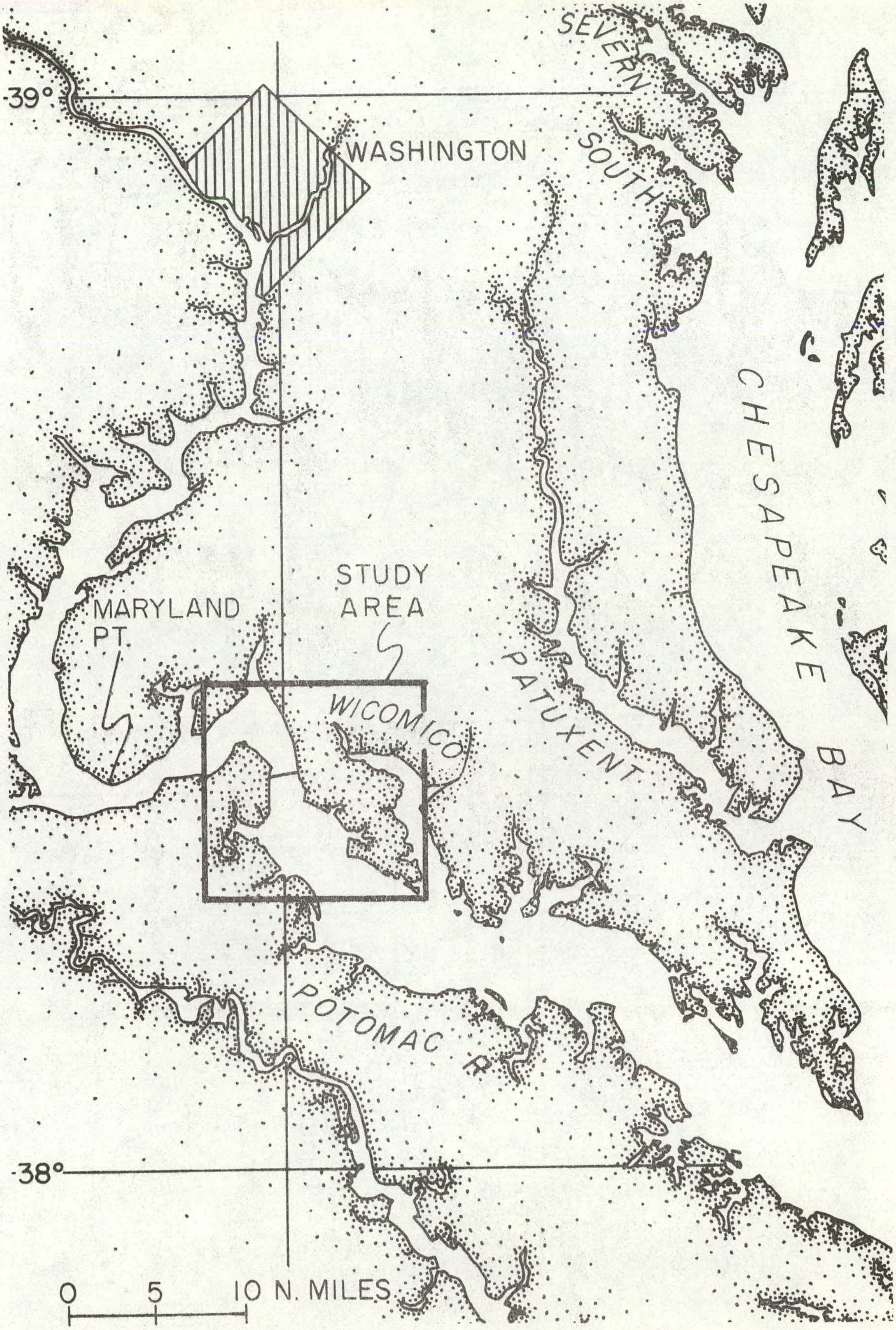


Figure 1. Chart of the Potomac River showing the location of the study area.

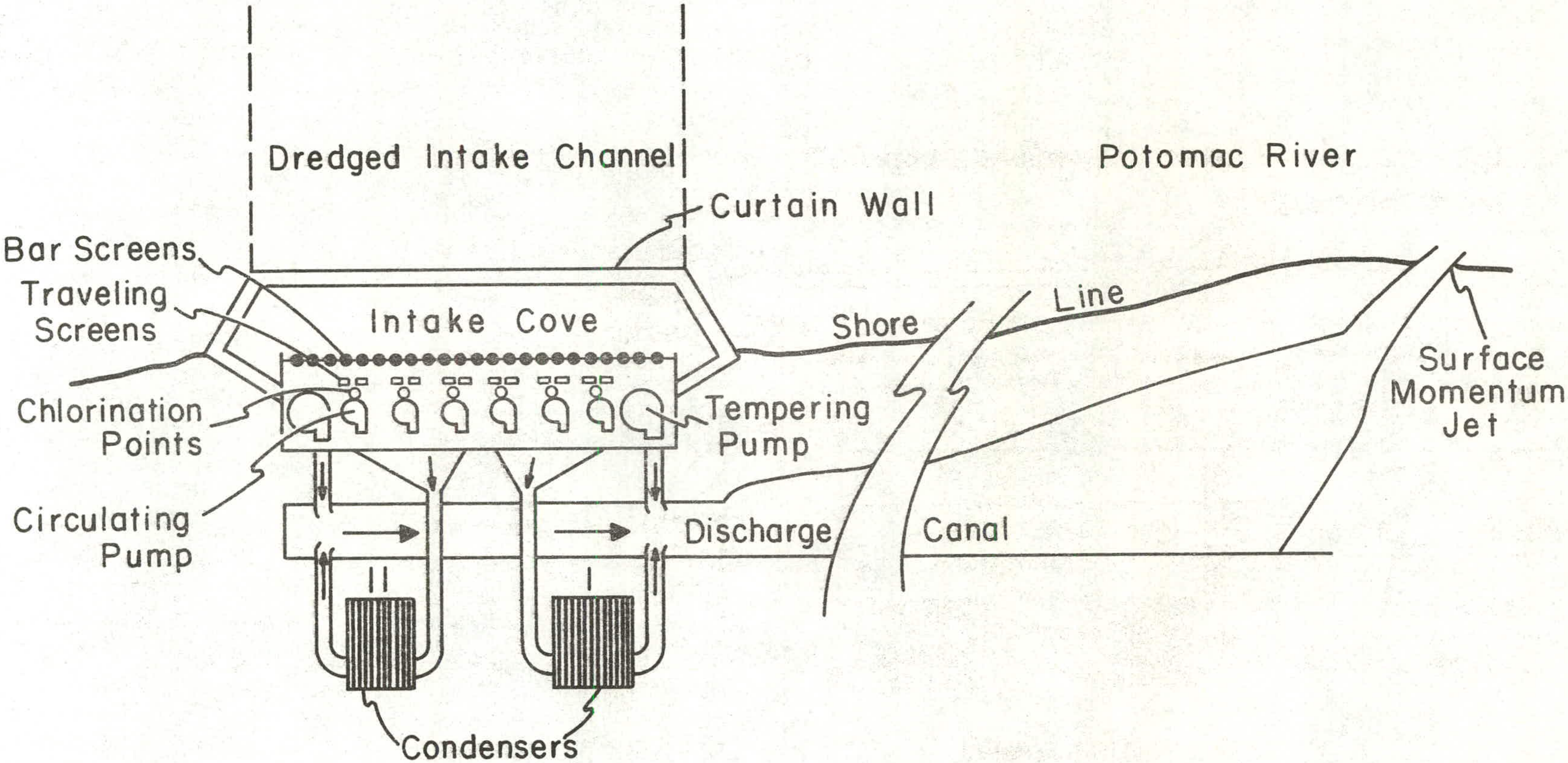


Figure 2. Schematic of Morgantown Generating Station Cooling Water System (Plan) (reprinted with permission of Martin-Marietta Laboratories).

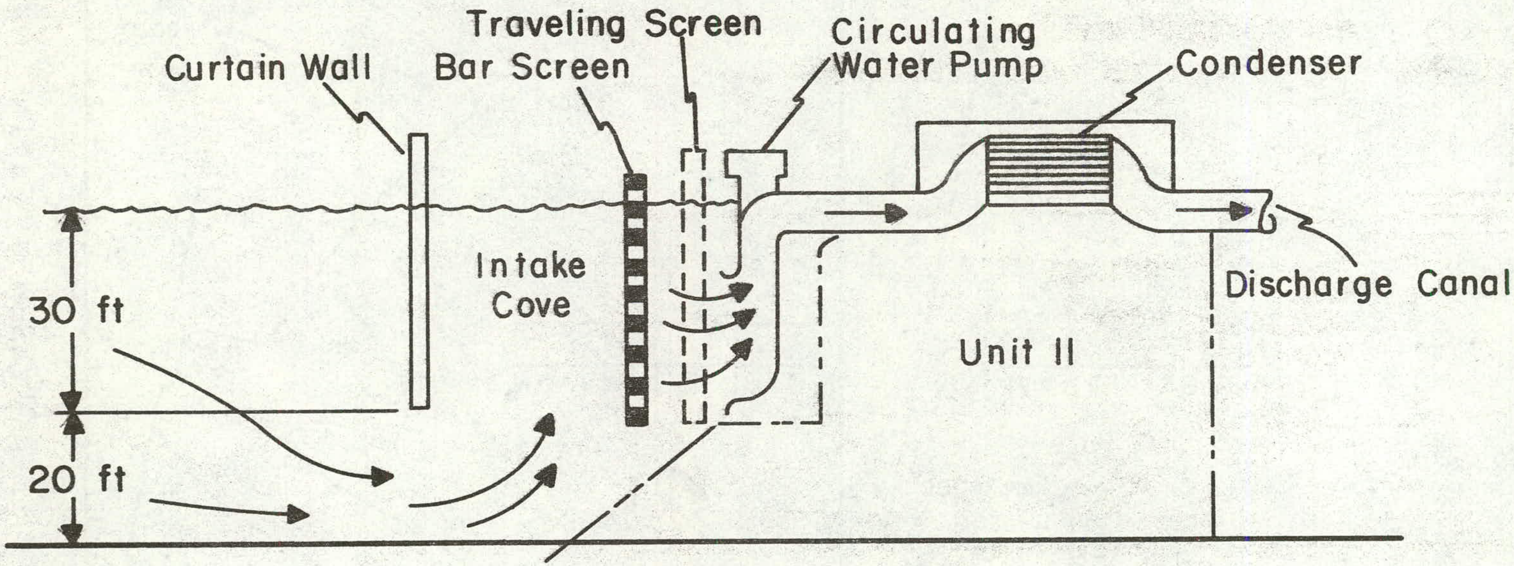


Figure 3. Schematic of Morgantown Generating Station Cooling Water System (Cross section) (reprinted with permission of Martin-Marietta Laboratories).

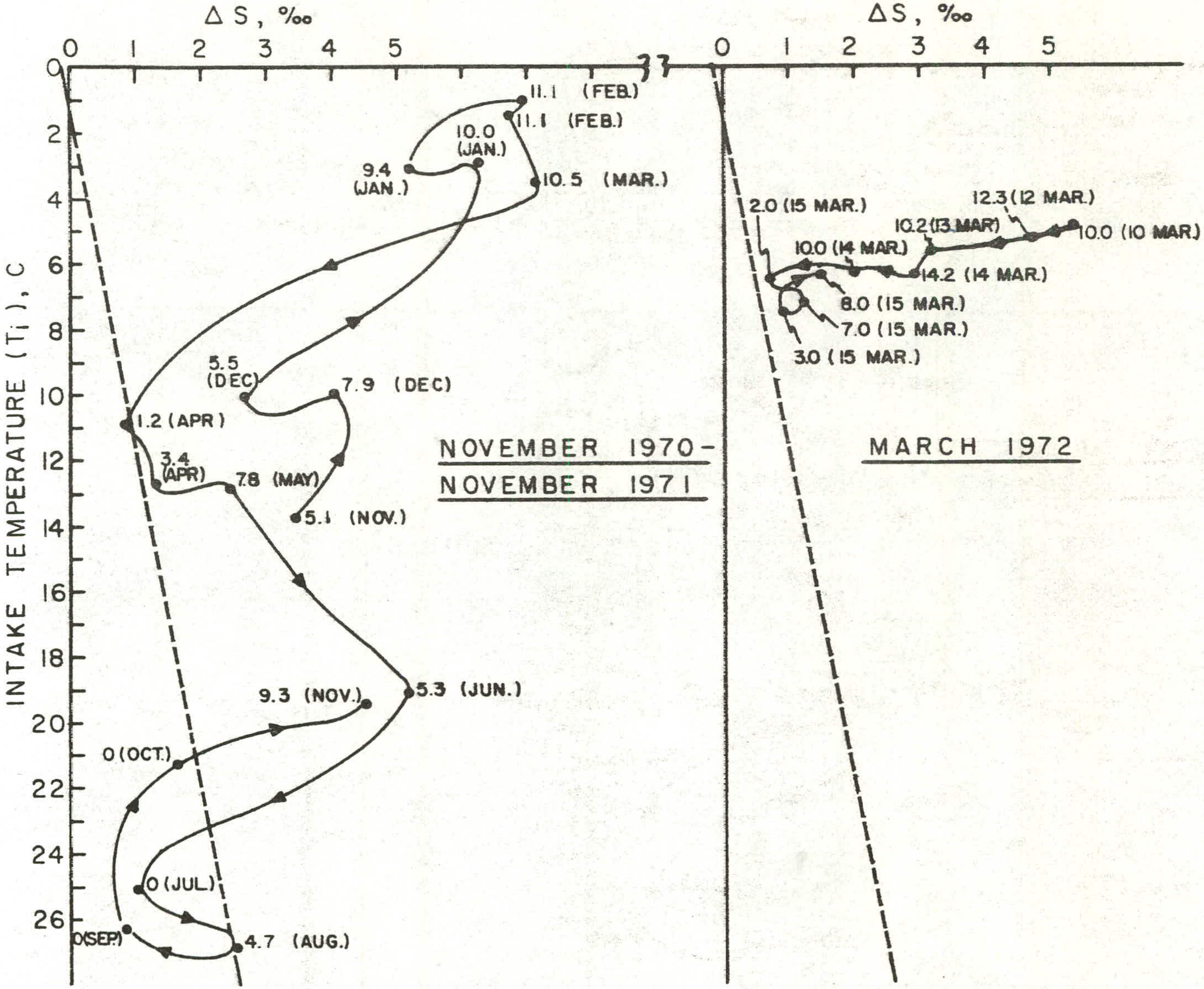


Figure 4. The salinity increase ΔS required to exactly offset the density decrease due to the temperature rise θ_o across the condensers for various intake temperatures T_i.

are heavier than the receiving waters at the surface and points to the left represent parcels that are lighter. The data points on the right-hand side of Figure 4 represent conditions that existed during the 1972 field study. To obtain these points, the actual intake temperatures and salinities were compared with surface conditions, i.e., temperature and salinity, at the deep station closest to the point of discharge. On the other hand, the data points on the left-hand side of Figure 4 were obtained by treating data retrieved from the CBI data bank for Station P-40 which is located just south of the US 301 Highway Bridge. Intake temperatures and salinities were estimated from the station data by the following formulae:

$$\text{Estimated Intake Temperature} = \frac{T_{10M} + 3 \cdot T_{12M} + T_{14M}}{5}$$

$$\text{Estimated Intake Salinity} = \frac{S_{10M} + 3 \cdot S_{12M} + S_{14M}}{5}$$

where the subscripts indicate depth in meters. These estimated intake temperatures and salinities were then compared with surface conditions at the same station. In addition to the foregoing, the discharge density (or estimated discharge density from P-40) was computed and compared with the vertical distribution of density at the closest deep station (or P-40). The depth in meters at which the two were equal is shown alongside each plotted point in Figure 4 together with the appropriate month or day of observation.

Data points on the left side of Figure 4 are suggestive of an annual cycle of submergence with the plumes tending to surface in the spring and fall. On the other hand, it is not clear from an examination of the data points on the right side of Figure 4 whether their trend is part of the annual cycle or is a shorter period cycle (of the order of a few days) superimposed on the longer period oscillation shown on the left. In any event, it is clear that this tendency to intermittent submergence is a very effective mechanism for enhancing vertical mixing. That is, when the plume submerges navifacial reflections are reduced with vertical mixing now taking place around the entire periphery of the plume. A two-fold increase in dilution is possible as a result. In addition, the plume is being diluted by deeper and hence cooler water which results in a lower overall temperature distribution in the system.

Because of our inability to simulate a submerging plume (a simulation of flow rate, Q_c, as well as density is required) during the preoperational field study, the results of the two field studies should not be viewed as a prediction and verification of the same phenomenon but rather as separate determinations of two different phenomena, i.e., a surface plume and a submerged plume. The 1969 results should be considered as indicative of conditions when the plume is buoyant and the 1972 results as indicative of conditions when the plume sinks. They are directly comparable only in the sense that together they set limits on the distribution of excess temperature that might be observed on any given occasion.

II. The Morgantown Generating Station.

The Morgantown generating station is a conventional plant utilizing fossil fuel. There are two turbine-generators, Unit No. 1 with a rated generator capacity of 572.9 MWe and Unit No. 2 with a rated generator capacity of 575.17 MWe. The cooling water arrangement was shown previously in Figures 2 and 3. As shown there are three circulating water pumps for each unit with a rated capacity of 167,000 gpm each for a total per unit of 501,000 gpm (1116.16 cfs). There is also a supplemental cooling water pump for each unit rated at 325,000 gpm. The design net plant heat rate is 8600 BTU/kwh for a designed temperature rise across the condensers at full power of 9.2°F. Intake velocities range from 0.16 fs^{-1} with one unit on line and no cooling water augmentation to 0.52 fs^{-1} with both units operating and full augmentation. Travel times between the intake pumps and the discharge orifice range from 42.5 minutes to 128.33 minutes depending on the combination of circulating and augmentation pumps. The discharge orifice, described previously, is adjustable in width so as to maintain a discharge velocity of between 8 and 9 fs^{-1}.

During the 1969 field study, the plant was under construction; during the 1972 field study, both units were in operation continuously although not at rated generation at all times. A constant amount of cooling water was being circulated during this period, however, so that the temperature rise across the condensers, θ_0, was a direct measure of the power being generated. Generation, as indicated by θ_0, for the period 0100, 27 February 1972 to 2300, 15 March 1972 is shown in Figure 5. It may be seen from Figure 5 that except for part of 8 March 1972, both units were operating at essentially rated capacity during the dye tracer study (0805, 2 March 1972 to 1407, 15 March 1972). Because of the season, there was no flow augmentation during our 1972 study.

III. The 1969 Field Experiment (Preoperational).

Ideally we would like to know the time history of tracer or excess temperature at every point in the estuary where measurable values occur. Practically however, this is difficult to achieve in a tidal estuary because of temporal and spatial variations in the velocity field related

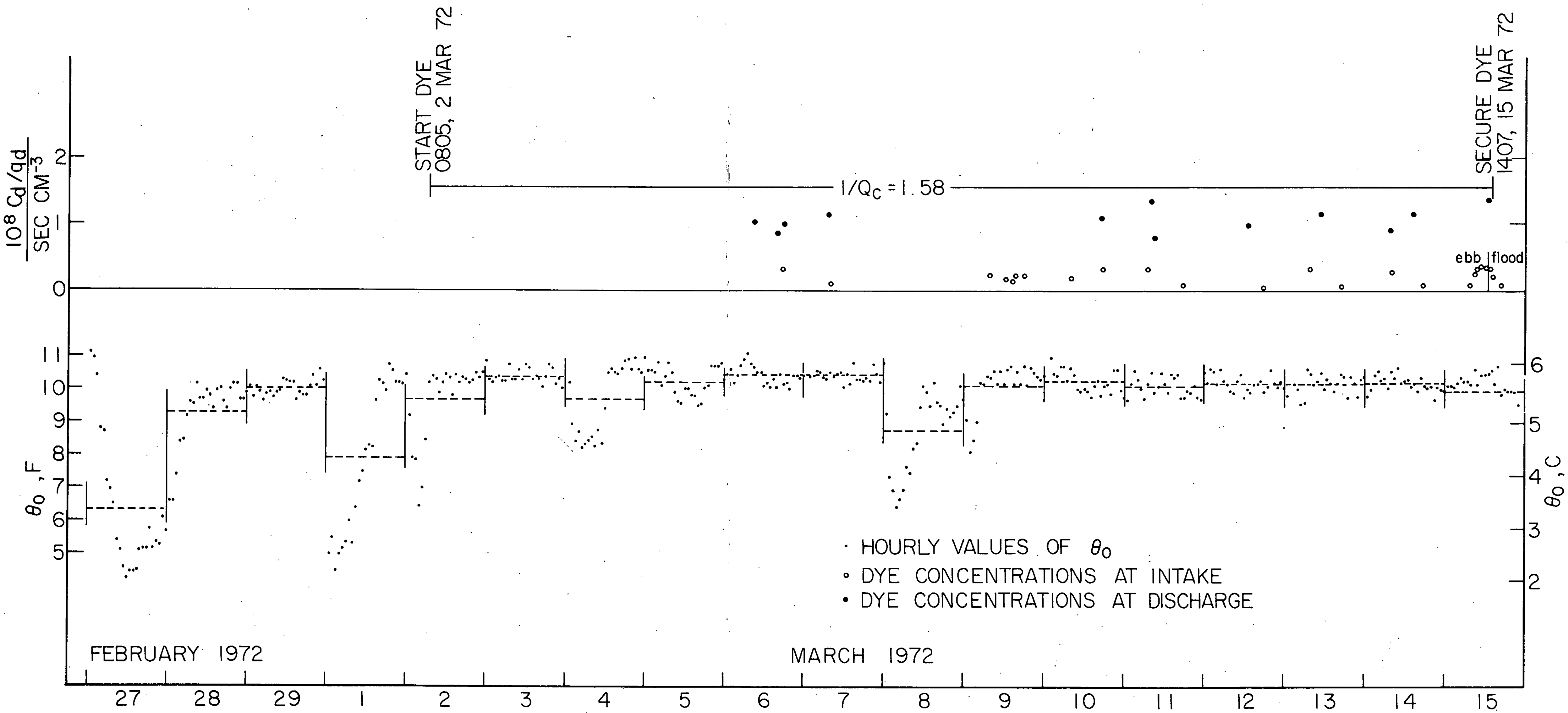


FIGURE 5. HOURLY VALUES OF θ_0, THE TEMPERATURE RISE ACROSS THE CONDENSERS, DURING THE 1972 STUDY.

to the astronomical tides. That is the concentration or excess temperature of a small parcel of water at a given point and time is highly dependent on the phase of the tidal current that prevailed at the time the parcel was in the vicinity of the source or discharge and on the time that has elapsed since then. A qualitative description of the functional dependence of concentration or excess temperature on tidal phase was given in Carter (1968) and will not be repeated here. It suffices to say that any attempt to sample a significant portion of a tidal estuary with one or two sampling vessels must provide for elimination of the bias which will result from combining data taken at different places and tidal phases. In our view, the only practical way to accomplish this is to sample repeatedly over a full tidal cycle both laterally and vertically at a single section. This process is then repeated at a sufficient number of sections both up- and downstream from the source or discharge to delineate the field of tracer or excess temperature. Since it is only possible to sample one section a day with two sampling boats by this method, longer period changes in wind, river flow, tidal currents, and plant loading (for measurements of excess temperature) will require consideration when comparing results from one section to another. However, since these parameters are continually changing in a natural system, a realization (if possible) of the complete field of tracer or excess temperature in one tidal cycle is probably no more typical of the system than a series of sections taken over a week or 10 days. This comment may not apply to effects of seasonal changes in these parameters. Their significance must be quantitated by repeating the entire experiment, for example, during the spring freshets and in the fall when the river flow is low.

a. The Experiment.

The R/V MAURY was anchored bow and stern at the approximate location of the end of the proposed discharge canal. This location is labelled (S) in Figures 6 and 7. Dye solution was dispensed from a location on the stern of the MAURY as follows. A 30% solution of Rhodamine B was metered into a flow of 4 gpm of surface water at the rate of 32.53 pounds of solution per day. This combination was then discharged through an ordinary 8" diameter garden spray at a depth of one foot. The solution was dispensed in this manner so as to facilitate its simulation in the physical model at the Alden Research Laboratories should this prove to be desirable at some time in the future. Pumping was commenced at 1600, 5 June 1969 and was secured at 1005, 20 June 1969.

Hourly vertical casts at 2 meter intervals were made from the R/V MAURY during the study for temperature, conductivity, and velocity. Temperature and conductivity were measured by ICTI (Schiemer and Pritchard, 1961) and velocity by current drags (Pritchard and Burt, 1951). As an additional aid in interpreting the data, two Braincon Type 316 Histogram current meters and two Braincon Type 381 Histogram current meters were installed at the position shown on Figures 6 and 7 at depths of 2, 6, 12, and 18 meters. A recording tide gauge was also installed at a small dock on the east side of the river just underneath the US 301 Highway Bridge.

The dye sampling program was carried out with two boats, the TRACER a 20' Alim V-20, and the LYDIA LOUISE II, a 40' Chesapeake Bay Cabin Cruiser. In general, the TRACER made repeated crossings over a tidal cycle at a given section while the LL-II made vertical casts at the same section.

On the TRACER, temperature and dye concentration (fluorescence) were sampled laterally by continuous underway sampling at 0.6 meters depth.

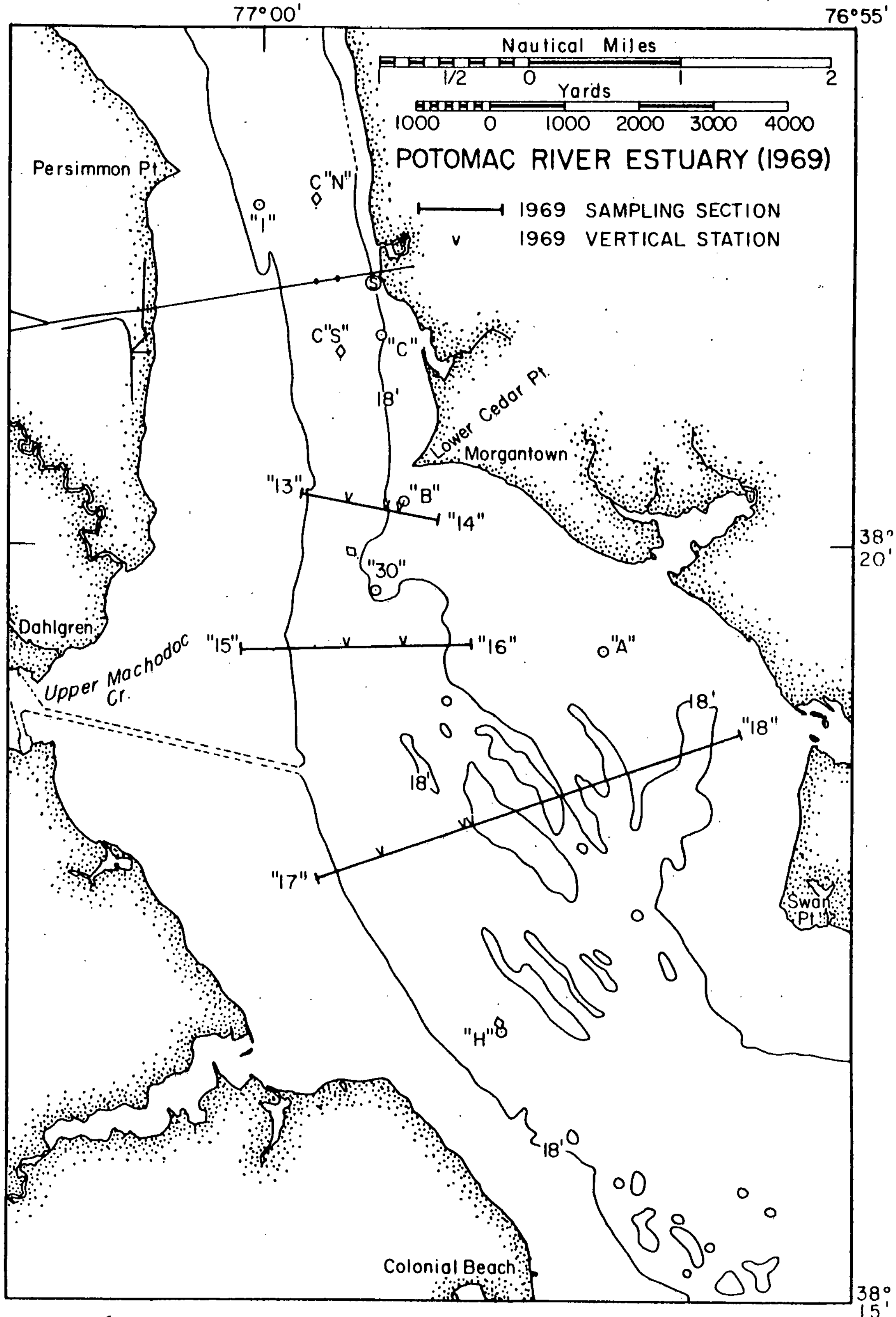


Figure 6. Chart of the Potomac River showing the location of the downstream sampling sections and tracer source (1969).

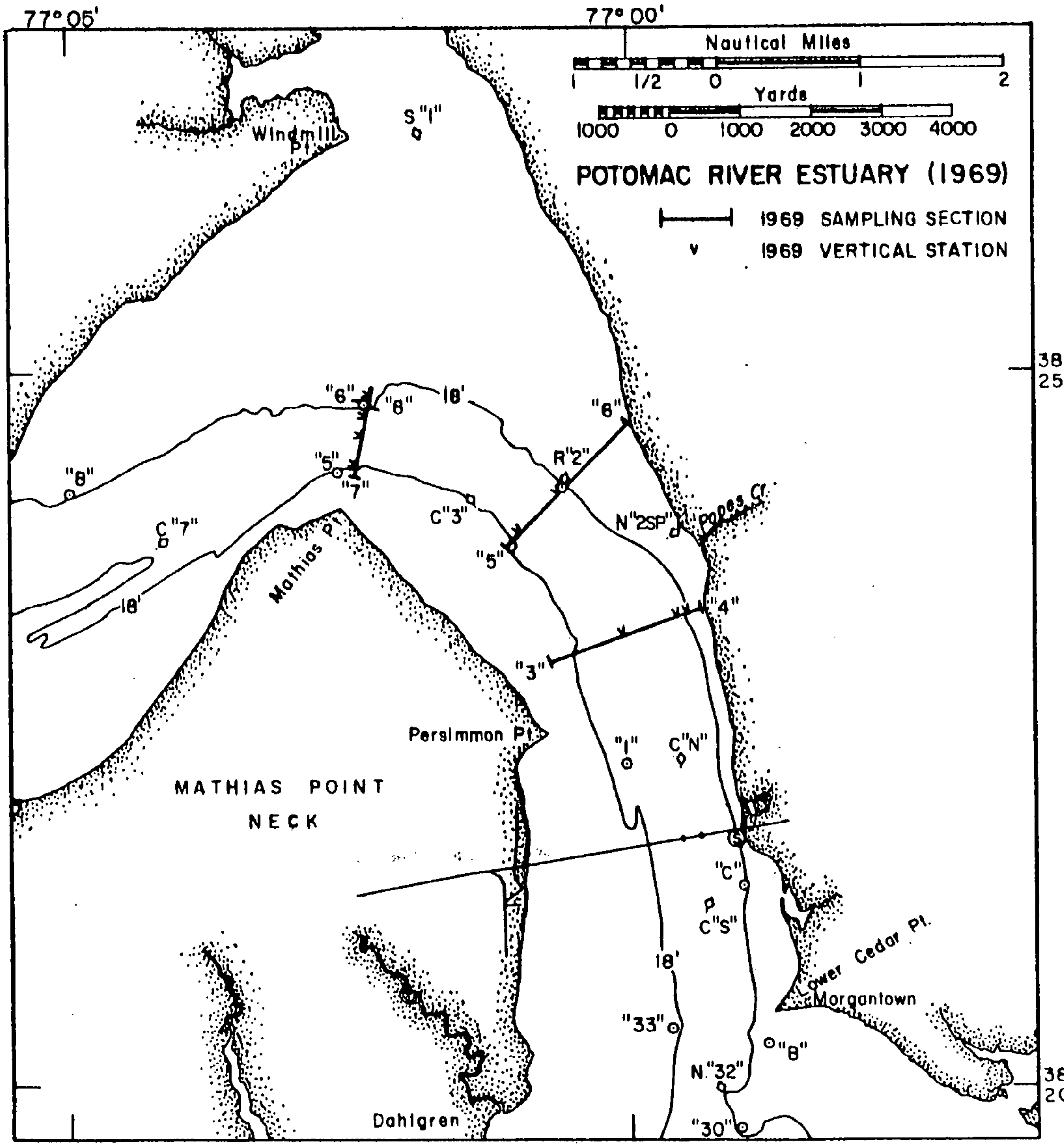


Figure 7. Chart of the Potomac River showing the location of the upstream sampling sections and tracer source (1969).

The continuous underway samples were drawn by pumping from the intake through a Model 111 Turner Fluorometer, a flow cell, the pump, and thence over the side. One-half inch clear polyethylene (poly-flo) tubing was used for all piping. Temperature was monitored continuously in the flow cell by a PTI (Schiemer, 1962) and recorded on a YSI Model 80 Laboratory Recorder. The intake was at the bottom, forward edge of an aluminum faired strut mounted vertically about one foot from the side of the port quarter of the sampling boat. The strut was mounted so that it could swing in a short arc about a vertical axis approximately one foot forward of the strut thus minimizing lateral forces.

On the LYDIA LOUISE II, vertical casts for temperature, dye concentration, and conductivity were made by lowering poly-flo tubing to the desired depth and pumping water through the fluorometer, the ICTI flow cell, and the pump in series. Difficulty was experienced with the ICTI on occasion, however, and measurements of conductivity are lacking at many vertical casts.

The field program commenced on 3 June 1969 and ended on 20 June 1969.

b. Results.

