1971

The Effect of Run-off from Hurricane Camille on the Continental Shelf Waters of the Chesapeake Bight

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Recommended Citation

Elder, Robert Bruce, "The Effect of Run-off from Hurricane Camille on the Continental Shelf Waters of the Chesapeake Bight" (1971). *Dissertations, Theses, and Masters Projects.* Paper 1539617431.
https://dx.doi.org/doi:10.25773/v5-e49c-8988

THE EFFECT OF RUN-OFF FROM HURRICANE CAMILLE ON THE CONTINENTAL SHELF WATERS OF THE CHESAPEAKE BIGHT

A Thesis

Presented to

The Faculty of the School of Marine Science

The College of William and Mary in Virginia

In Partial Fulfillment

Of the Requirements for the Degree of

Master of Arts

by

Robert Bruce Elder

1971

APPROVAL SHEET

This thesis is submitted in partial fulfillment of
the requirements for the degree of

Master of Arts

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Approved, August 1971

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ACKNOWLEDGMENTS

The writer wishes to express his appreciation to Dr. Robert J. Byrne, under whose guidance this investigation was conducted, for his patient guidance and thoughtful criticism throughout the investigation. Special acknowledgment is due John J. Norcross, whose freely shared wealth of experience contributed greatly to the study. The author is also indebted to Evon P. Ruzecki for his review of the manuscript. The author is also greatly indebted to those personnel associated with the Virginia Institute of Marine Science, especially Evon P. Ruzecki and John J. Norcross for the careful collection of the data which was made available to him.

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ABSTRACT

Huge amounts of rain fell on the water sheds and drainage basins of the James and York rivers as late stages of Hurricane Camille passed over the area. As a result an atypically high volume of fresh water flowed through the estuaries and into the sea. Personnel of the Virginia Institute of Marine Science conducted two cruises to study the distribution of this discharge in the marine environment.

By analysis of these and other supplementary data and by relating them to similar oceanographic data obtained during the previous several years, a fairly good idea of the chronology of the Camille discharge and its effect on the shelf waters of the Chesapeake Bight was obtained.

The distribution within the Chesapeake Bight of fresh water discharge from Hurricane Camille was found to be closely associated with local surface winds. The amount of admixed fresh water in general was found to be a function of the sum of fresh water discharge into the area over several previous months.

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INTRODUCTION

Hurricane Camille was one of the most severe hurricanes on record, having winds up to 175 knots and causing record storm surges along the Gulf Coast and record rains and floods in southwestern Virginia (DeAngelis, 1970). Hurricane Camille originated just west of Dakar, Senegal, on August 5, 1969, continued to develop and was responsible for widespread rains when she passed through the Leeward Islands on the 10th of August. She crossed Cuba on the night of the 15th with winds between 80 and 100 knots and then intensified greatly in the Gulf of Mexico. On August 17 the Air Force reported her near the mouth of the Mississippi River with winds at 175 knots. Many Mississippi coastal towns were destroyed by tides as much as 24.2 feet above mean sea level. Camille weakened as she passed through Mississippi and on the 18th of August, Jackson, Miss., reported comparatively low winds of 58 knots in gusts. Camille continued to weaken as she traveled eastward, dumping up to six inches of rain in parts of Tennessee, Kentucky and West Virginia. "As the storm's remnants moved into the Appalachian and Blue Ridge mountains of southwestern Virginia on the 19th, they intensified rapidly and produced record rainfall amounts in a small concentrated area over the James River Basin" (DeAngelis, 1970). Up to 28 inches of rain fell in Nelson County within an eight hour period, causing record high floods along the James River from Lynchburg, Virginia, to Richmond, Virginia. In Richmond the flood waters peaked on the 22nd of August at a depth of 28.6 feet.

The York River drainage basin was also affected by rainfall from Camille. Here rainfall was augmented by water from several reservoirs in which the retaining structures failed (Brehmer, 1970). River discharge records show a peak discharge in the York River System near Beulahville, Virginia, and near Hanover, Virginia, on the 23rd of August. Although not as seriously affected by Camille, the Rappahannock had a maximum discharge on the 21st of August.

Records indicate that these river flows peaked very rapidly and returned to almost normal nearly as rapidly (Fig. 1). It is with the subsequent effect of this abnormally high surge of water on the shelf waters of the Chesapeake Bight that this study is concerned.

OBJECTIVES

The basic objective of the study is to describe the influence of the atypically high fresh water discharge caused by Hurricane Camille (hereafter called Camille discharge) on the content and distribution of admixed fresh water in the area of study within the Chesapeake Bight (Fig. 2).

A second objective is to describe the oceanographic conditions that prevailed in the study area in previous years in an attempt to provide a reference with which to compare the oceanography of the area while the Camille discharge was present.

A third objective is to describe the movement of the Camille discharge within the study area and relate this to causative forces.

PREVIOUS RESEARCH

Continental shelf waters of the East Coast of the United States have been studied extensively during this century. As early as 1912 Henry B. Bigelow initiated studies of the temperature and salinity distribution of the shelf waters between Cape Cod and the Chesapeake Bay (Bigelow, 1913). A. E. Parr (1933) studied the distribution of temperature based on observations from lightships. One of the first thorough descriptions of the temperature distribution from a seasonal point of view was presented by Bigelow (1933). A similar description of the seasonal salinity distribution was presented soon thereafter (Bigelow and Sears, 1935). Building on these investigations as well as several other subsequent studies (e.g., Miller, 1952; Bumpus, 1957; Day, 1959a, 1959b; and Joseph, et al., 1960), Norcross and Stanley (1967) presented a comprehensive account of the oceanography of the Chesapeake Bight. They reported the results of a program which included monthly releases of drift bottles and seabed drifters from cooperating Navy aircraft. Releases were made at selected stations over a period of 17 consecutive months, beginning in 1963. This information was supplemented by a systematic collection of temperature and salinity data by surface vessels from the Virginia Institute of Marine Science and the U. S. Coast and Geodetic Survey. This work contributed greatly to establishing the seasonal circulatory features of the Chesapeake Bight, particularly from the standpoint of bottom drift. In none of the work cited above was there an account of a sudden discharge of an atypically large amount of fresh water into the system relative to the seasonal norm such as that which occurred after the heavy rainfall from Hurricane Camille.

Literature on estuarine systems in other geographic areas shows no situation directly comparable to that resulting from Hurricane Camille. Other information germane to the research was included in the literature, however. Ketchum, Redfield and Ayers (1951) presented a study of the New York Bight based on data collected over several years. In addition to a monthly and seasonal description of the oceanographic features they included a brief description of the re-establishment of normal circulation after a southwest storm had destroyed the salinity pattern. Henry and Elder (1958) presented a study of the estuary-shelf system of the Mississippi River. Although almost continuous current measurements at several locations were obtained for approximately a year, a high sudden discharge of fresh water was not encountered.

Budinger, Coachman and Barnes (1964), and Duxbury, Morse and McGary (1966) presented the results of an extensive study of the Columbia River effluent. It is doubtful that a situation analogous to the effect of Hurricane Camille on Chesapeake Bay could occur in the Columbia River shelf area since the average annual discharge of the Columbia River is over twenty times that of the average of the combined annual discharge of the James, York, and Rappahannock rivers. Dissimilar shelf topography in the two areas also make comparison of mixing and dispersion of limited value. In addition to the literature cited above, informal inquiries failed to disclose investigations of sudden large discharges of water such as that caused by Hurricane

Camille. Therefore, the description contained herein should provide an additional step to a more complete understanding of the circulation of the area.

DATA AVAILABLE

In order to measure the effect of the Hurricane Camille discharge on the shelf waters of the Chesapeake Bight, personnel of the Virginia Institute of Marine Science conducted two surveys of the area seaward of the mouth of the Bay. Each of the surveys involved two ships. The area studied extended from the coast eastward to 75°22.5'E (approximately 40 miles) and from a southern boundary of 36°30'N to a northern boundary at 37°15'N, a distance of 45 nautical miles. The two surveys were entitled Operation Override I and II. Operation Override I (OOR-I) was conducted on the 28th and 29th of August, 1969, somewhat more than one week after Hurricane Camille passed over Virginia. Operation Override II (OOR-II) was conducted less than a week later on the 2nd and 3rd of September, 1969. Data from OOR-I and OOR-II are the main source of information used for determining the distribution of Camille water in the Chesapeake Bight (Fig. 2). Coincident to OOR-I the U. S. Coast Guard made an overflight of the study area to obtain the temperature distribution by airborne infrared radiation thermometry. In addition to data collected specifically to analyze the results of Camille, scientists from the Virginia Institute of Marine Science conducted a time series investigation at three locations within the study area. These were conducted over two complete tidal cycles (25 hrs.) on the 25th and 26th of August. Fortuitously at one location the effect of the Camille discharge was observed.

There also exists, in both published and unpublished form, a considerable amount of applicable data that has been collected routinely over a period of years. A major source of reference data was that collected during the VIMS "Shelf Hydrographic Survey" program conducted during the years 1966-1969. These data were in a form that allowed some quantitative comparisons to be drawn between the different cruises. In a less quantitative way, accounts of temperature and salinity distribution which appear in the literature were also used (Bigelow and Sears, 1935; Ketchum, Redfield, and Ayers, 1951; and Norcross and Stanley, 1967).

Other sources of data included surface and subsurface temperature and salinity data collected at Chesapeake Light Tower, Diamond Shoals Light Tower and Delaware Light Tower, by the U. S. Coast Guard. Wind observations from the above listed light towers plus observations at Wallops Island, Norfolk, Oregon Inlet, and Cape Hatteras were also available. Stream discharge data into Chesapeake Bay for years 1965-1969 were used to correlate with salinity distribution in the study area. Hourly tidal heights and times of high and low water for Hampton Roads and Virginia Beach were also used.

PROCEDURE

An important part of the interpretation of the regime of water properties of the area was based on fraction of fresh water. The amount of admixed fresh water in a marine system has been calculated a number of ways. Ketchum and Keen (1955) studied the accumulation of river water between Cape Cod and Chesapeake Bay and calculated the fraction of river water at any given point using the expression:

$$f = \frac{\sigma - s}{\sigma}$$

where f = fraction of river water

s = salinity of waters of the point in question

σ = salinity of the undiluted sea water of the area (35 ‰) (35.0 ‰ is the salinity of water found near the bottom along the continental slope).

Budinger, Coachman and Barnes (1964) used what they termed "the equivalent height of fresh water" in their study of the Columbia River discharge area. This is the equivalent height of the fraction of fresh water present if it could be separated from the ocean water. The equation used was:

$$H = \frac{32.5\, z^{*} - \int_{0}^{z} s\, dz}{32.5}$$

where H = equivalent height of fresh water

s = observed salinity

32.5 = salinity of the ocean background

z = the depth

z^* = the depth of the 32.5 isohaline

Tulley and Barber (1960) used an approach similar to that used by Budinger, Coachman and Barnes (1964).

The method used by Ketchum and Keen (1955) was employed in this study. Computation of fraction of fresh water allowed several quantitative comparisons to be made. Since the computed value of the fraction of fresh water is based solely on salinity the same comparisons could have been made with salinity values; however, fraction of fresh water seemed preferable for comparison with river discharge and for illustrative purposes. A computer program was written to convert individual salinity observations to fraction of fresh water and then to determine the weighted mean fraction of fresh water at each station. The output of this program was used as an input to a second program to determine the weighted mean fraction of fresh water in a given section. For these programs a linear distribution of salinity with depth and distance between stations was assumed. Depth used was the depth of water at the station and the distance between stations was determined in the program from the geographic position of the stations. This program also printed out the cross sectional area of the section which was later used to determine the weighted mean fraction of fresh water within the study area.

Vertical sections of temperature were constructed with a U. S. Coast Guard computer driven automatic plotter using a computer program developed by Coast Guard personnel. The resulting sections were quality controlled and smoothed by hand to yield figures of acceptable quality. A total of 102 sections was constructed and examined. Only those necessary for illustrative purposes are included in the thesis.

Contours showing the two-dimensional horizontal distribution of variables were drawn by hand.

In determining the effect of wind on the distribution of variables it was necessary to examine the wind regime from a local as well as regional point of view. To determine the regional wind effect, wind observations taken at six locations from Cape Hatteras to Wallops Island were used. Running five-day means were determined at each of the stations. Since three of the stations had observations only at six hour intervals, wind values recorded every six hours were used at all stations to compute the five day means.

In determining local wind effect, one-day running means at half-day intervals were determined. To reduce aliasing, hourly observations were desirable so data from the Norfolk Weather Bureau office were selected. Running means were determined with a computer program developed for the study which separates the wind observations into east and north components, sums and averages these components, and then recombines them into a mean wind. The number of observations per interval and the amount of overlap can be varied as desired.

The correlation coefficient used in comparing fraction of fresh water to river discharge was determined with a computer program prepared by programmers at the Virginia Institute of Marine Science.

Travel time for flood waters observed at Richmond to reach Newport News was computed using the relationship:

$$Q = A V$$

where Q = measured discharge rate (ft^3/sec)

A = cross-sectional area (determined from a chart)

V = discharge velocity

The river downstream from Richmond was divided into representative segments and a mean cross-sectional area for each segment was determined. Using the assumptions that discharge is conserved and that the discharge occupied the entire cross-sectional area, velocity for each segment was determined using the relationship:

$$V_1 A_1 = V_2 A_2 = \ldots = V_n A_n$$

where n = segments of the river. This results in an over estimate of the time required for the discharge to travel to the marine environment since the fresh water discharge does not occupy the entire channel from surface to bottom but rather only from the surface to the top of the salt water intrusion. Both the depth and the upstream limit of the salt wedge is variable and not quantitatively known.

OCEANOGRAPHY OF THE AREA

Temperature

The time of Camille discharge into the continental shelf waters of the Chesapeake Bight coincided with the approximate time of the beginning of the autumn transitional period. Norcross and Stanley (1967) state that this transition "commonly commences sometime in September." As a consequence, the presence of any set of conditions that can be considered steady state is extremely doubtful. This is best illustrated by examining the temperature distribution of the area. In general, the temperature distribution determined on the cruises in September are much less stratified than those in August. An example of the autumnal transition can be seen by comparing Figures 3 and 4; the vertical temperature distribution along 37°10' during August and September 1967. These sections are representative of the August and September cruises. There is considerable evidence that shorter period temperature changes are not unusual. Figure 5 shows the daily sea surface temperature observations at Chesapeake Light. The absolute accuracy of these observations can be questioned; however, they are of sufficient accuracy to show the magnitude of temperature changes.

One must keep in mind the magnitude and frequency of temperature changes that are possible (or even probable) in the area when analyzing cruise data. For example, Figure 6 presents the horizontal distribution of surface temperature as deduced from observations obtained on a cruise in August 1967. What appears to be a strong temperature gradient exists between 36°40' and 36°50' latitude. The cause of this apparent gradient must be questioned, however, for there were approximately four days between the observations taken along 36°40' latitude and those taken along 36°50' latitude. A similar but less severe horizontal gradient occurred between 36°50' and 37°00' latitude in August 1966. Again there were approximately four days between observations along the two latitudes. Although there is no conclusive proof that these apparent gradients were a function of time rather than space it seems more likely that they were time dependent when changes that are shown to occur at Chesapeake Light are considered and also because of the general absence of extreme gradients between observations taken more synchronously. Changes in temperature with time will be discussed further when considering the temperature regime after the Camille discharge entered the study area.

Salinity

Bigelow and Sears (1935) in their discussion of autumnal progression stated that "the slight increase in the rate of discharge from the rivers, from summer through autumn, is not sufficient to counteract the effect of surface cooling in reducing the vertical stability of the water column, and permitting increasingly active mixing." This process is evident in the salinity data of the "Shelf Hydrographic Survey" cruises. Vertical sections of salinity taken in August and September 1966-1968, along latitudes 37°10'N, 37°00'N, 36°50'N, and 36°40'N show that in each year, along each section, the salinity distribution is less stratified in September than in August

(Figs. 7, 8). Another typical characteristic of the salinity distribution was the increased quantity of admixed fresh water along the coast south of the mouth of the Chesapeake Bay along 36°50'N and 36°40'N latitude. The presence of considerable vertical mixing is shown by the almost vertical salinity contours in this area (Figs. 9, 10). (This is accented by the vertical scale exaggeration).