During the 1969 study we sampled 3 sections downstream (13-14, 15-16, and 17-18) from the proposed discharge canal and 3 sections upstream (3-4, 5-6, and 7-8). The locations of these sections are shown on Figures 6 and 7. Our results are presented in *three* types of figures. First of all, we have shown the time history of the maximum surface (0.6 meters) tracer concentration (scaled to excess temperature for two units at rated generating capacity($\approx$ 1148 MWe)) at a particular section. In order to combine data taken at the same section but on different days, the actual times of observation were referred to a reference time which was arrived at as follows. At the upstream sections located at distances from the discharge canal greater than a tidal excursion, the reference time ($\Delta T = 0$) was taken as the time of slack water before ebb (SBE). At comparable distances downstream from the discharge canal, the reference time used was the time of slack water before flood (SBF). When the section was within a tidal excursion from the discharge canal, both up- and downstream, all times were referred to the time of arrival of the temperature front at the section. Having thus determined the reference time, individual measurements of the maximum value of excess temperature were plotted as functions of time, ΔT, in accordance with the following relationship

$$\Delta T \equiv \text{time of observation} - \text{reference time}$$

Tracer concentrations were scaled to excess temperature according to the following relation

$$\theta = \left\{\frac{C}{q_d}\right\} \theta_0 Q_c \qquad (1)$$

where C is the tracer concentration,

q_d is the *dry* dye pumping rate,

θ_0 is the temperature rise across the condensers, and

Q_c is the flow rate of cooling water through the condensers.

In scaling the 1969 results, a Q_c of 2232.32 cfs and a θ_0 of 9.91°F were used.

Figures 8, 13, 16, 21, 24, and 27 show the surface excess temperature, θ, as a function of time (or tidal phase) referenced as described above for sections 3-4, 5-6, 7-8, 13-14, 15-16, and 17-18 respectively.

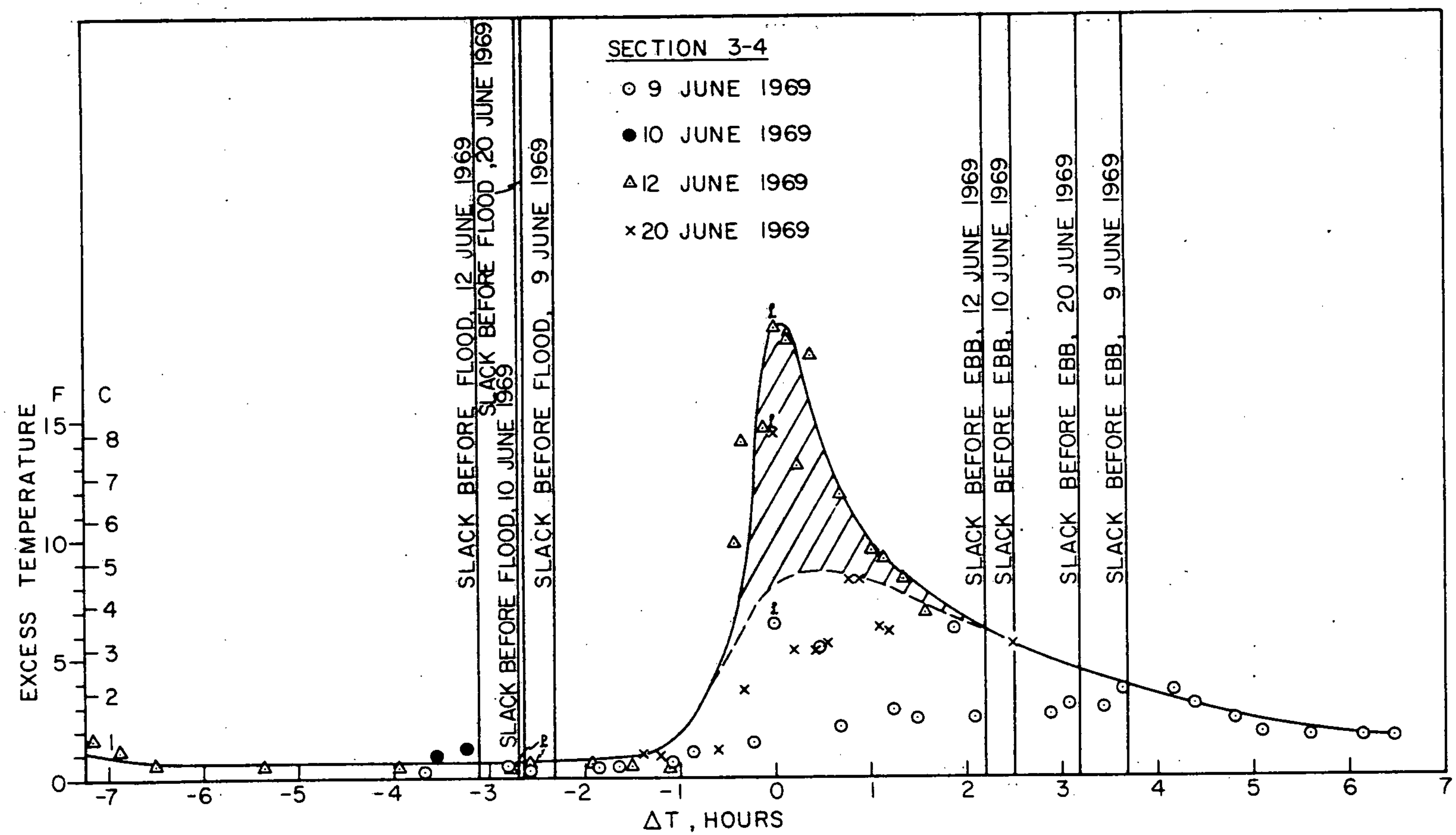
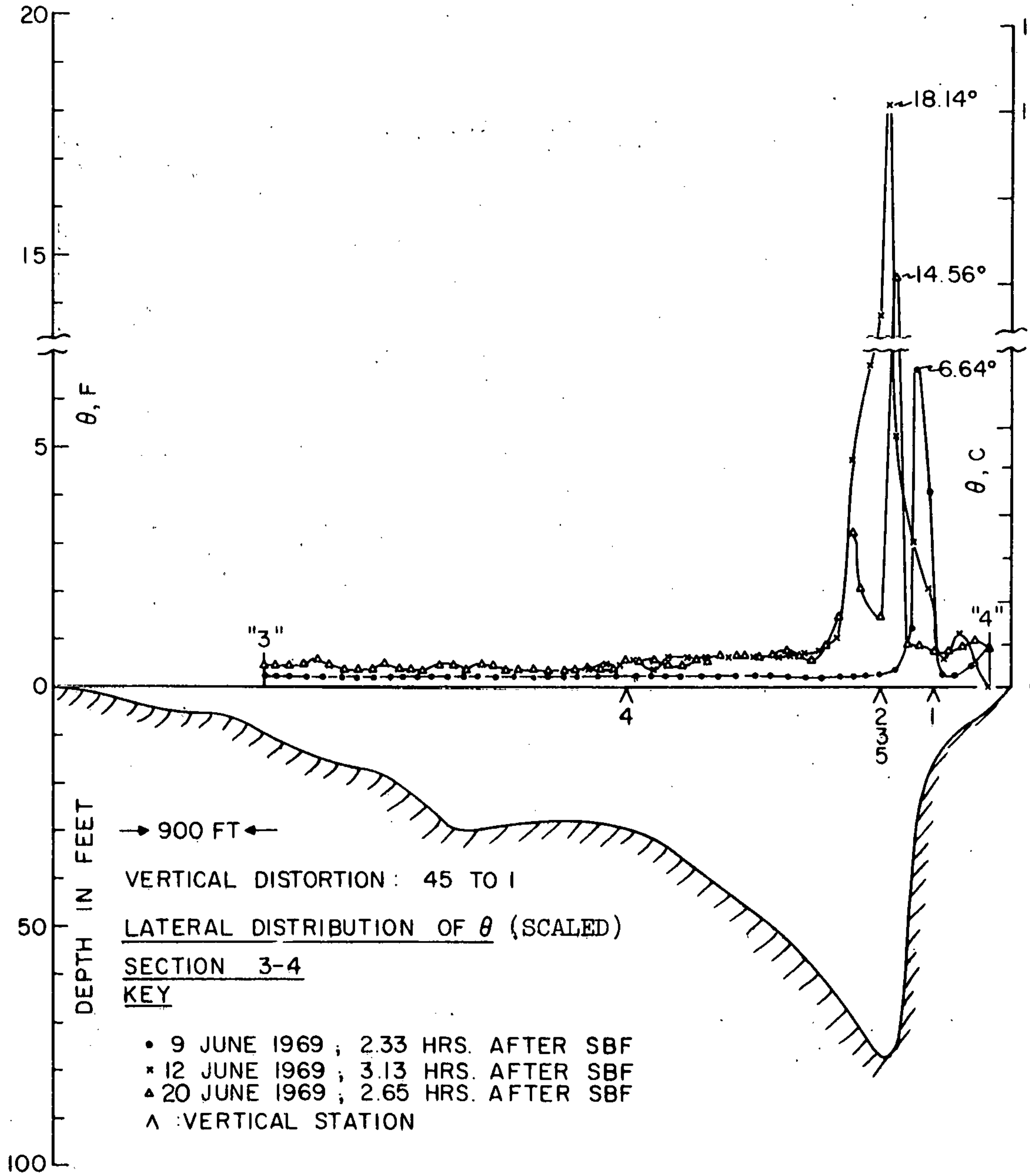


Figure 8. Excess temperature θ (scaled) as a function of time during flood tide at Section 3 - 4 upstream from the dye source.

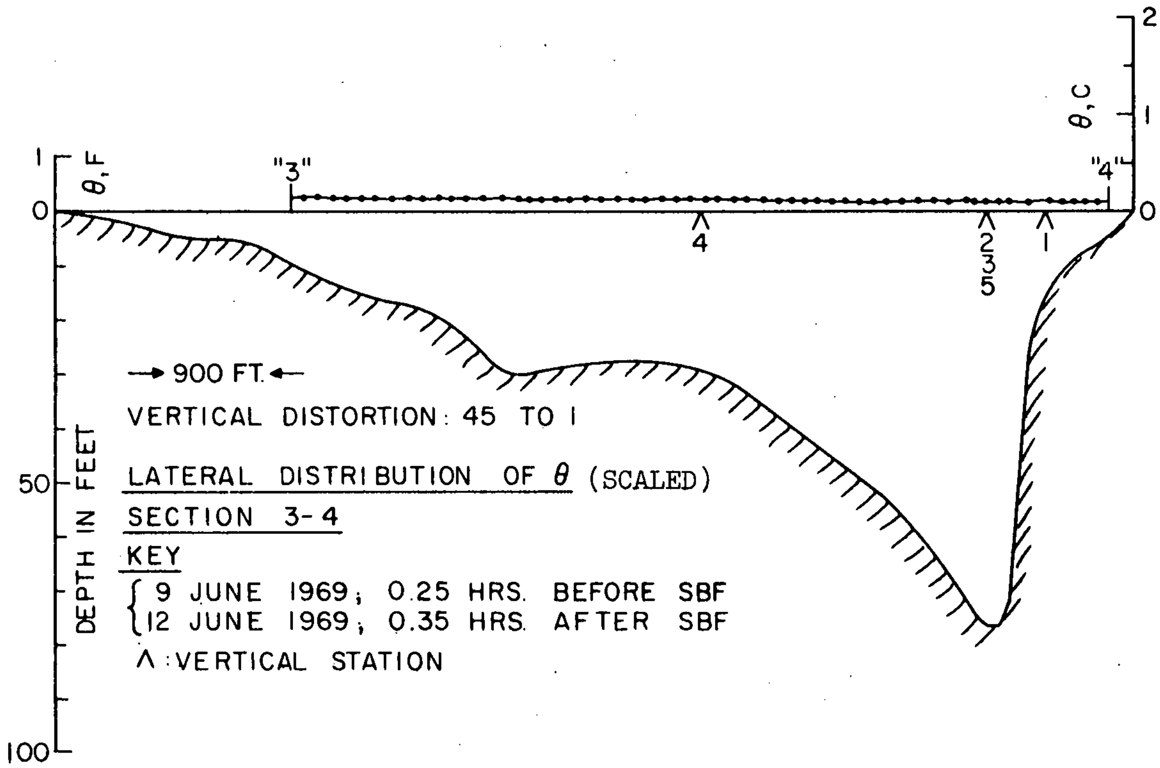
A second set of figures was prepared (one or two figures for each section) showing the lateral distribution of tracer concentration at the surface (scaled to excess temperature, θ) at or near the time when maximum values of excess temperature were measured($\Delta T = 0$) and at or near the time when minimum values were measured. All other realizations of the lateral distribution of θ during this study lie within these envelopes. Figures 9, 10, 14, 17, 18, 22, 25, and 28 show these maximum and minimum lateral distributions of excess temperature, θ. Also shown on these figures are the locations of the selected vertical casts shown in Figures 11, 12, 15, 19, 20, 23, 26, and 29. These figures (the third type) depict the vertical distribution of excess temperature, θ, at various locations along the section and at times corresponding to maximum and minimum conditions with respect to the excess temperature.

Results of the records obtained from the four current meters in place during this study are shown as progressive vector diagrams in Figures 30, 31, 32, and 33. It is not the intent of this report to analyze these records in any great amount of detail; it suffices to say that they show a pattern which is typical for tributary estuaries of the Chesapeake Bay, namely, net flow seaward in the upper layers and net flow toward the river in the lower layers. The record of tidal heights, not shown here, do not show any long-term trend in upstream storage or depletion of water for the period of record (1255, 2 June 1969 to 0606, 12 June 1969). The tidal range varied from 1.4 feet to 2.0 feet over the period of record with a mean range of 1.7 feet. The Tide Tables (1972) list a mean range of 1.6 feet and a spring range of 1.8 feet for Dahlgren, Virginia just across and down the river from the plant.



20
15
5
0
50
100
θ, F
θ, C
DEPTH IN FEET
11
10
9
8
3
2
1
0
~18.14°
~14.56°
~6.64°
"3"
"4"
4
2
3
5
1
→ 900 FT ←
VERTICAL DISTORTION: 45 TO 1
LATERAL DISTRIBUTION OF θ (SCALED)
SECTION 3-4
KEY
• 9 JUNE 1969 ; 2.33 HRS. AFTER SBF
× 12 JUNE 1969 ; 3.13 HRS. AFTER SBF
▵ 20 JUNE 1969 ; 2.65 HRS. AFTER SBF
Λ :VERTICAL STATION

Figure 9.



2
1
θ, C
θ, F
"3"
"4"
0
4
2
3
5
1
50
100
DEPTH IN FEET
→ 900 FT. ←
VERTICAL DISTORTION: 45 TO 1
LATERAL DISTRIBUTION OF θ (SCALED)
SECTION 3-4
KEY
{ 9 JUNE 1969; 0.25 HRS. BEFORE SBF
12 JUNE 1969; 0.35 HRS. AFTER SBF }
Λ : VERTICAL STATION

Figure 10.

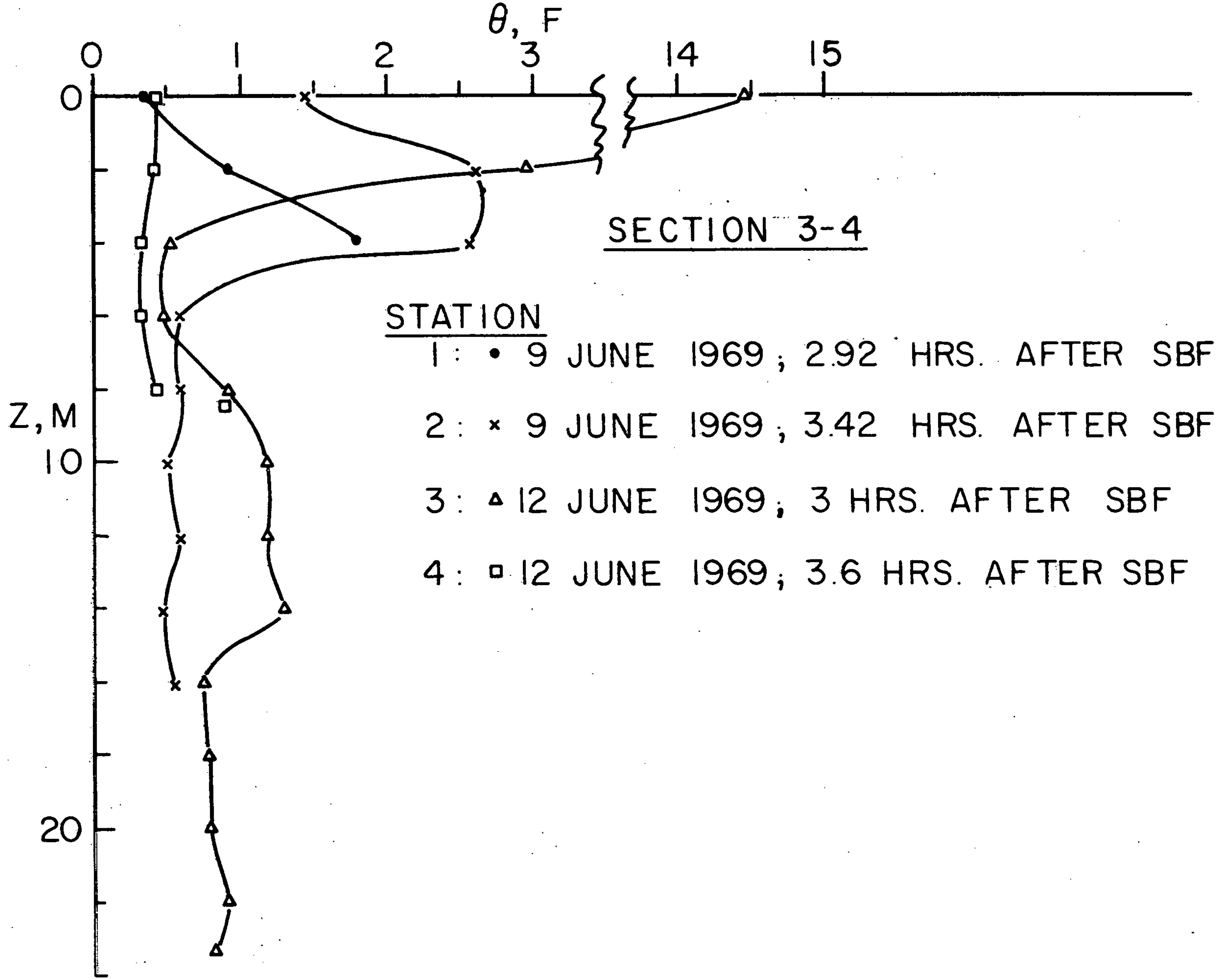


Figure 11. Vertical distribution of excess temperature θ (scaled) at Section 3 - 4 at various tidal phases. Station locations are shown on Figs. 9 and 10.

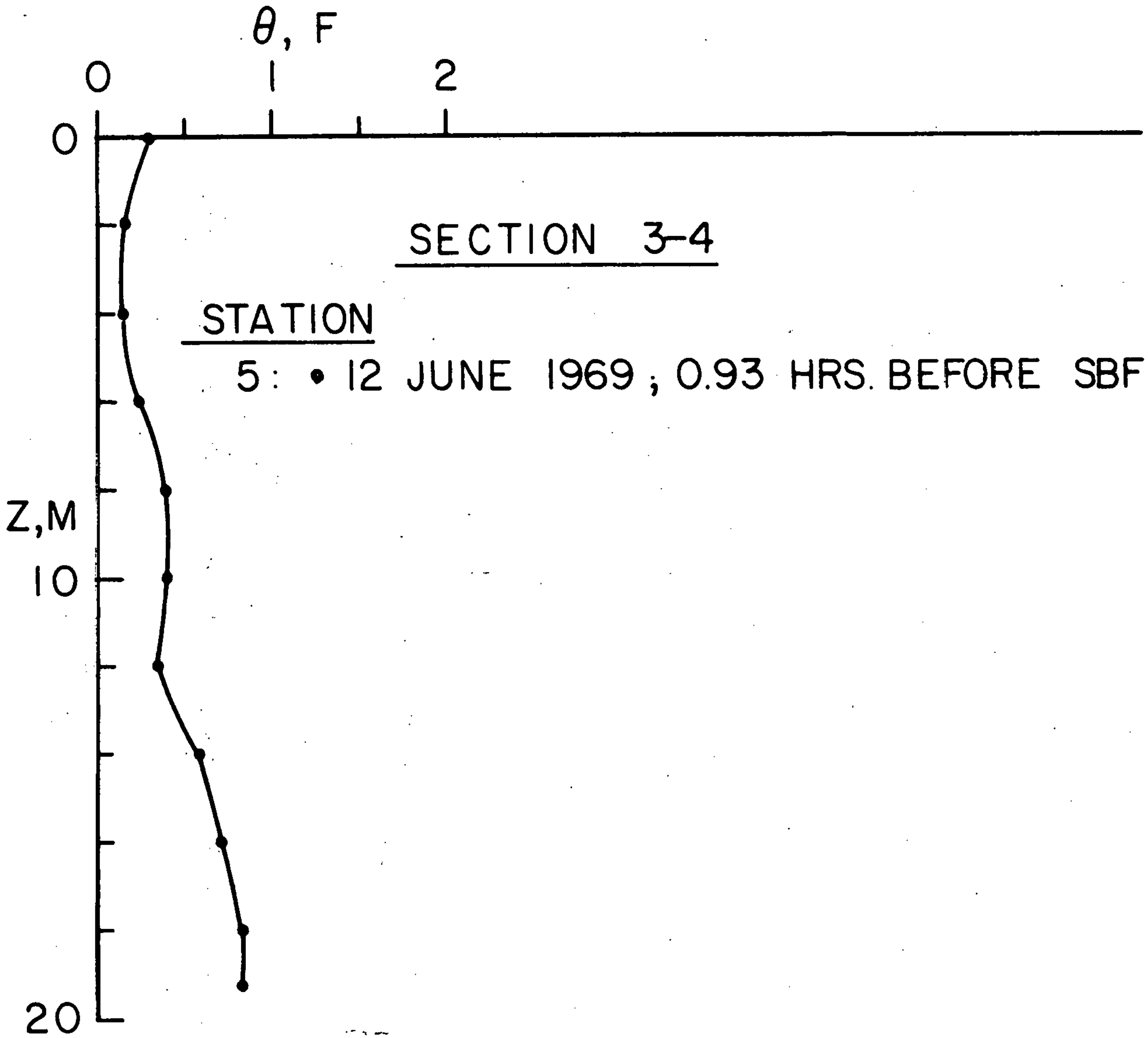


Figure 12. Vertical distribution of excess temperature θ (scaled) at Section 3 - 4 at various tidal phases. Station locations are shown on Figs. 9 and 10.

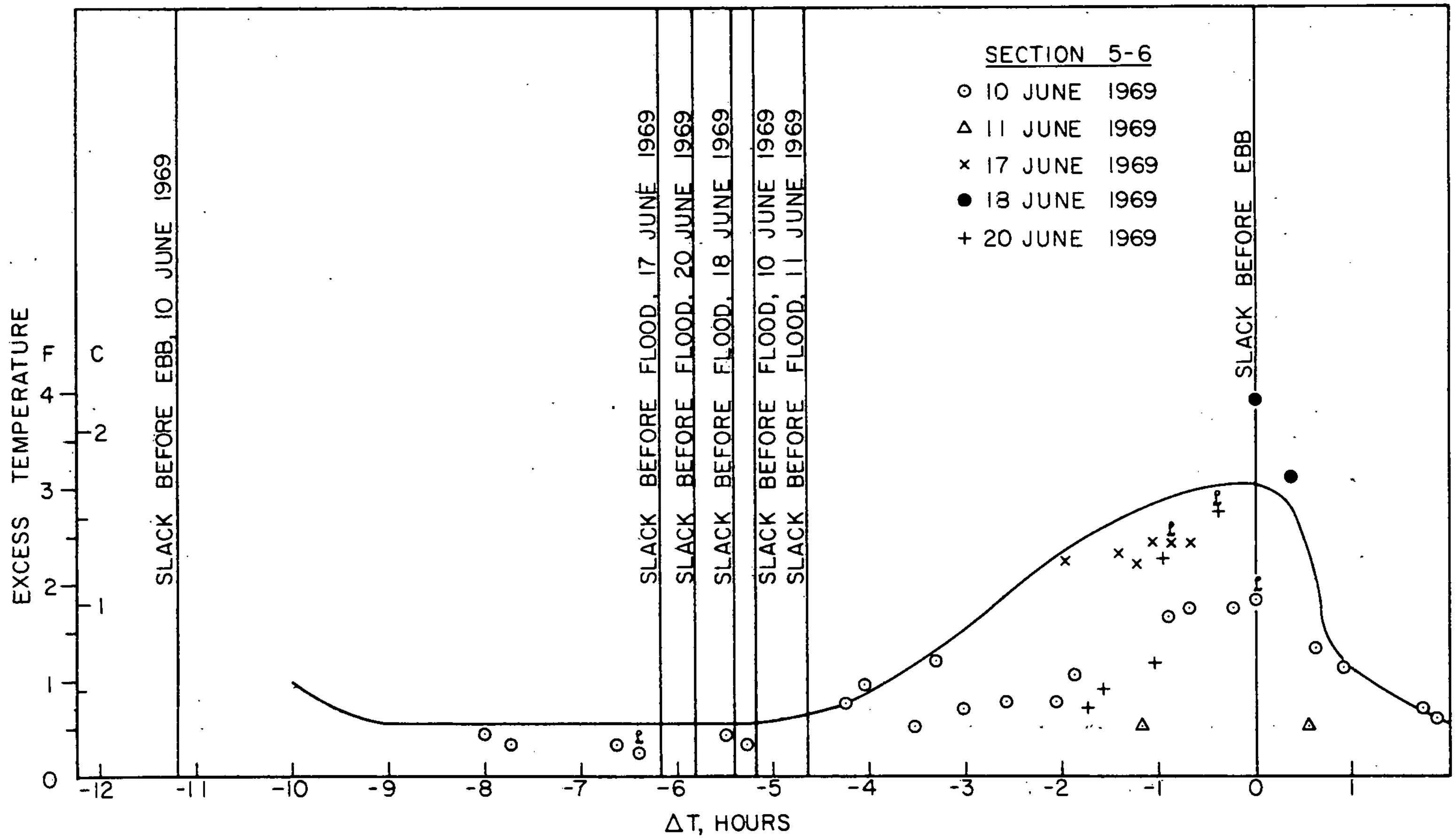


Figure 13. Excess temperature θ (scaled) as a function of time during flood tide at Section 5 - 6 upstream from the dye source.

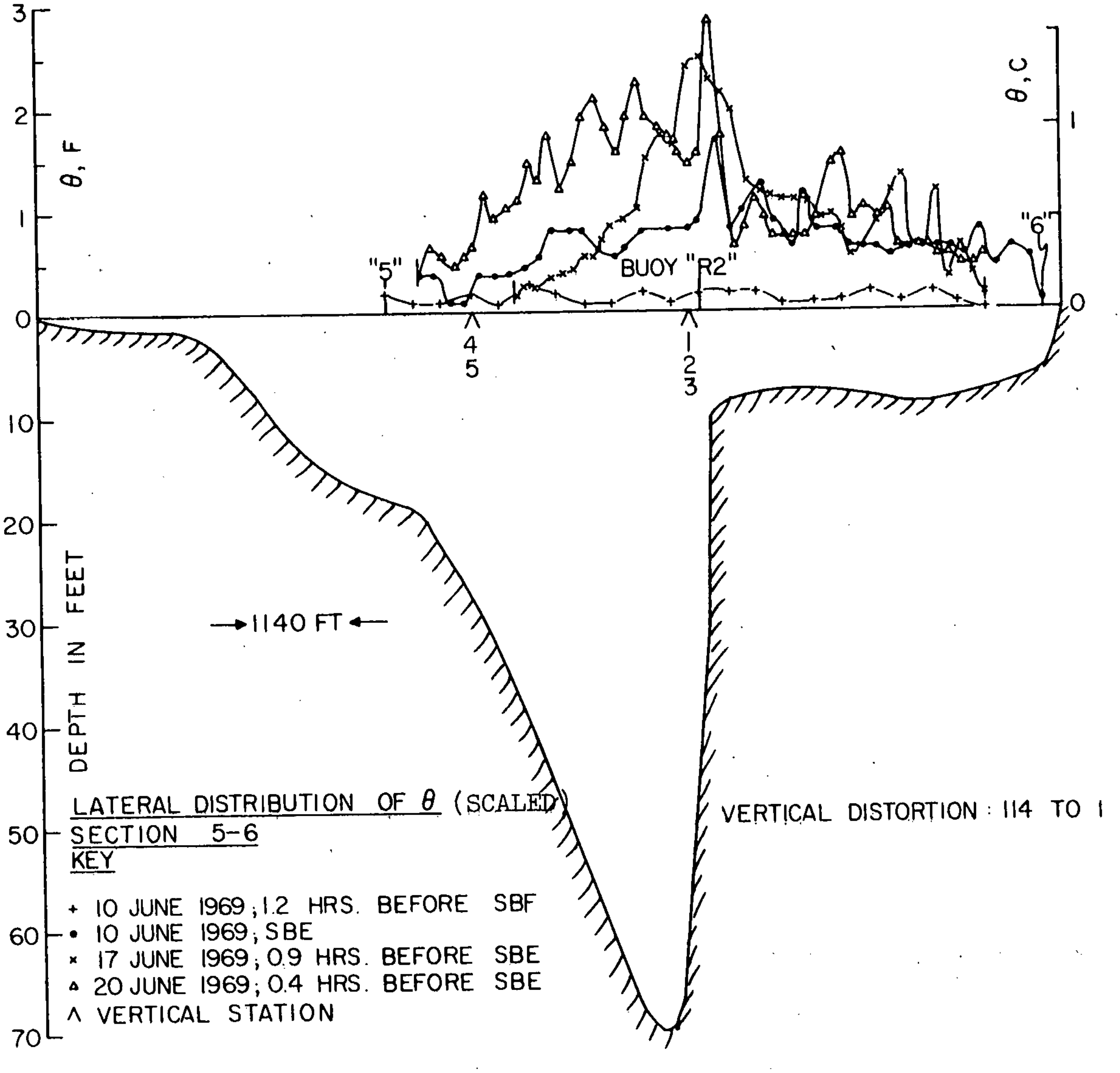

θ, F
θ, C
"5"
"6"
BUOY "R2"
4
5
1
2
3
DEPTH IN FEET
→1140 FT←
LATERAL DISTRIBUTION OF θ (SCALED)
SECTION 5-6
KEY
+ 10 JUNE 1969; 1.2 HRS. BEFORE SBF
• 10 JUNE 1969; SBE
× 17 JUNE 1969; 0.9 HRS. BEFORE SBE
△ 20 JUNE 1969; 0.4 HRS. BEFORE SBE
∧ VERTICAL STATION
VERTICAL DISTORTION : 114 TO 1

Figure 14.

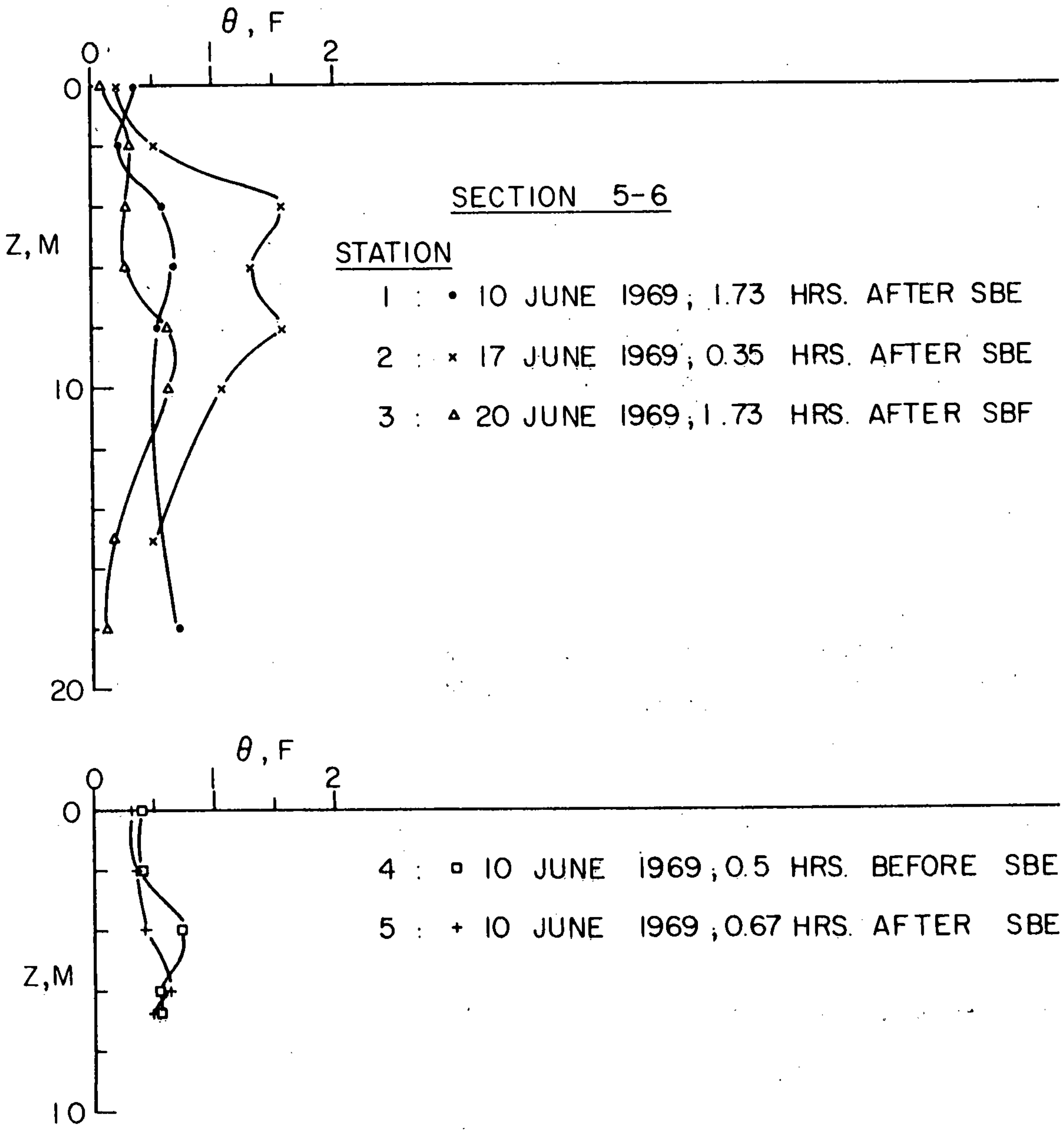


Figure 15. Vertical distribution of excess temperature θ (scaled) at Section 5 - 6 at various tidal phases. Station locations are shown on Fig. 14.

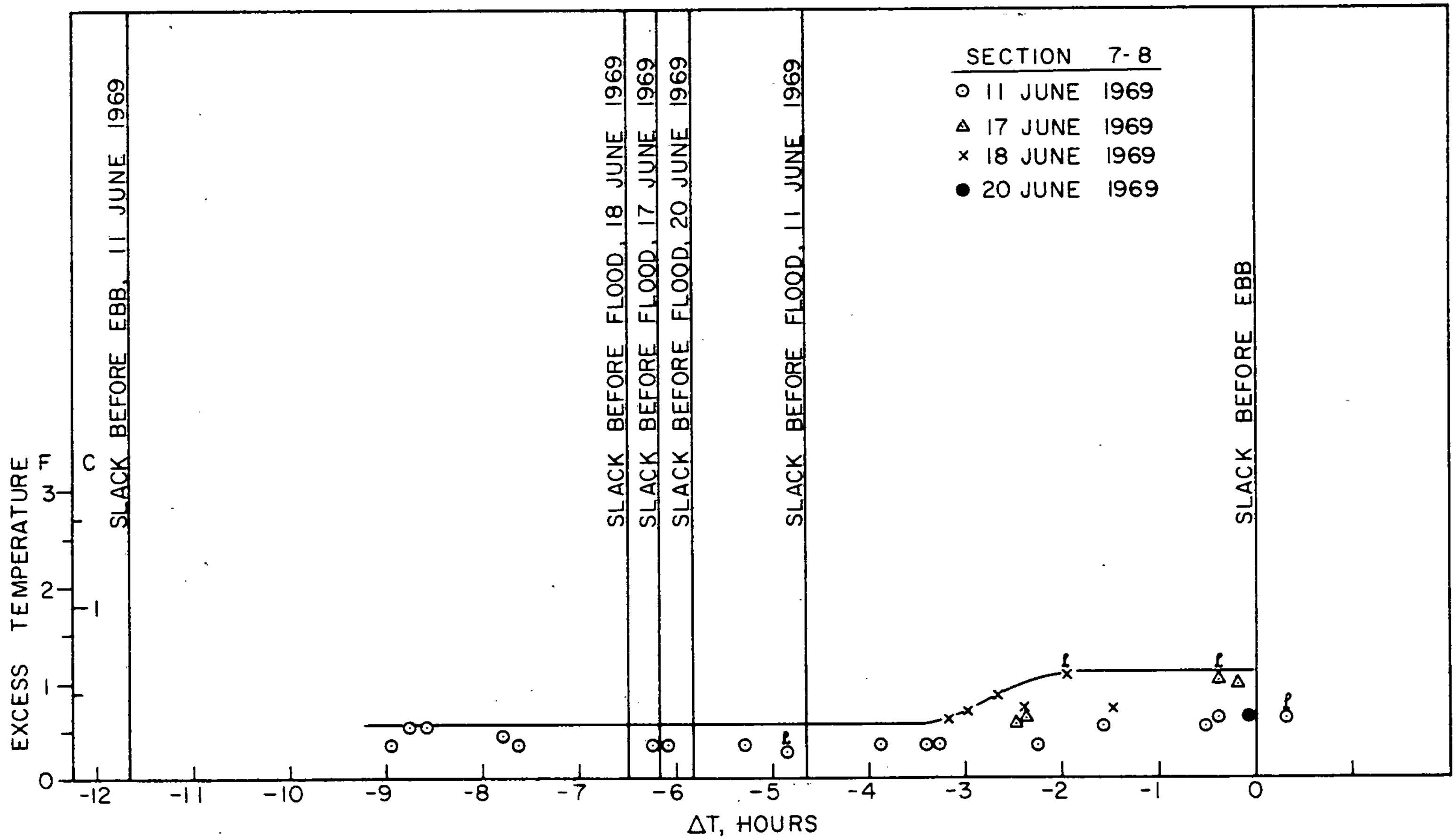


Figure 16. Excess temperature θ (scaled) as a function of time during flood tide at Section 7 - 8 upstream from the dye source.

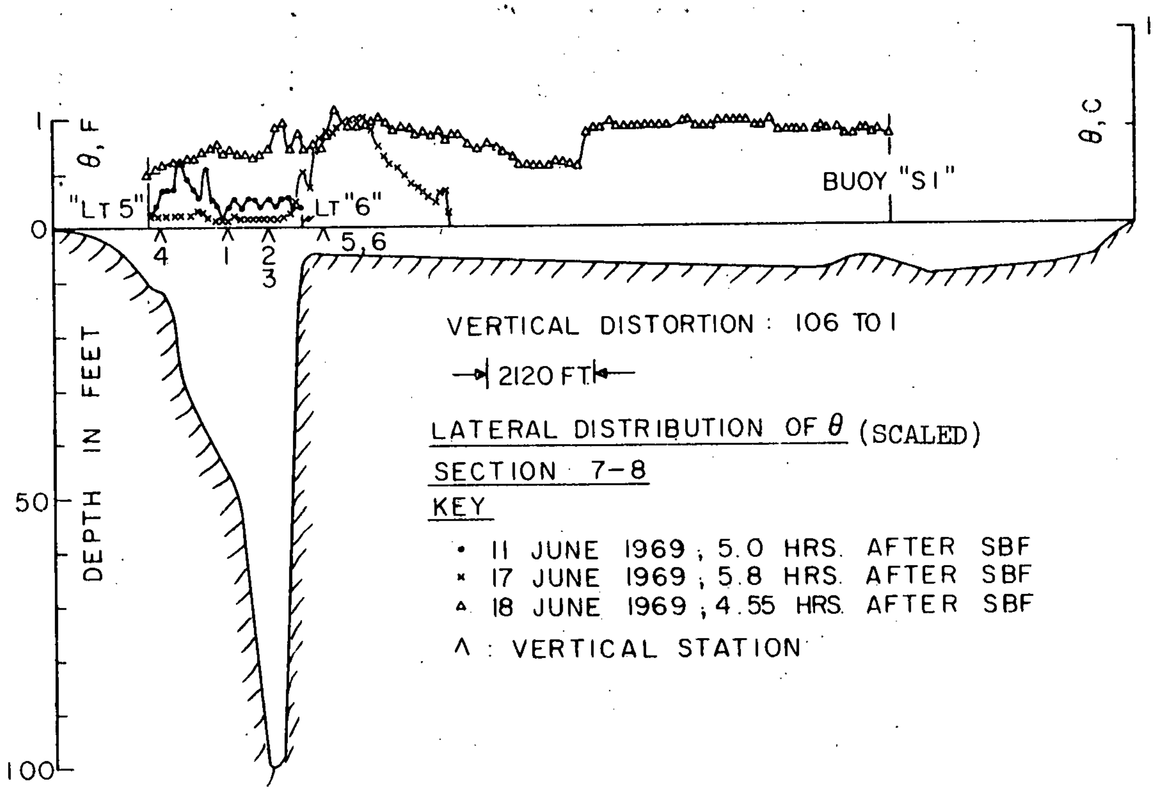
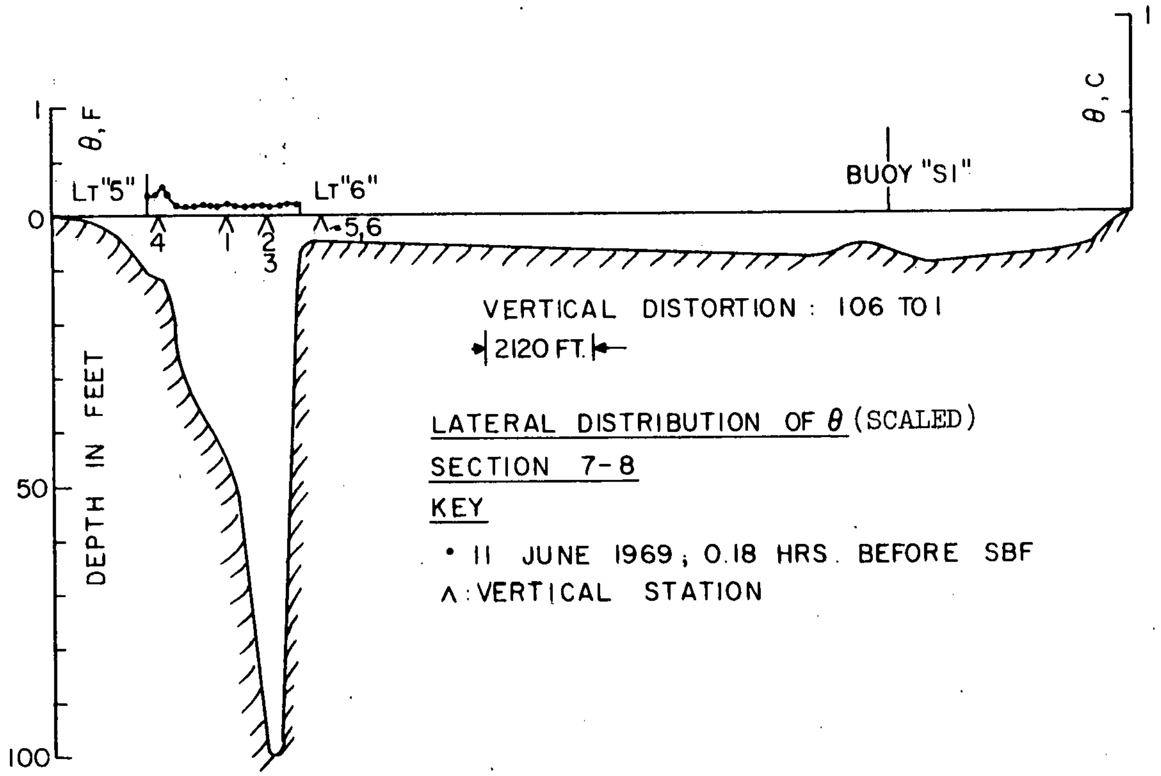

θ, F
θ, C
"LT 5"
LT "6"
BUOY "S1"
4
1
2
3
5, 6
0
50
100
DEPTH IN FEET
VERTICAL DISTORTION : 106 TO 1
2120 FT.
LATERAL DISTRIBUTION OF θ (SCALED)
SECTION 7-8
KEY
• 11 JUNE 1969 ; 5.0 HRS. AFTER SBF
× 17 JUNE 1969 ; 5.8 HRS. AFTER SBF
▵ 18 JUNE 1969 ; 4.55 HRS. AFTER SBF
∧ : VERTICAL STATION

Figure 17.



1
θ, F
0
50
100
DEPTH IN FEET
LT"5"
LT"6"
4
1
2
3
5,6
BUOY "S1"
θ, C
1
VERTICAL DISTORTION : 106 TO 1
2120 FT.
LATERAL DISTRIBUTION OF θ (SCALED)
SECTION 7-8
KEY
• 11 JUNE 1969; 0.18 HRS. BEFORE SBF
Λ : VERTICAL STATION

Figure 18.

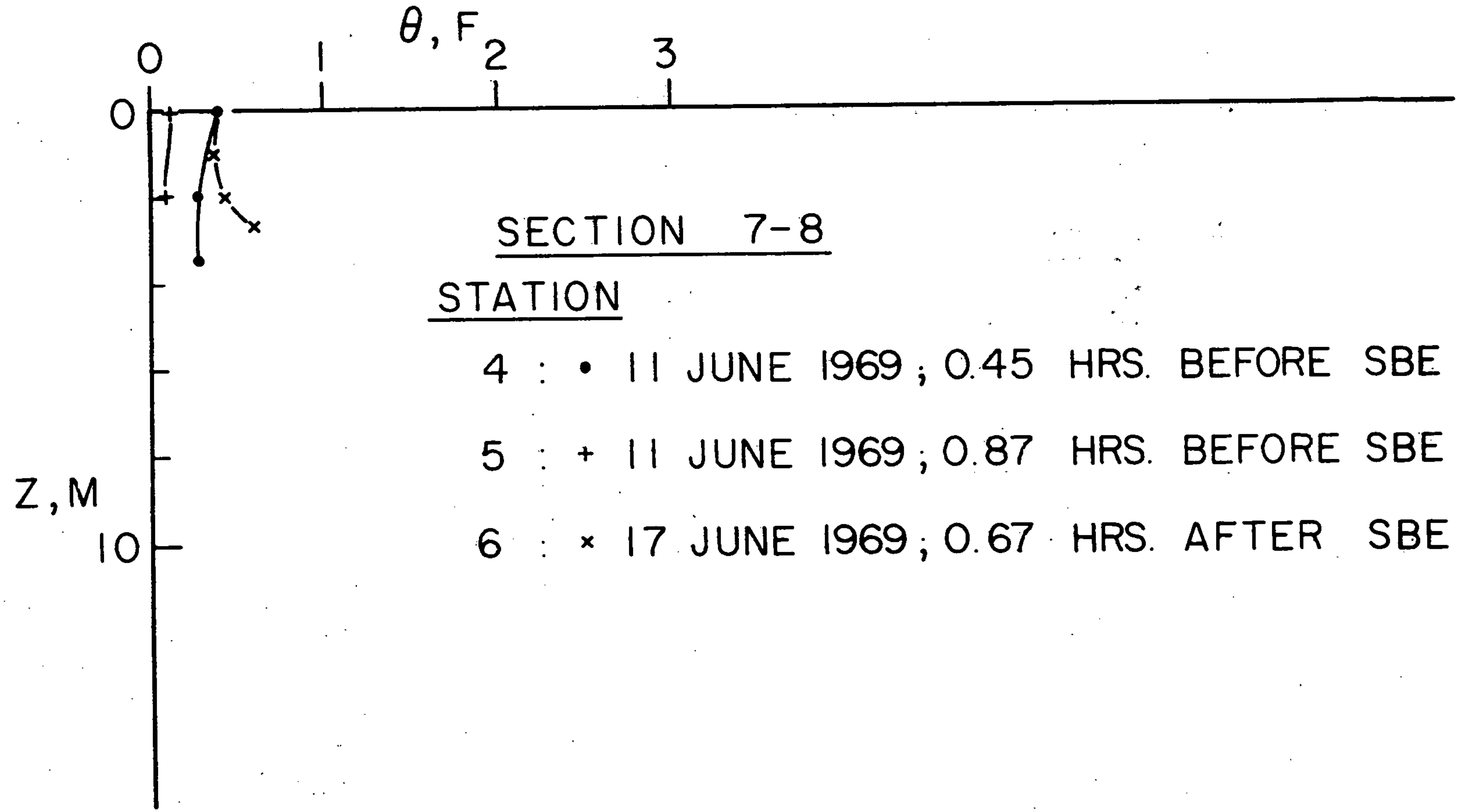


Figure 19. Vertical distribution of excess temperature θ (scaled) at Section 7 - 8 at various tidal phases. Station locations are shown on Figs. 17 and 18.

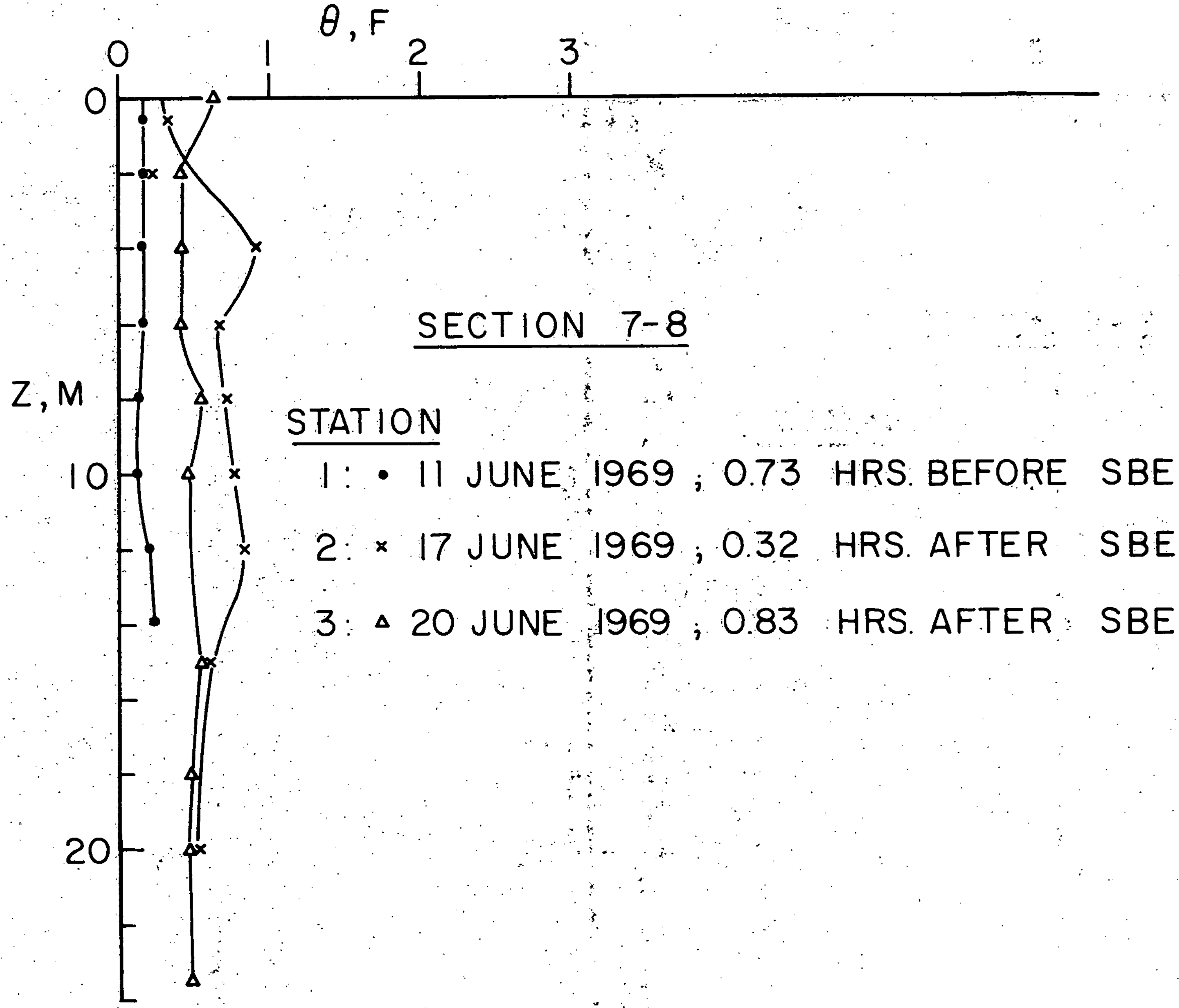


Figure 20. Vertical distribution of excess temperature θ (scaled) at Section 7 - 8 at various tidal phases. Station locations are shown on Figs. 17 and 18.

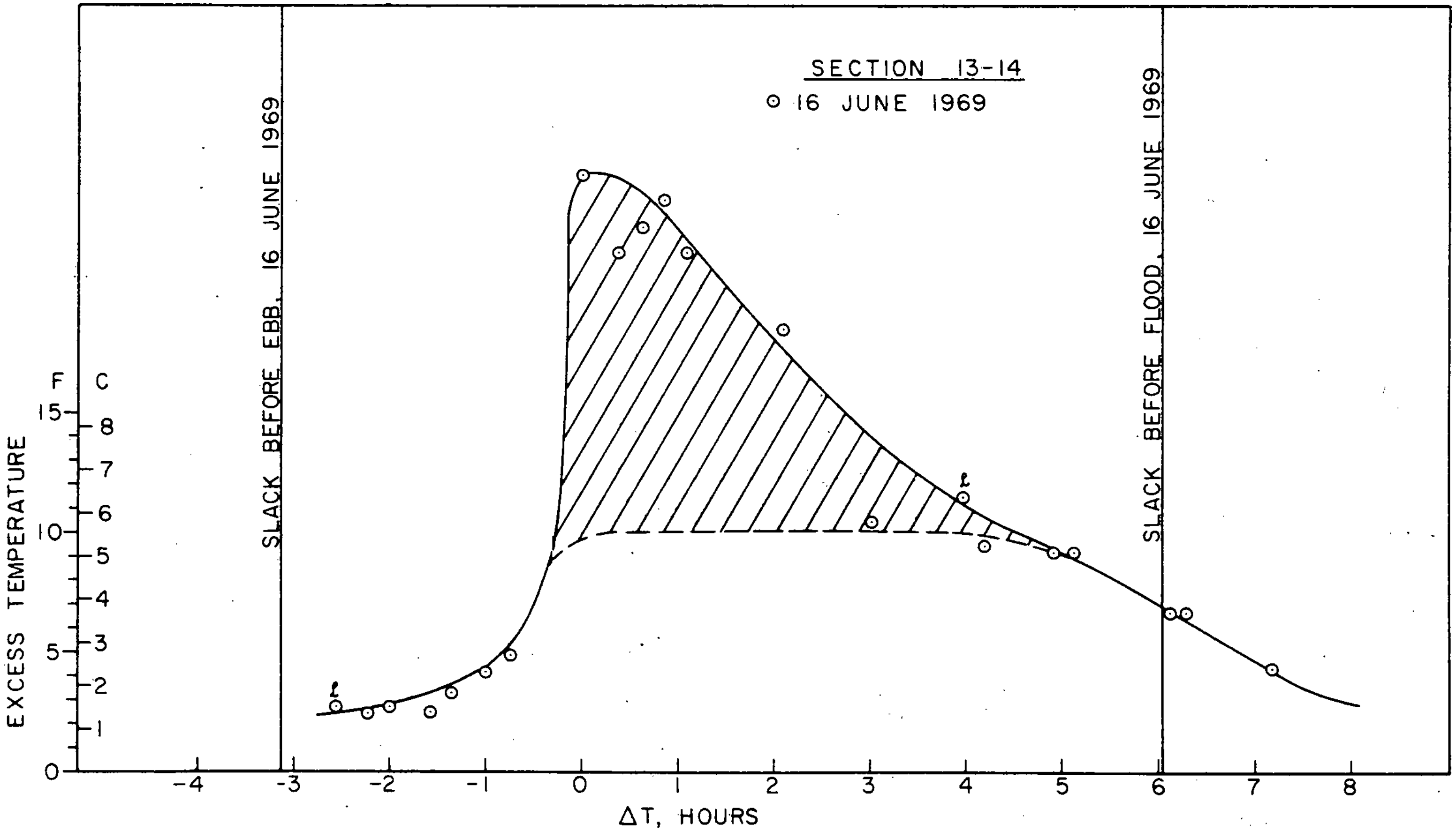
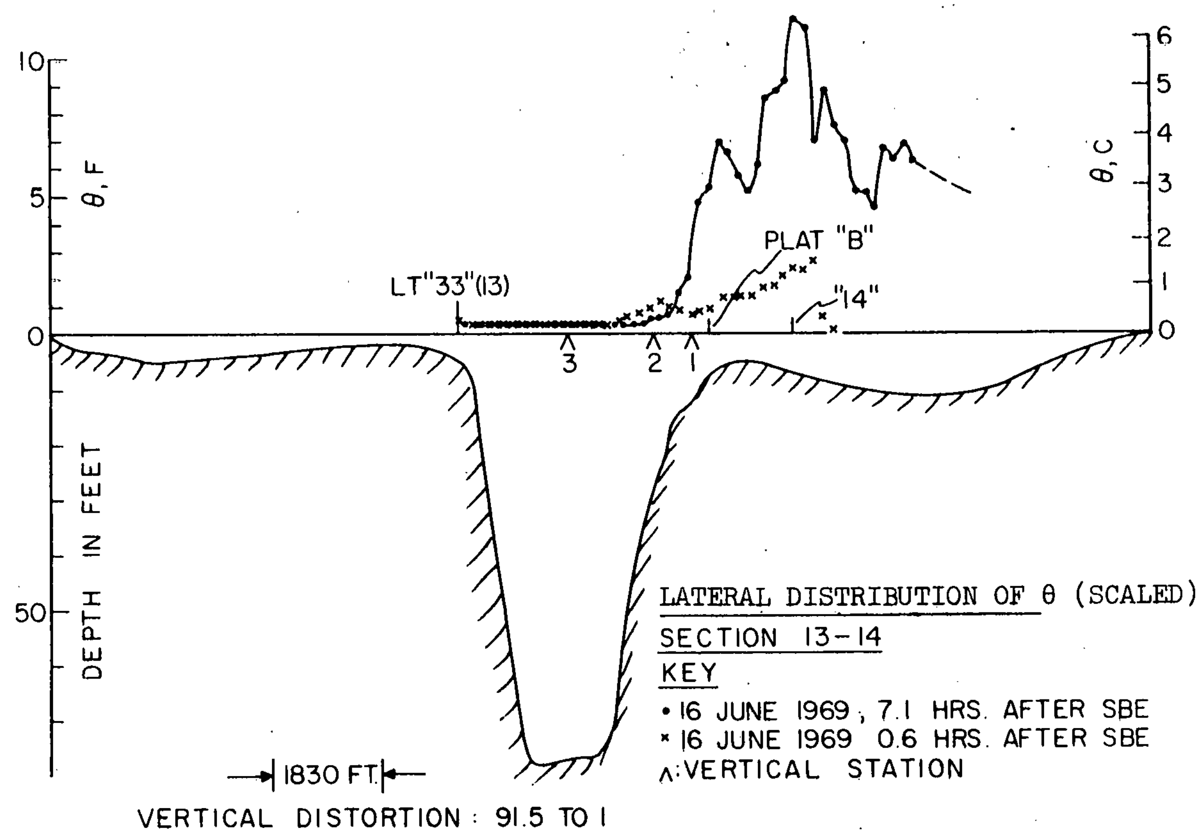


Figure 21. Excess temperature θ (scaled) as a function of time during ebb tide at Section 13 - 14 downstream from the dye source.



10
5
0
50
θ, F
DEPTH IN FEET
6
5
4
3
2
1
0
θ, C
LT"33"(13)
PLAT "B"
"14"
3
2
1
1830 FT.
VERTICAL DISTORTION : 91.5 TO 1
LATERAL DISTRIBUTION OF θ (SCALED)
SECTION 13-14
KEY
• 16 JUNE 1969 , 7.1 HRS. AFTER SBE
× 16 JUNE 1969 0.6 HRS. AFTER SBE
∧:VERTICAL STATION

Figure 22.

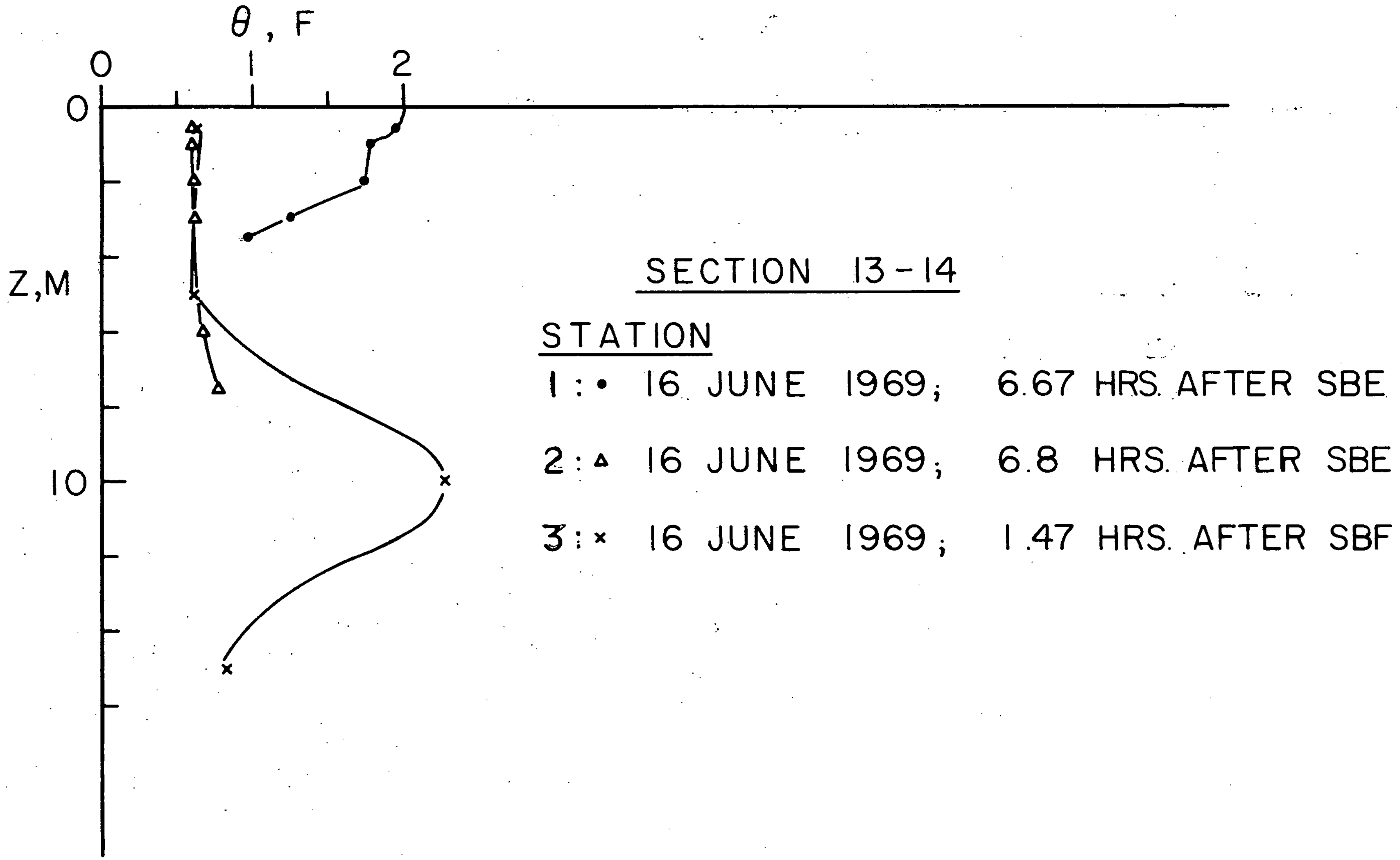


Figure 23. Vertical distribution of excess temperature θ (scaled) at Section 13 - 14 at various tidal phases. Station locations are shown on Fig. 22.

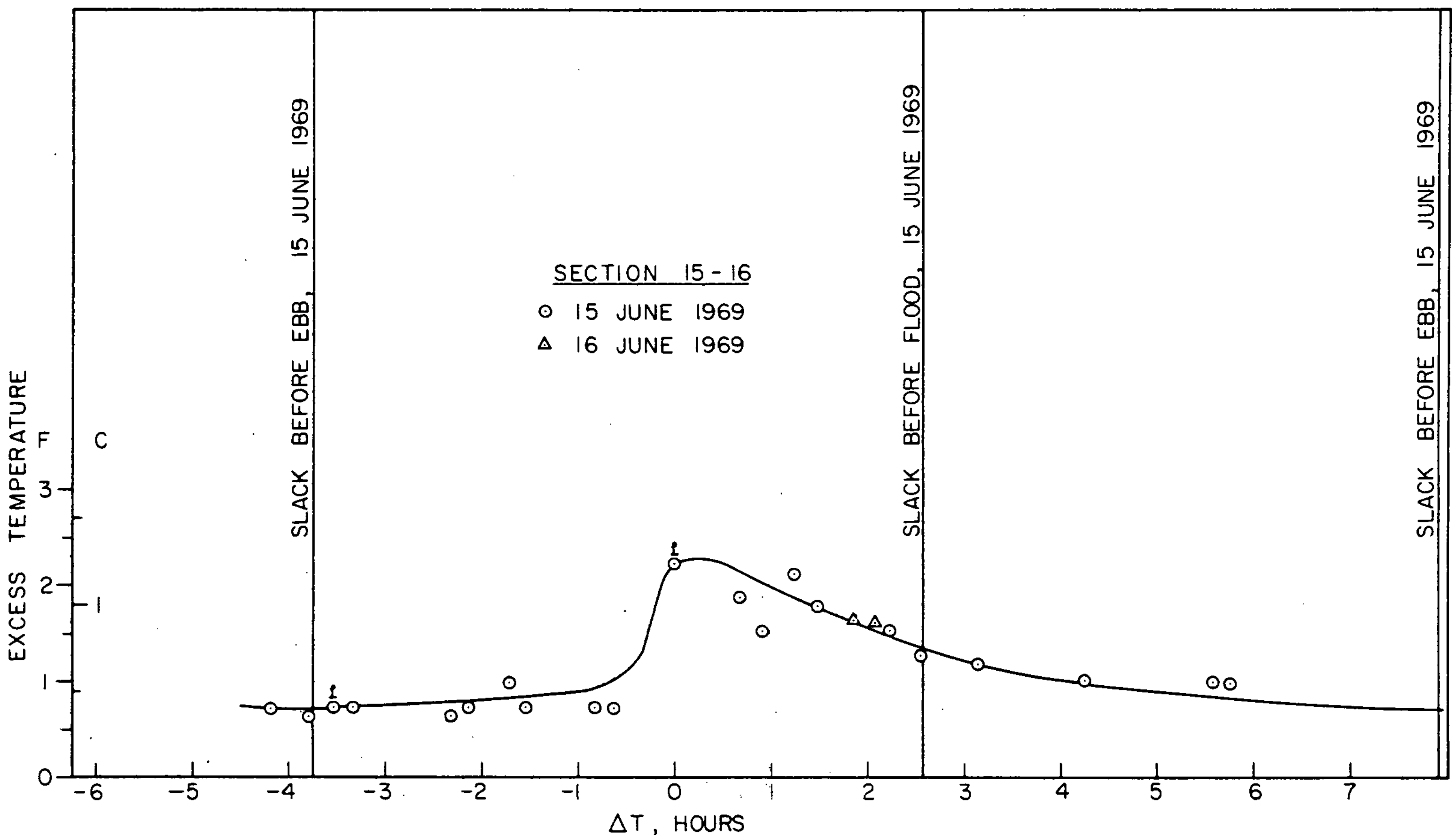


Figure 24. Excess temperature θ (scaled) as a function of time during ebb tide at Section 15 - 16 downstream from the dye source.