The characteristic presence of the area of low salinity water next to shore, south of the mouth of Chesapeake Bay, is better seen in the contours showing the horizontal distribution of the fraction of admixed fresh water. The data obtained in August and September, 1966 and 1967, had observations near shore and thus show the nearshore area of relatively high concentration of fresh water quite well (Figs. 11-16). The same condition is present in other years but is not as easily demonstrated owing to less frequent near-shore observations. Aside from the area of relatively high quantities of fresh water near shore south of the Bay, it is difficult to point out any other similarity in the horizontal distribution of fresh water from cruise to cruise. There is a very general north-south orientation to the lines of equal fresh water. Norcross and Harrison (1967) state that "isohalines tend to parallel the coast, but the pattern is often very irregular, particularly about the mouth of large estuaries." The data presented herein would tend to bear this out. Variations from year to year are quite apparent both in the orientation of the lines of equal fresh water and in the gradients. For example, the data collected in September 1968 (Figs. 17-19) show little horizontal gradient.

In order to make some quantitative comparisons of the data, four east-west oriented sections were selected along which several observations had been taken during most of the cruises. The weighted mean fraction of admixed fresh water was computed for each section and is shown in Table 1. From examination of these results two general conclusions can be reached: There is generally an increase in the quantity of fresh water present toward the south and there is considerable variation in the quantity of fresh water present from cruise to cruise. This will be discussed further when the Camille discharge is considered.

Examination also indicates distribution of fresh water during May, 1967, differed from that observed in autumn observational periods. Total volume of fresh water within the area in May, 1967, was similar to that found during several of the autumn cruises; however, the distribution in May reflects the less stable conditions of the season. In autumn the summer stability is not yet broken down, therefore, vertical mixing is retarded, fresh water remains in the surface layers and spreads laterally. In May summer stability is not yet developed so vertical mixing occurs more readily and the fresh water mixes vertically rather than spreading laterally and remains closer to shore. In Table 1 this is indicated by relatively higher fractions of fresh water south of the mouth of the Bay during May, 1967, than during the other cruises.

Currents

After their systematic study of the circulation of the Chesapeake Bight using drift bottles and surface drifters, Norcross and Stanley (1967) concluded that: "The surface circulation of the shelf water off the Chesapeake Bight is seasonal in character, varying with changes in

TABLE 1

Fraction of Admixed Fresh Water Observed Along East-West Oriented Sections.

Section Along	Aug. 1966	Sept. 1966	May 1967	Aug. 1967	Sept. 1967	Aug. 1968	Sept. 1968	OOR-I	OOR-II
37°10'N	.093	.093	.089	.105	.120	.106*	.093	.084	.104
37°00'N	.105	.105	.111	.120	.116	.115*	.093	.089	.115
36°50'N	.118	.105	.128	.125	.133	-	.095	.094	.099
36°40'N	.120	.106	.135	.117	.142	-	.098	.090	.099
Area Average**	.109	.103	.116	.118	.127	.109	.095	.087	.104

*Based on only two stations

**Weighted by volume

river discharge and local winds and, to a lesser degree, with changes in the stability of the water column." Their analysis of bottom drifters showed a shoreward or southwest to westerly drift into the Chesapeake Bay along the bottom from releases north of the latitude of Cape Henry.

The bottom drifters released south of that latitude generally had a southwesterly drift except during periods of high discharge from the Bay, at which time an increased number of drifters moved northwestward toward the mouth of the Chesapeake Bay. Norcross and Stanley (1967) state that "....these flow patterns suggest that the volume discharge from the Bay may be instrumental in the development of a bottom drift toward Chesapeake Bay from the southeast."

Some inferences can be made with the information used in this study to bear out these conclusions. The bottom drift toward the mouth of the Chesapeake Bay north of approximately 37°00'N latitude is particularly well demonstrated in the data obtained in September 1967 (Fig. 16). This shows a marked encroachment of high salinity (low fraction of fresh water) into the northeast corner of the study area. Although September 1967 provides the most striking example, the majority of the cruises show the same phenomenon to a lesser extent.

The September 1967 data also show less directly the possibility of an increased flow toward the Bay mouth from the southwest. The volume of fresh water in the area during September 1967 was higher than during any other observational period used in this study. The following year in September the fraction of fresh water was the lowest for the same time of year. Comparison of the bottom fraction of the two cruises (Figs. 16 and 19) indicate that higher salinity water extends farther west during September 1967 along the western edge of the area than during September 1968. Although this is too subjective to stand alone it does add to evidence given by Norcross and Stanley (1967) of an enhanced bottom drift toward the Bay mouth during periods of high discharge. Defant (1961) refers to similar currents as compensation currents. Additional evidence along these lines was found during Operation Override cruises and will be discussed later.

The presence of high percentages of fresh water along the coast south of Cape Henry also indicates circulation in a south to southwesterly direction in that area. Doebler (1966) states that in the current observations he obtained from Coast Guard lightships at Frying Pan Shoals and Five Fathom Bank, "changes in the wind direction and speed produced immediate changes in the current." Agreement with this conclusion is found indirectly in relating the observed tides of the area to the observed winds. Plots of observed and predicted high and low water were made for Sewell's Point during the August and September 1969 study period (Fig. 20). On three occasions during this period observed tides were markedly higher than predicted. Similar records were obtained at Virginia Beach. In each case northerly winds were responsible and within the limits of the data available, response to the wind was immediate.

Haight (1942) computed tidal currents from observations at two locations within the study area. Eighty-seven days of observations were available from the Cape Charles Lightship (37°05.3'N, 75°43.5'W) and 375 days of observations were available from the Chesapeake Lightship (36°58.7'N, 75°42.2'W). (The location of the Chesapeake Lightship was approximately 5 miles north of what is now the location of Chesapeake Light Tower.) From these data Haight (1942) computed the speed and direction of the tidal currents for each hour after Greenwich transit. His analysis shows that at both points there is essentially an east-west reversing current. At Chesapeake Lightship the flood strength was approximately 0.15 knots in a direction of 278° true and the ebb strength was the same speed in a direction of 94° true. This would cause no net drift but would cause a total east-west excursion of about 0.6 nautical miles during a tidal cycle. At Cape Charles Lightship the total excursion would be approximately twice that at Chesapeake Lightship.

Wind

Wind data from Cape Henry (U. S. Congress, 1953) summarized from 16 years of observations show that there is an autumnal transition in wind direction. During the period July to September the monthly resultant wind changes from a south wind in July to a southeast wind in August and finally to a north-northeast wind in September.

INFLUENCE OF CAMILLE DISCHARGE ON AREA

Movement of the Camille discharge water can be traced and timed to a limited extent by examining the gaged stream flows in the affected rivers and the subsequent changes in salinity after the discharge reached the marine environment (Table 2). The James River peaked at Richmond, Virginia, on the 22nd of August and the Mattaponi and Pamunkey rivers peaked at Beulahville and Hanover, Virginia, respectively, on the 23rd of August (Fig. 1). Estimates based on the discharge rate observed at Richmond and average cross sectional areas of segments of the James River downstream indicate that approximately two to three days would be required for flood waters to travel from Richmond to Newport News. On the 26th of August, the salinity dropped at a time-series station off False Cape approximately 3.5 ‰, indicating the passage of the leading edge of the Camille discharge (Fig. 21). On the 31st of August surface salinity observations taken at Chesapeake Light fell almost 5.5 ‰, again indicating the passage of the leading edge (Fig. 22). Using these two time series observations in the shelf waters, the salinity and current information obtained during the two Operation Override surveys, the wind observations available, and relating this to the knowledge gained during the "Shelf Hydrographic Survey" and earlier cruises, a reasonable deduction of the Camille discharge can be made.

TABLE 2

Chronology of Discharge from Hurricane Camille.

Time	Location	Occurrence
22 August '69	Richmond, Va.	Peak discharge, James River
23 August '69	Beulahville, Va.	Peak discharge, Mattaponi River
23 August '69	Hanover, Va.	Peak discharge, Pamunkey River
26 August '69 0100-0500 Z	Time Series Station off False Cape	Salinity dropped from 31.09 ‰ to 27.59 ‰
29 August '69	Chesapeake Bight	Discharge Water located along coast south of Cape Henry.
31 August '69	Chesapeake Light Tower	Salinity dropped from 32.32 ‰ to 26.88 ‰
3 Sept. '69	Chesapeake Bight	Discharge water in dominant plume east of mouth of Chesapeake Bay

We can deduce from the time of passage of the leading edge of the discharge water off False Cape that it apparently flowed out of the Chesapeake Bay and hugged the coast between Cape Henry and False Cape. A few days later, on the 28th and 29th of August the data from OOR-I indicate this pattern of the Camille discharge to be unchanged, or if anything pushed slightly closer to the coast (Figs. 23-25). The surface fraction of fresh water at the site of the time series station occupied 3 days earlier decreased from 0.20 to approximately 0.17.

On the subsequent OOR-II cruise a predominant plume of low salinity water was present extending almost due east of the Bay mouth (Figs. 26-28). From this distribution it is at first confusing why the discharge water remained along the coast as long as it did; not reaching Chesapeake Light until the relatively late time of the 31st of August. This may be explained by examining local wind observations at the time (Fig. 29). As the leading edge of the Camille discharge came out of the Chesapeake Bay it followed the normal circulation pattern south along the coast. On the 26th of August a wind shift occurred which increased the shoreward component of current motion and lasted until approximately the 29th of August. Beginning the 29th and lasting until the 31st the local winds were from the east which would cause a surface drift almost directly opposite the apparently typical southerly flow along the coast. On the 31st, winds became more southerly, having the effect of forcing the major portion of Camille discharge into the dominant plume observed in the OOR-II data taken the 2nd and 3rd of September. In addition to the major plume extending eastward from the mouth of the Chesapeake Bay, there is evidence of two separated cells having high quantities of fresh water lying to the south of the major plume (Fig. 26). This is possibly the Camille discharge water which had earlier been held against the coast. It is also interesting to note that in the southwest section of the study area a general reduction in the quantity of fresh water occurred between OOR-I and II. This also indicated a change in the circulation pattern brought about by the wind.

Drift bottle releases during both OOR-I and OOR-II can be interpreted to support some kind of current regime such as that just described. Analysis by John J. Norcross (unpublished) of the returns from 199 releases made in the ocean during OOR-I and II indicated the estimated minimum rate of drift was on the order of 2.1 miles per day. This is only about 2 to 3 tenths the drift rates Norcross and Stanley (1967) found from releases made in August and September, 1963 and 1964. Bumpus (1965) reported minimum drift rates of 4 to 7 nautical miles per day during August and September based on all available data collected between 1948 and 1962. Although the drift rates during Operation Override were slower than previously found the recovery points indicated a net travel in about the same direction noted from previous releases. This could have been caused by temporary displacement of the bottles from their normal course by the surface drift resulting from winds such as those which caused the fresh water plume during OOR-II.

To study the circulation along the bottom, 90 bottom drifters were released at various locations during OOR-I and OOR-II. Only those that were recovered within 20 days of release were used in estimating the bottom circulation during the period of Camille discharge influence.

Although only 11 recoveries were made within this period the distribution of release points covered the area fairly well. Without exception the bottom drifters indicated a movement of water in the general direction of the mouth of the Chesapeake Bay (Fig. 30). This agrees with findings by Norcross and Stanley (1967) for bottom circulation during periods of high fresh water discharge and adds additional evidence to their suggestion that "...the volume discharge from the Bay may be instrumental in the development of a bottom drift toward Chesapeake Bay from the southeast." The drift rates of 9 of the drifters recovered were somewhat higher than average. This is to be expected due to selecting only those drifters recovered within 20 days of release. The remaining two, released in the southeast quadrant of the study area (36°10'N; 75°20'W) both had the remarkably high drift rate of 3.5 nautical miles per day. This rate is so high that one might question its accuracy, however, there is nothing in the records to indicate it to be erroneous. If the drift rate is correct, it indicates that a high fresh water discharge from the Bay has an extraordinary effect on the bottom circulation in the area southeast of the mouth of the Bay. Additional evidence of a bottom circulation toward the mouth of the Bay is the decrease in admixed fresh water at the bottom along the western and southern boundaries of the study area during OOR-II as compared to OOR-I (Figs. 25 and 28).

It was initially surprising to find, even with the high amount of discharge from Hurricane Camille, that the fraction of fresh water was less during OOR-II than during some of the previous "Shelf Hydrographic Survey" cruises. To investigate this apparent inconsistency the

the monthly cumulative inflow to the Chesapeake Bay was obtained from the U. S. Geological Survey for the years 1965 to 1969 and compared to the fraction of fresh water present. A number of investigations have correlated salinity distributions (or fresh water content) along the east coast to fresh water discharge. For example, Ketchum and Corwin (1964) found the salinity of the shelf waters south of Long Island was correlated with the mean Connecticut River discharge of the preceding six months. Howe (1962) compared Potomac River discharge with mean surface salinity at Chesapeake Light and found the highest correlation between the salinity and the discharge gaged two months earlier. Since there seemed to be no general agreement in the literature regarding what period of discharge would best correlate with the quantity of fresh water in the study area, the discharge was summed for increasingly longer periods prior to each survey and linear correlation coefficients were computed between the fraction of fresh water calculated for a cruise and the mean of the preceding one month to 19 months discharge. The mean of the preceding eleven, twelve, and thirteen months, when compared with the fraction of fresh water, gave the highest correlation coefficient (Table 3). Figure 31 shows a plot of fraction of fresh water versus the mean of the preceding 12 months discharge. One must limit conclusions based on these correlation coefficients for at least three reasons. First, there were variations in the time between the observations of shelf water and the cutoff point of the discharge calculations. For example, the August '66 data were collected as late as the 27th of August, near the end of the month, while the August '68 data were collected on August 6 and 7 near the beginning of the month, yet both were compared to the preceding discharge for July. Secondly,

TABLE 3

Correlation Coefficient between the Fraction of Admixed Fresh Water of the Study Area and the Mean Discharge from the Chesapeake Bay for Preceding Months.

Cumulative Discharge Duration (months)	Correlation Coefficient
1	0.29
2	0.29
3	0.32
4	0.42
5	0.53
6	0.41
7	0.45
8	0.39
9	0.30
10	0.28
11	0.85
12	0.87
13	0.75
14	0.54
15	0.44
16	0.28
17	0.17
18	0.09
19	0.08

the volume of fresh water in the area is not determined frequently enough to avoid aliasing. There are certainly fluctuations in the percentage of fresh water present in the study area throughout the year but these are not known and therefore cannot be considered. Thirdly, the volume of fresh water present in the study area is not solely a function of fresh water discharge from the Chesapeake Bay but is influenced by fresh water entrainment from other areas. Ketchum and Keen (1955) calculated a flushing time of 125 days for the area shoreward of the 20 fathom curve between Cape Cod and the Chesapeake Bay. The twenty fathom curve coincides approximately with the western boundary of the area of study and therefore one would expect their calculation of the flushing time to agree more closely with the period of discharge that was found to correlate well with the volume of fresh water present on the shelf. It does not, probably because all sources of fresh water have not been considered in determining the correlation coefficients. It seems that one is justified, however, in concluding that the fraction of fresh water present in the area is a function of fresh water discharge over some considerable length of time preceding the observations. This is sufficient to explain the overall relatively low content of fresh water in the study area even with the presence of the Camille discharge water.

Calculations of the fraction of fresh water along sections were made with the OOR-I and OOR-II data in an attempt to quantitatively compare the volume changes of fresh water between the two cruises. Comparison is facilitated because the same station locations were used on the two surveys. Table 4 presents the results of these calculations, some of which were already presented in Table 1. Three sections

TABLE 4

Fraction of Admixed Fresh Water Observed Along Sections taken during Operation Override I and II.