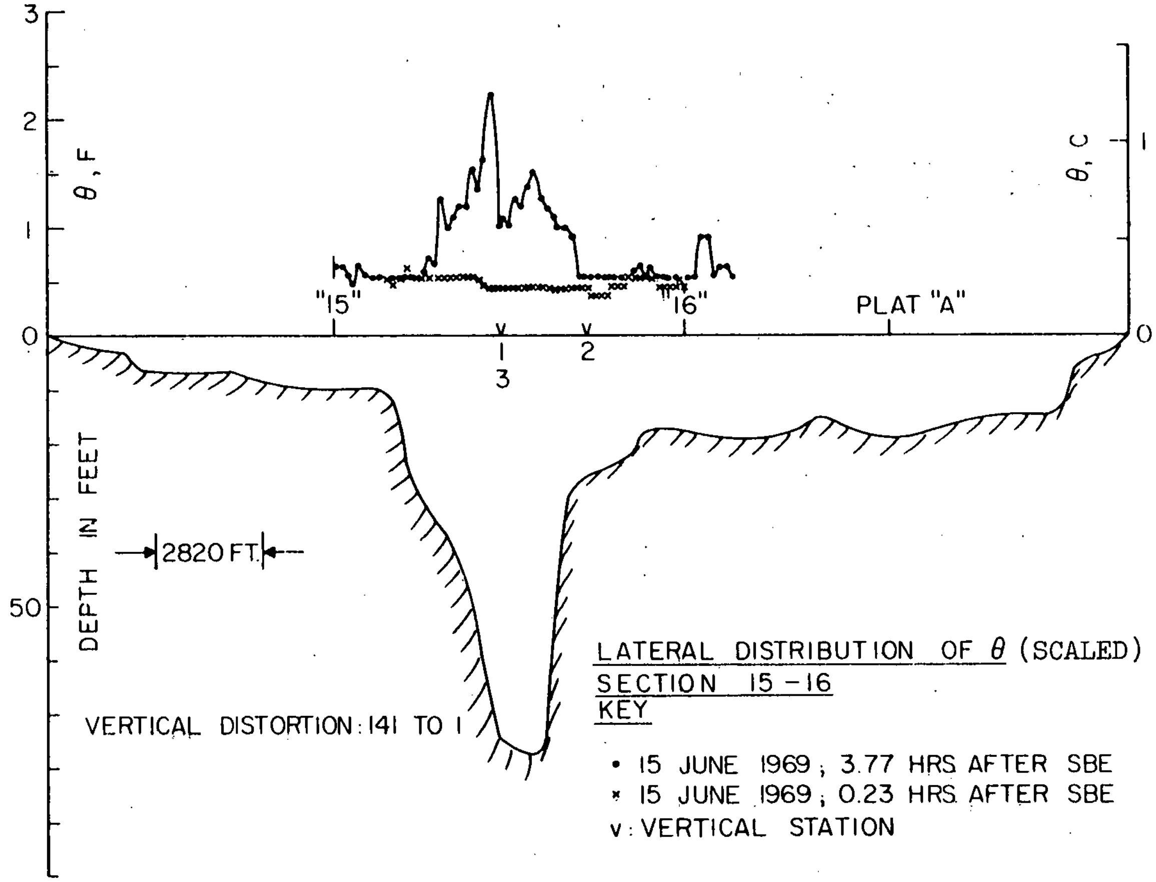

3
2
1
0
50
θ, F
θ, C
1
0
"15"
"16"
PLAT "A"
V
1
3
V
2
DEPTH IN FEET
2820 FT.
VERTICAL DISTORTION: 141 TO 1
LATERAL DISTRIBUTION OF θ (SCALED)
SECTION 15 - 16
KEY
• 15 JUNE 1969; 3.77 HRS AFTER SBE
× 15 JUNE 1969; 0.23 HRS AFTER SBE
v: VERTICAL STATION

Figure 25.

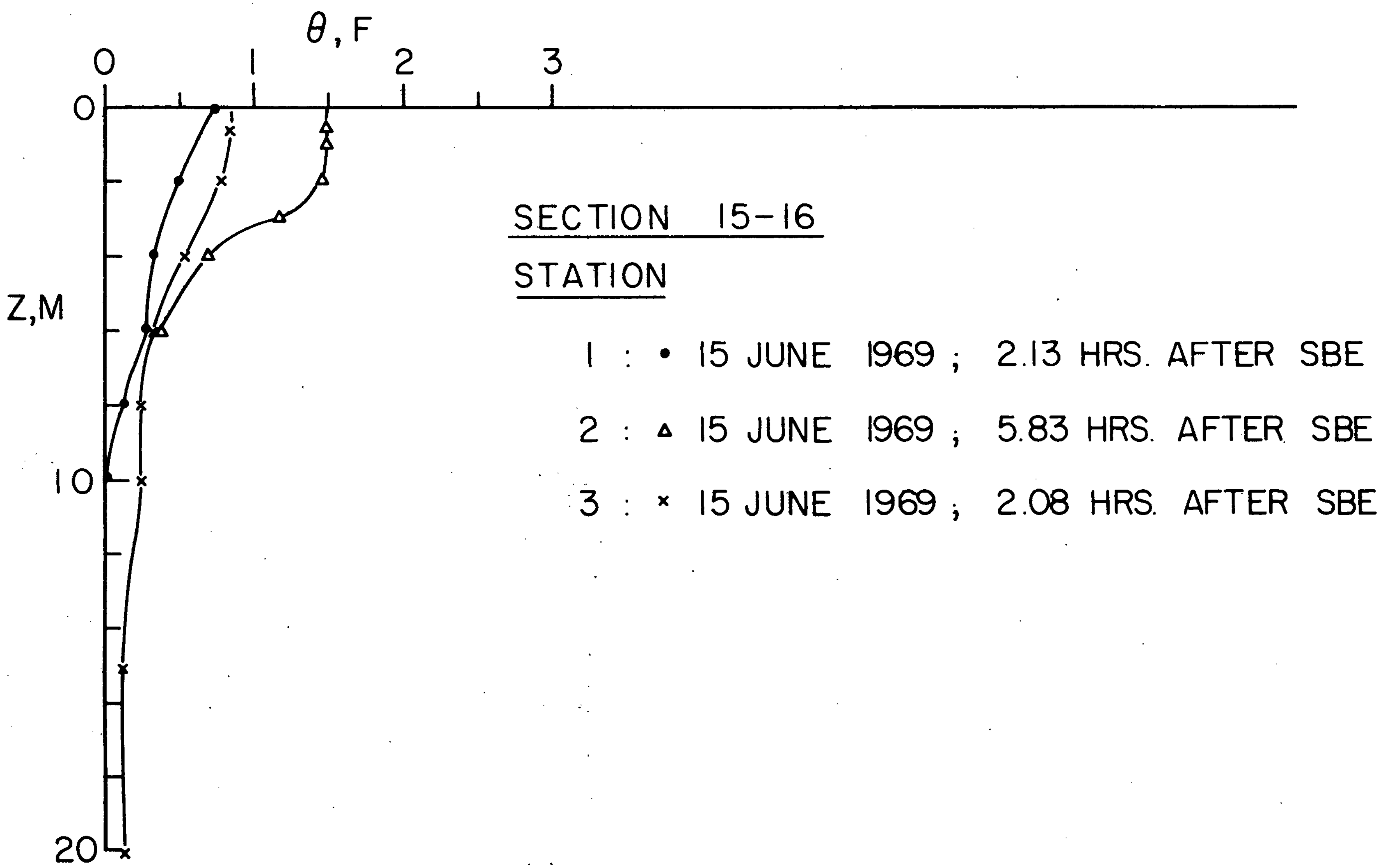


Figure 26. Vertical distribution of excess temperature θ (scaled) at Section 15 - 16 at various tidal phases. Station locations are shown on Fig. 25.

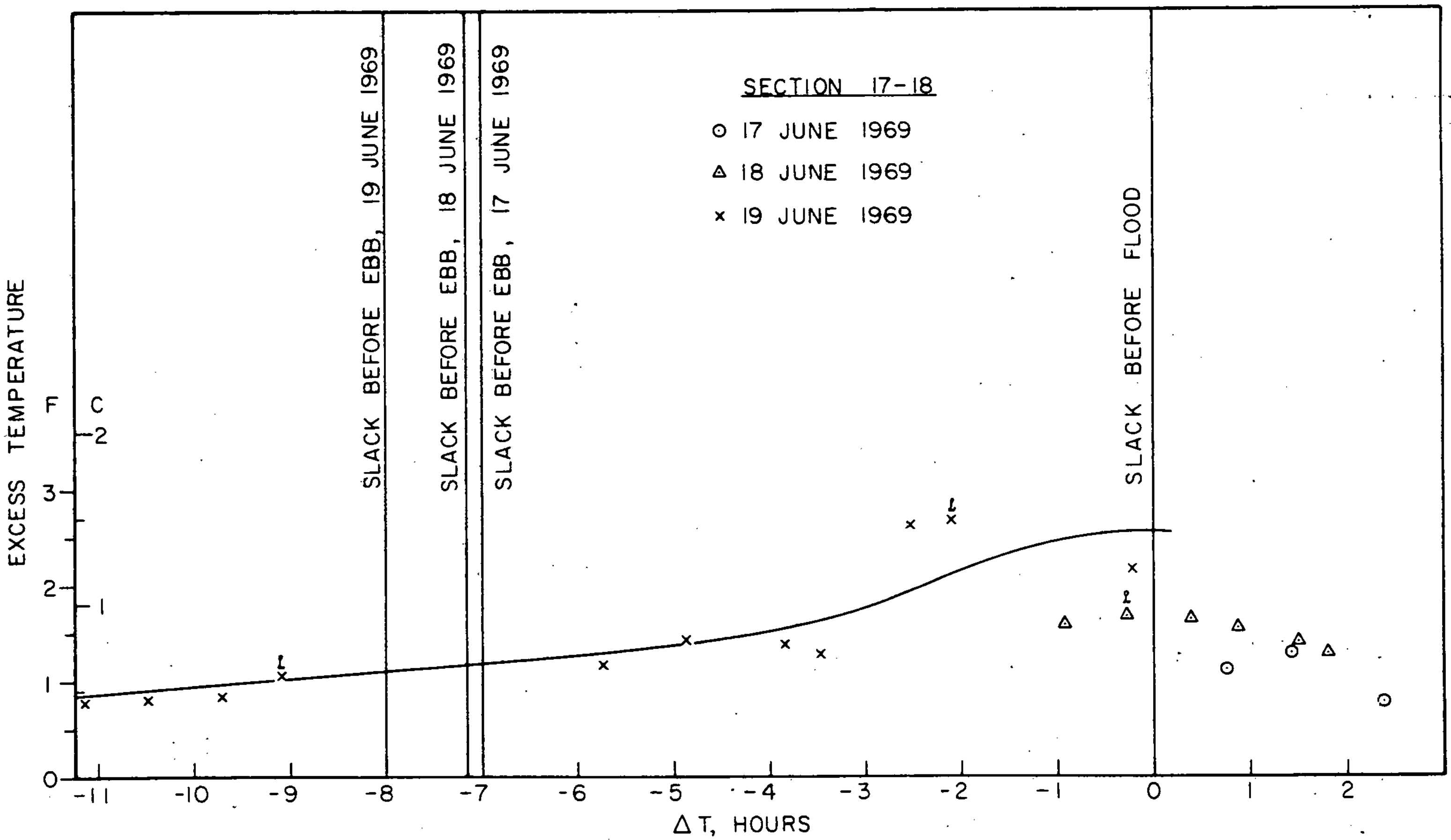
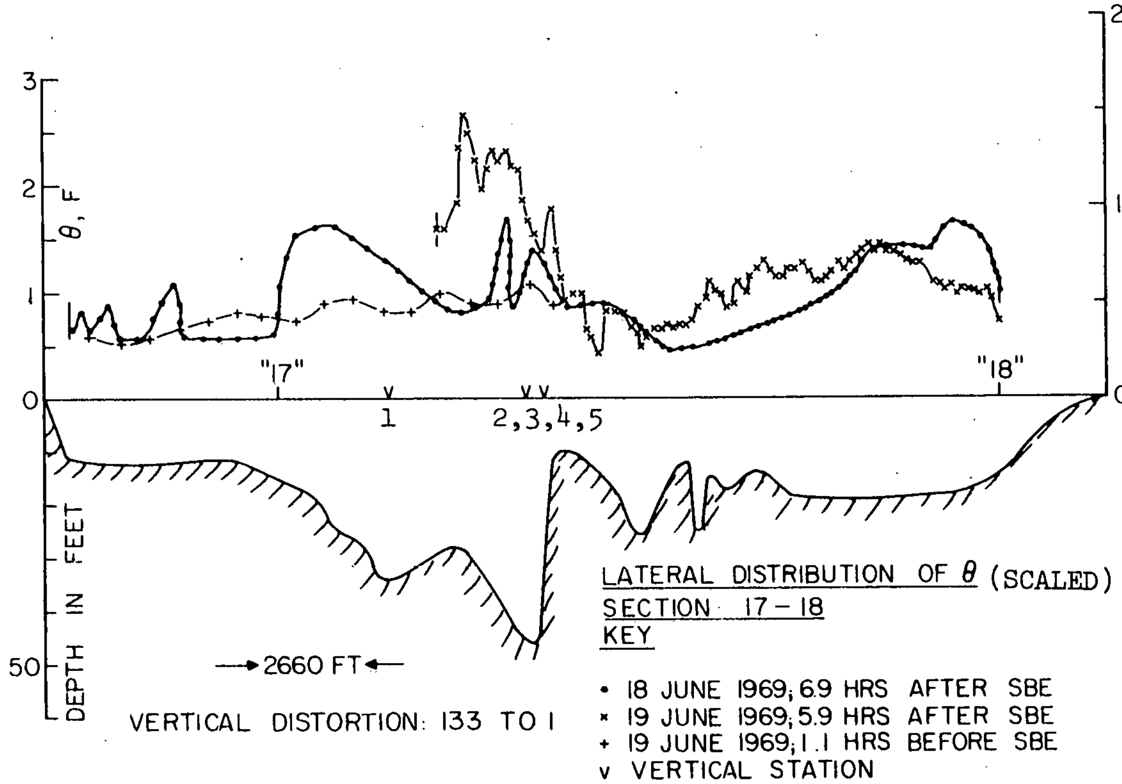


Figure 27. Excess temperature θ (scaled) as a function of time during ebb tide at Section 17 - 18 downstream from the dye source.



3
2
1
0
50
θ, F
θ, C
DEPTH IN FEET
"17"
"18"
v
1
v v
2,3,4,5
→2660 FT←
VERTICAL DISTORTION: 133 TO 1
LATERAL DISTRIBUTION OF θ (SCALED)
SECTION 17 - 18
KEY
• 18 JUNE 1969; 6.9 HRS AFTER SBE
× 19 JUNE 1969; 5.9 HRS AFTER SBE
+ 19 JUNE 1969; 1.1 HRS BEFORE SBE
v VERTICAL STATION

Figure 28.

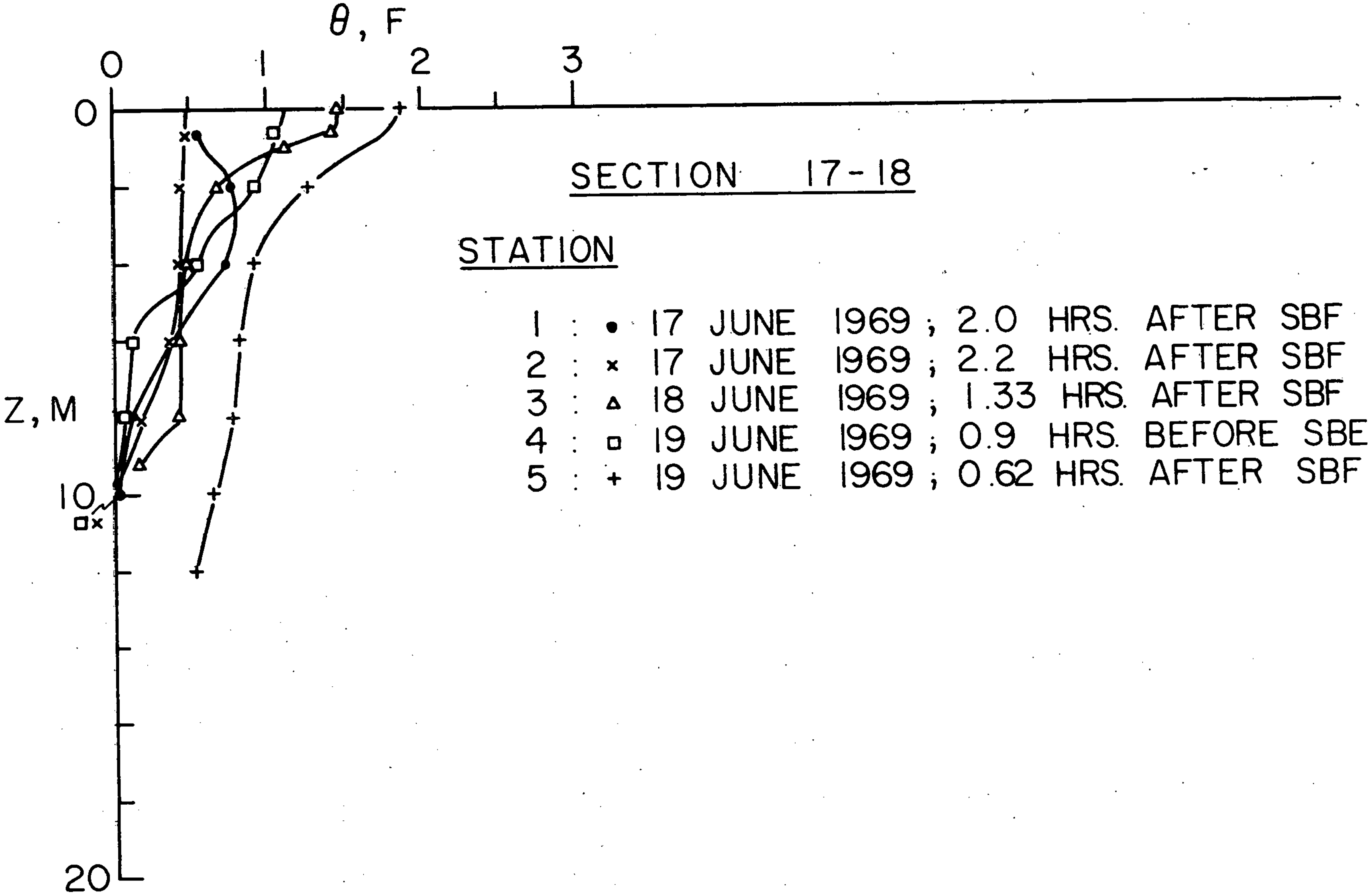
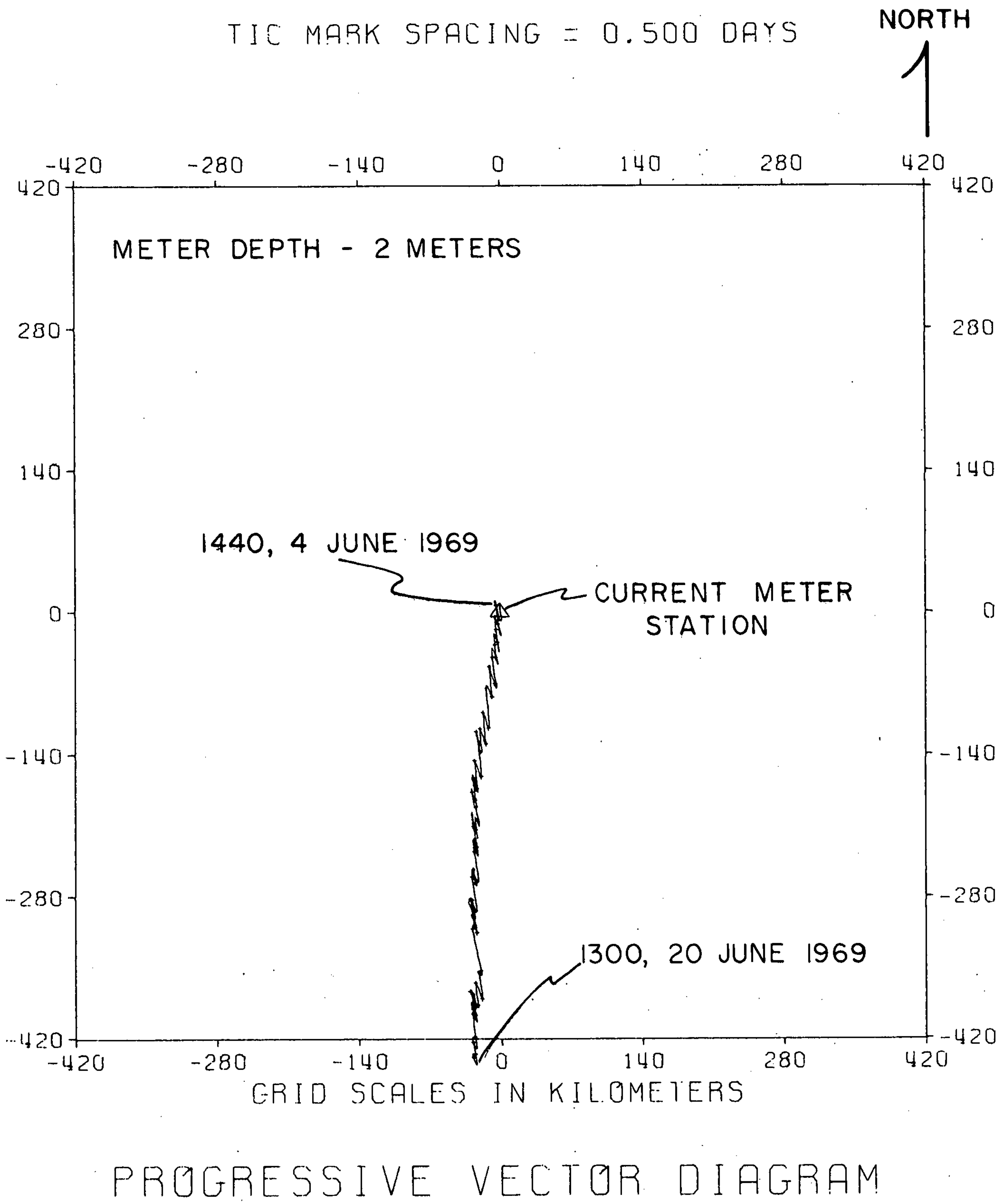


Figure 29. Vertical distribution of excess temperature θ (scaled) at Section 17 - 18 at various tidal phases. Station locations are shown on Fig. 28.



TIC MARK SPACING = 0.500 DAYS
NORTH
-420
-280
-140
0
140
280
420
METER DEPTH - 2 METERS
1440, 4 JUNE 1969
CURRENT METER
STATION
1300, 20 JUNE 1969
GRID SCALES IN KILOMETERS
PROGRESSIVE VECTOR DIAGRAM

Figure 30.

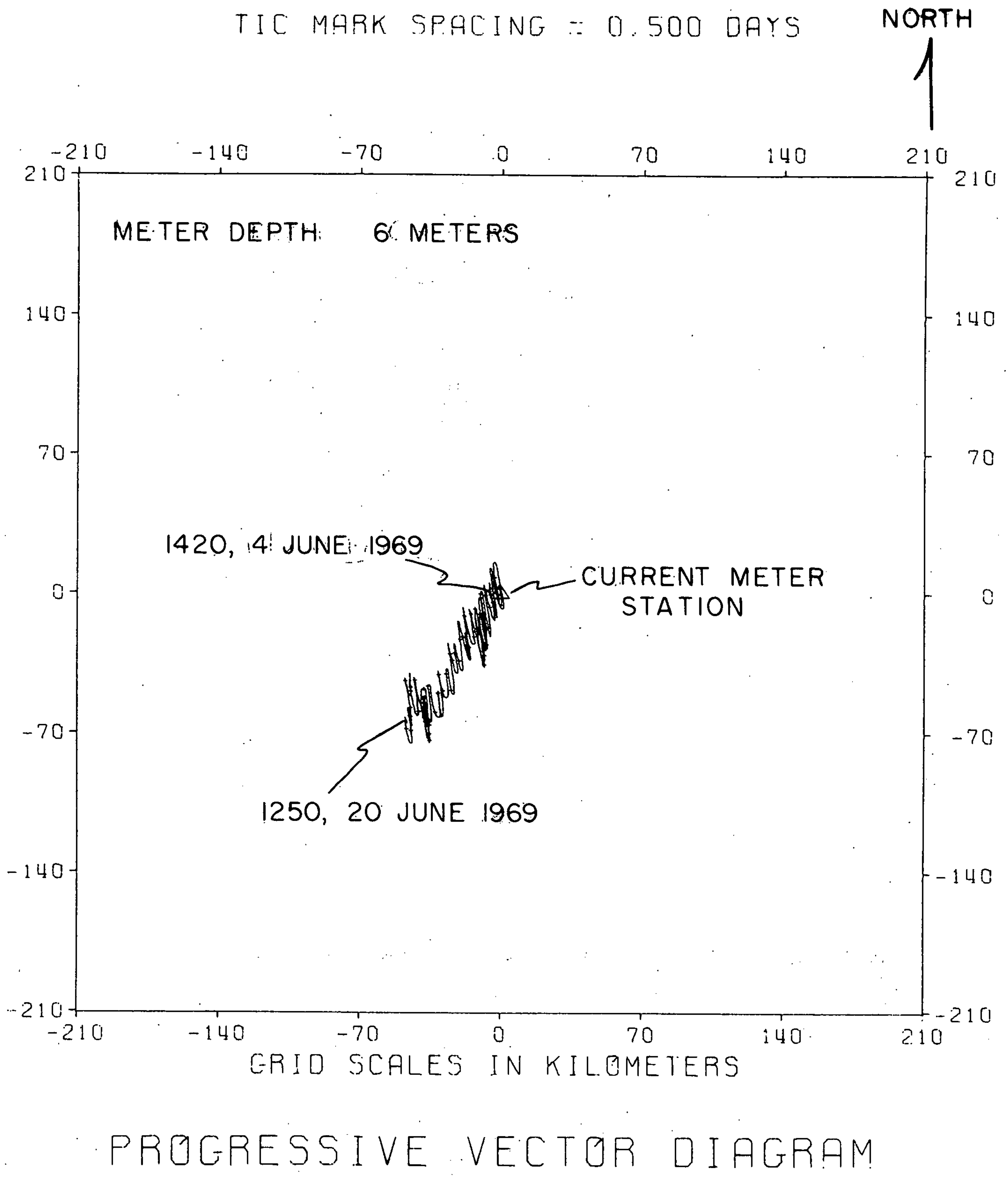

TIC MARK SPACING = 0.500 DAYS
NORTH
METER DEPTH 6 METERS
1420, 4 JUNE 1969
CURRENT METER STATION
1250, 20 JUNE 1969
-210 -140 -70 0 70 140 210
210 140 70 0 -70 -140 -210
GRID SCALES IN KILOMETERS
PROGRESSIVE VECTOR DIAGRAM

Figure 31.

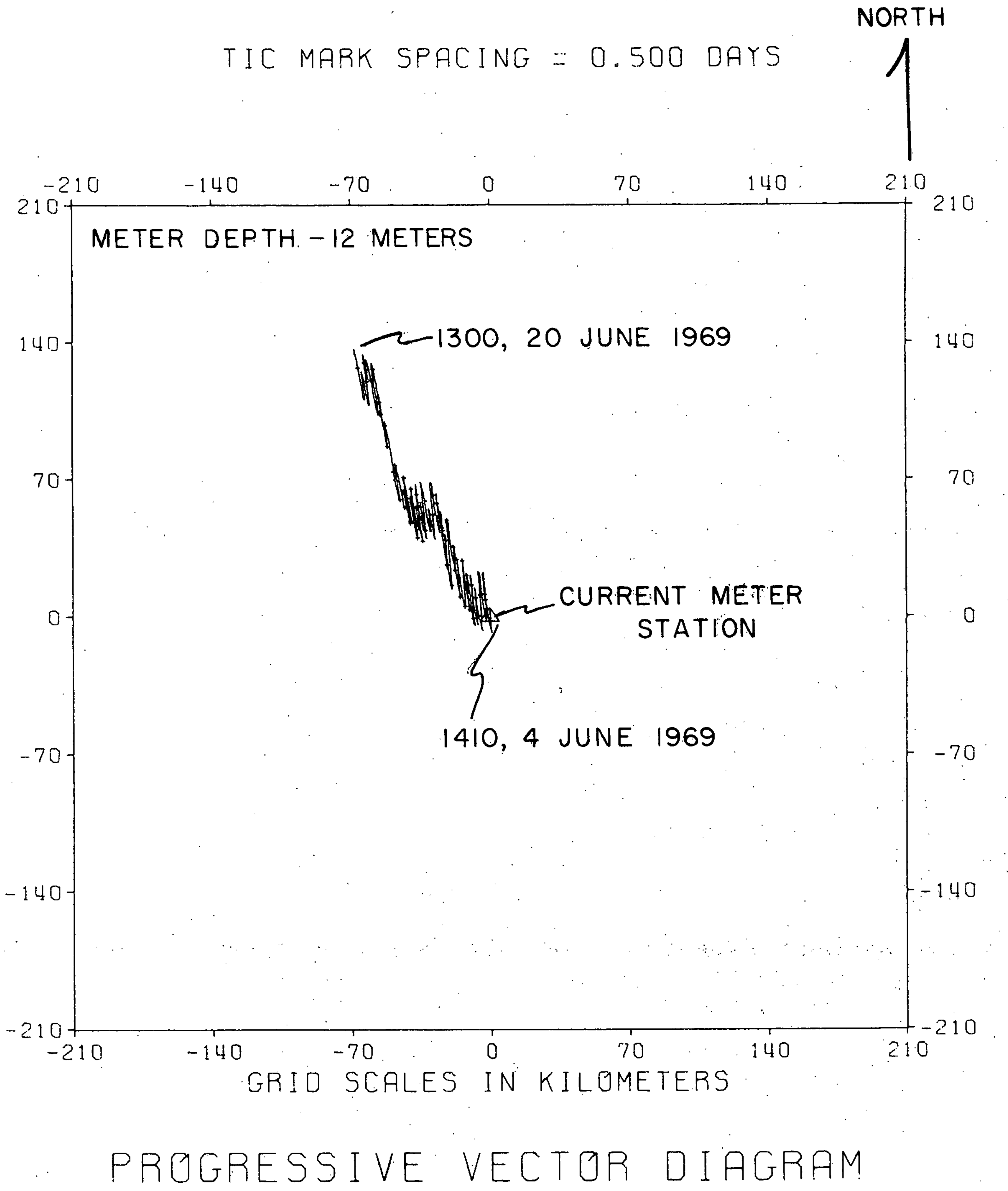

NORTH
TIC MARK SPACING = 0.500 DAYS
METER DEPTH - 12 METERS
1300, 20 JUNE 1969
CURRENT METER
STATION
1410, 4 JUNE 1969
-210
-140
-70
0
70
140
210
GRID SCALES IN KILOMETERS
PROGRESSIVE VECTOR DIAGRAM

Figure 32.

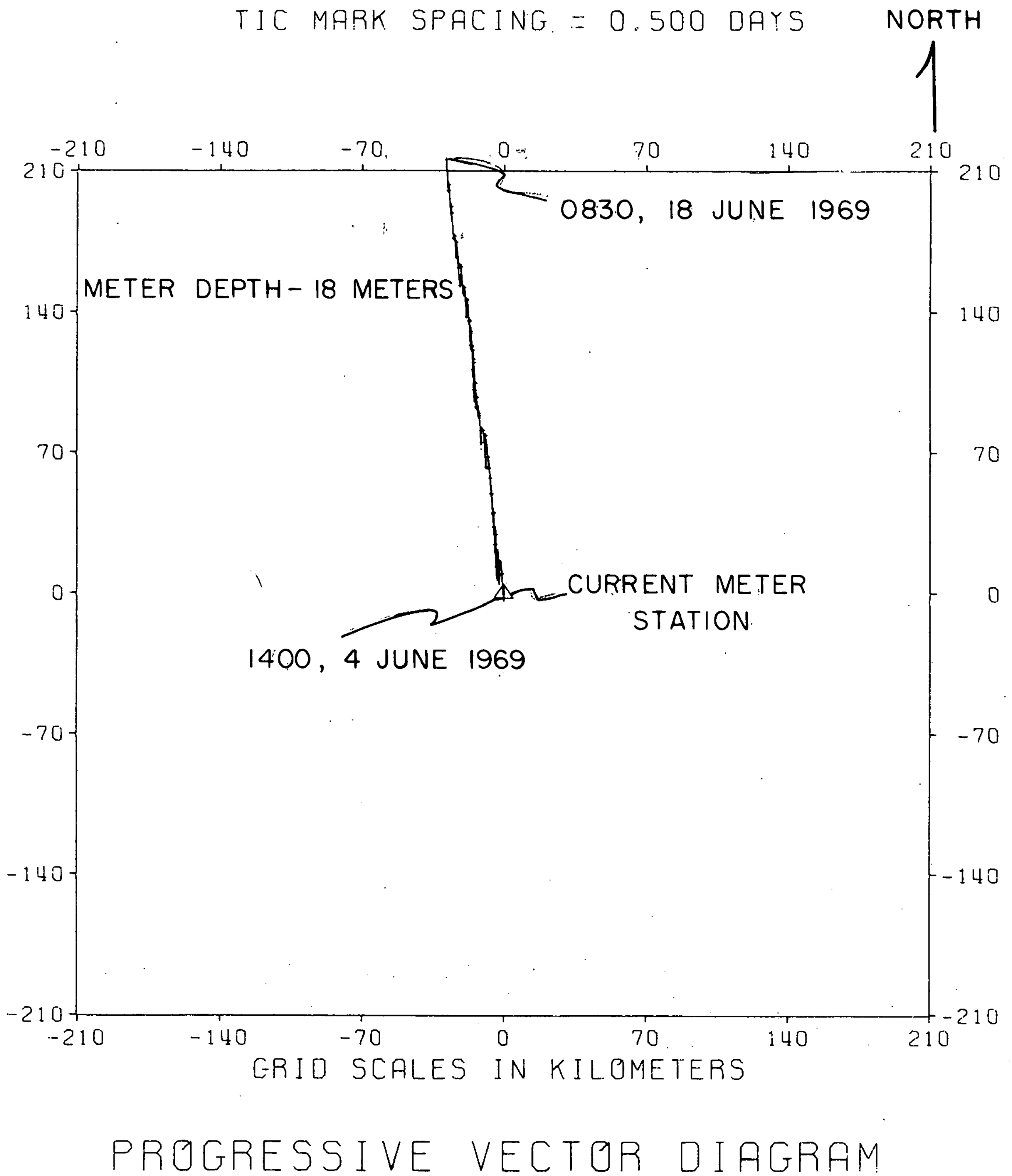

TIC MARK SPACING = 0.500 DAYS
NORTH
0830, 18 JUNE 1969
METER DEPTH - 18 METERS
CURRENT METER STATION
1400, 4 JUNE 1969
-210
-140
-70
0
70
140
210
GRID SCALES IN KILOMETERS
PROGRESSIVE VECTOR DIAGRAM

Figure 33.

IV. The 1972 Field Study (Postoperational).

Our comments regarding sampling requirements and techniques for the 1969 study apply equally to the 1972 study as well and will not be repeated here. See Section III.

The study area, Figure 1, unfortunately lies almost entirely within a danger zone controlled by the Commander, U.S. Naval Weapons Laboratory, Dahlgren, Virginia. Normally, firing and ordnance testing take place in this danger zone daily between 0800 and 1600 except for Saturday and Sunday and National Holidays. In both 1969 and 1972, Sections 15-16, 17-18, and occasionally Section 13-14 were unavailable for sampling due to this prohibition. Our experience was that it was impossible to carry out any routine sampling program in the area between Lower Cedar Point and St. Clements Island during daylight hours. Even on weekends, it was not always possible to sample these sections properly if tidal current phasing and daylight were not in agreement. In 1972, Section 17-18 could not be sampled in the time available because of this problem. *The allocation of a large segment of the Potomac River for the purpose of weapons testing seems questionable in this day and age, to say the least.*

a. The Experiment.

In 1972 the dye solution was dispensed into the traveling screen wash water just prior to its release into the discharge canal. The dye dispenser and dye barrel and contents were placed on top of a beam type scale accurate to ± 0.1 pounds. This entire arrangement was then placed inside a temporary shelter to protect it from the elements. The purpose of the scale was to monitor the discharge rate of the dye solution. As in 1969, a 30% solution of Rhodamine B was discharged; this time, however, at a rate of 61.53 pounds of solution per day. Pumping was commenced at 0805, 2 March 1972 and was secured at 1407, 15 March 1972.

One Braincon Type 1381 Histogram current meter was installed off the discharge canal (see Figure 43) at a depth of 8 feet from 1425, 14 March 1972 to 1555, 15 March 1972.

The dye and temperature sampling program was carried out with two boats, the R/V MAURY, a steel hulled 65-footer, and the LYDIA LOUISE II. The LYDIA LOUISE II made repeated crossings over a tidal cycle at a given section while the MAURY made vertical casts at the same section.

The LYDIA LOUISE II sampling arrangement for continuous underway lateral samples was identical to the TRACER's in 1969 except that temperature was recorded on a Model 400 Rustrak Recorder vice a YSI Model 80 Laboratory Recorder. On the MAURY, vertical casts for temperature and conductivity were made by lowering poly-flo tubing to the desired depth and pumping water through the ICTI flow cell and pump in series. A portion of the intake flow was diverted to the fluorometer for tracer concentrations.

The field program commenced on 28 February 1972 and ended on 15 March 1972.

b. The Base Temperature.

We are concerned here with the distribution of heat rejected by the plant; therefore, we must know what the water temperature would have been in the study area had the plant not been operating. This temperature is called the background or base temperature; it is designated ν_b, and it is a function of both space and time.

One approach to this problem is to take a time series of temperatures, say at the intake, and to remove the plant effect by spectral analysis of

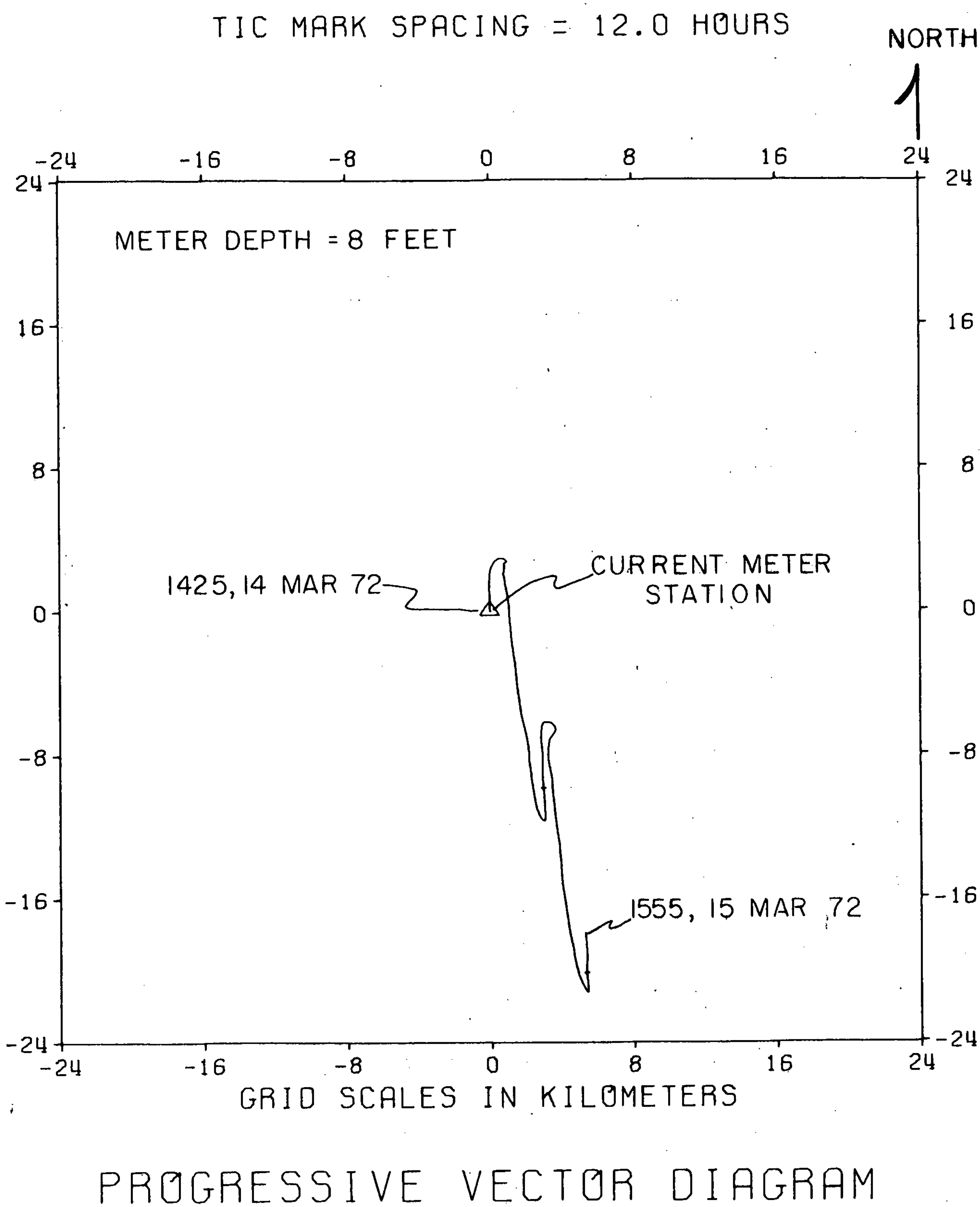

TIC MARK SPACING = 12.0 HOURS
NORTH
METER DEPTH = 8 FEET
1425, 14 MAR 72
CURRENT METER STATION
1555, 15 MAR 72
-24 -16 -8 0 8 16 24
24 16 8 0 -8 -16 -24
GRID SCALES IN KILOMETERS
PROGRESSIVE VECTOR DIAGRAM

Figure 34.

the temperature record and recirculation data from a tracer experiment. This approach was utilized by Carter (1968) in quantitating the distribution of excess heat from the Chalk Point Generating Station on the Patuxent River (Potomac Electric Power Co.) and yielded useful results.

Another approach and the one used during the 1972 study is to dye the heated condenser discharge with a fluorescent tracer dye whose natural background is low and constant. After pumping the dye for a sufficiently long enough period of time for our system to approach steady state, the dye concentrations and excess heat concentrations will be related in a way which depends upon the amount of dry dye discharged per unit of time, q_d, the rate of heat rejection across the condensers, $\theta_o \rho c_p Q_c$, and cooling at the air-sea interface. With the exception of surface cooling, this relationship is expressed by equation (1), above. Sources of error associated with this approach are (1) excess heat has been discharged from the plant since startup. Tracer must be discharged, therefore, for a long enough period of time so that the dye and heat will be in approximately the same equilibrium state, (2) tracer is added to the cooling water at a constant rate whereas the release rate of heat may be highly variable at times since it depends on electrical demand, (3) chlorine and blowdown chemicals, which may be added to the cooling water in relatively large amounts during the warmer months of the year, transform the dye into a non-fluorescent form, unless special tracers are used, and (4) the correction that must be applied to a tracer concentration to account for surface cooling depends on the parcel's age or elapsed time since it passed through the plant. Each parcel, however, is made up of molecules whose ages range from essentially 0 to the time since dye pumping began.

With respect to these sources of error, our 1969 study indicated that 9 to 10 days of tracer pumping would ensure that the dye field would be reasonably close to equilibrium at the sections planned for sampling during 1972. In addition, the 1972 study was scheduled for a time when both units of the plant were programmed for constant operation at or near rated load. It may be seen from Figure 5 that except for a short period on 8 March, this goal was achieved. Further, since water temperatures were low, i.e., 5° to $8^\circ C$, no chlorine or other blowdown chemicals were added to the cooling water during the study. No attempt has been made in either the 1969 or 1972 results to correct the tracer concentrations for surface cooling. As a result, the excess temperatures based on tracer concentrations are somewhat high for both 1969 and 1972 and the estimated field of base temperature, ν_b, somewhat low (1972 study). This procedure is considered acceptable, however, since omission of the cooling correction errs on the side of conservatism. An attempt will be made below to estimate the size of this error.

Pritchard and Carter (1965) have shown that if the tracer concentration is measured at a given point in space as a function of time (measurements are made at the same phase of the tide), a sigmoid curve will result. Analytically this may be expressed as

$$C_t = C_\infty (1 - \exp(-\eta t)) \tag{2}$$

where C_t is the tracer concentration

C_∞ is the equilibrium or steady state tracer concentration

$1/\eta$ is the average age of the parcel, age being reckoned since pumping began, and

t is the time since pumping began.

It was also shown that for a small volume of unit surface area and depth D that the rate of change of concentration without cooling is related to the rate of change of concentration with cooling according to the following relation

$$\frac{\partial \theta_t}{\partial t} = k \exp \left\{- \frac{\gamma}{D} t\right\} \frac{\partial C_t}{\partial t} \tag{3}$$

where k is the scaling factor for tracer and excess temperature, i.e., equation (1)

γ is the surface cooling coefficient, and

θ_t, D, and t are as defined previously.

Integration of equation (3) together with equation (2) results in

$$\theta_t = \frac{\eta}{\eta+\gamma/D} k C_t \left\{ \frac{C_\infty}{C_t} + \exp \left\{- \frac{\gamma}{D} t\right\}(1 - \frac{C_\infty}{C_t}) \right\} \tag{4}$$

at equilibrium, $C_t = C_\infty$ and equation (4) reduces to

$$\theta_t = \frac{\eta}{\eta+\gamma/D} k C_t \quad . \tag{5}$$

That is, the factor f that must be applied to the excess temperatures scaled from the tracer concentrations ($k C_t$) to correct for surface cooling is

$$f = \eta \ / \ \eta+\gamma/D \tag{6}$$

According to D.W. Pritchard (unpublished manuscript), γ is a function of the excess temperature θ, the natural or background temperature ν_b, and the wind velocity W. Typical values of γ and f are listed in Table 1.

It may be seen from Table 1 that in the near field or plume, scaled temperatures will be too high by approximately 0.25°F and in the far field the error will be of the order of 0.20°F for the season of the year during

Table 1

Typical Values of γ, the Surface Cooling Coefficient and f the Surface Cooling Correction Factor

Near Field: W = 10 mph; θ = 5°F; η = 3 days^{-1}; D = 10 feet

ν_b, °F	γ, feet days^{-1}	f
40 (winter)	1.365	0.96
50 (spring & fall)	1.577	0.95
85 (summer)	3.058	0.91

Far Field: W = 10 mph; θ = 0°F; η = 0.3 days^{-1}; D = 30 feet

ν_b, °F	γ, feet days^{-1}	f
40 (winter)	1.268	0.88
50 (spring & fall)	1.497	0.86
85 (summer)	2.879	0.76

Far Field: W = 10 mph; θ = 0°F; η = 0.1 days^{-1}; D = 60 feet

ν_b, °F	γ, feet days^{-1}	f
40 (winter)	1.268	0.83
50 (spring & fall)	1.497	0.80
85 (summer)	2.879	0.68

which our 1972 experiment was conducted (spring). Therefore, the estimated field of background temperature ν_b was calculated by simply scaling the tracer concentrations to excess temperature by equation (1)[3] and then subtracting these values from the measured field of temperature. Estimated background temperatures, ν_b, as functions of time and space are presented in Figures 35 through 42.

c. Results.

During the 1972 study we sampled 4 sections downstream (intake, 11-12, 13-14, and 15-16) from the discharge canal and 2 sections upstream (1-2 and 3-4). The locations of these sections are shown on Figure 43. For the 1972 study, our results are presented in *two* types of figures vice *three* as a higher frequency of vertical sampling in 1972 permitted combining the lateral and vertical distributions of tracer concentration (scaled to excess temperature, θ) at a particular tidal phase and section on one figure. Figures 45, 46, 47, 49, 50, 51, 53, 54, 56, 57, 58, 60, 61, 62, and 64. The time histories of the maximum surface excess temperature (scaled) at the various sections were prepared as in 1969 and are shown in Figures 44, 48, 52, 55, 59, and 63.

The progressive vector diagram for the single current meter installed during the 1972 study is shown in Figure 34.

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[3] θ_o appropriate for the date was used in the scaling.

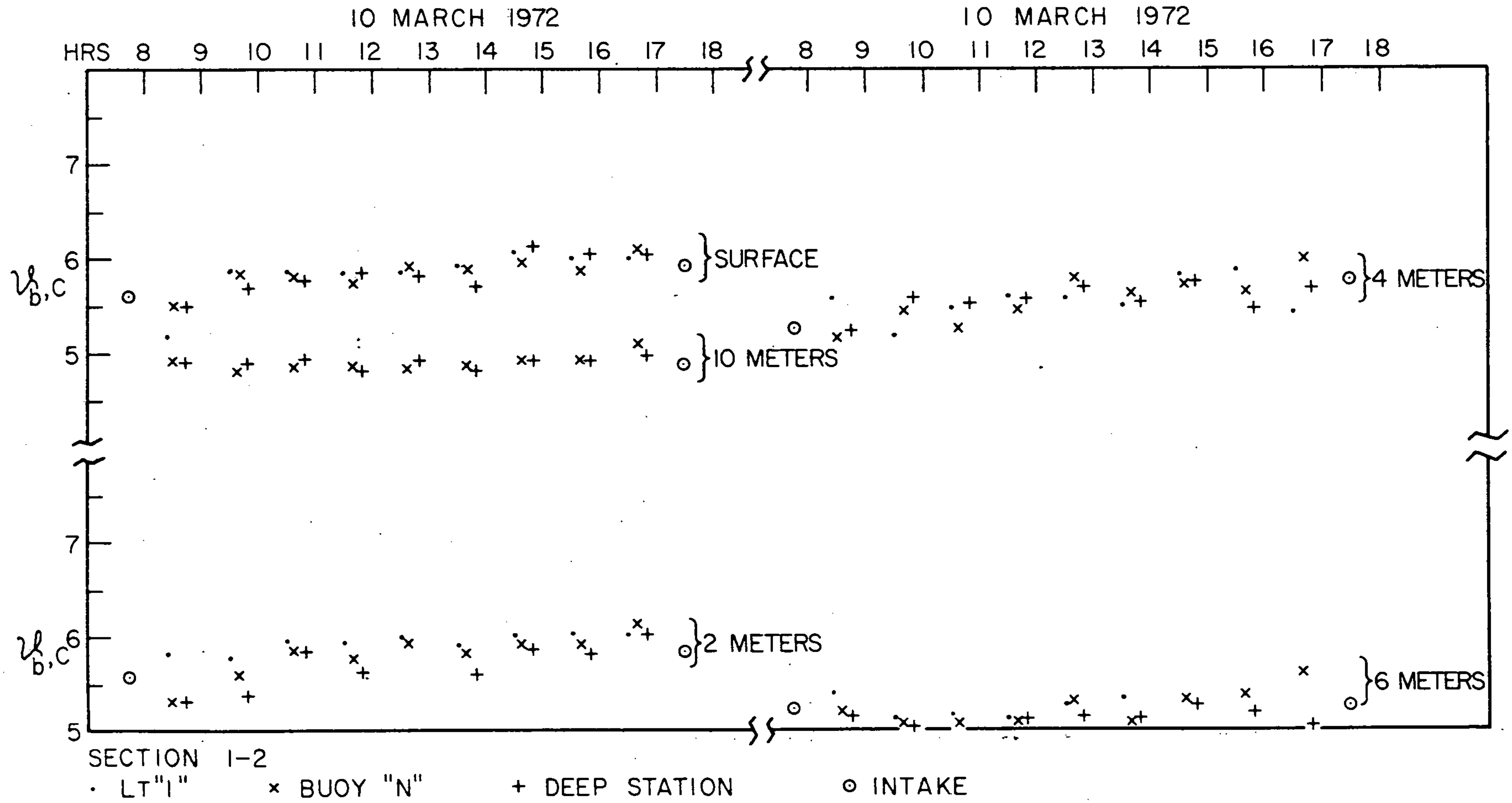

Figure 35. Estimated background temperature, ν_b, as a function of time and space at Section 1 - 2.

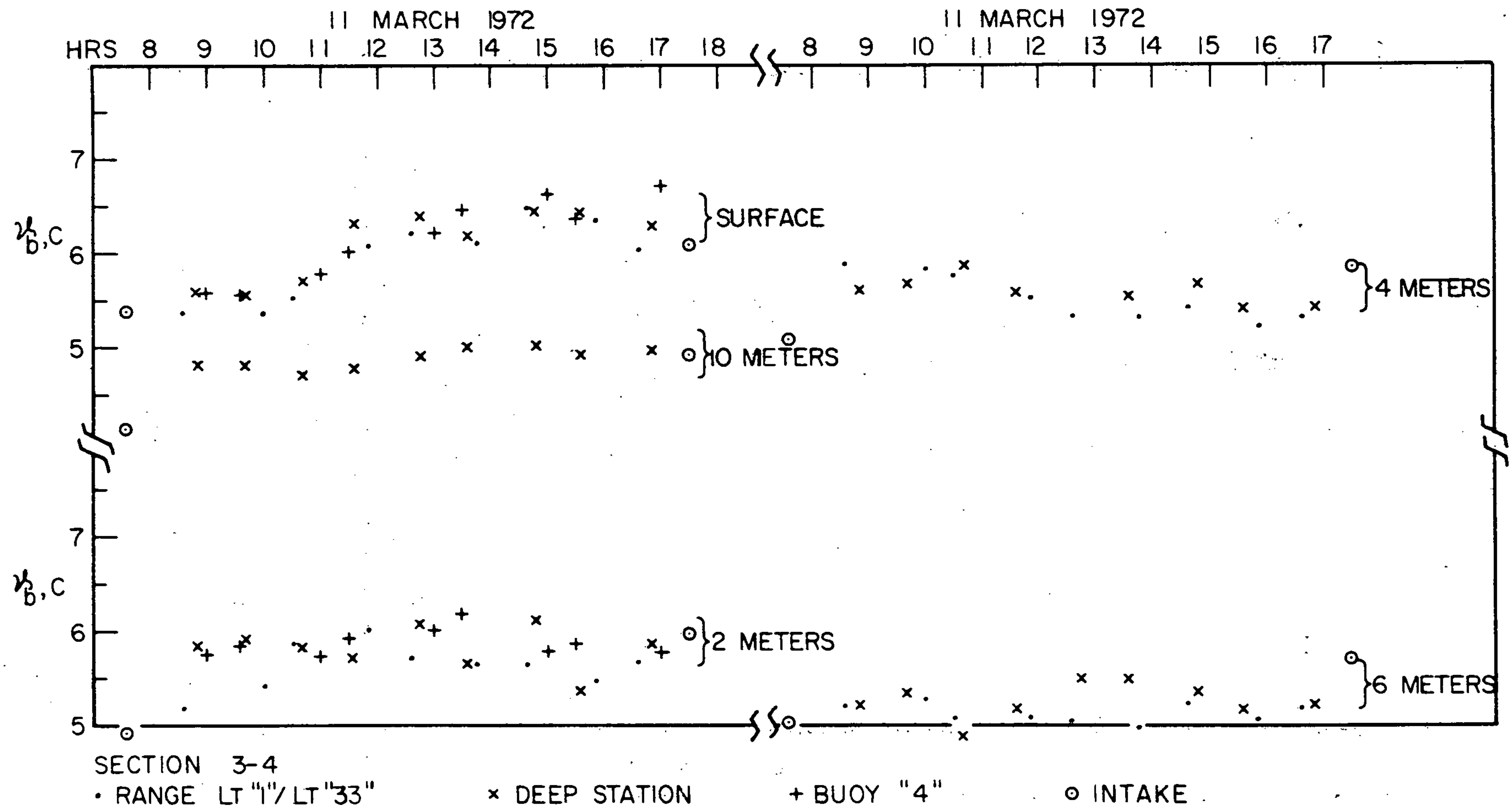

Figure 36. Estimated background temperature, ν_b, as a function of time and space at Section 3 - 4.

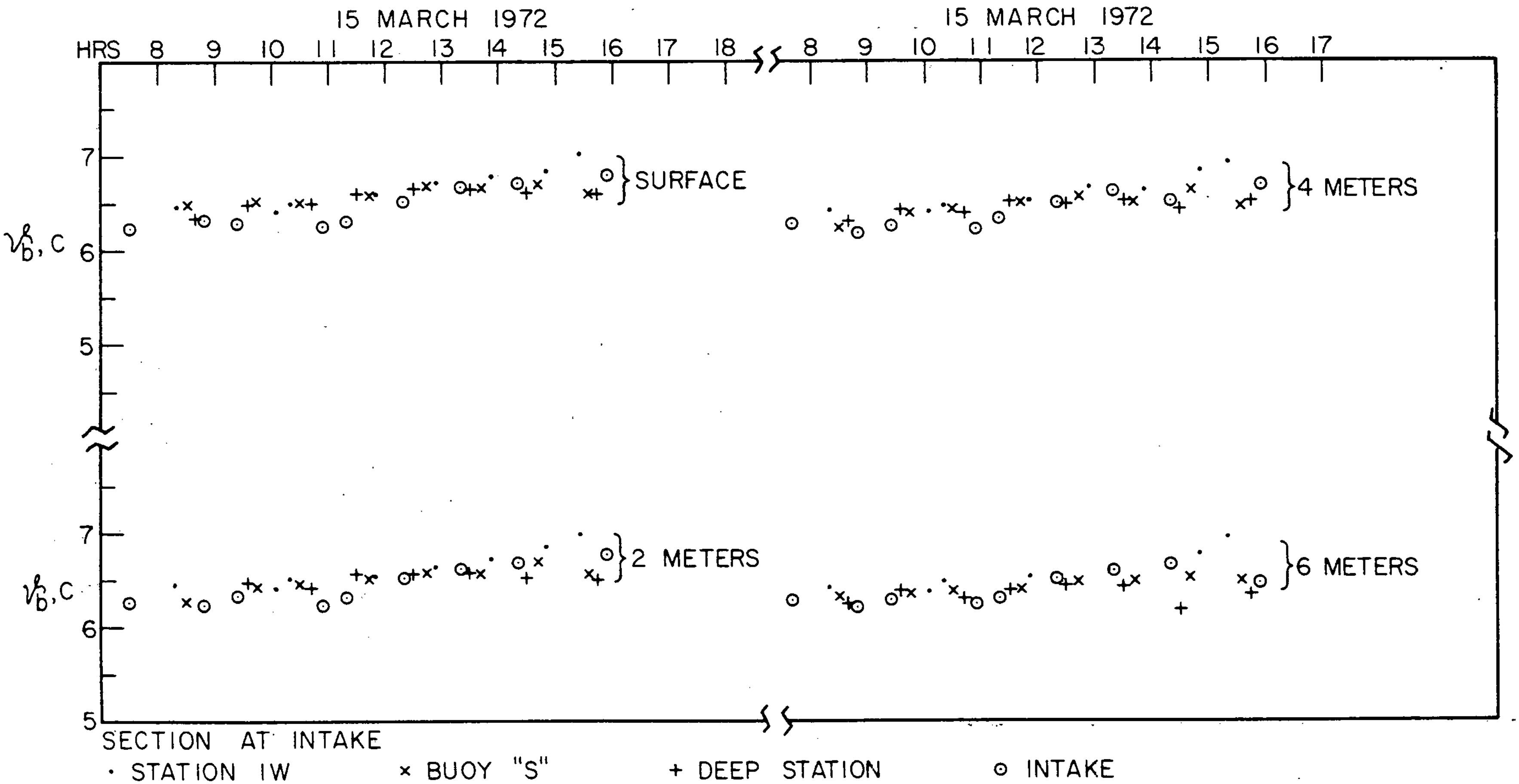

Figure 37. Estimated background temperature, ν_b, as a function of time and space at section at intake.

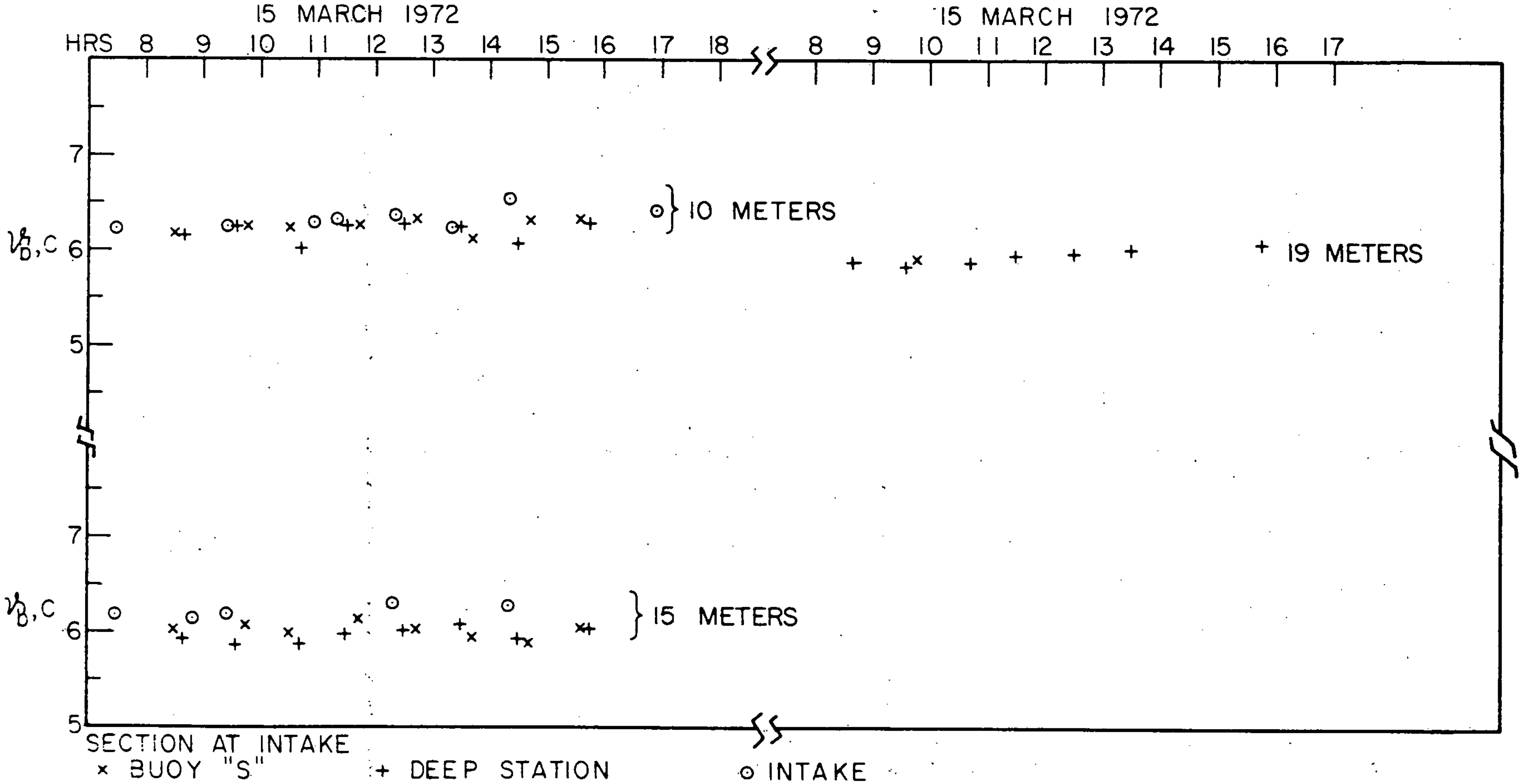

Figure 38. Estimated background temperature, ν_b, as a function of time and space at section at intake.

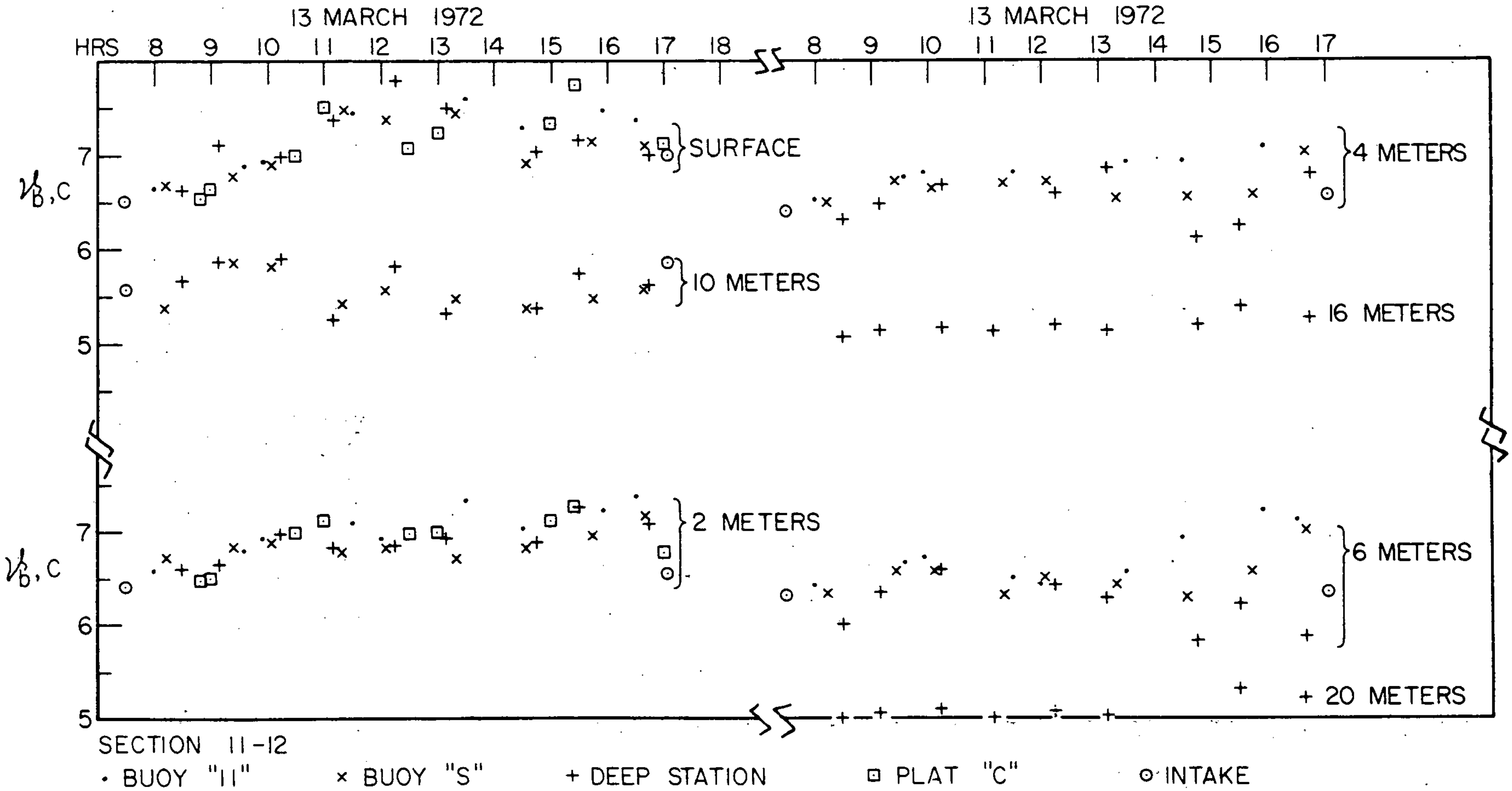

Figure 39. Estimated background temperature, ν_b, as a function of time and space at Section 11 - 12.