Survey	Section Location	Fraction of Fresh Water
	East-West Sections Along	
OOR-I	37°10'	.084
OOR-II	37°10'	.104
OOR-I	37°05'	.083
OOR-II	37°05'	.107
OOR-I	37°00'	.089
OOR-II	37°00'	.115
OOR-I	36°55'	.095
OOR-II	36°55'	.117
OOR-I	36°50'	.094
OOR-II	36°50'	.099
OOR-I	36°45'	.097
OOR-II	36°45'	.090
OOR-I	36°40'	.090
OOR-II	36°40'	.099
OOR-I	36°35'	.083
OOR-II	36°35'	.084
	North-South Sections Along	
OOR-I	75°53'	.117
OOR-II	75°53'	.132
OOR-I	75°47.5'	.105
OOR-II	75°47.5'	.121
OOR-I	75°35'	.086
OOR-II	75°35'	.105
OOR-I	75°22.5'	.080
OOR-II	75°22.5'	.079

deserve comment. The easternmost north-south oriented section along 75°22.5' shows virtually no change in fresh water content between OOR-I and II. This indicates that the influence of Camille discharge did not exceed the eastern boundary of the study area during the period of study. One cannot make the same conclusion from comparison of the two sets of data collected along the southernmost (36°35'N) east-west oriented section. The similarity in fraction of fresh water here is due to coincidence for comparison of the surface distribution of fresh water during OOR-I and II (Figs. 23 and 26) indicates that Camille discharge did reach that parallel. The east-west oriented section along 36°45'N shows a higher quantity of fresh water during OOR-I than OOR-II. This is a result of redistribution of the Camille discharge water in the southwest section of the study area as discussed earlier.

Examination of the distribution of the surface isotherms observed during the two cruises (Figs. 32 and 33) shows an increase of one to two degrees Celsius at each station. No discernible relationship to the distribution of Camille discharge can be seen. This temperature increase is apparently due to an increased amount of solar radiation as a result of clear skys throughout the period. It was thought that the effect of surficial heating could be at least partially eliminated by determining a weighted mean station temperature (by depth) which excluded the surface observation. The horizontal distribution of these values (Figs. 34 and 35) do not show a general warming trend as does the surface distribution. Within the dashed line on Figure 35 the mean temperature showed a cooling trend while the remainder of the stations still indicated a warming trend. Neither this area of cooling nor any other facet of the mean temperature distribution showed any apparent relationship to the distribution of Camille discharge. Examination of the temperature distribution observed by Coast Guard personnel using airborne infra-red equipment, likewise failed to show any relationship of temperature to Camille discharge. Apparently, if there were any changes in the temperature distribution as a result of Camille, it was not discernible as a result of the usual fluctuations in temperature which occur at this time of year.

DISCUSSION

Regional Considerations

Some considerations were made of the effect of the regional environment on the study area. Because of the study area's small size and proximity to Chesapeake Bay it was felt that relatively rapid changes in its fresh water volume would be predominately a function of discharge from Chesapeake Bay. However, a major short term increase in fresh water content from a source other than the Bay might cause an erroneous interpretation of the data taken to study the distribution of Camille discharge. Such an increase would have to be caused by a large discharge at some other point and it would have to remain relatively concentrated until it arrived at the study area. To determine whether such a discharge occurred at the most logical source, the Delaware Bay, salinity data observed at the Delaware Bay Lightship were examined for the previous two months. No unusually low salinity values were found and therefore it was concluded that the observed changes in the fresh water distribution within the study area was predominately caused by the discharge from Hurricane Camille. To examine the possibility that the Camille discharge remained concentrated and drifted south the salinity observations taken at Diamond Shoals Light Station through October were examined. No fluctuations that could be attributed to Camille were evident. It is doubtful that such a fluctuation could have been identified at Diamond Shoals because of its proximity to the edge of the Gulf Stream and hence its frequent fluctuations in salinity. It is hypothesized that if the Camille discharge eventually moved south in the normal circulation pattern, it would not be nearly as prominent as during OOR-II. The wind pattern for most of the ten days after OOR-II would cause an easterly surface drift and thus allow the discharge sufficient time to become entrained with high salinity slope waters. Some of the discharge was probably lost to the shelf while the remainder, as indicated by the drift bottles, eventually flowed south along the coast.

The regional winds from Cape Hatteras to Wallops Island were examined for any major deviation from the local winds which might induce a surface drift contrary to that caused by the local wind. No conditions that would appear contrary to the drift pattern previously described were found. It is noteworthy that the winds observed at Oregon Inlet from the 26th of August to the 1st of September were from the east-northeast which would tend to keep any southerly surface flow from occurring, and in effect block any Camille discharge from entering that area. This agrees with the conditions observed.

Fresh Water Volume

To check the validity of the computation of fresh water fraction a comparison of the total Camille discharge with the volume of fresh water in the study area that could be attributed to Hurricane Camille was made. The Hurricane Camille discharge was determined by summing the stream discharge measured on the James, Mattaponi, and Pamunkey rivers during the period 20 to 26 August inclusive. This quantity was 64.5×10^9 cubic feet. The volume of Camille discharge within the study area was calculated by subtracting the volume of fresh water in the area during OOR-I from that found during OOR-II. The resulting volume was 31.5 x 10^9 cubic feet, approximately 49% of the total discharge. These two figures agree quite well considering that some Camille discharge was present in the study area during OOR-I and almost certainly some of the Camille discharge was already south of the study area during OOR-II. To assume that all of the Camille discharge had not yet left the Bay is equally plausible because the fraction of fresh water at the mouth of the Bay during OOR-II was much higher than during OOR-I.

CONCLUSIONS

The vanguard of the atypically high fresh water discharge caused by Hurricane Camille moved south from the mouth of the Chesapeake Bay and was initially held against the coast by northeasterly winds. Subsequent veering of the wind to easterly and finally to south-southeasterly caused the discharge water to move east-southeasterly from the mouth of the Chesapeake Bay. It is hypothesized that as a result of continued south-southeasterly winds the drift pattern remained relatively unchanged for approximately ten days, allowing the discharge water to become mixed with higher salinity water prior to a portion of it resuming a more normal southerly drift.

As a result of relatively low fresh water discharge from the Chesapeake Bay during the preceding year, the admixed fresh water content of the study area was lower than usual. Consequently when compared to previous data taken the waters were less stratified than normal. The stratification shown in a vertical salinity section obtained during OOR-I (Figs. 36 and 37) is more typical of the salinity pattern obtained after the autumnal transition period. The Camille discharge (coupled with surface heating) had the effect of restratifying the waters of the study area and making it more typical of the conditions found in previous late August cruises (Figs. 38 and 39).

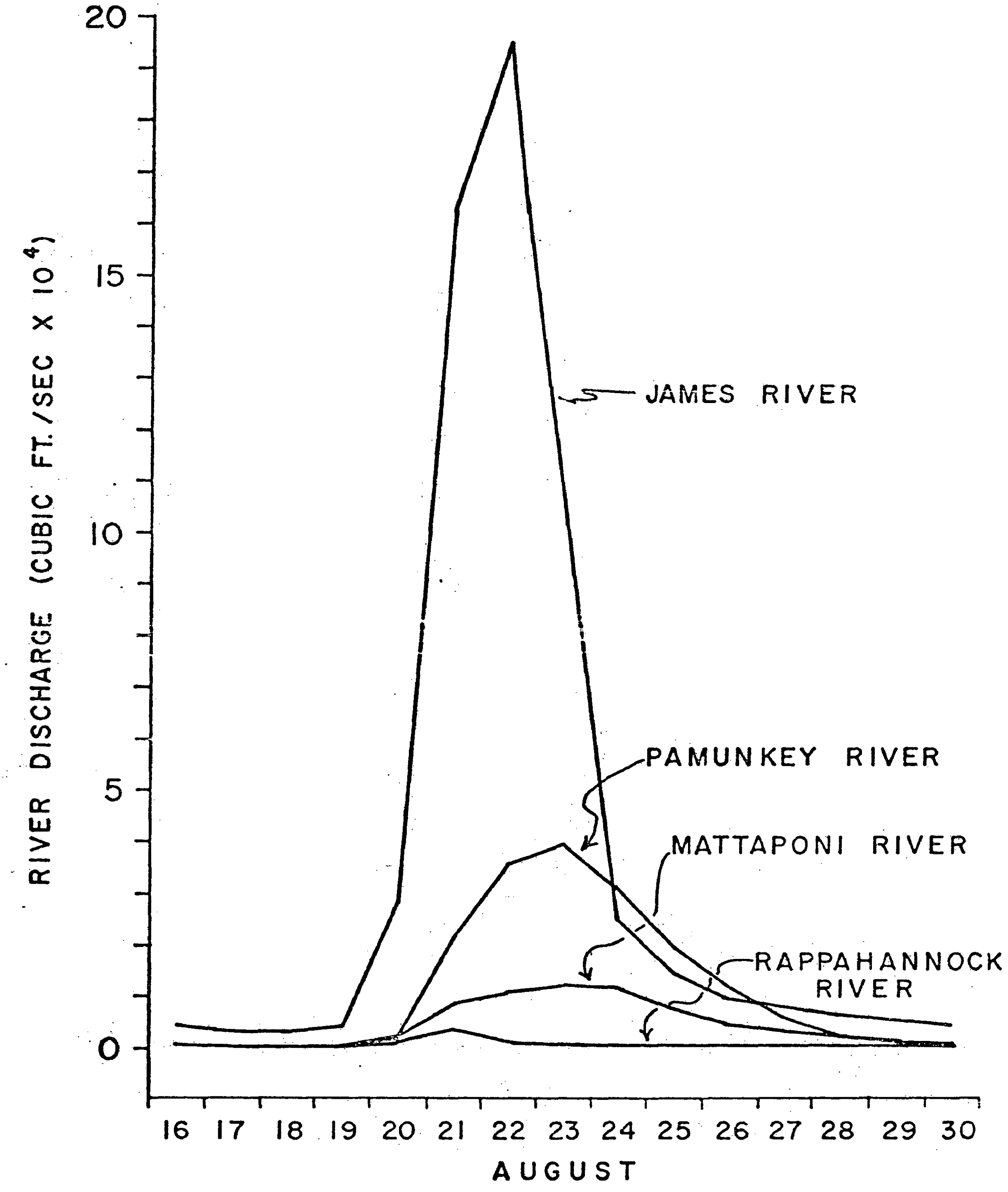

Figure 1. Gaged stream discharge showing increases caused by Hurricane Camille.

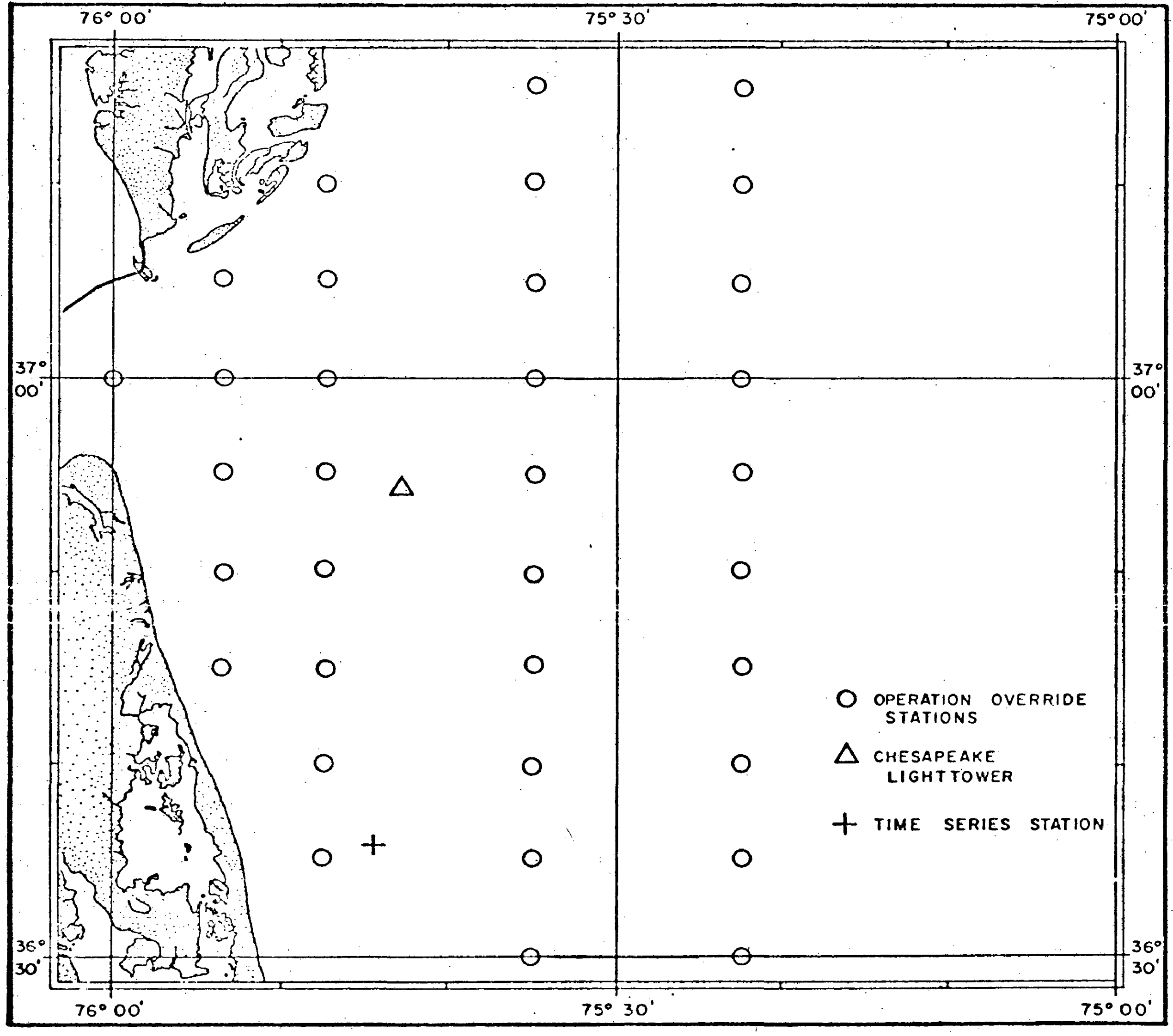

Figure 2. Area of study showing location of time series and Operation Override stations.

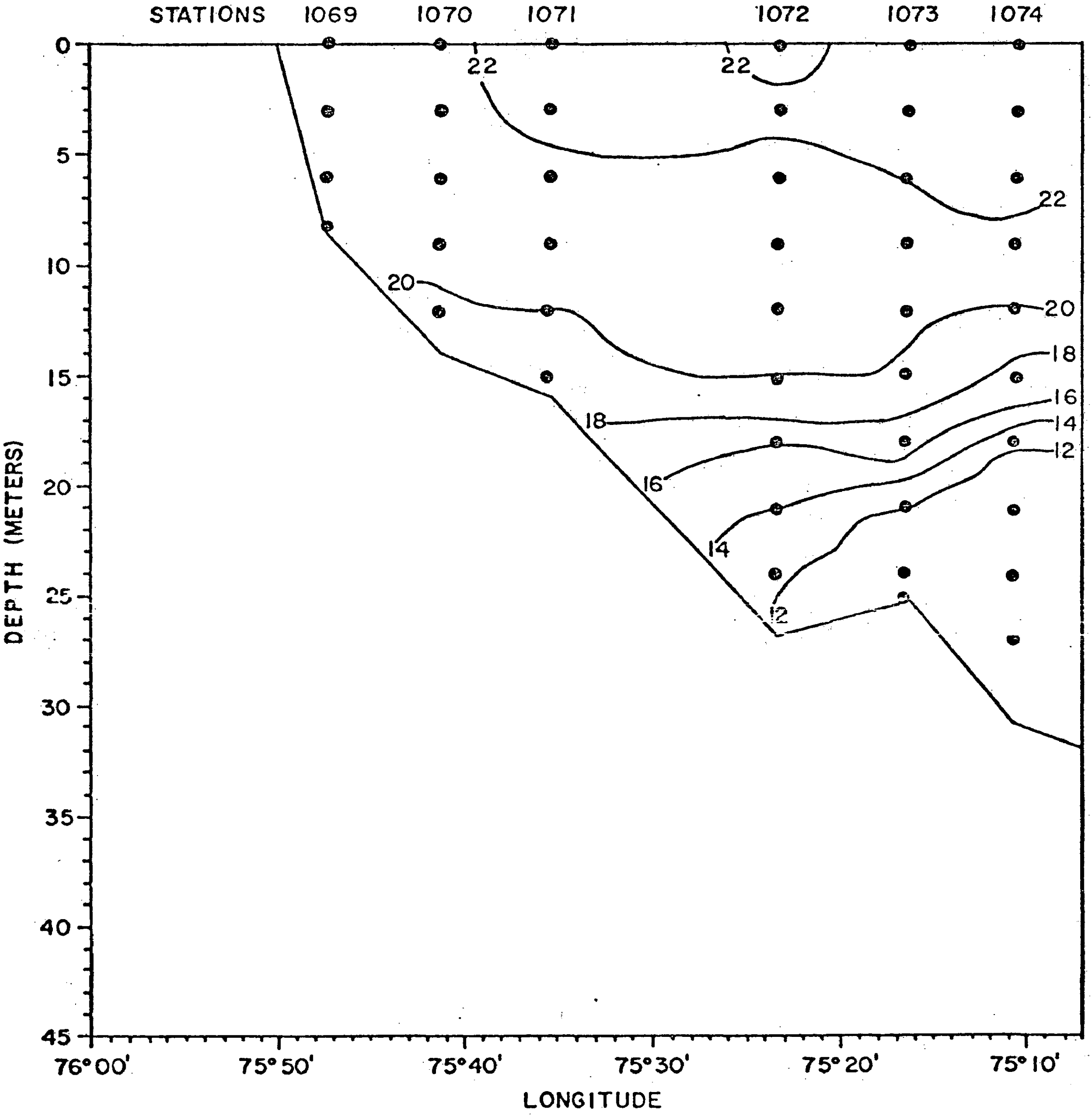

Figure 3. East-west oriented temperature section along 37°10'N; August, 1967.

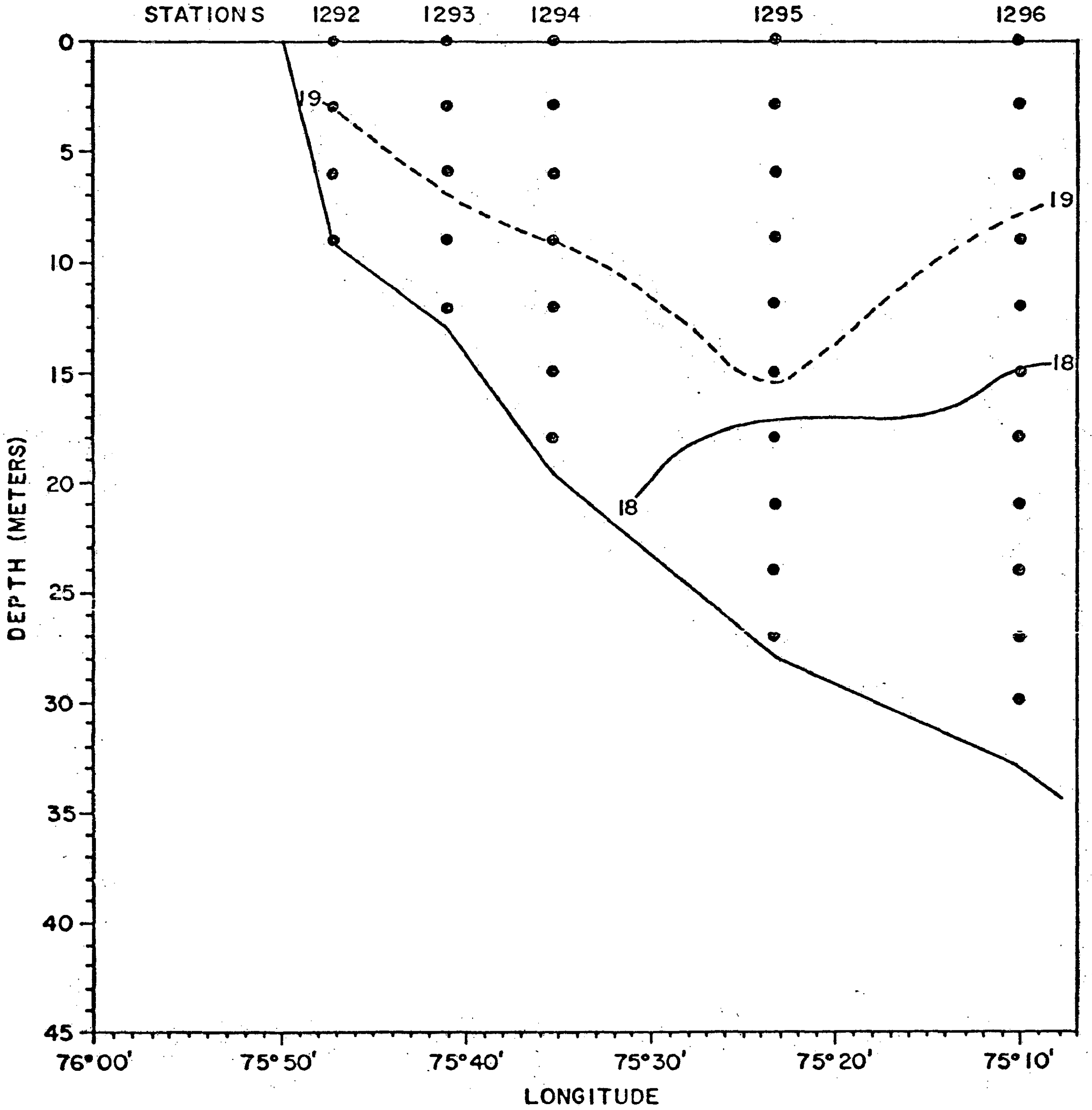

Figure 4. East-west oriented temperature section along 37°10'N; September, 1967.

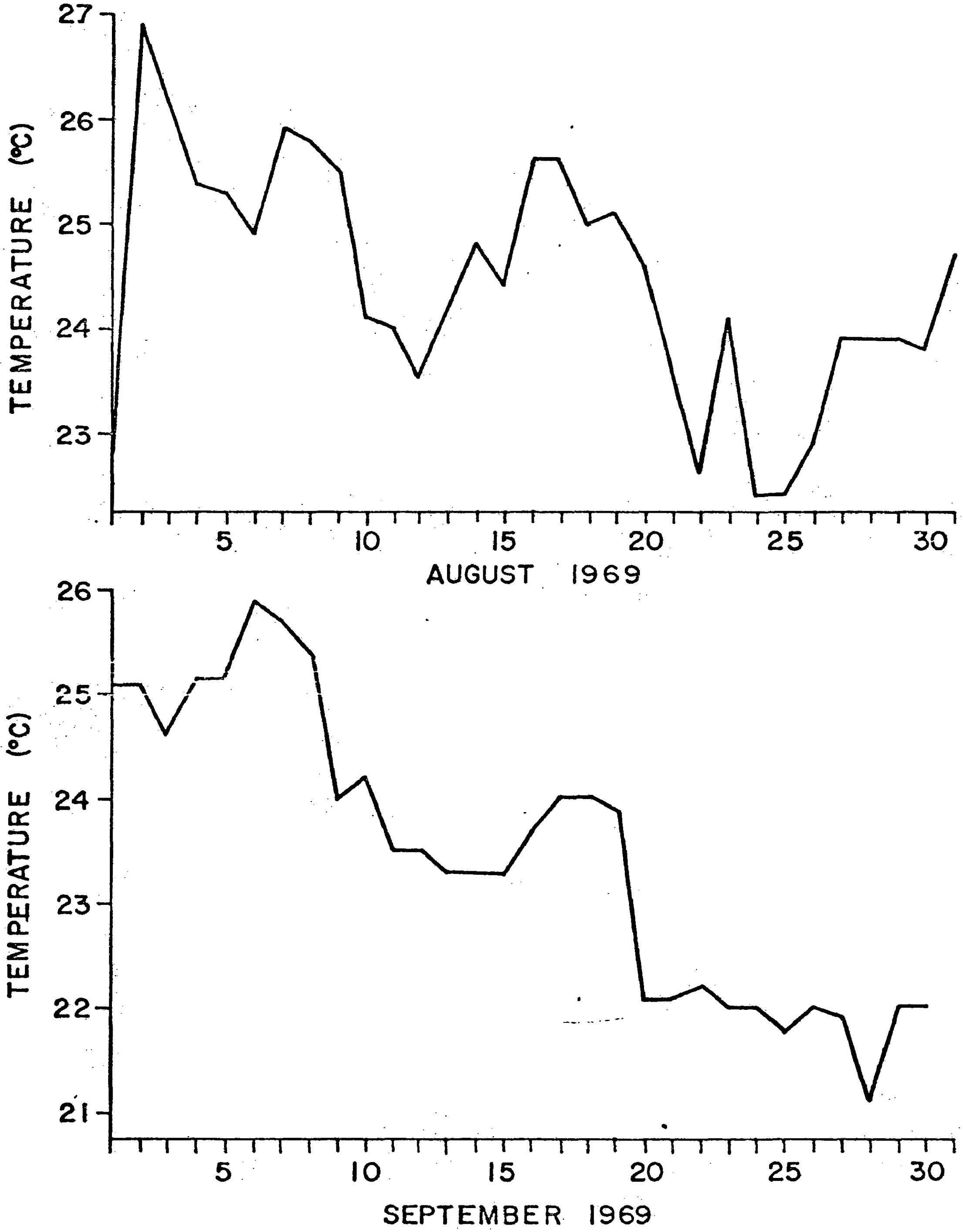

Figure 5. Surface temperature observations at Chesapeake Light Tower.

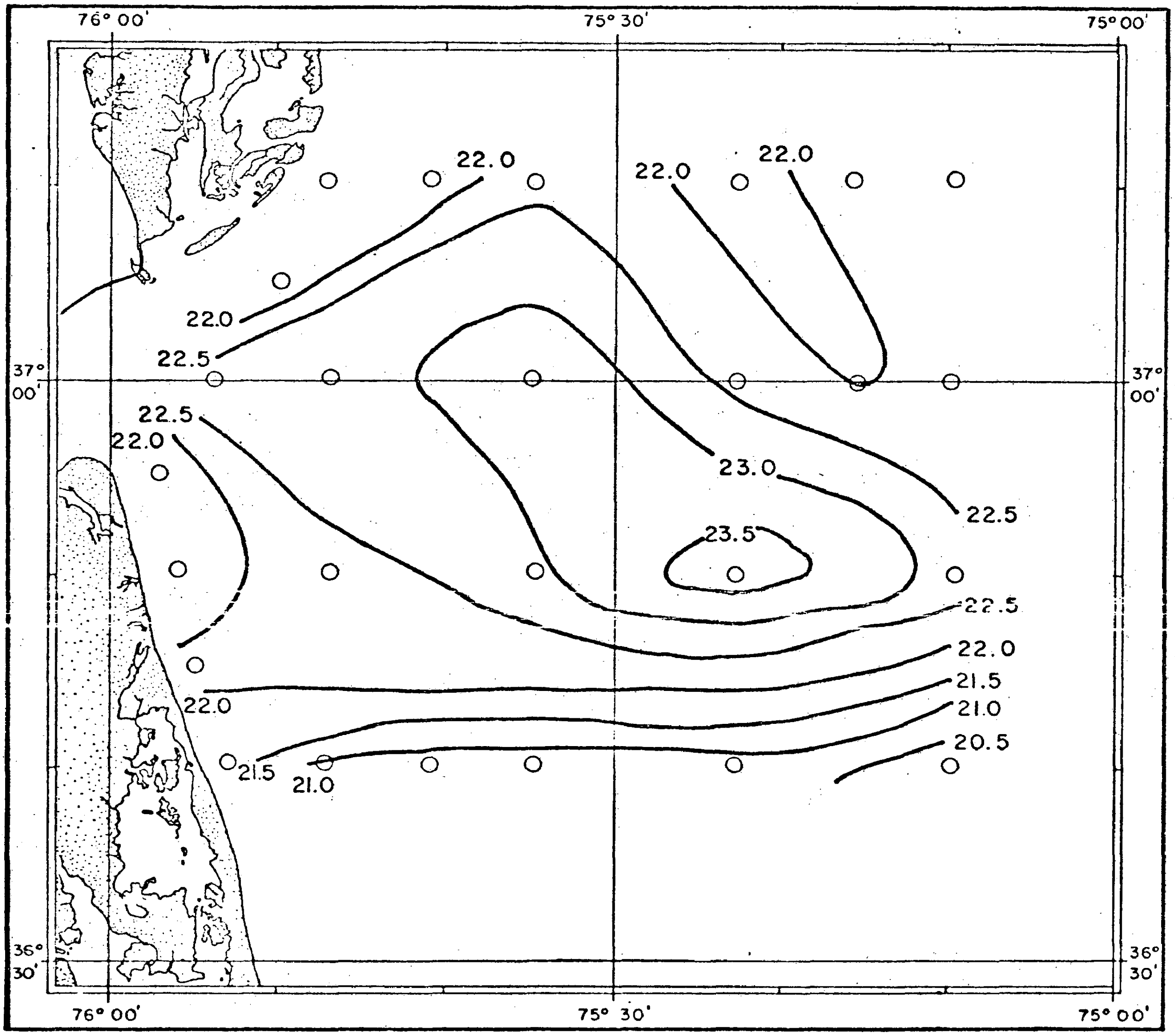

Figure 6. Distribution of surface isotherms; August, 1967.

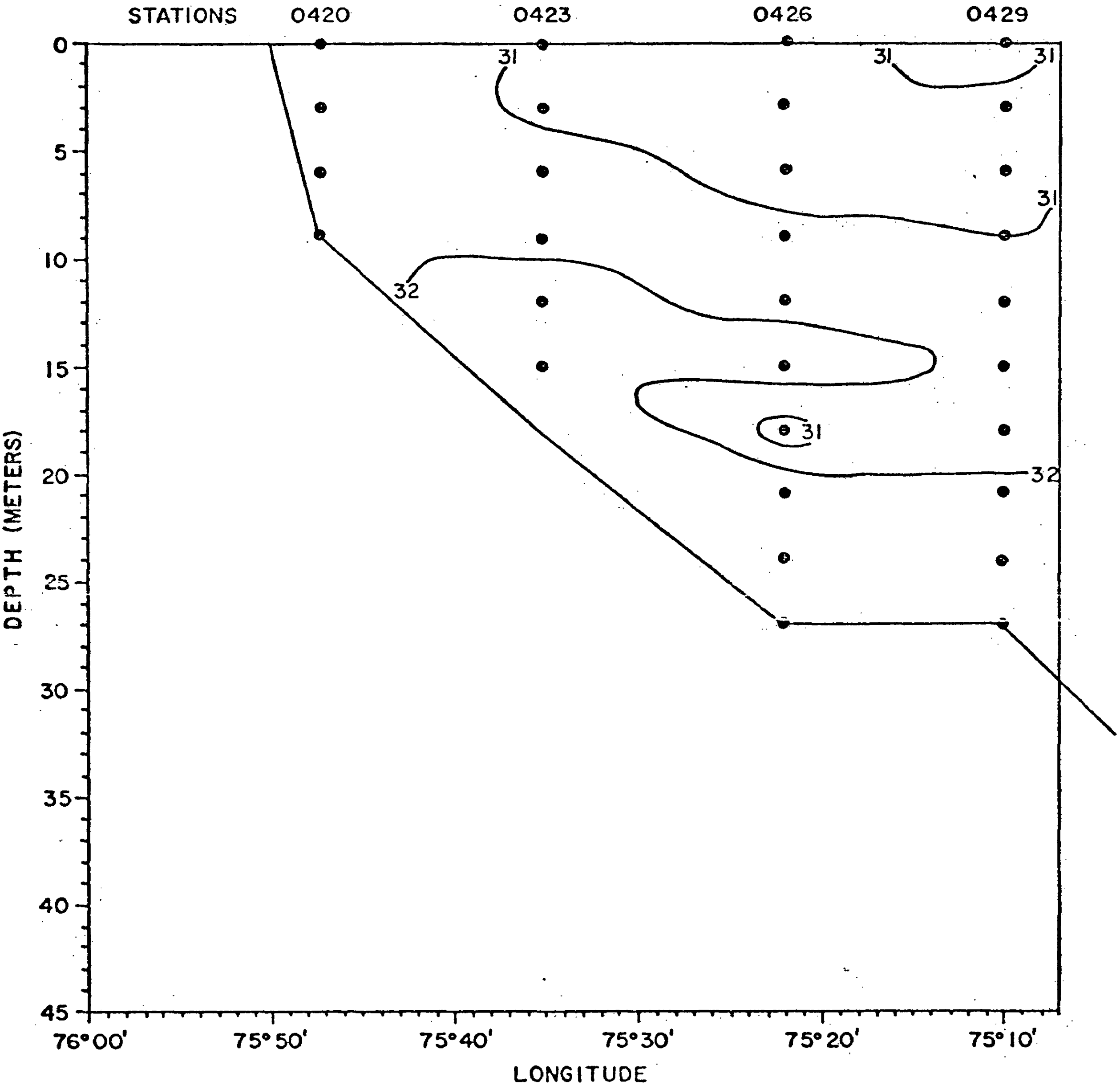

Figure 7. East-west oriented salinity section along 37°10'N; August, 1966.