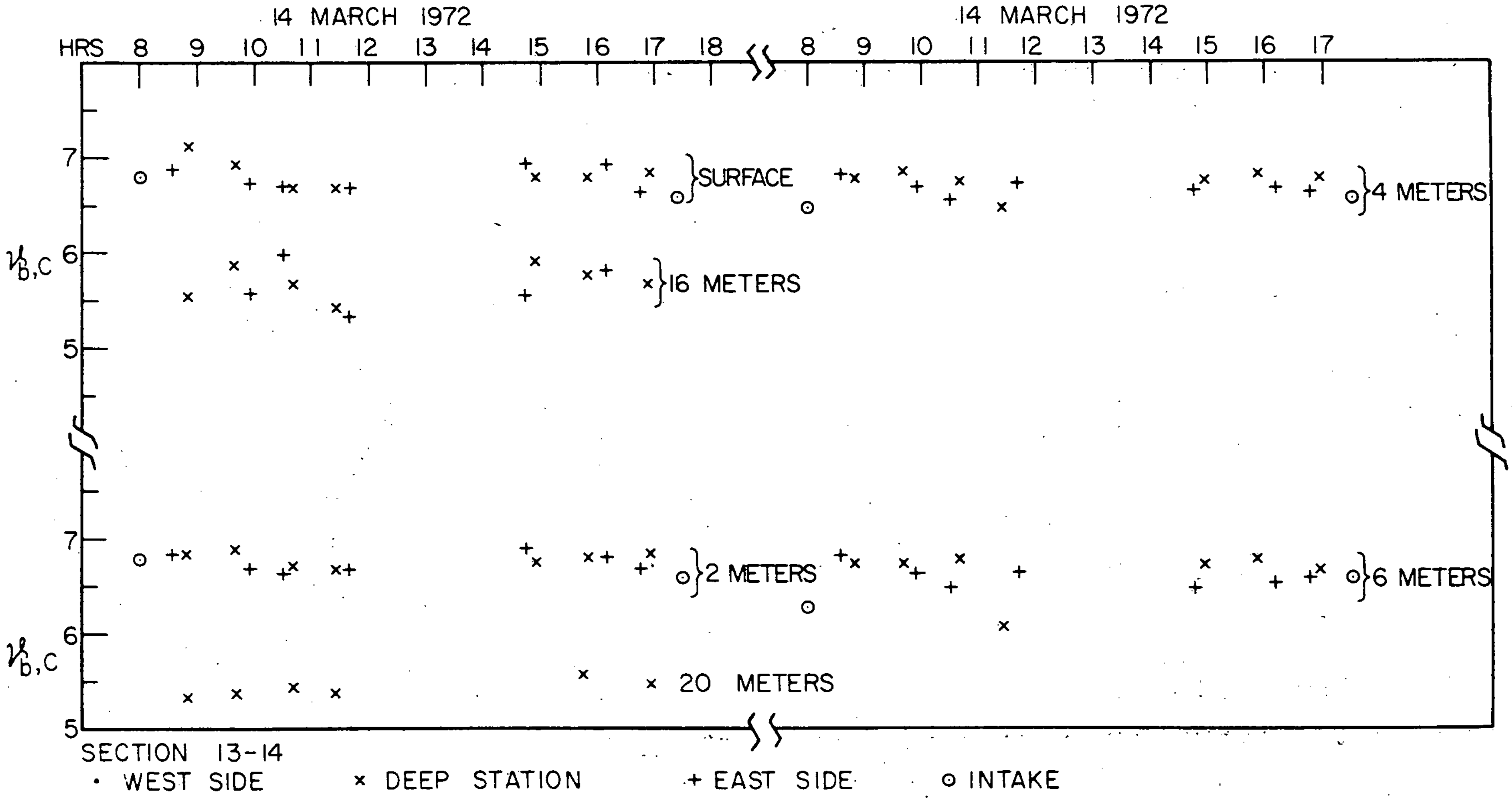

Figure 40. Estimated background temperature, ν_b, as a function of time and space at Section 13 - 14.

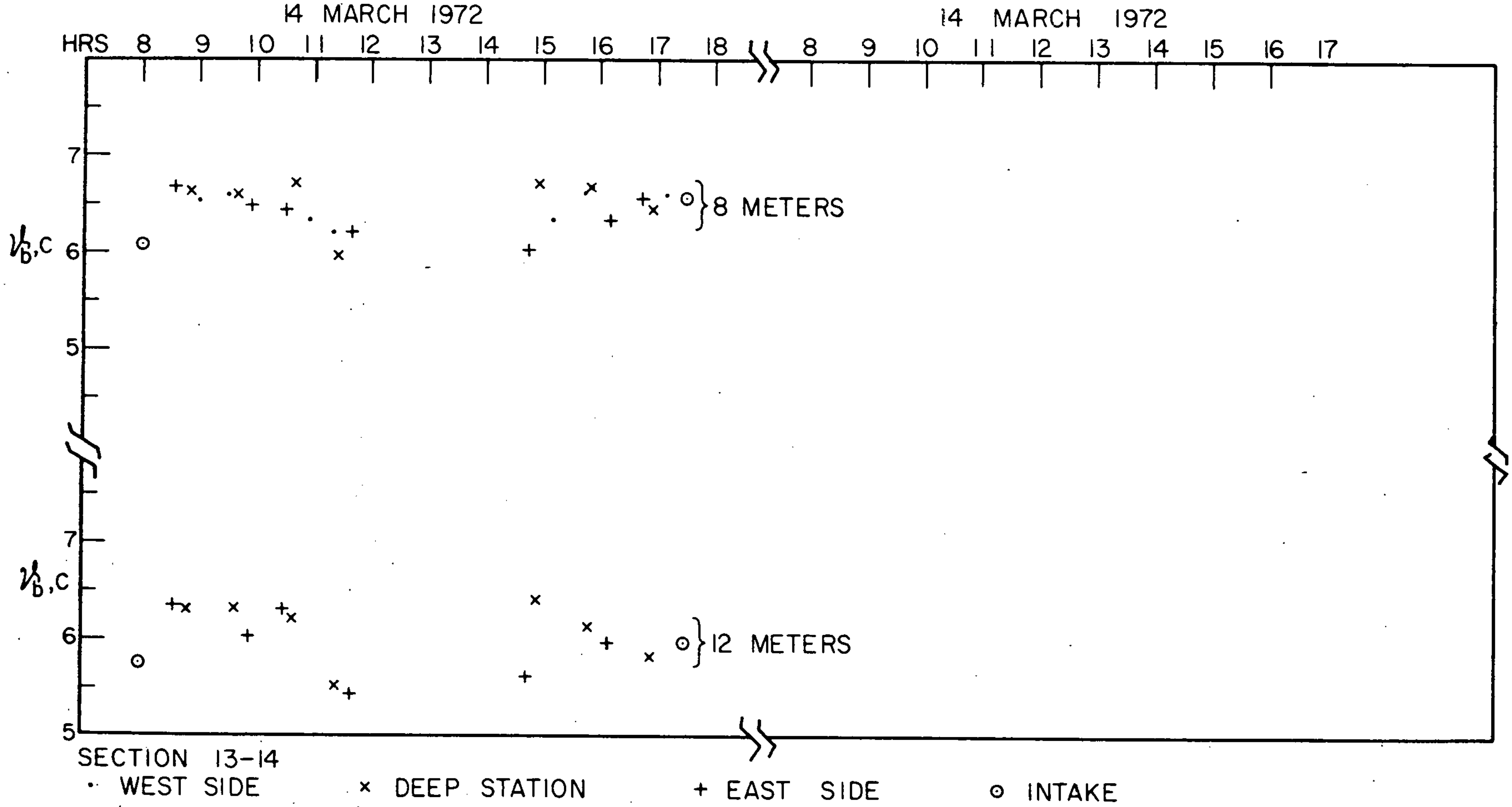

Figure 41. Estimated background temperature, ν_b, as a function of time and space at Section 13 - 14.

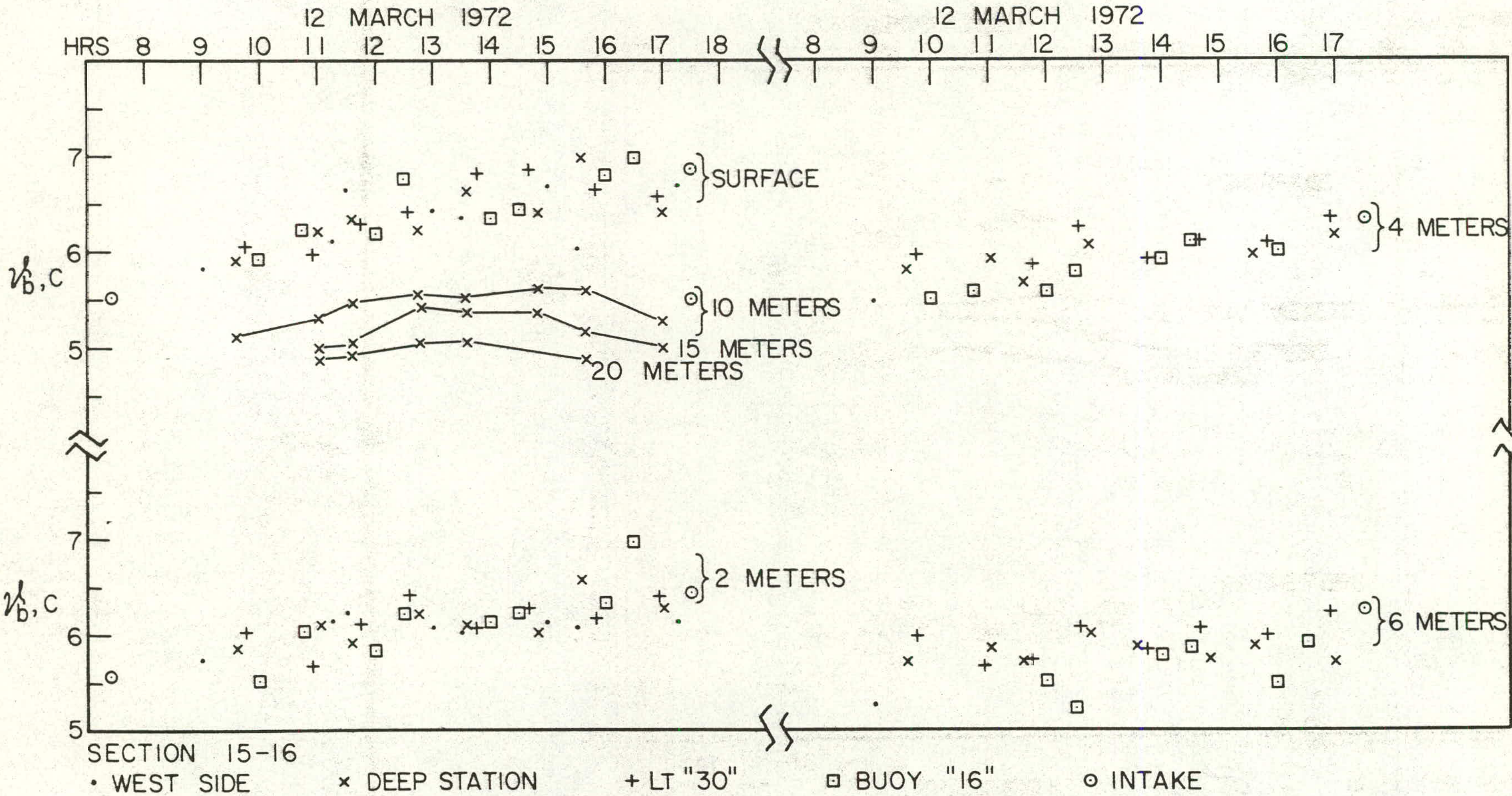

Figure 42. Estimated background temperature, ν_b, as a function of time and space at Section 15 - 16.

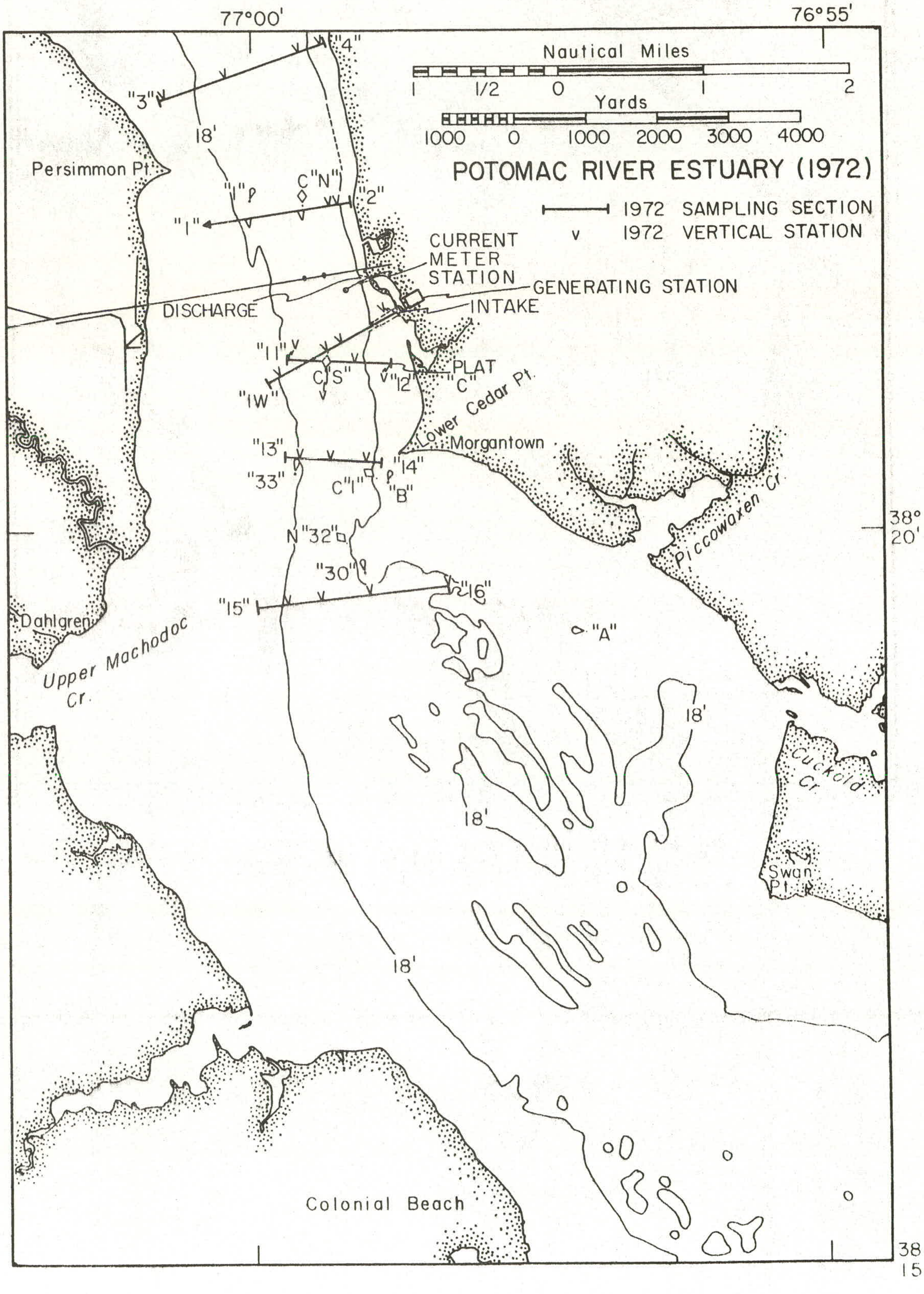

Figure 43. Chart of the Potomac River showing the location of the sampling sections.

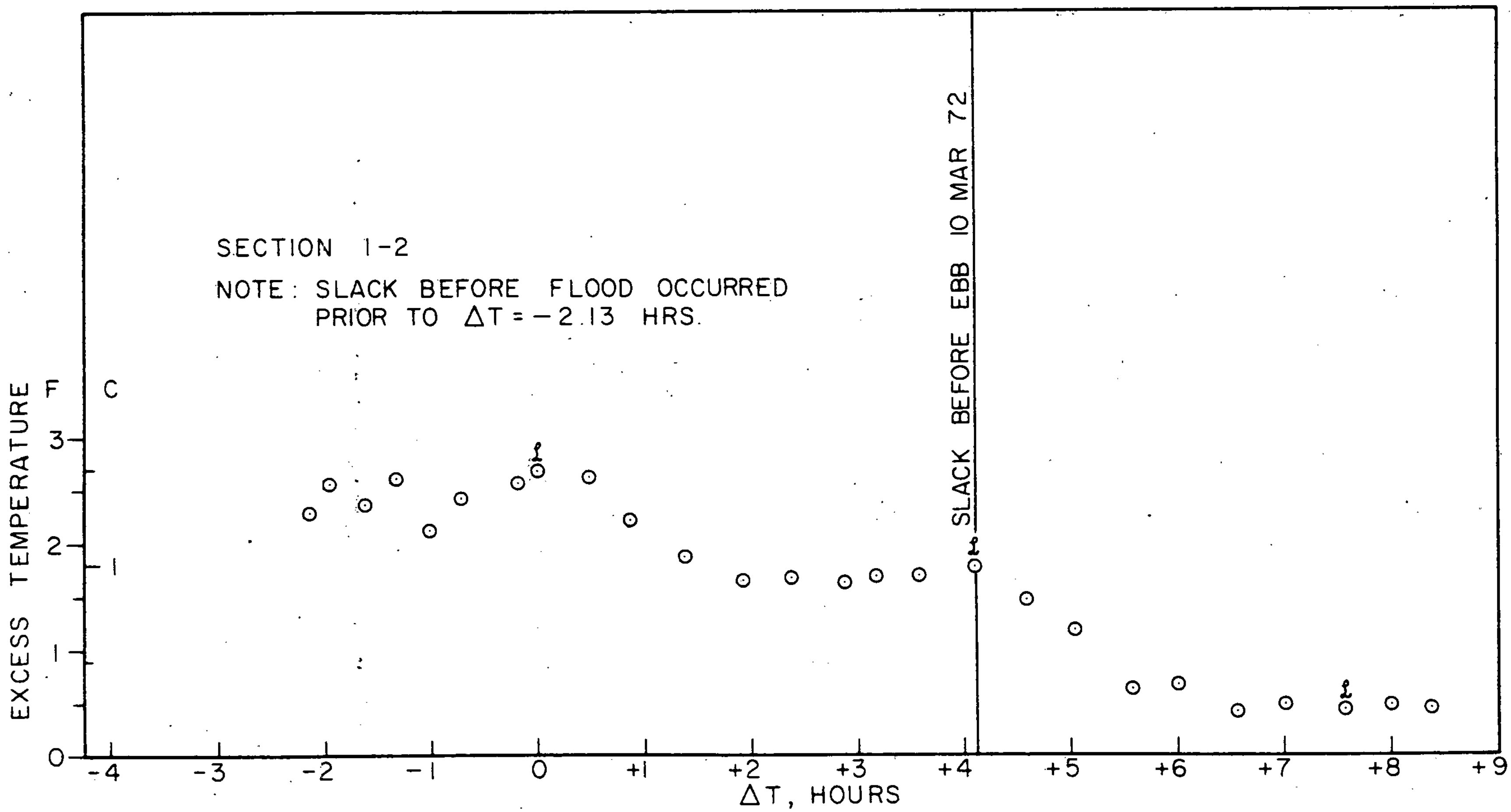

Figure 44. Excess temperature θ (scaled) as a function of time during flood tide at Section 1 - 2 upstream from the discharge.

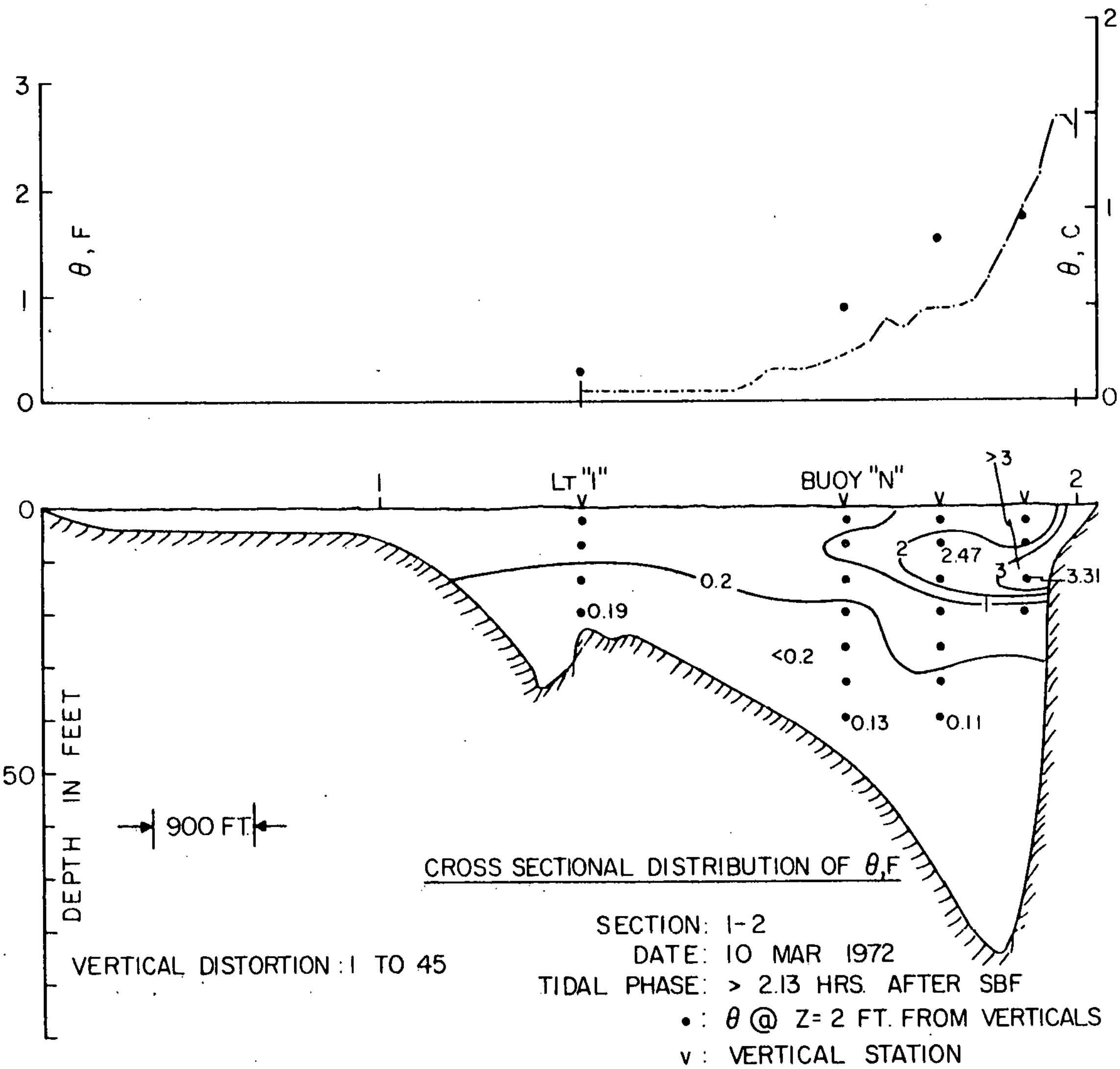

Figure 45. Cross-sectional distribution of excess temperature θ (scaled) at Section 1 - 2.

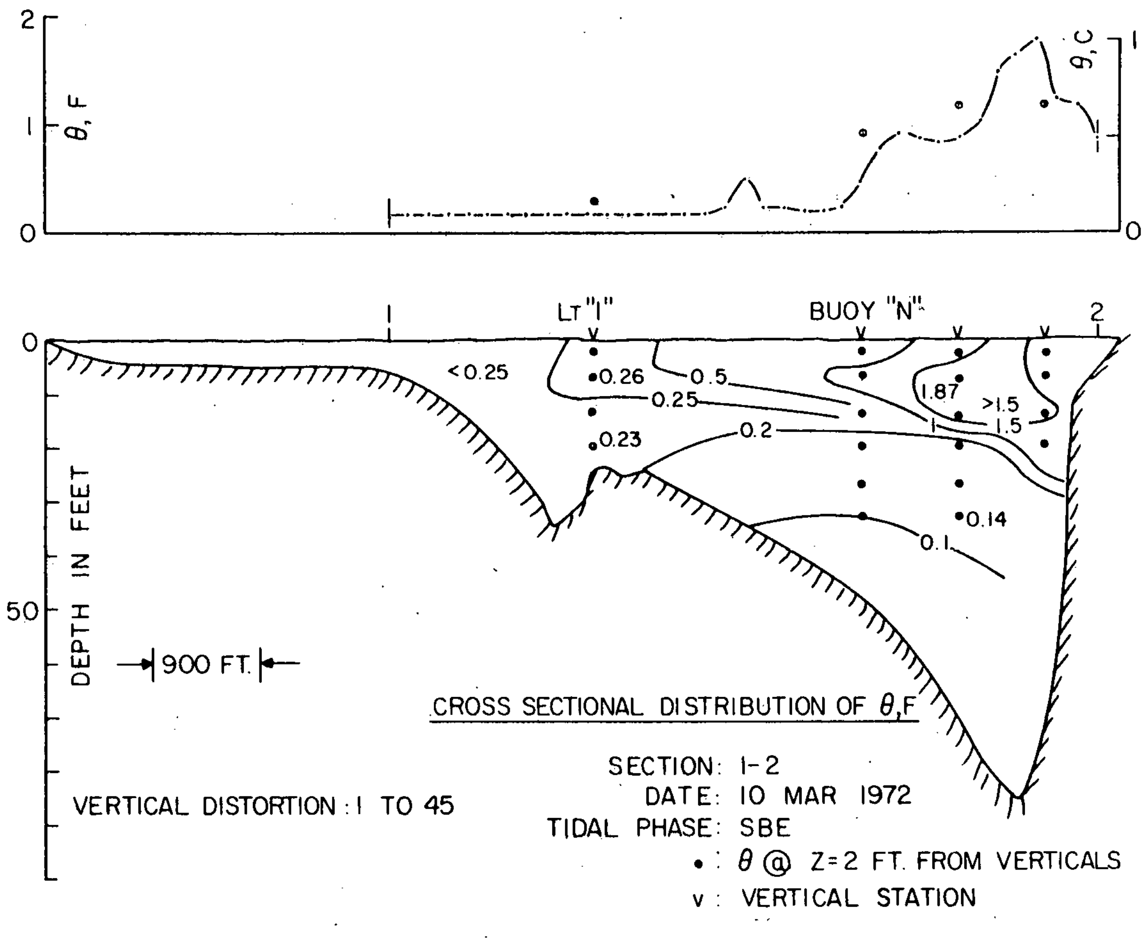

Figure 46. Cross-sectional distribution of excess temperature θ (scaled) at Section 1 - 2.

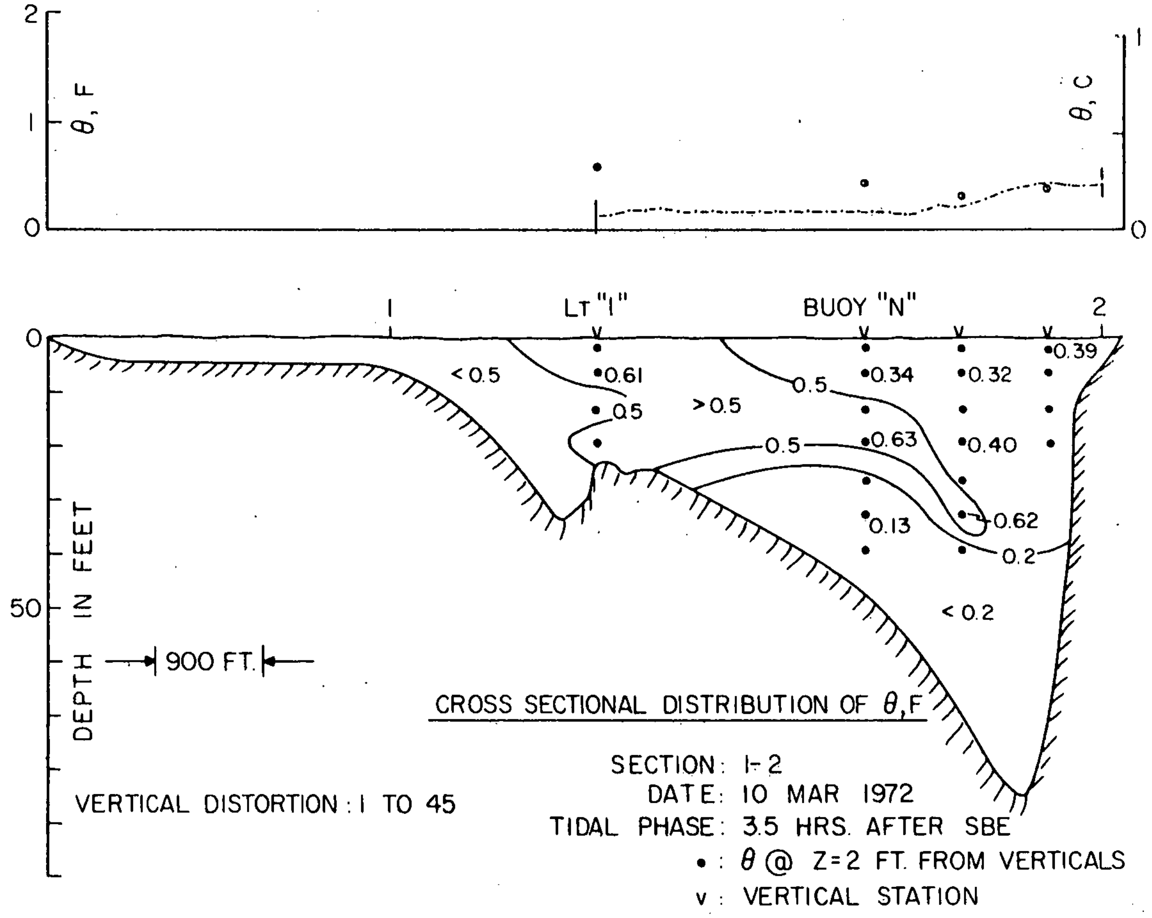

Figure 47. Cross-sectional distribution of excess temperature θ (scaled) at Section 1 - 2.

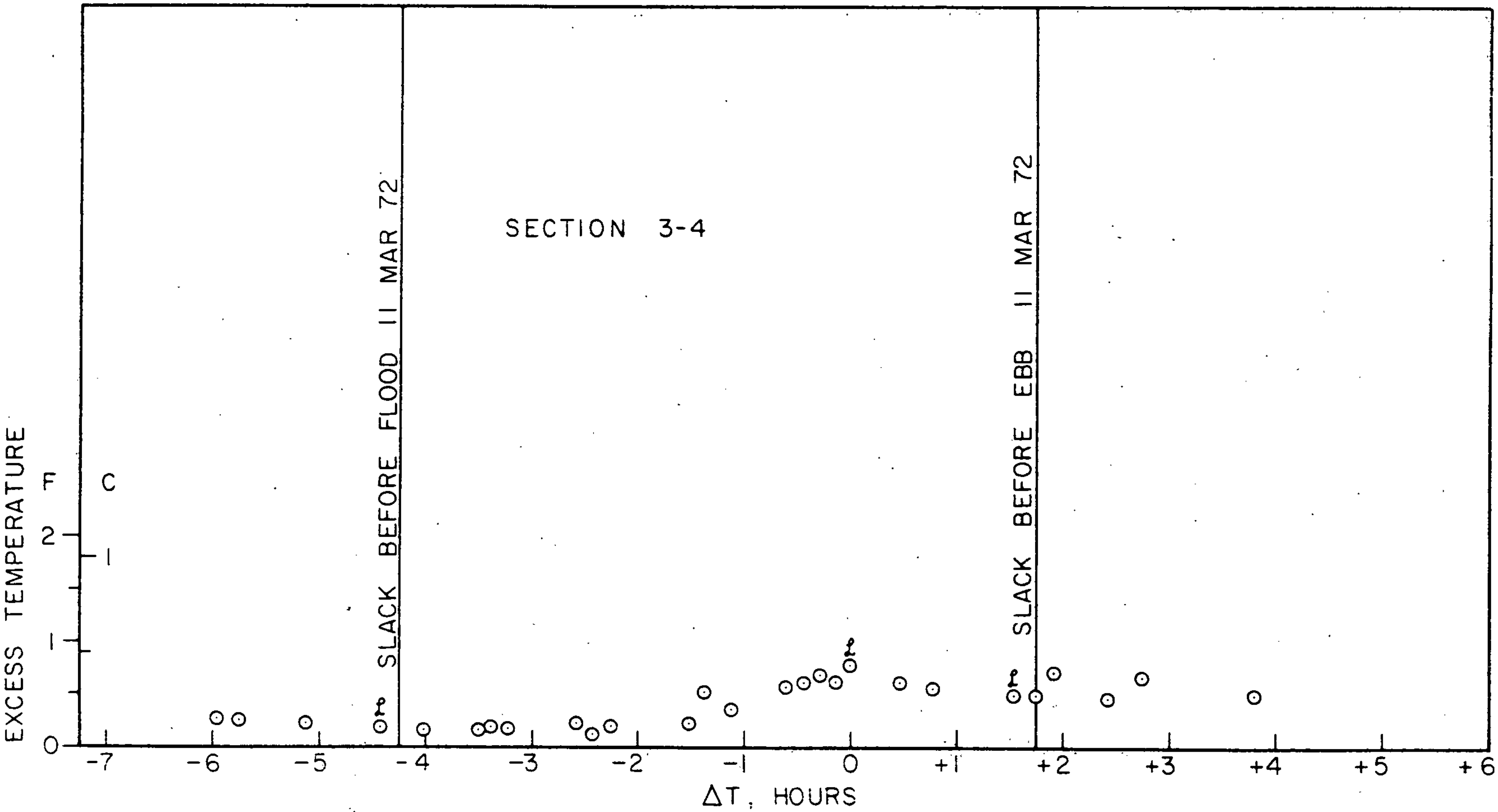

Figure 48. Excess temperature θ (scaled) as a function of time during flood tide at Section 3 - 4 upstream from the discharge.

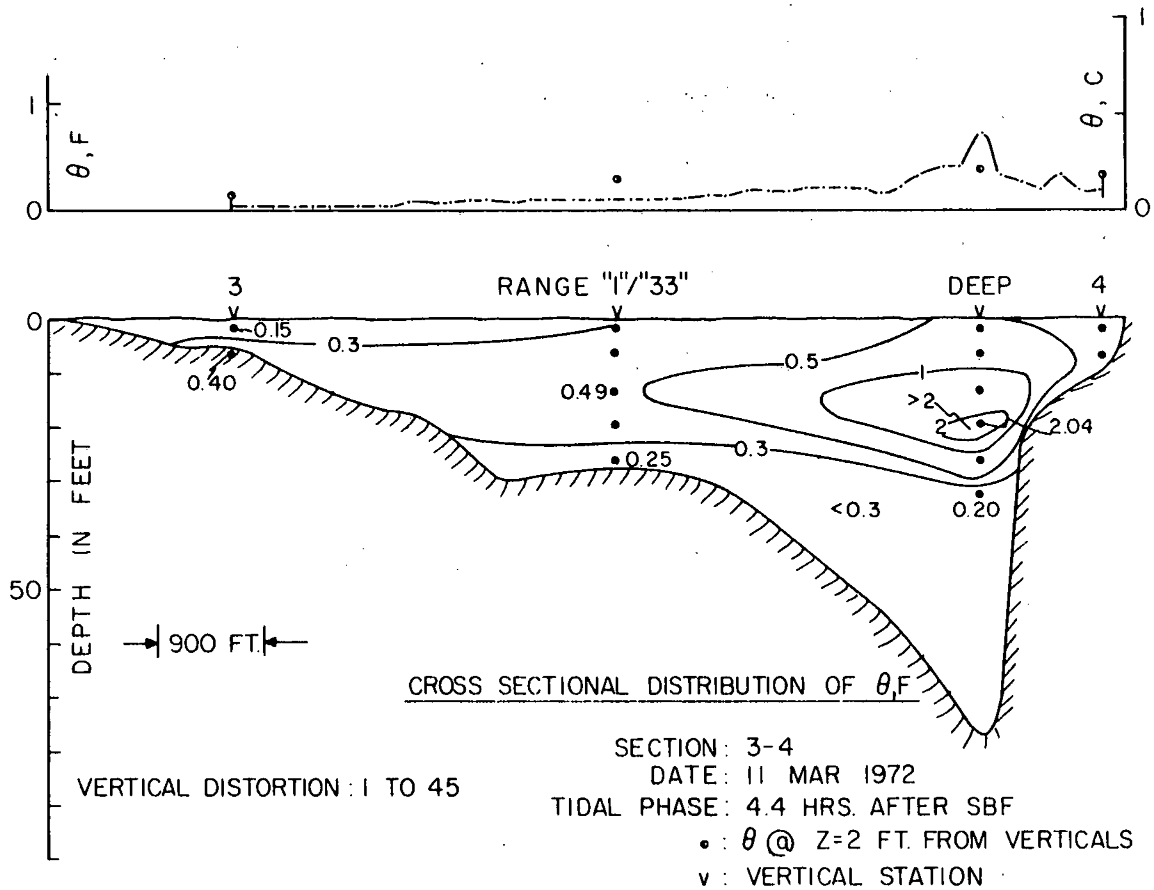

Figure 49. Cross-sectional distribution of excess temperature θ (scaled) at Section 3 - 4.