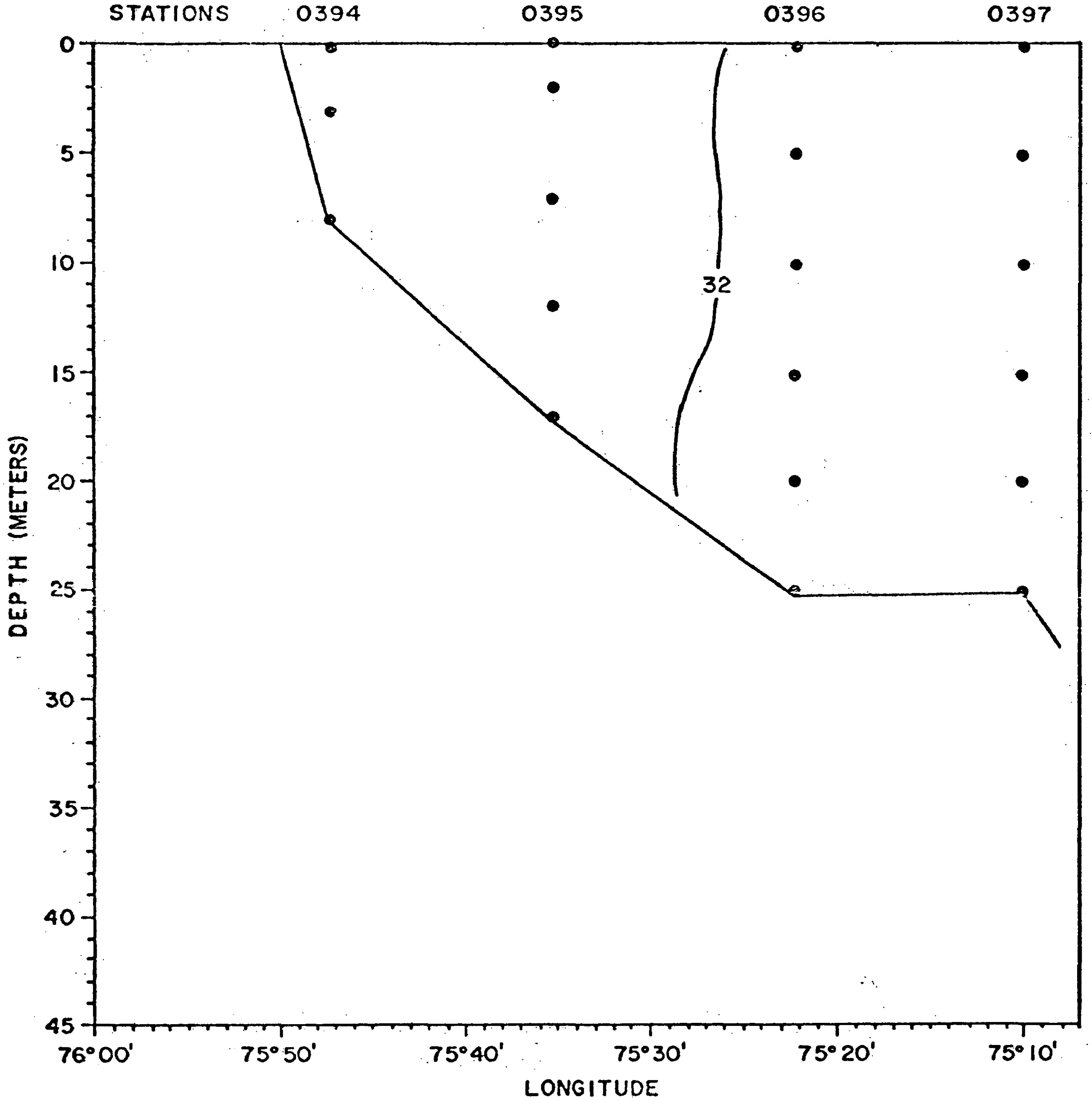

Figure 8. East-west oriented salinity section along 37°10'N; September, 1966.

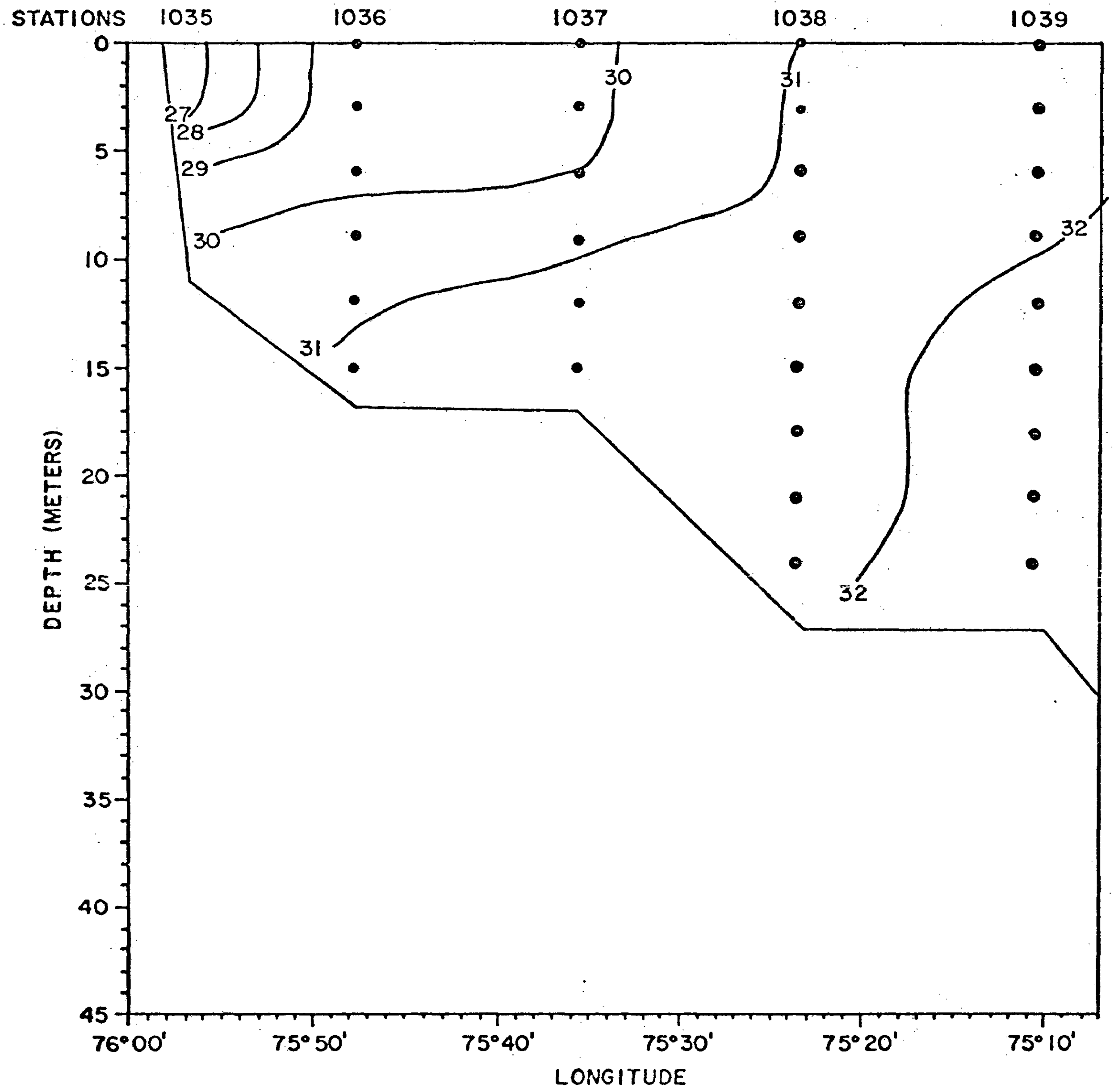

Figure 9. East-west oriented salinity section along 36°50'N; August, 1967.

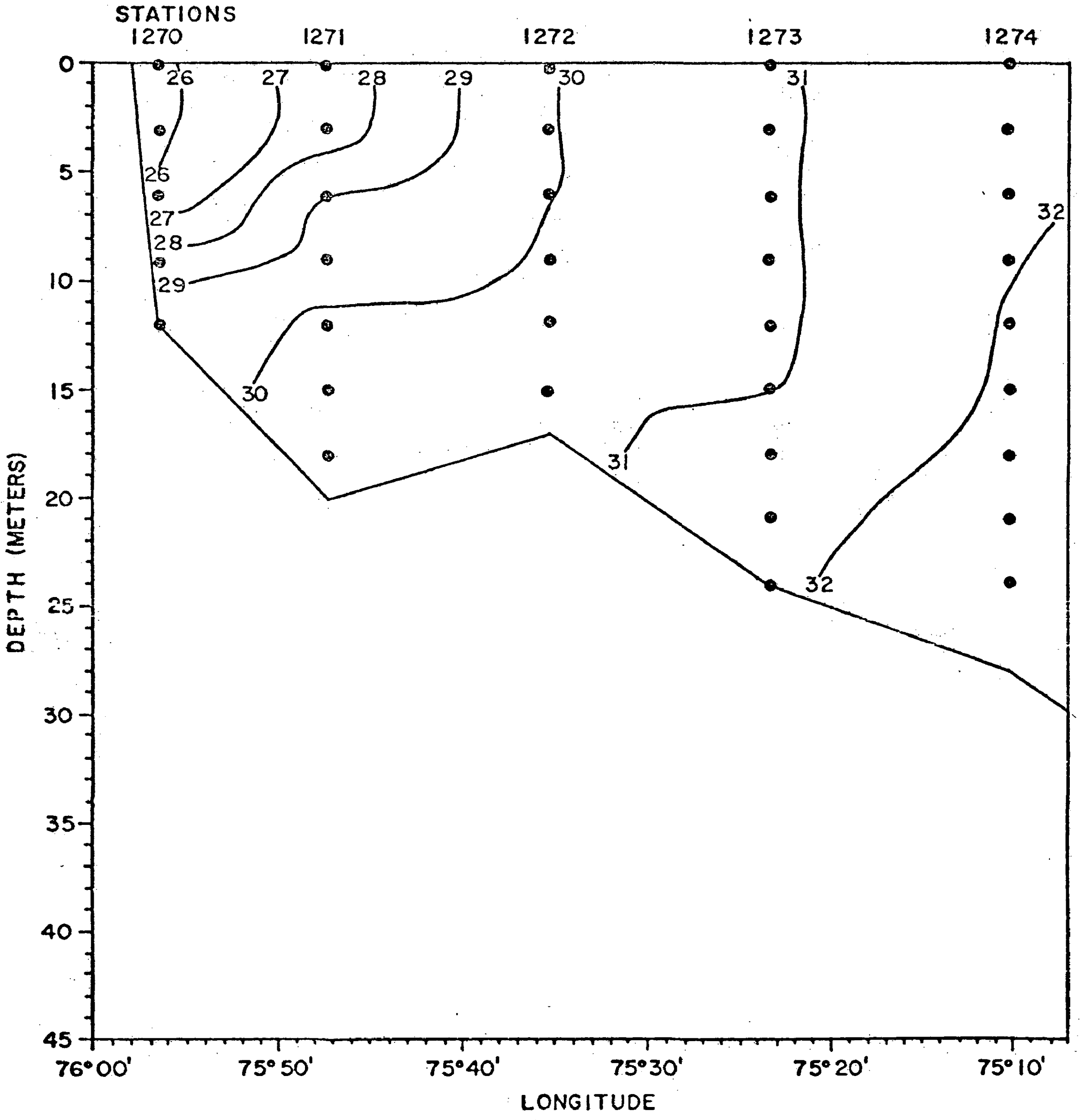

Figure 10. East-west oriented salinity section along 36°50'N; September, 1967.

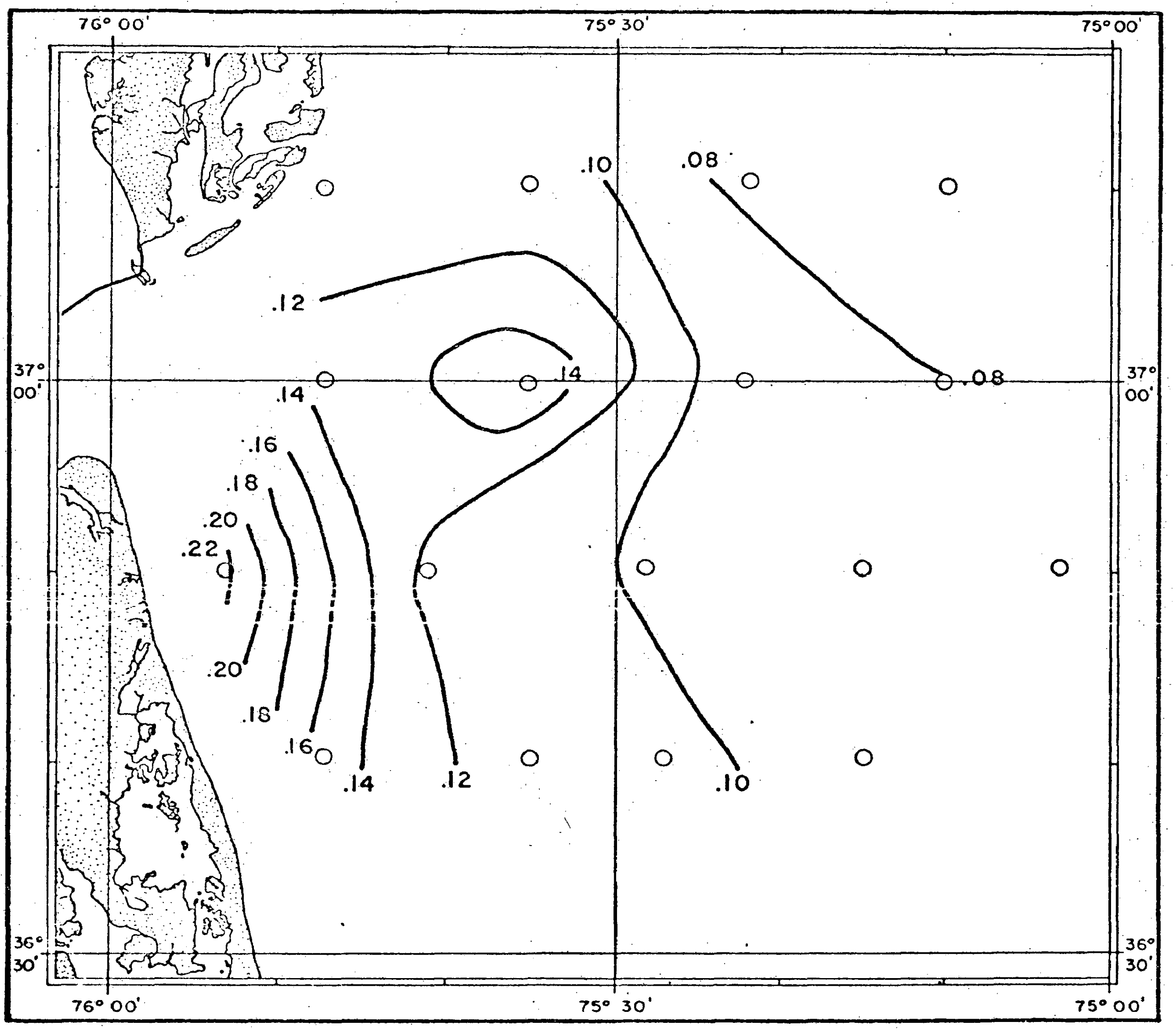

Figure 11. Horizontal distribution of fraction of admixed fresh water at the surface; September, 1966.

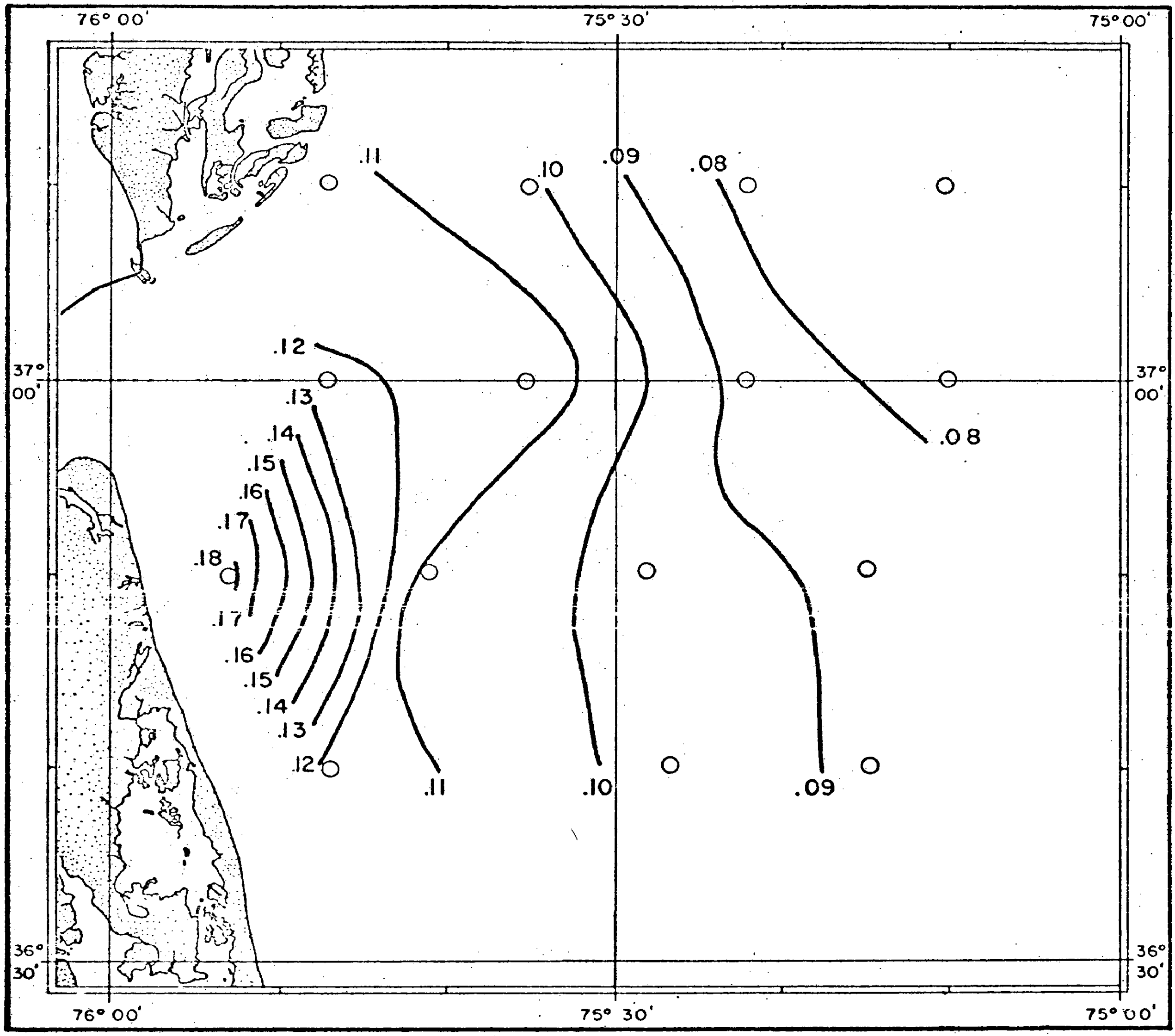

Figure 12. Horizontal distribution of mean fraction of admixed fresh water; September, 1966.

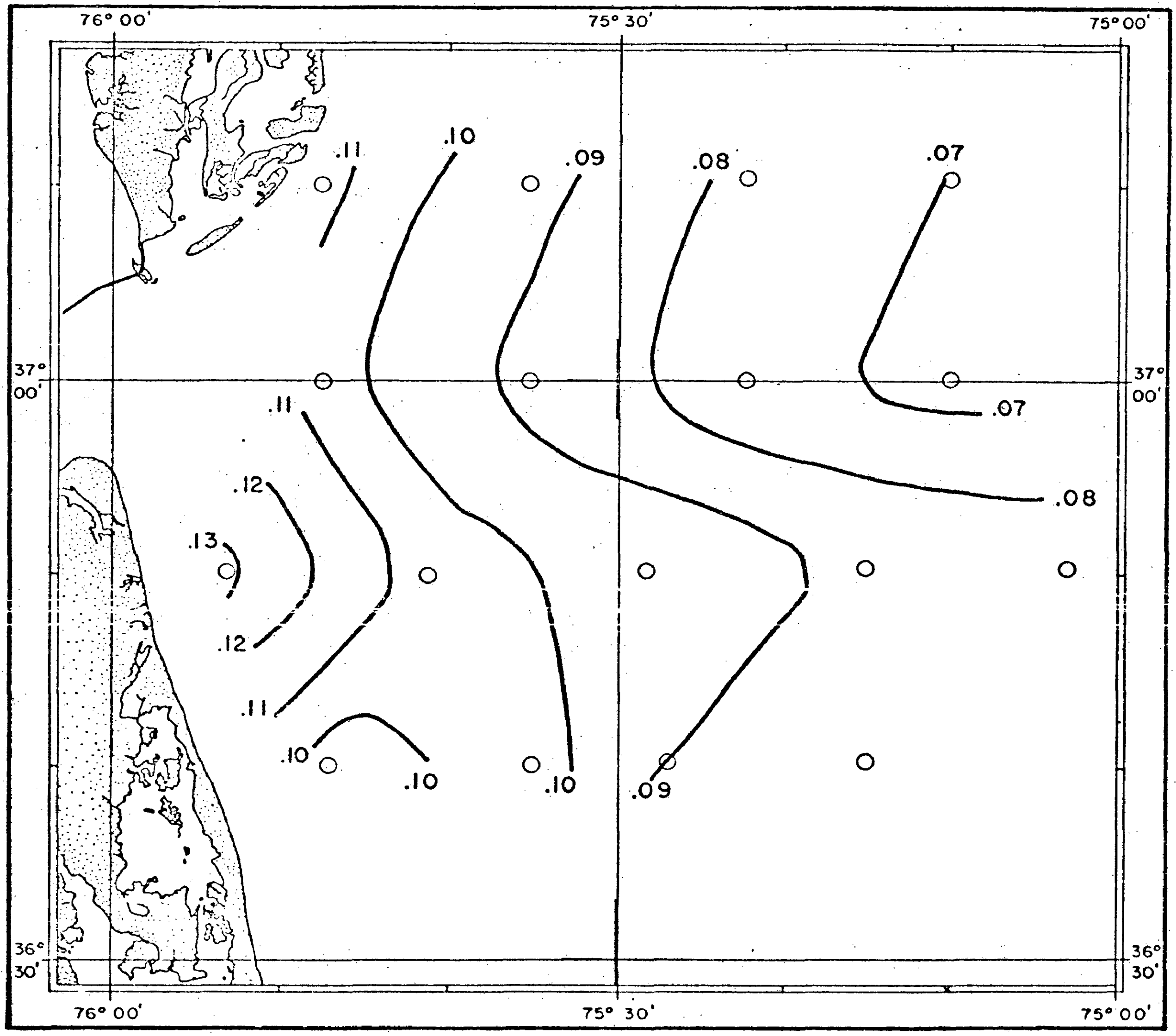

Figure 13. Horizontal distribution of fraction of admixed fresh water at the bottom; September, 1966.

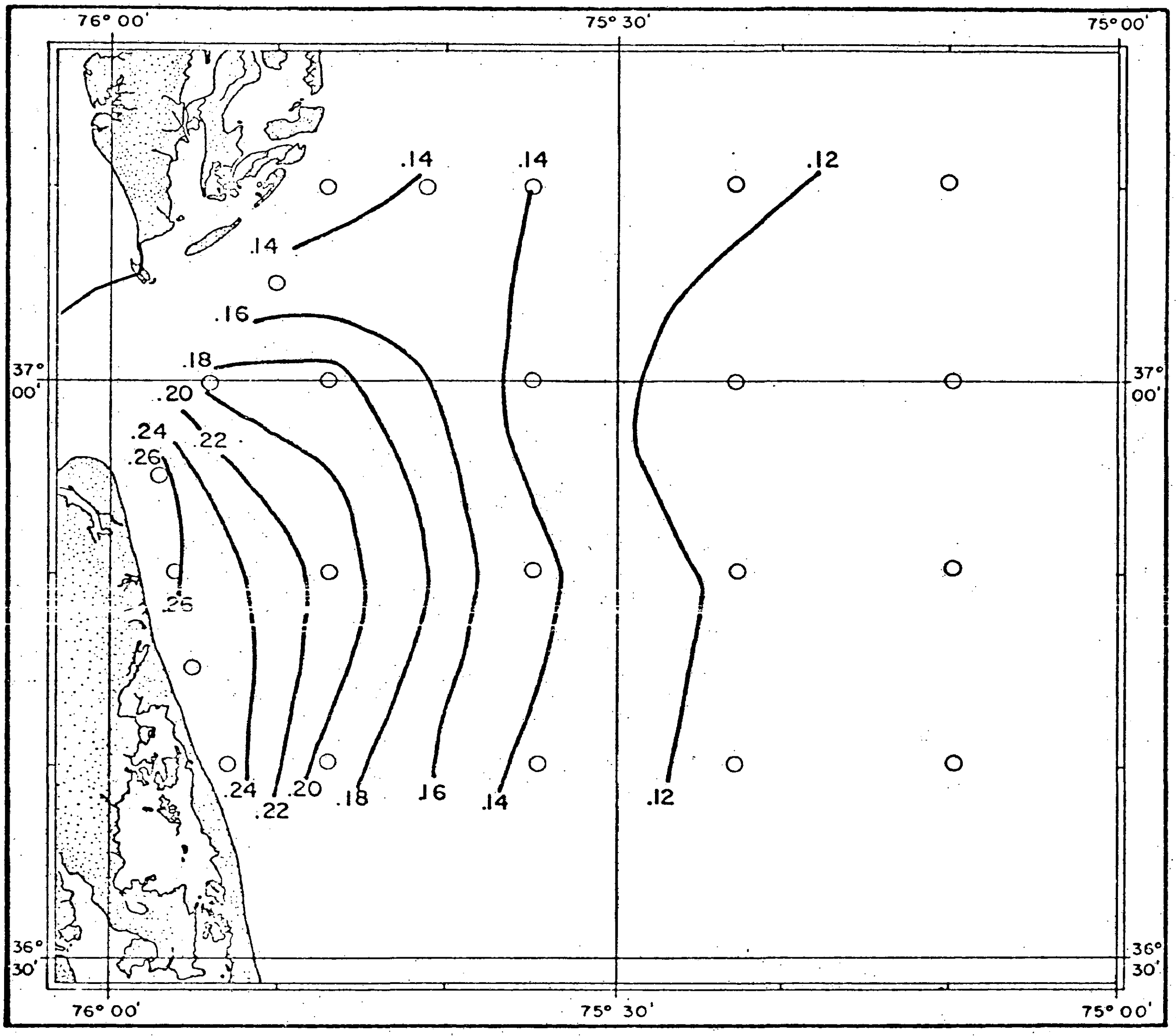

Figure 14. Horizontal distribution of fraction of admixed fresh water at the surface; September, 1967.

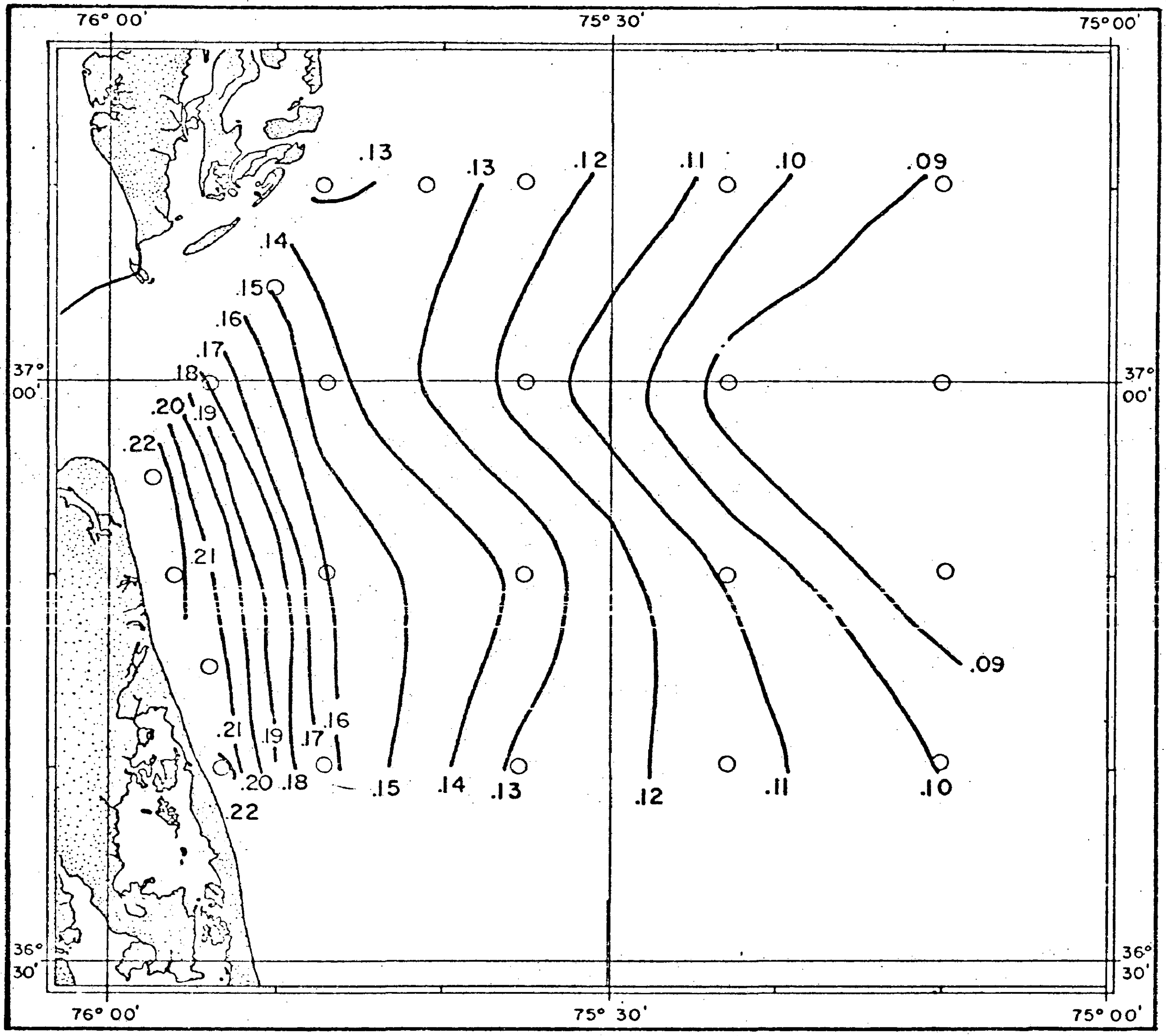

Figure 15. Horizontal distribution of mean fraction of admixed fresh water; September, 1967.