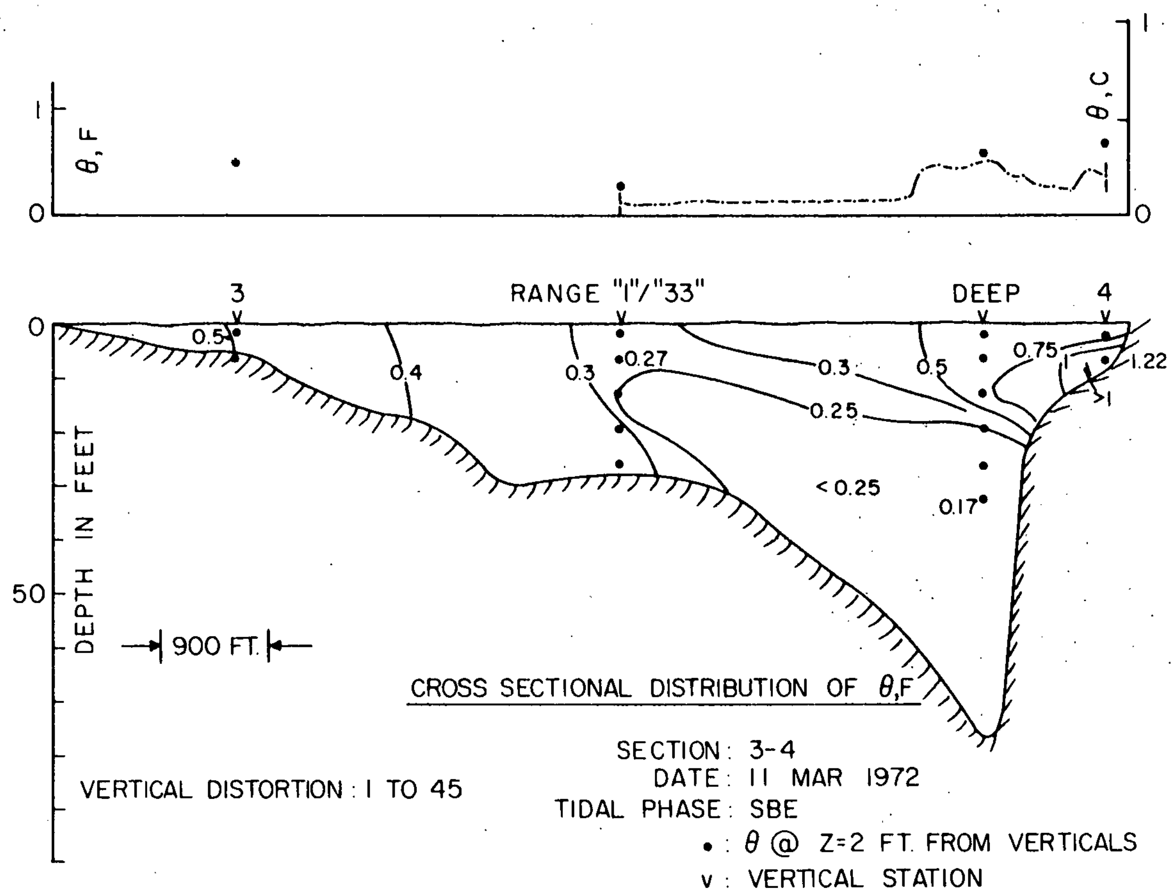

Figure 50. Cross-sectional distribution of excess temperature θ (scaled) at Section 3 - 4.

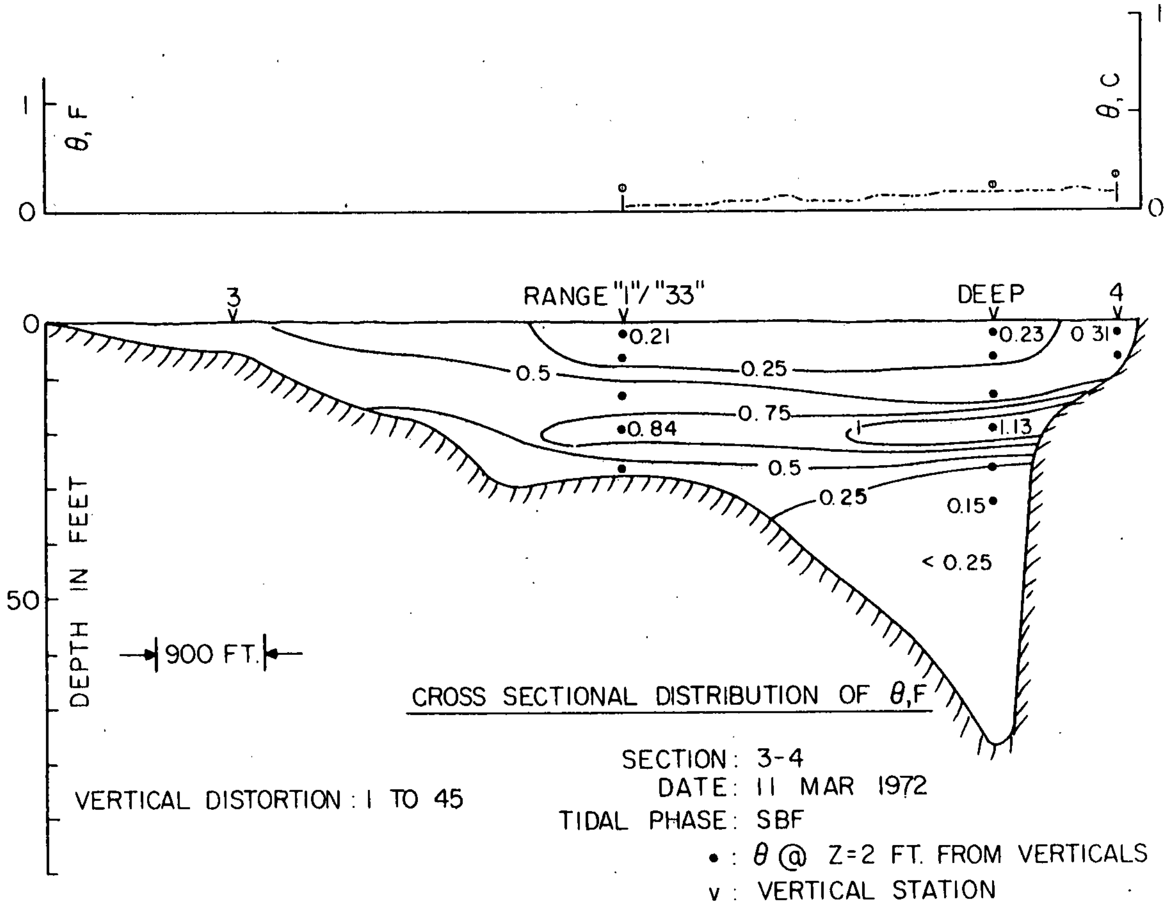

Figure 51. Cross-sectional distribution of excess temperature θ (scaled) at Section 3 - 4.

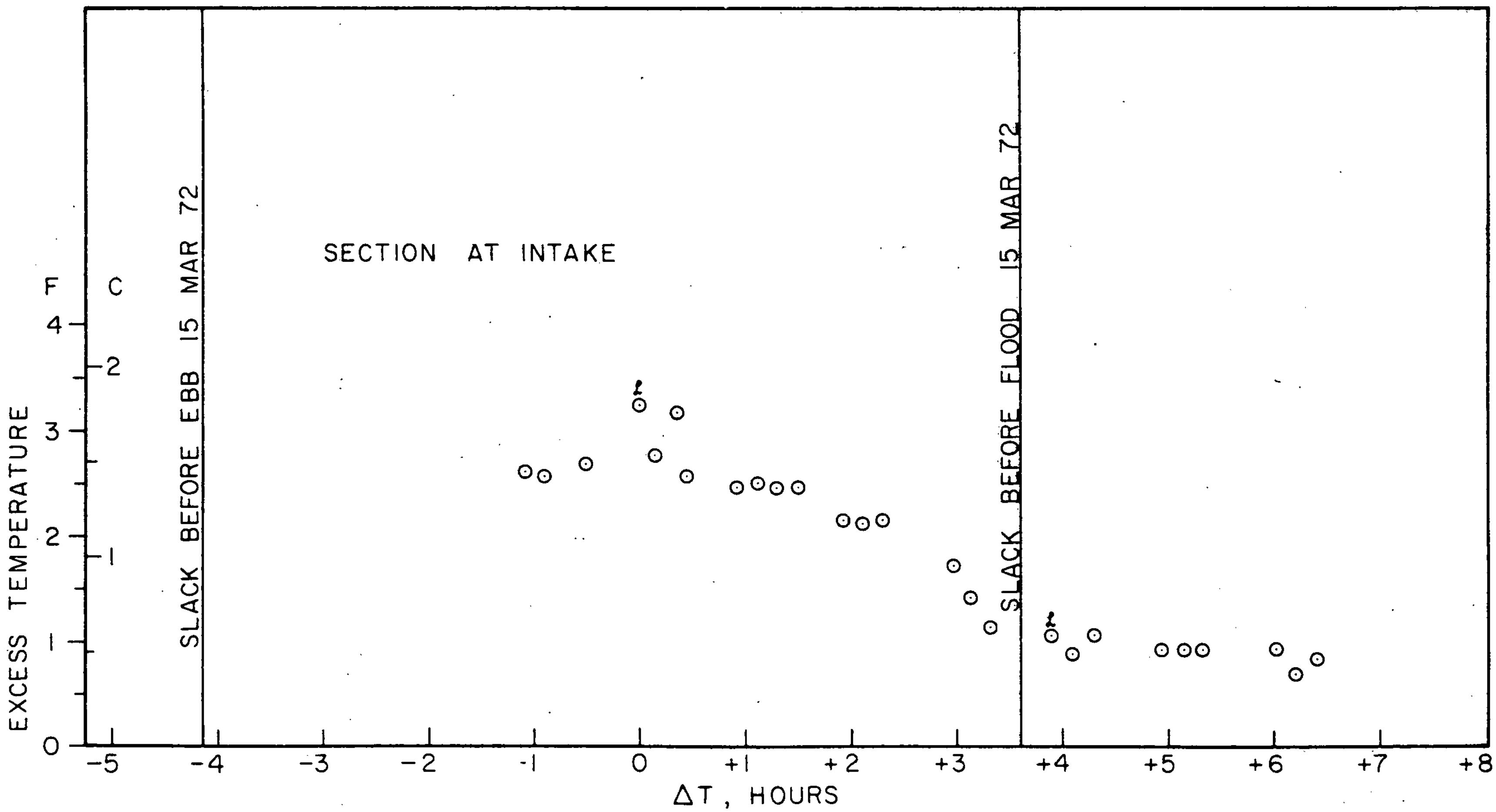

Figure 52. Excess temperature θ (scaled) as a function of time during ebb tide at section at intake.

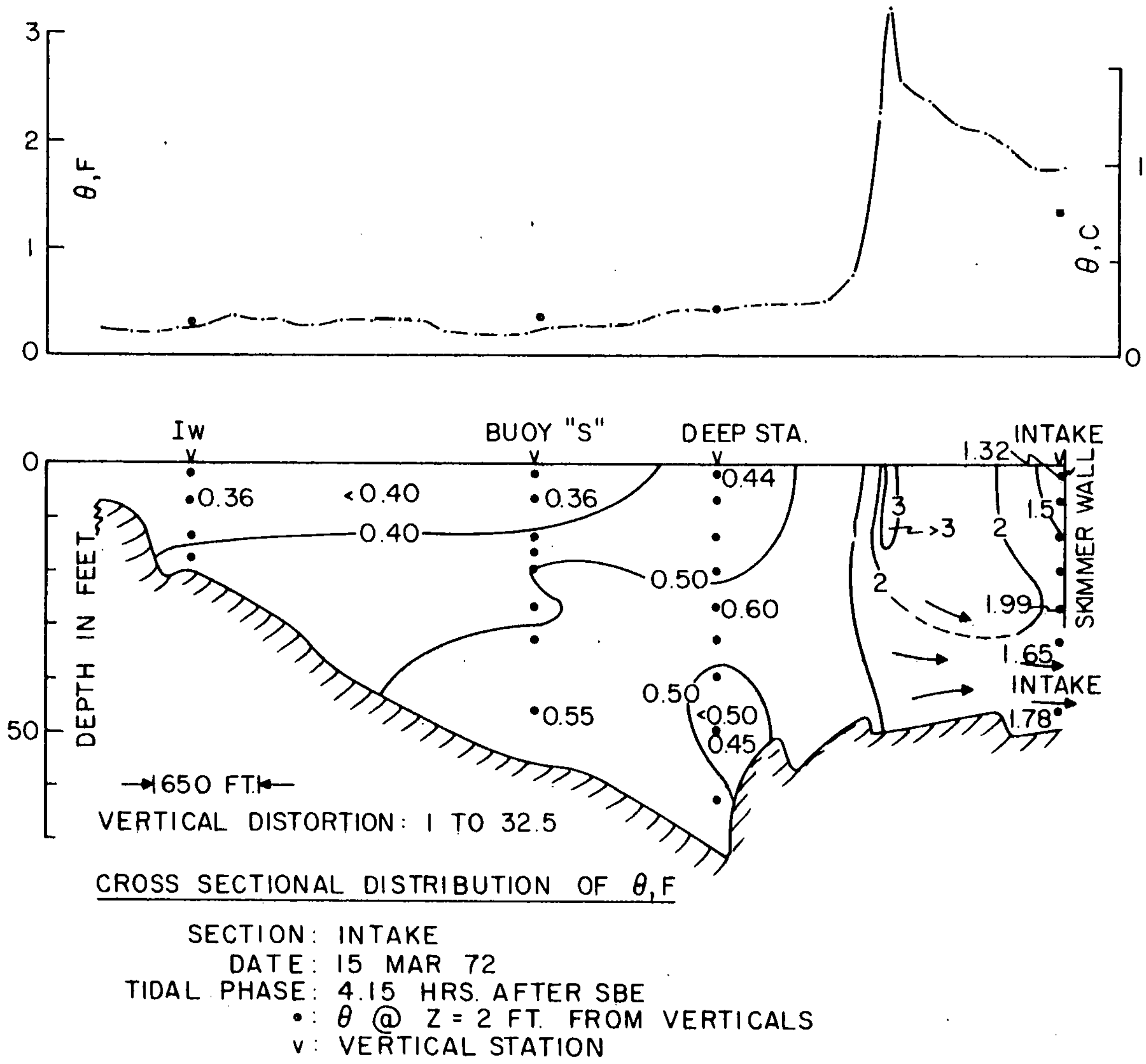

Figure 53. Cross-sectional distribution of excess temperature θ (scaled) at section at intake.

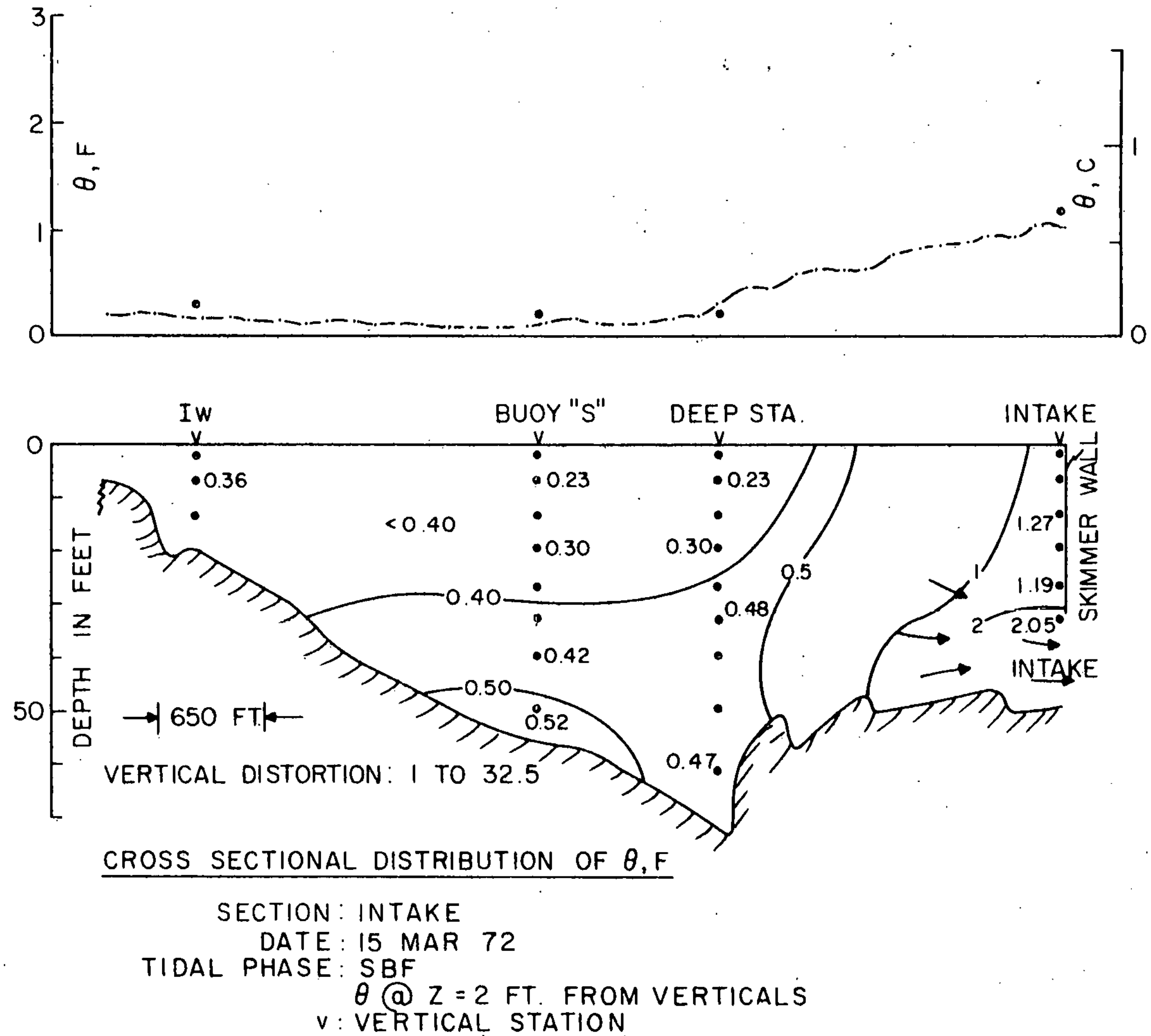

Figure 54. Cross-sectional distribution of excess temperature θ (scaled) at section at intake.

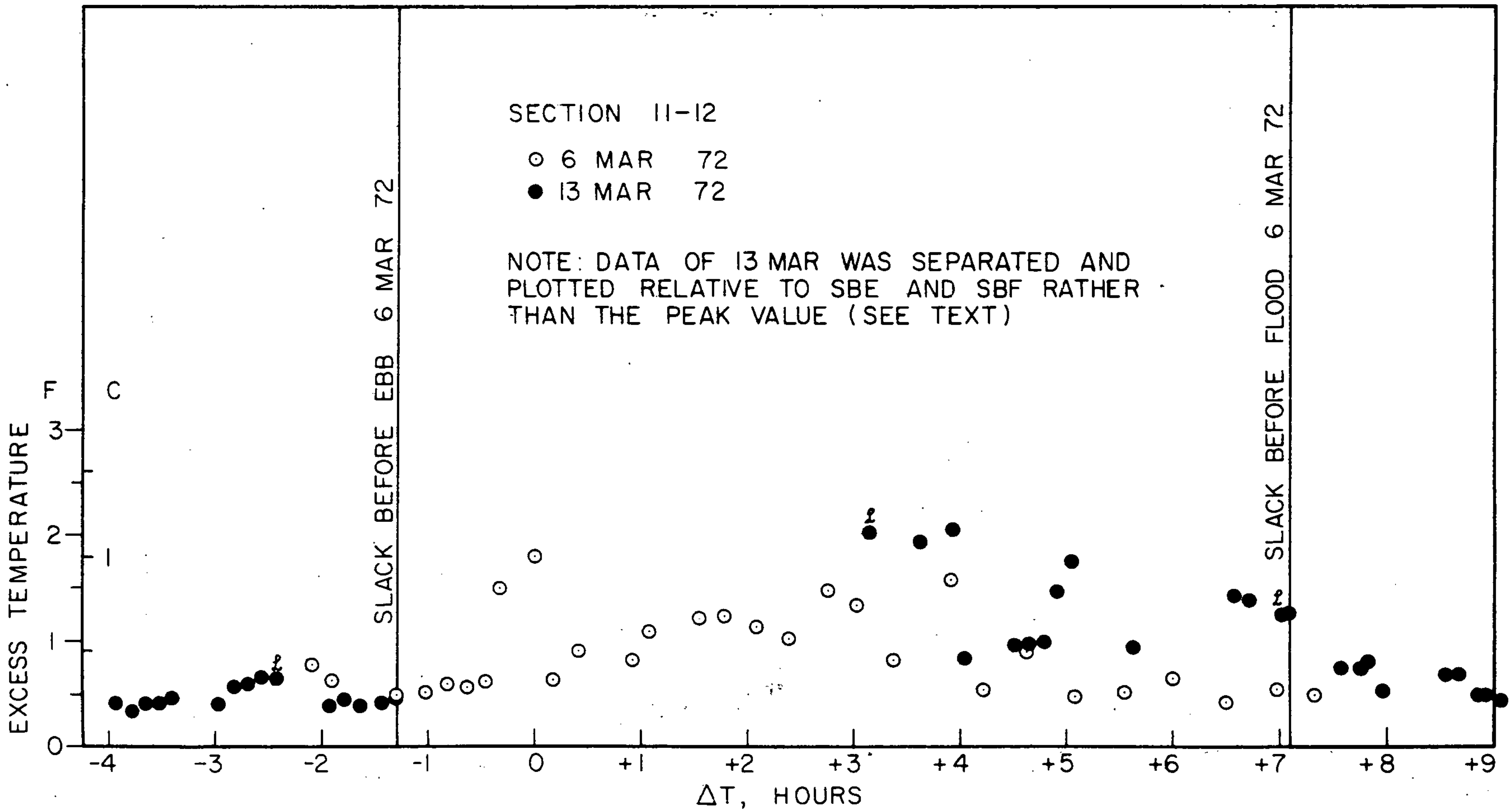

Figure 55. Excess temperature θ (scaled) as a function of time during ebb tide at Section 11 - 12 downstream from the discharge.

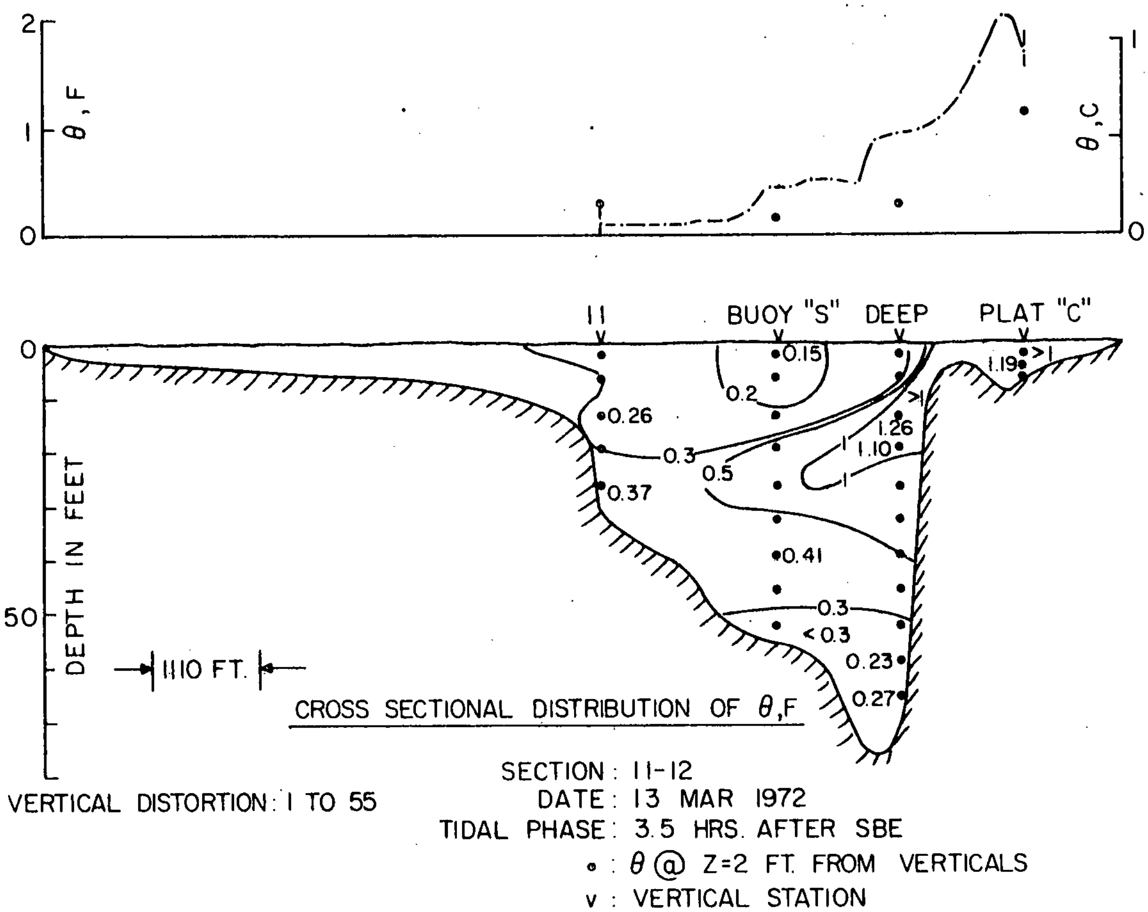

Figure 56. Cross-sectional distribution of excess temperature θ (scaled) at Section 11 - 12.

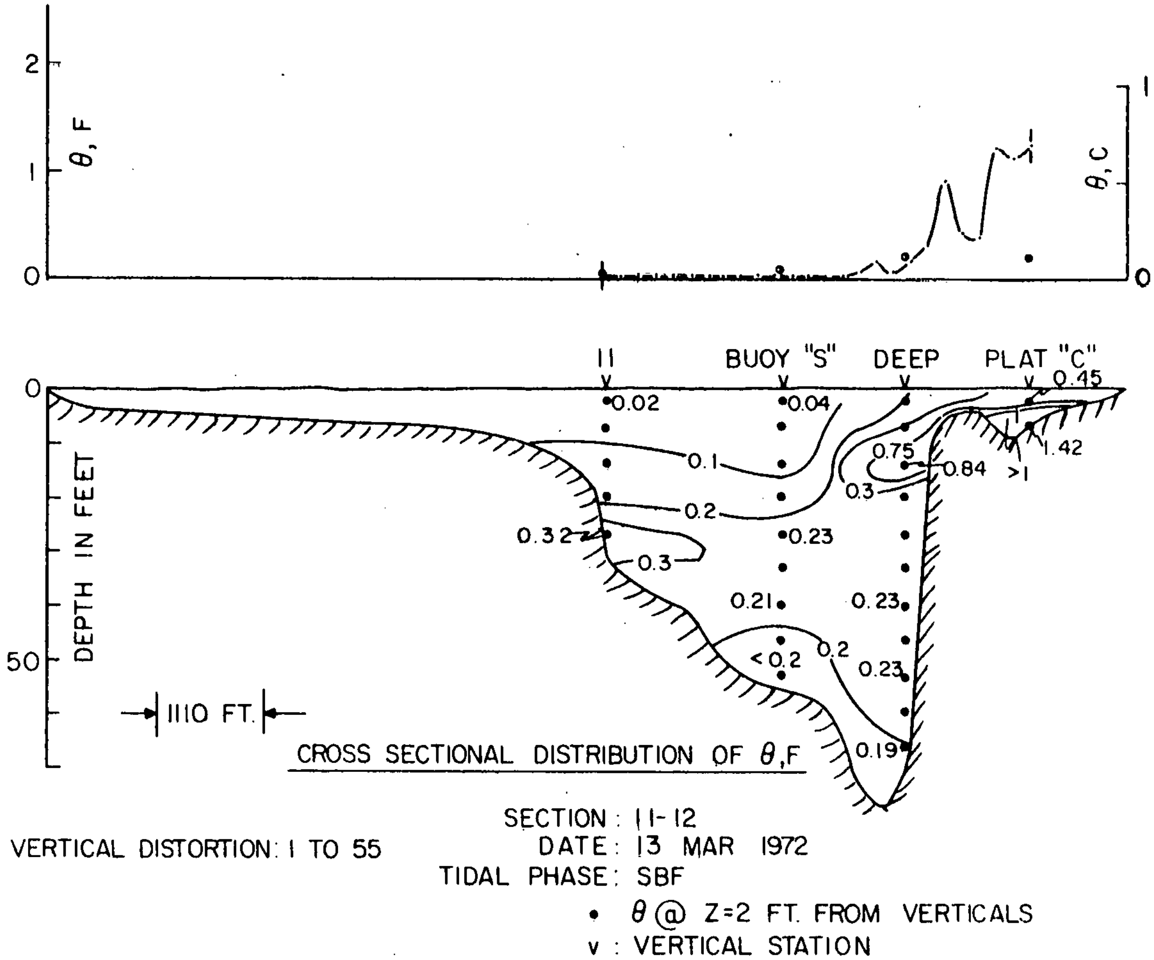

Figure 57. Cross-sectional distribution of excess temperature θ (scaled) at Section 11 - 12.

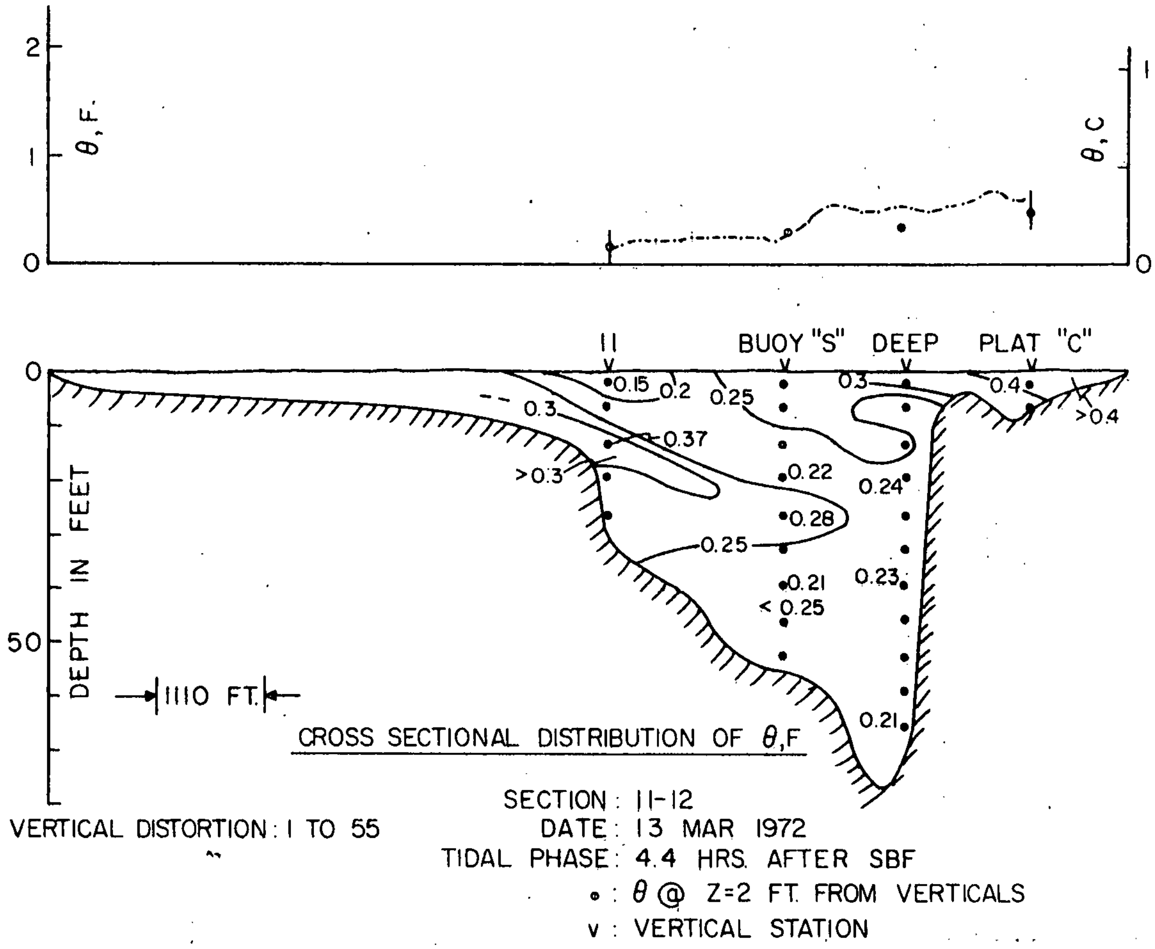

Figure 58. Cross-sectional distribution of excess temperature θ (scaled) at Section 11 - 12.