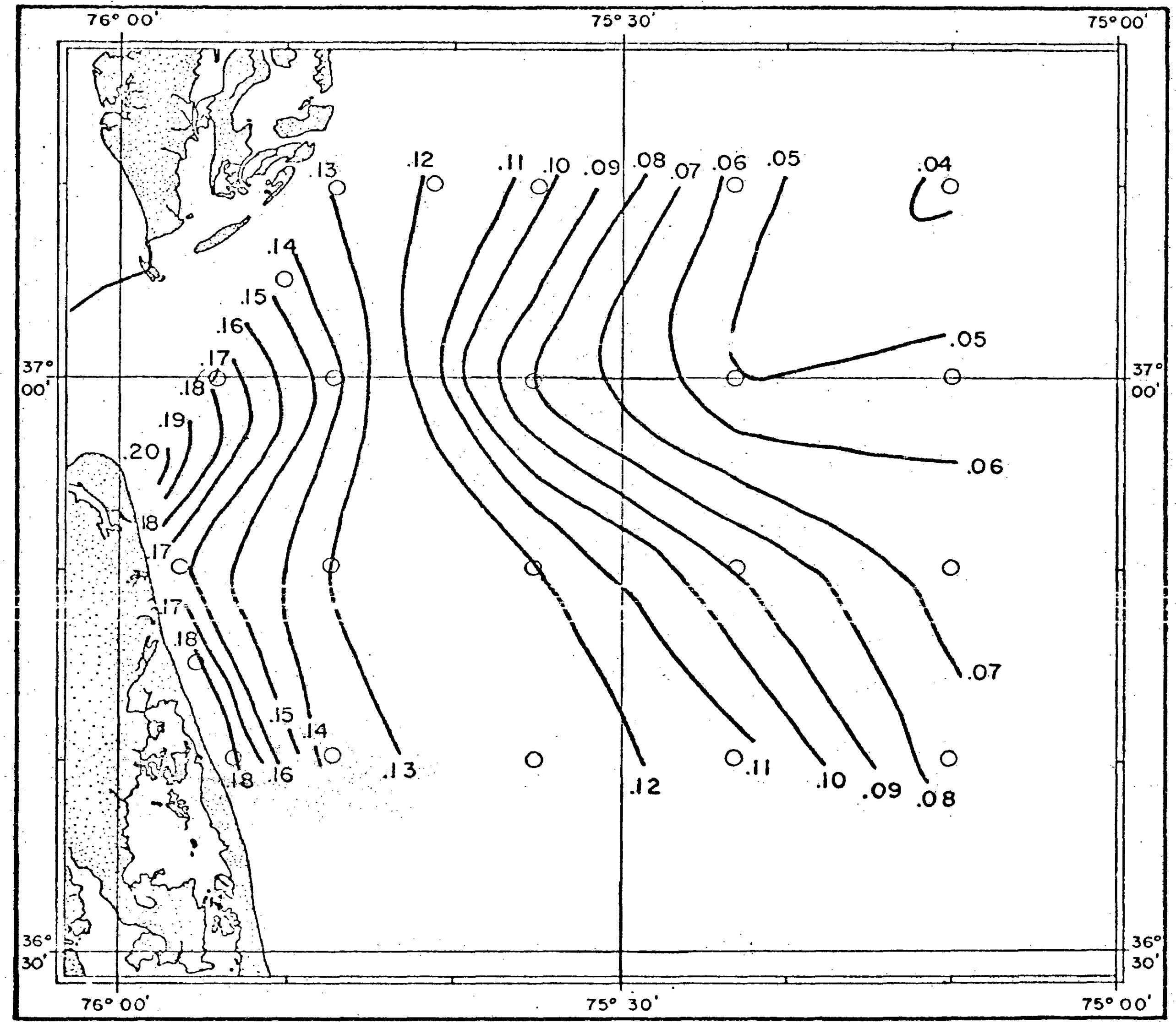

Figure 16. Horizontal distribution of fraction of admixed fresh water at the bottom; September, 1967.

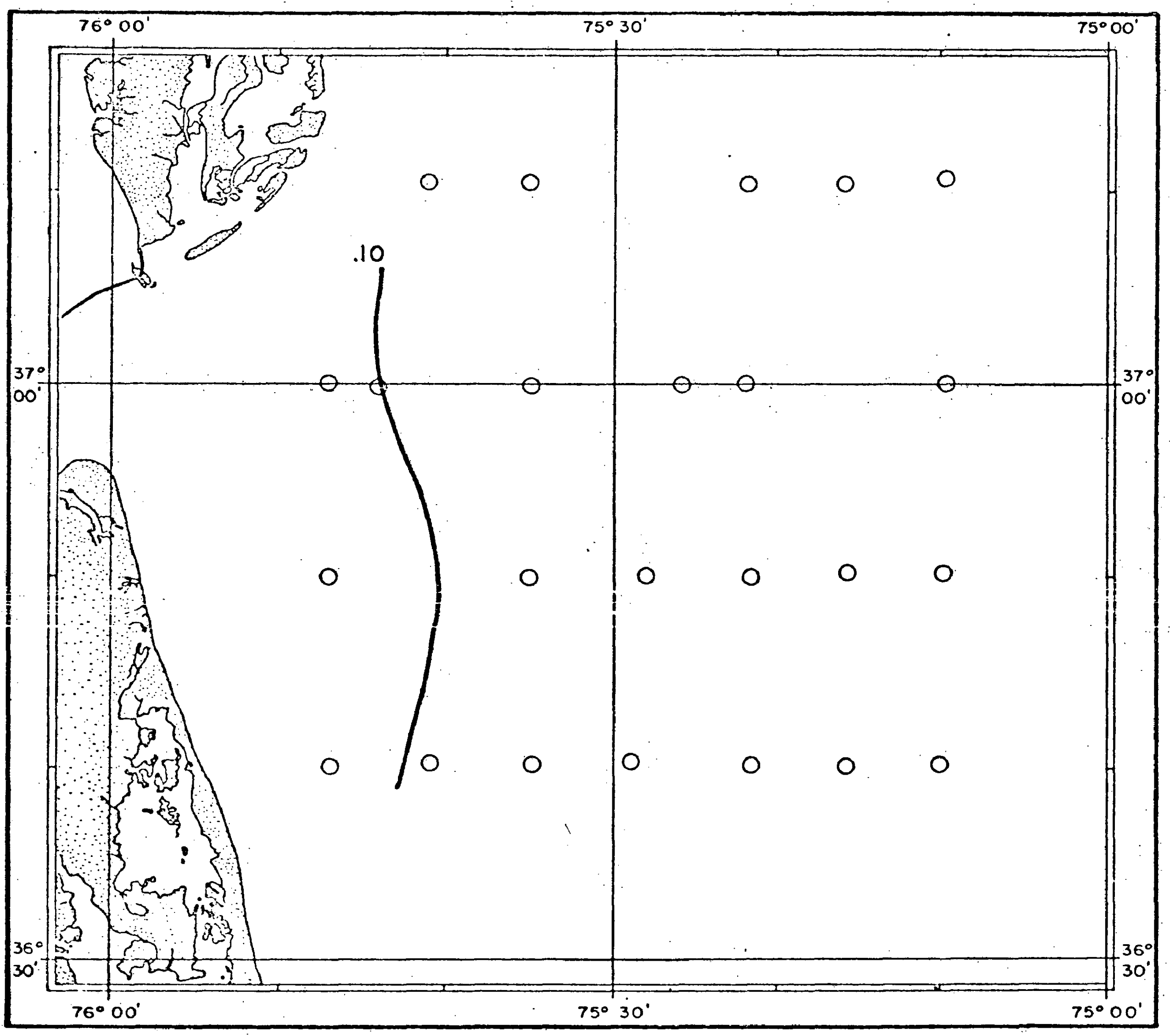

Figure 17. Horizontal distribution of fraction of admixed fresh water at the surface; September, 1968.

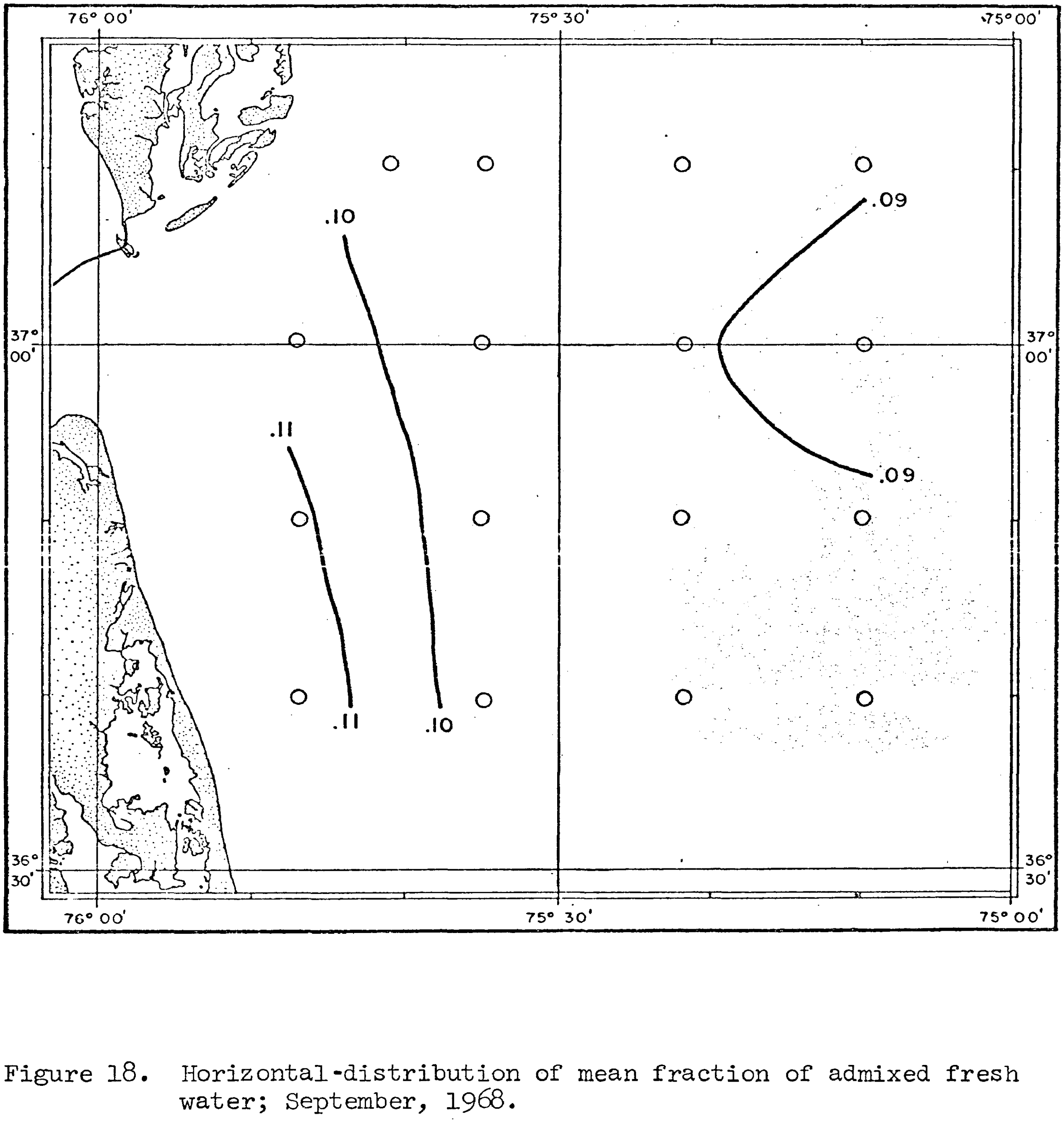

Figure 18. Horizontal-distribution of mean fraction of admixed fresh water; September, 1968.

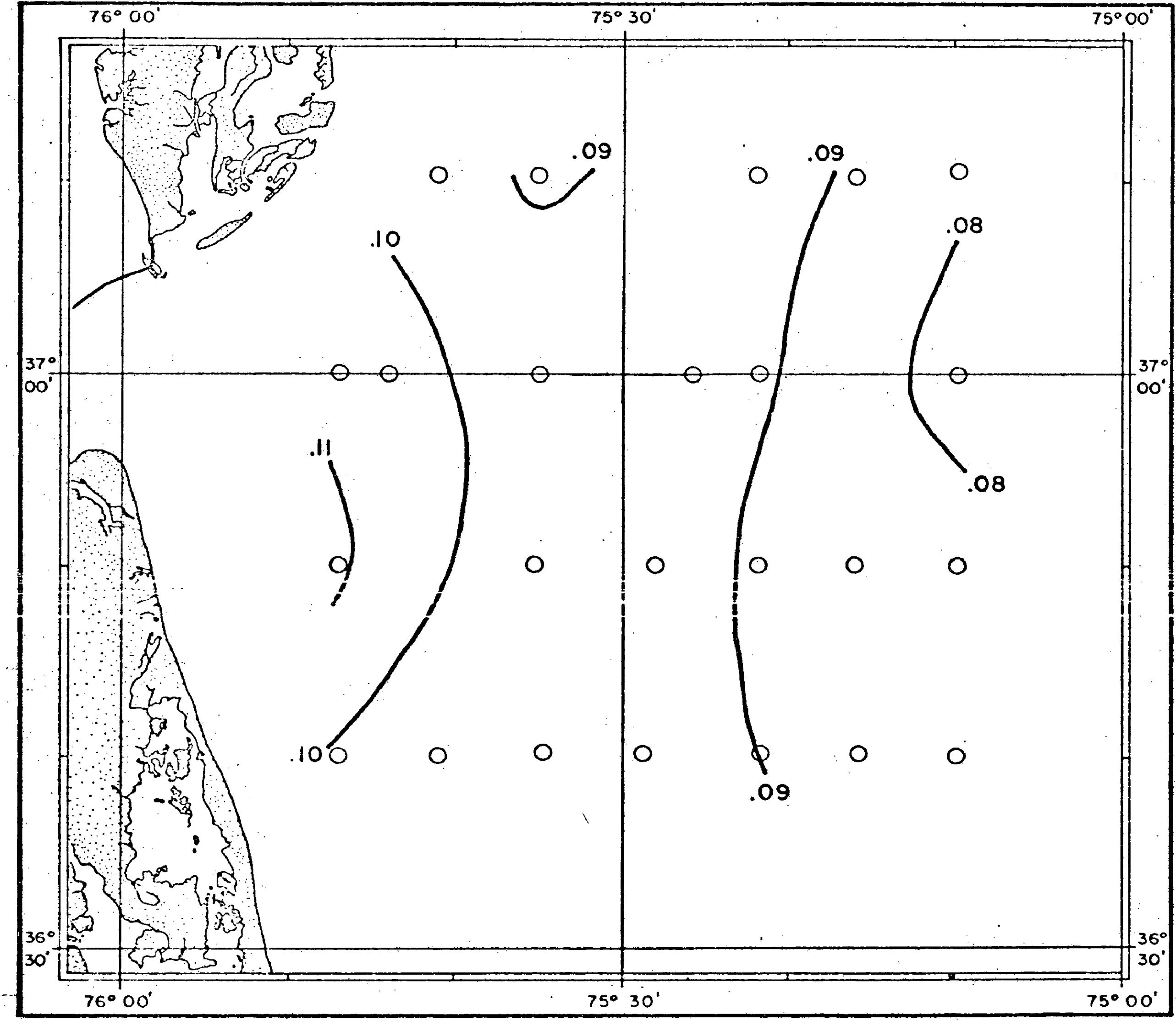

Figure 19. Horizontal distribution of fraction of admixed fresh water at the bottom; September, 1968.