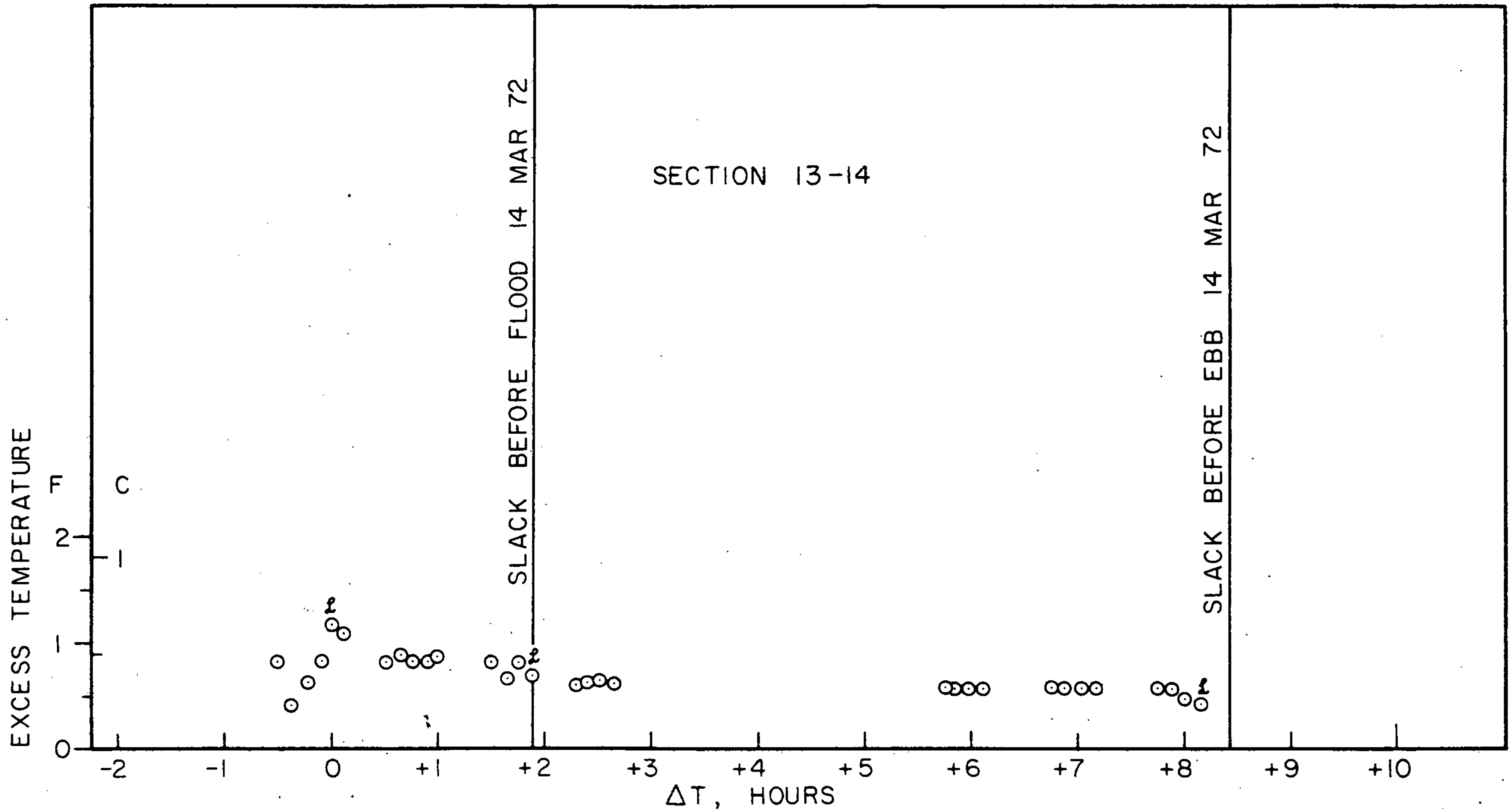

Figure 59. Excess temperature θ (scaled) as a function of time during ebb tide at Section 13 - 14 downstream from the discharge.

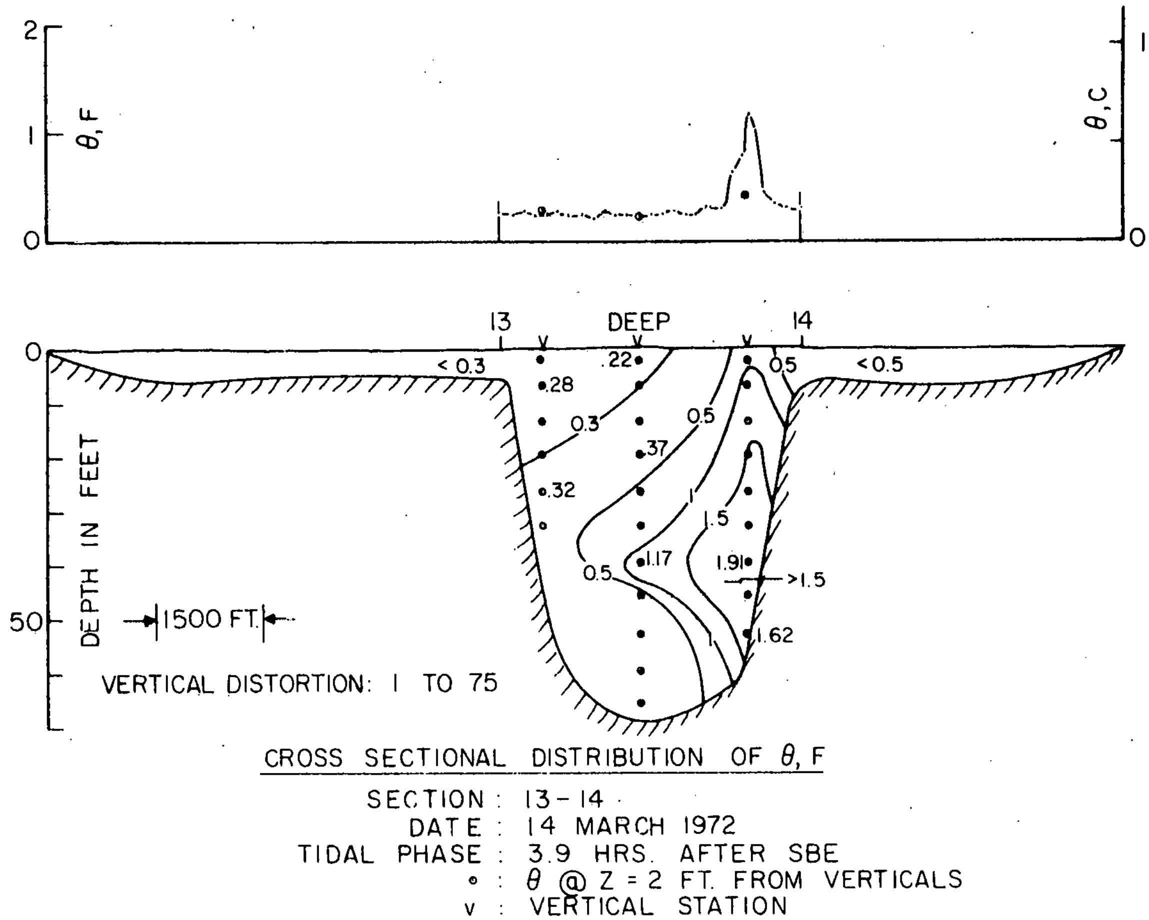

Figure 60. Cross-sectional distribution of excess temperature θ (scaled) at Section 13 - 14.

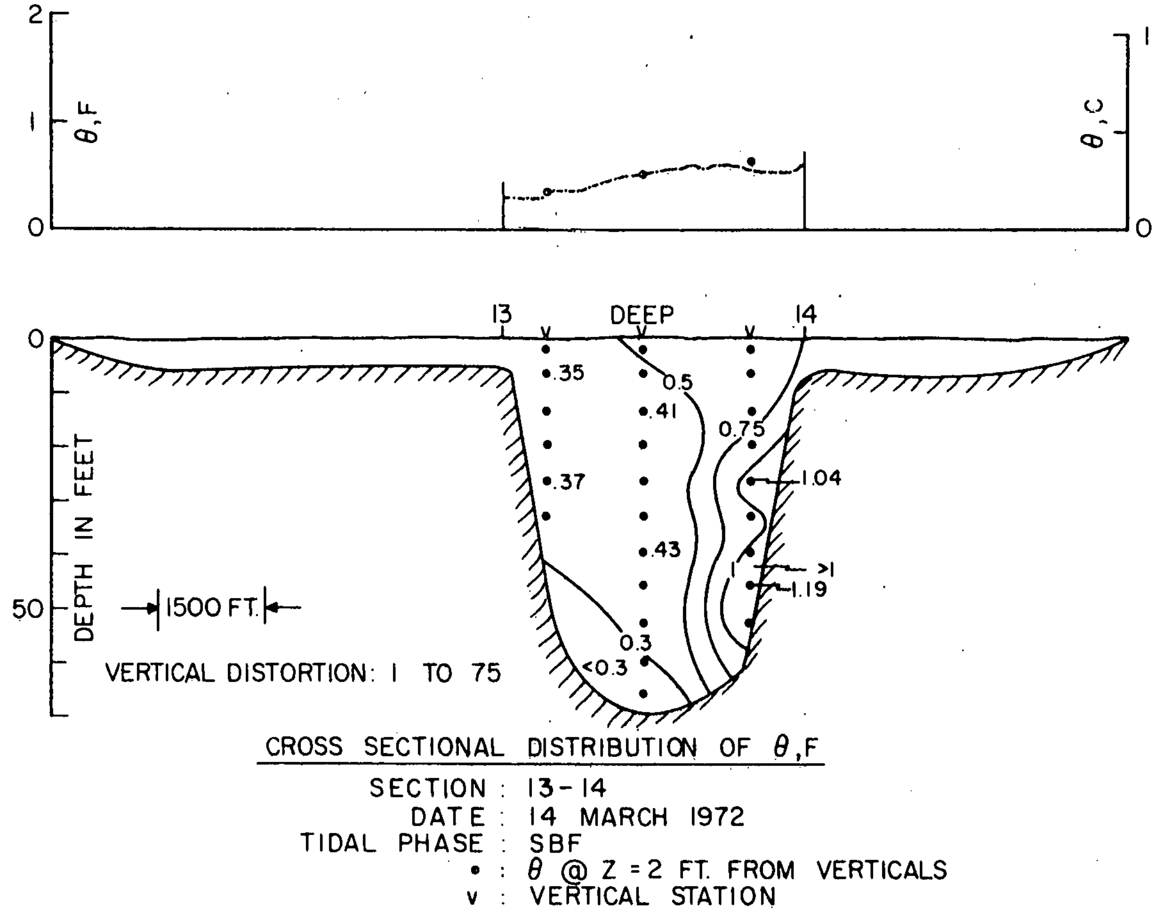

Figure 61. Cross-sectional distribution of excess temperature θ (scaled) at Section 13 - 14.

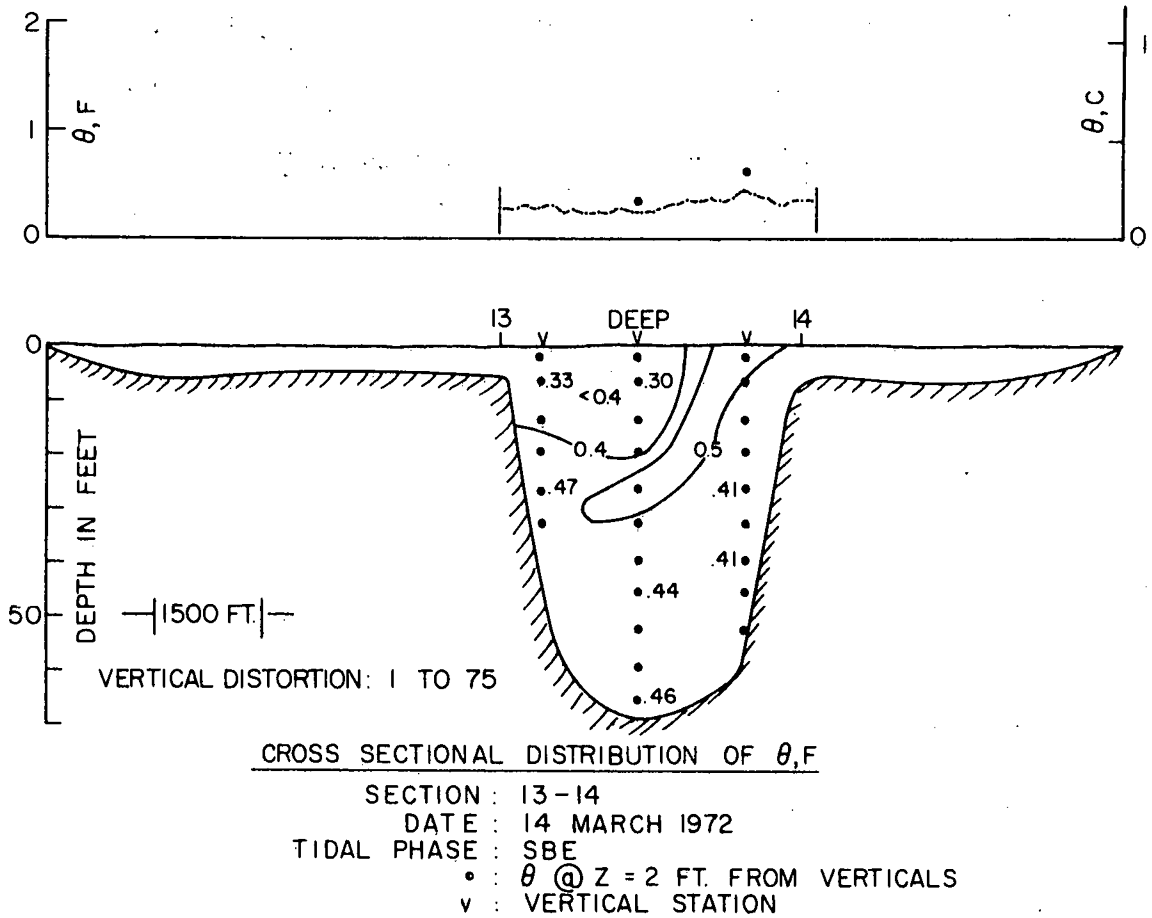

Figure 62. Cross-sectional distribution of excess temperature θ (scaled) at Section 13 - 14.

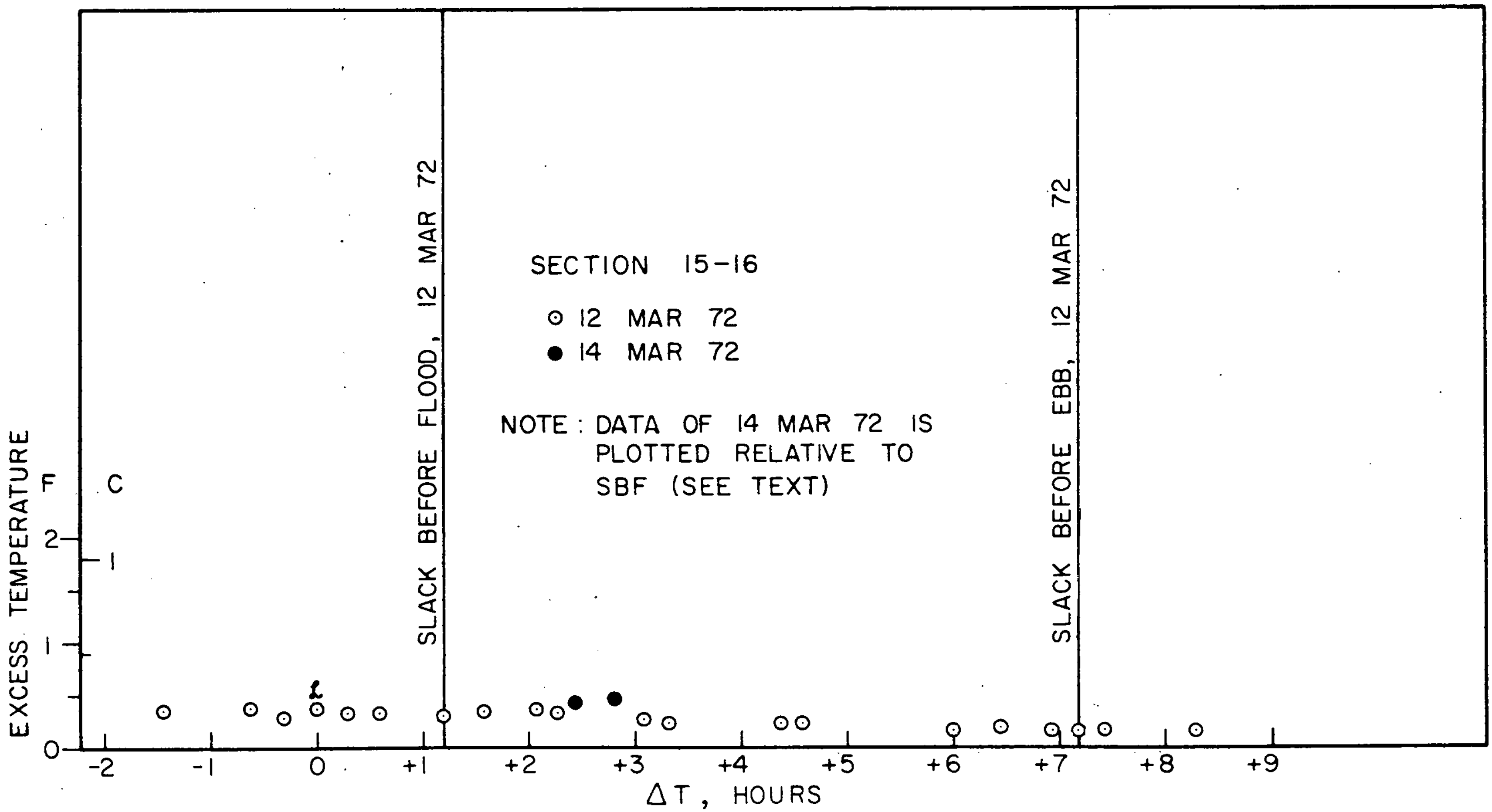

Figure 63. Excess temperature θ (scaled) as a function of time during ebb tide at Section 15 - 16 downstream from the discharge.

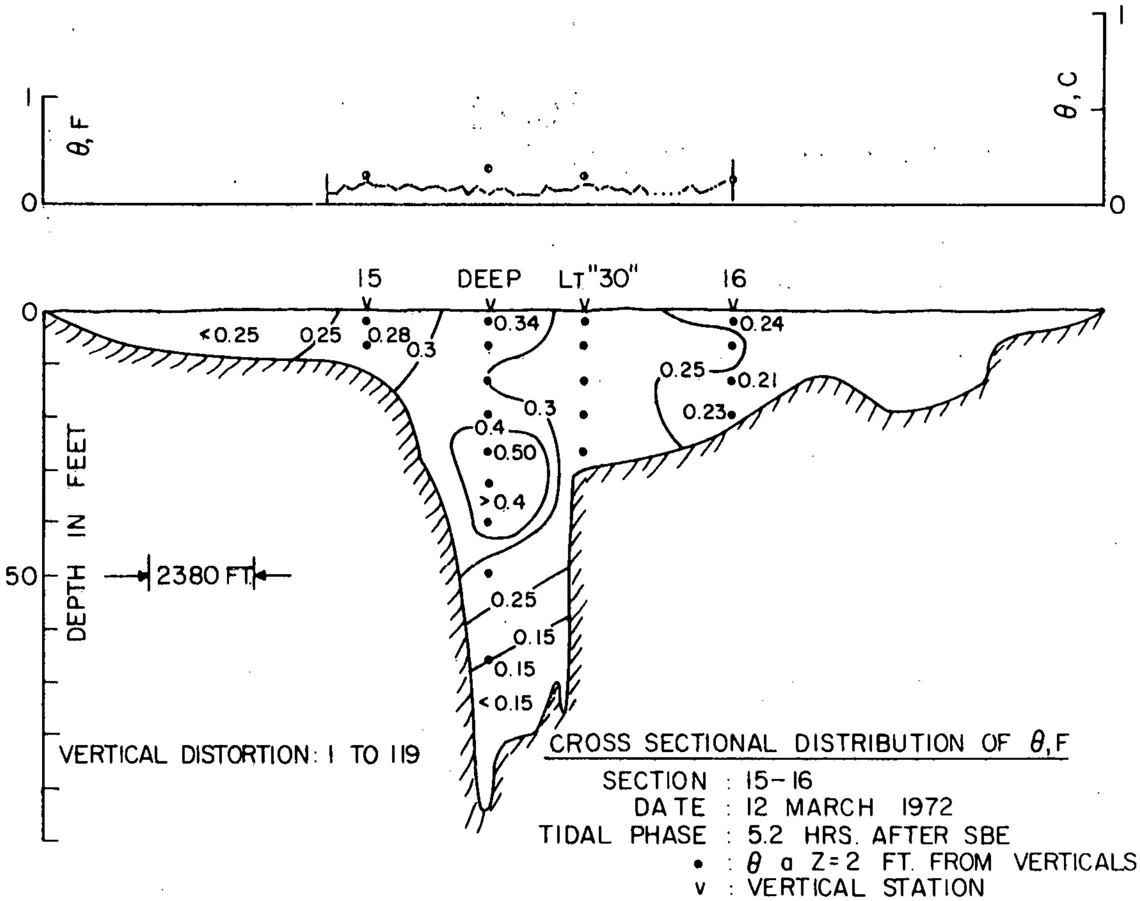

Figure 64. Cross-sectional distribution of excess temperature θ (scaled) at Section 15 - 16.

V. Discussion.

The Potomac River estuary may be classified as a partially mixed estuary; in such an estuary, the salinity decreases in a more or less regular manner from the mouth toward the head. The salinity also increases with depth at any given location. The upper, less saline, layer has a net non-tidal motion directed toward the mouth of the estuary, while the lower, more saline, layer has a net non-tidal motion directed toward the head of the estuary. This net non-tidal circulation pattern involves flow volumes large compared to the river discharge, Q_f, but small compared to the oscillatory tidal flow. In general, the volume rate of flow of the net non-tidal circulation increases toward the mouth of the estuary. As the river flow decreases, the salinity distribution moves up the estuary; thus in general, the higher the salinity, the larger the ratio of net non-tidal flow to river flow. At a given section, even though the water available for dilution of an introduced tracer increases with increasing salinity, it does not change in direct proportion to Q_f. That is, the estuary is somewhat buffered against large changes in available dilution water.

The tidally averaged cross-sectional mean concentrations(when the tracer or excess heat is fully mixed into the available dilution water) are given by

$$< \overline{C} > = q_d/\text{Available dilution water, and}$$

$$< \overline{\theta} > = \theta_o Q_c/\text{Available dilution water}$$

where q_d is the release rate of dry dye, Q_c is the cooling water flow rate, θ_o is the temperature rise across the condensers, overbar denotes a cross-sectional mean, and $< >$ denotes an average taken over a tidal cycle. $< \overline{C} >$ or $< \overline{\theta} >$ is termed the far field and is the concentration upon which the near field or plume is superimposed. It is apparent from the 1969 and 1972 results that the excess heat was not fully mixed into the available diluting water. However, it is estimated that $< \overline{\theta} >$ is of the order of 0.5 to 0.75°F or less[4] (Figures 25, 26, 28, 29, and 64) for both 1969 and 1972; the available diluting water is, therefore, of the order of 10 to 20 times the cooling water flow Q_c (2232,32 cfs).

It is clear from even a cursory examination of the 1969 and 1972 results (tracer concentrations scaled to excess temperatures at the same place and same tidal phase) that the added heat was much better mixed in the estuary in 1972 than in 1969. In 1972 peak temperatures were lower at all sections, the vertical extent of the excess heat was greater in 1972 at close-in sections (compare Figs. 11 and 49), and the horizontal extent of the excess heat was greater in 1972 at distance (compare Figs. 25 and 64). Based on the arguments of the first paragraph of this section, the available diluting water must have been larger in 1969 than in 1972 since the mean salinity in the vicinity of the plant was larger by a factor of 2 in 1969 than in 1972. In view of this, differences in available diluting water could not have contributed to the differences in the near and intermediate fields of excess temperature which we wish to account for.

In 1969, the tracer was introduced into the system in a small flow (4 gpm) at a relatively high concentration (200 ppm); in 1972 it was discharged into the system as a large flow (2232.32 cfs) at a low concentration (1.53 ppb). In 1972 the effluent was discharged with large ini-

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[4] Uncorrected for surface cooling.

tial inertia; in 1969 it was essentially without inertia. In 1972 the plume sank; in 1969 it remained on the surface. It is apparent from Figures 8, 9, 21, and 22 that Sections 1-2, 3-4 and 13-14 are within the influence of the discharge since the peak excess temperatures (scaled) exceed θ_o. In Table 2 are listed the peak excess temperatures (scaled) measured over a tidal cycle at sections common to both experiments. The values in parentheses for Sections 1-2, 3-4 and 13-14 for 1969 are estimated values based on injecting the same amount of tracer per unit time in a cooling water discharge of 2232.32 cfs. The tabulated values for 1972 are from 2 to 5 times lower than comparable values for 1969.

Table 2

	Peak Excess Temperatures, F	
Section	1969	1972
1 - 2	$> \theta_o$ (9)	3.83
3 - 4	$> \theta_o$ (7)	2.04
13 - 14	$> \theta_o$ (6)	1.91
15 - 16	2.24	0.50

( ) estimated correct value if tracer metered into Q_c .

A sinking plume, of course, is diluted by receiving waters (far field) being mechanically entrained into the jetted effluent around its entire periphery and not just the underside as is the case with a surface plume. Navifacial reflections are reduced if not eliminated and *a potential doubling of the dilution is possible.*

In addition, there is a downward vertical velocity introduced between the level of the discharge and the intake level by the pumping action of the plant. Its value is Q_c divided by the effective area from which the intake is drawing water. It is not possible to quantitate this effect in the instant case, but it is not negligible.

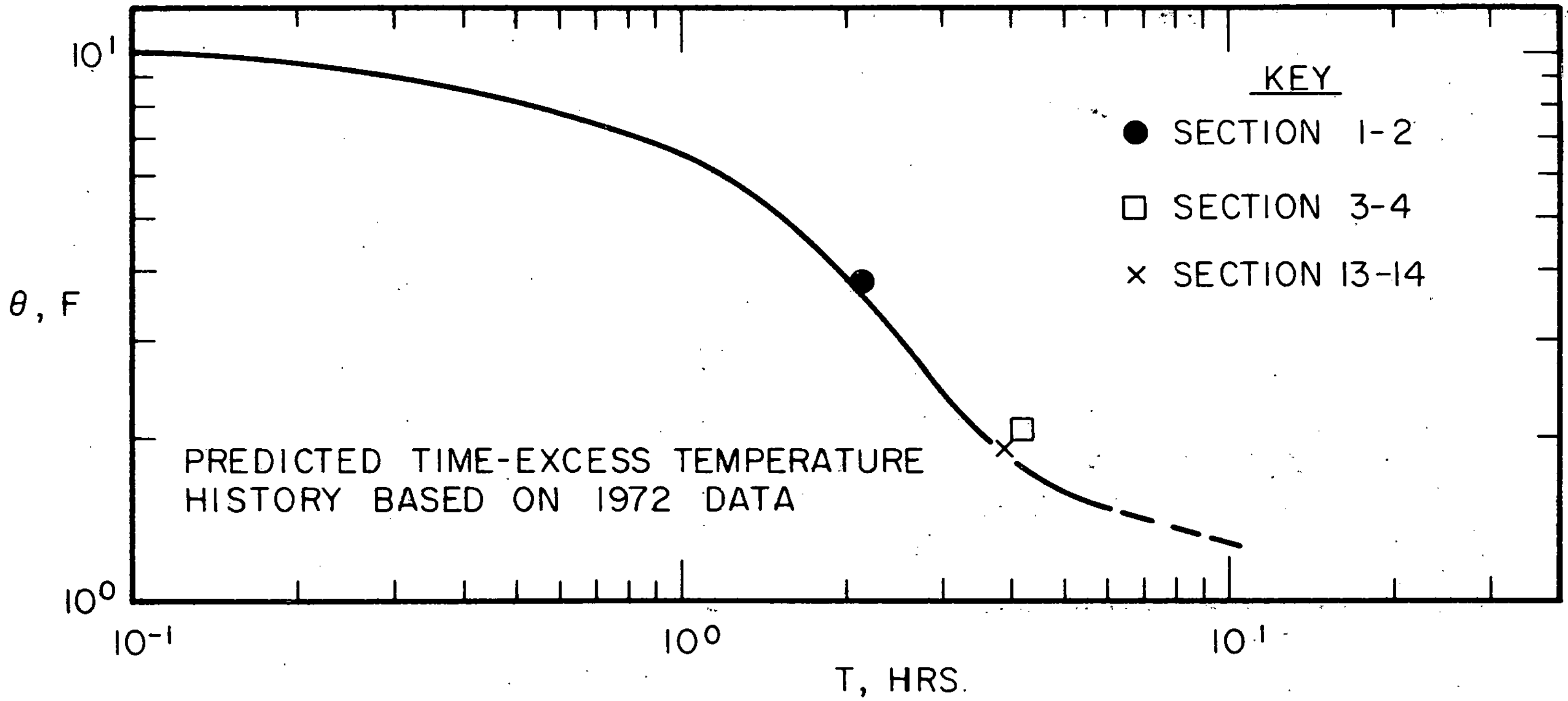
Although not pertinent to the 1969 results, a heated discharge can also affect the vertical turbulent thermal diffusivity in certain areas. That is, a sinking plume will sink until it is neutrally buoyant with respect to its surroundings whereas a surface plume will be positively buoyant. The turbulence structure at the interfaces will be quite different in these two cases with the former tending to enhance the vertical mixing and the latter to inhibit (in some cases prohibit) vertical mixing. This could not have been a factor in 1969 since the tracer was injected without excess heat and the estuary was essentially without thermal stratification at that time.

The primary reason for the differences noted in Table 2, however, is the difference in initial momentum between the two sources. The advantages of discharging heated effluents as high velocity jets are well-known and will not be repeated here; the results shown in Table 2 are considered to be proof of this assertion.

Our results have been examined superficially with respect to dependence of peak excess temperatures on downstream distance. This analysis, not presented here, shows that available momentum jet models of heated discharges need modification to account for negative buoyancy, entrainment of ambient fluid at concentrations other than zero (the far field and intermediate field), and oscillatory flow. It is our intent to utilize these results in future predictive modeling for natural systems of this type.

A word or two about ν_b, the background temperature. Figures 35 through 42 show variations in the background temperature with depth, time (diurnal), and lateral (cross-estuary) distance at various sections. The data are presented here to illustrate some of the problems associated with interpreting thermal plume measurements under the assumption of a constant background temperature. These figures show that the background temperature varied during the 1972 experiment by as much as 1.0°F diurnally, by as much as 2.5°F with depth, and by as much as 0.5°F laterally. Some of this variance is probably due to misestimating the background temperature by not correcting for surface cooling. However, it is felt that these background variations are real for the most part and must be taken into account if a thermal plume analysis is to properly delineate the field of excess temperature. It is hard to understand the value of collecting baseline temperature data since it is so highly dependent on position, time of day, season, and even year. The thermal effect of the plant can only be arrived at by the techniques described in this report.

It is hoped that the 1972 results will have value to aquatic biologists working on thermal effects problems. That is, typical time-excess temperature relationships for benthic organisms are readily obtainable from the figures; for organisms that are carried through the plant with the cooling water, a *worst case* time-excess temperature history has been constructed from the data and is shown in Figure 65. In constructing this history, it has been assumed that the organism was discharged with the cooling water at slack water. This is considered to be the worst case since the effluent is less diluted in the vicinity of the discharge at slack water than at other times in the tidal cycle. From the point of discharge on, the organism remains at all times in the zone of highest excess temperature, Finally, from approximately 12 hours on (a complete tidal cycle), the organism is



KEY
SECTION 1-2
SECTION 3-4
SECTION 13-14
θ, F
10¹
10⁰
10⁻¹
10⁰
10¹
T, HRS.
PREDICTED TIME-EXCESS TEMPERATURE
HISTORY BASED ON 1972 DATA

Figure 65.

exposed continuously to the far field excess temperature (0.5 to 0.75°F) unless it is reentrained into either the cooling water intake or effluent.

It is of interest to note that coincidentally Figure 65 is almost identical[5] with time-excess temperature history labelled B3 used by Schubel (1973) in his classic studies of the effect of typical time-temperature exposure histories on blue-back herring, alewife, American shad, white perch, and striped bass eggs. Schubel's studies show that the hatching success and development of eggs of these species are essentially unaffected by time-temperature exposures typical of the time of spawning and existing Maryland power plants. Significant damage, if it occurs, must result from abrasion, pressure changes, or chlorination. This suggests that there is an optimum combination of condenser flow and θ_o for a minimal biological impact. Schubel has shown that because of the short period of time that an egg spends in the high temperature region of the plume, temperature rises of 20°F or less have little or no effect. *At the same time, however, reduction in the condenser flow decreases the probability that an egg will be drawn into the condenser intake.*

It was pointed out previously that an estimate of the "available dilution water" or "new" water that enters a segment off the plant per unit of time is given by

$$\text{Available dilution water} = \theta_o \, Q_c / \langle \overline{\theta} \rangle$$

or that the ratio of condenser flow Q_c to "new" water is

$$Q_c / \text{Available dilution water} = \langle \overline{\theta} \rangle / \theta_o \quad . \tag{7}$$

[5] Schubel's temperature maximum was 7°C whereas ours was approximately 6°F.

It should be noted that $\langle \bar{\theta} \rangle$ depends on the product of θ_o and Q_c, i.e., the heat rejection rate (not just θ_o), and ambient conditions in the receiving waters. Our estimate of this ratio was 0.05 to 0.10 (see page 83) or that 5 to 10% of the "new" or "available dilution water" passes through the plant. From equation (7) it may be seen that doubling θ_o reduces the probability of an organism passing through the plant by a factor of two (of the order of 1 in 20 to 40). *In light of this and Schubel's studies, it is felt that the Morgantown plant impact on the population at the time of spawning could be reduced by a factor of two by halving the condenser flow and doubling* θ_o *to 20°F.* It is understood that present water pollution control regulations (Rules and Regulations promulgated by the State of Maryland, Water Resources Administration 08.05.04.01 to 08.05.04.11) permit temperature rises across the condenser of greater than 10°F and it is hoped that future plant designs will incorporate the concept of variable θ_o and Q_c to accommodate seasonal biological requirements.

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