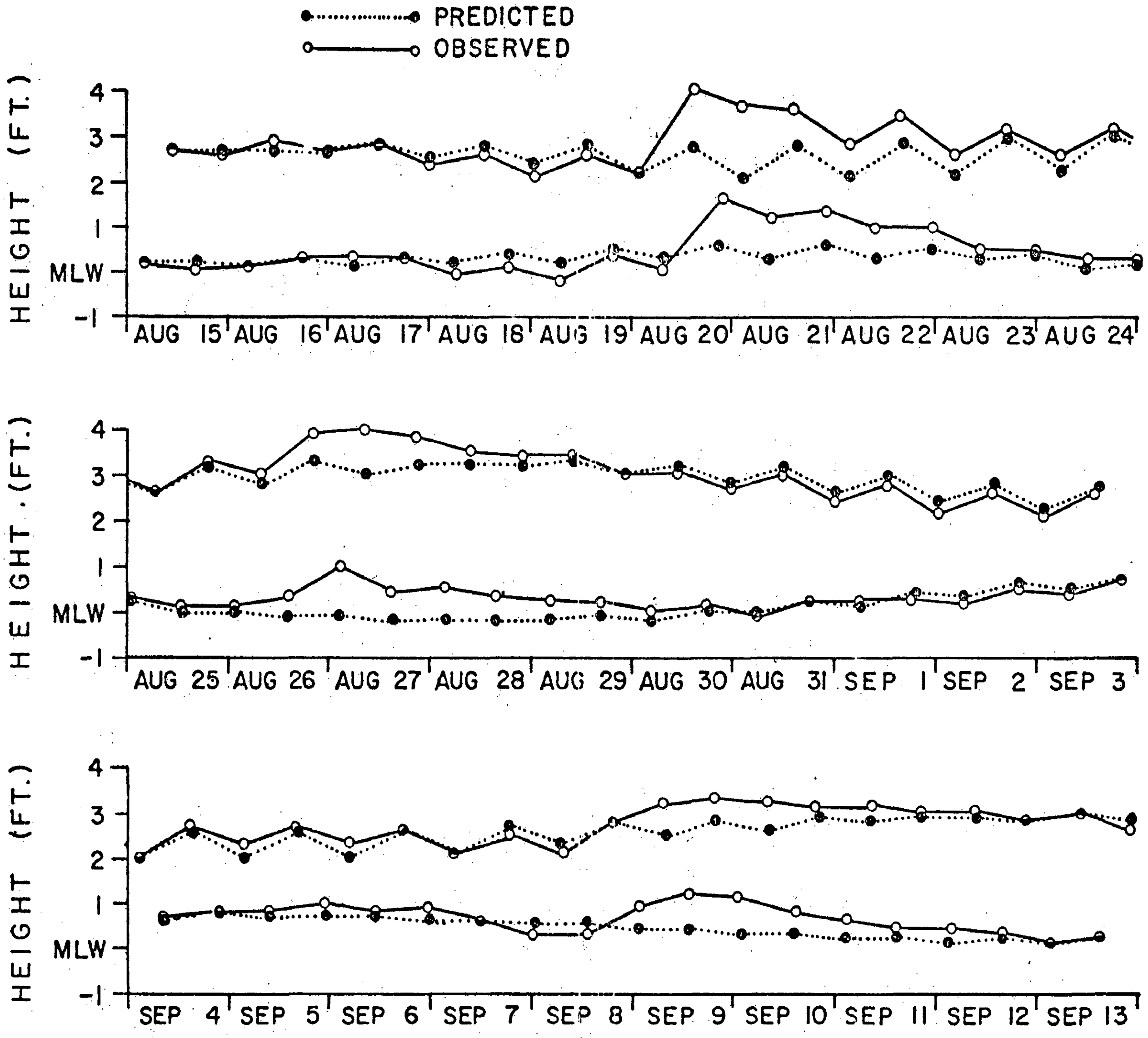

Figure 20. Heights of predicted and observed high and low water at Sewells Point.

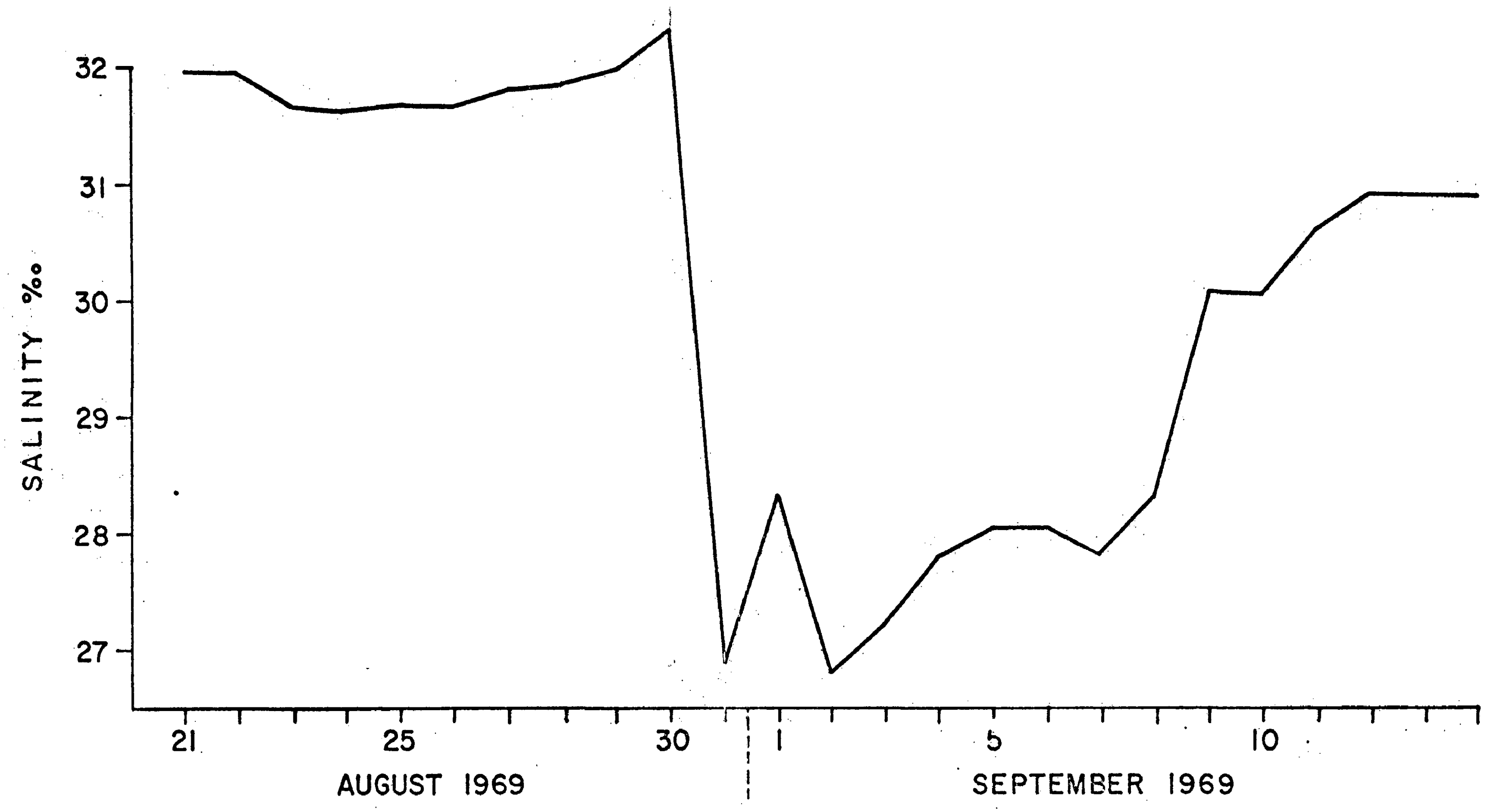

Figure 21. Time series salinity observations at surface off False Cape (36°35.6'N, 75°44'W).

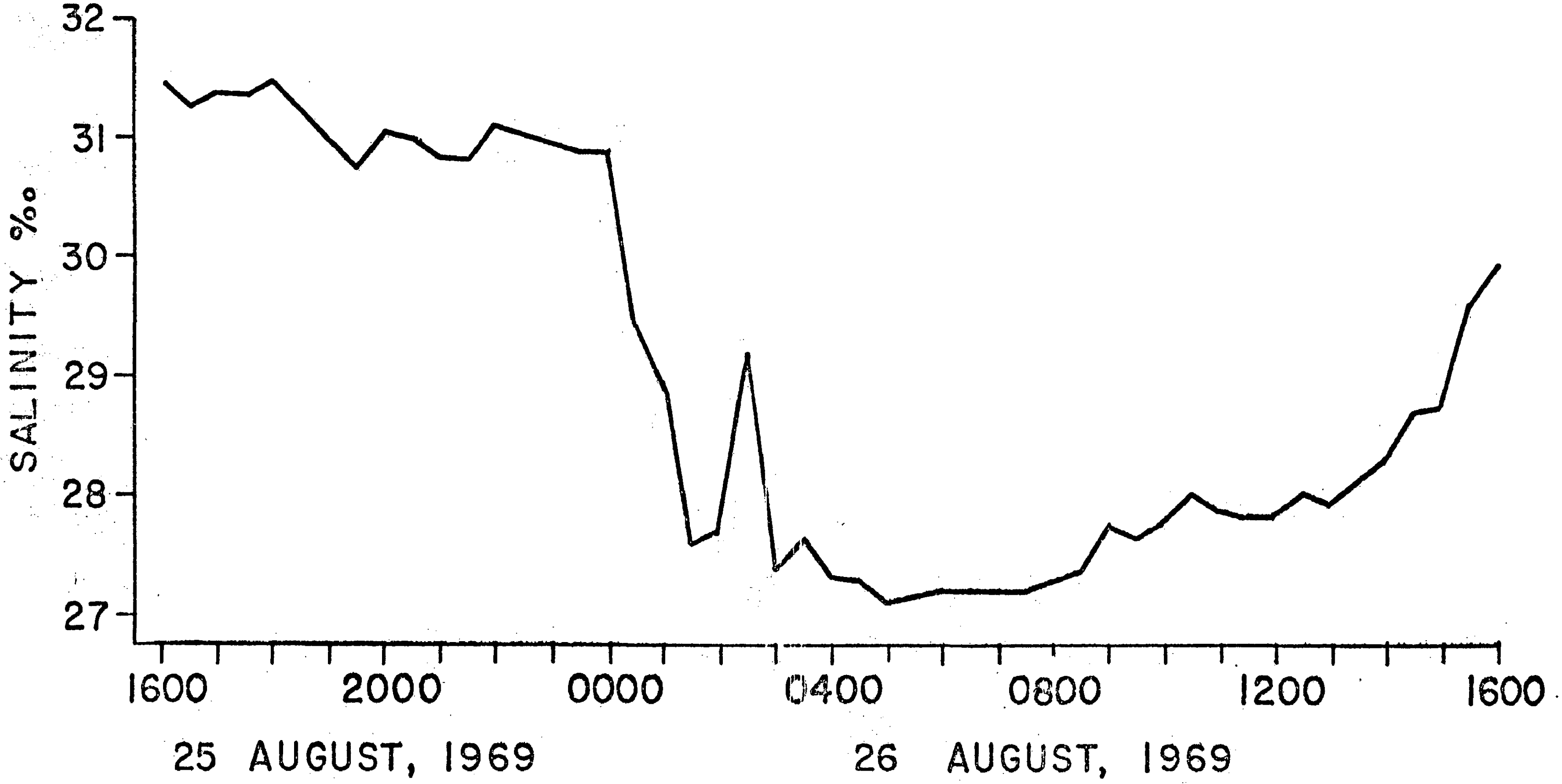

Figure 22. Daily salinity observations at surface at Chesapeake Light.

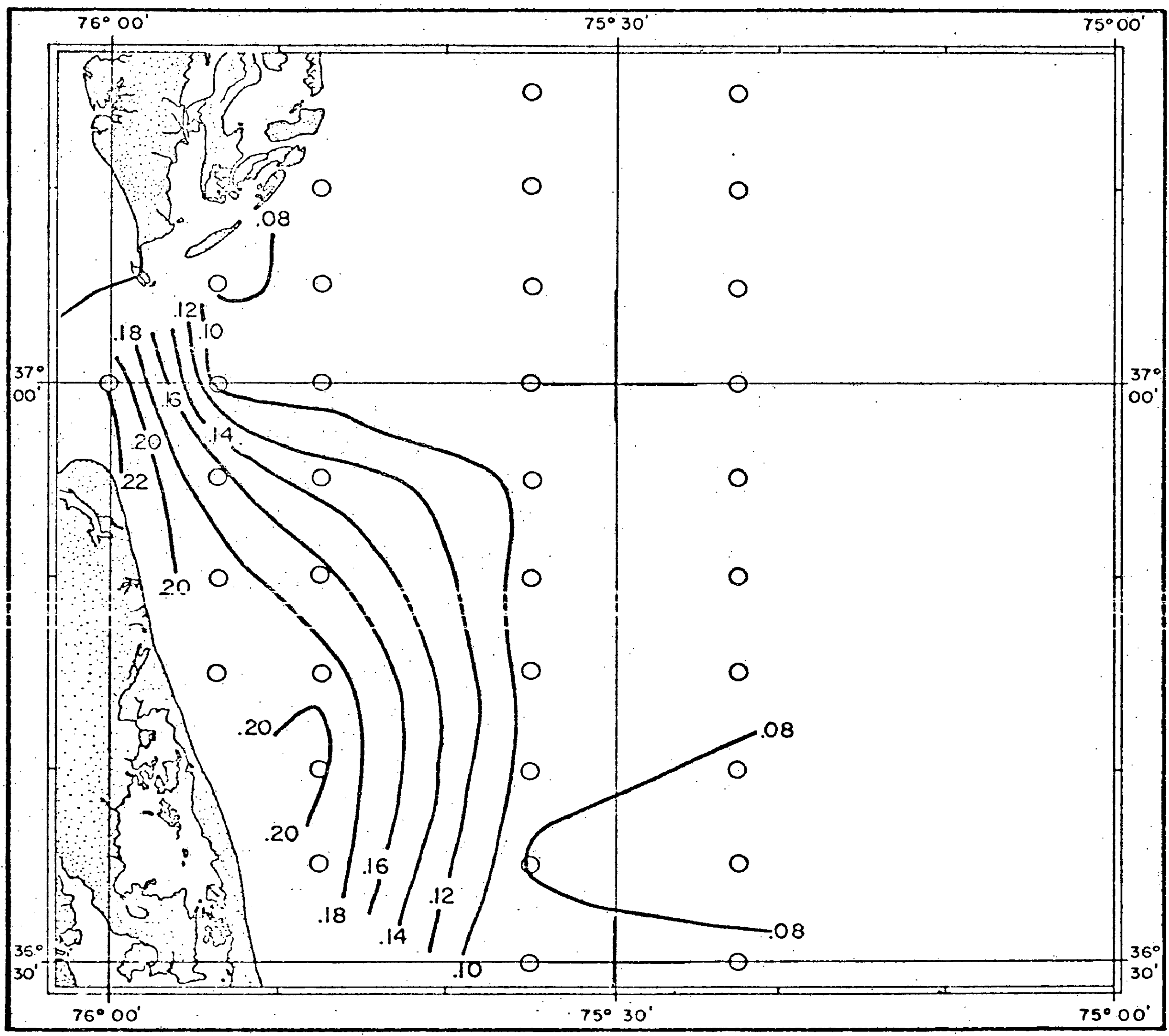

Figure 23. Horizontal distribution of fraction of admixed fresh water at the surface; Operation Override I; August, 1969.

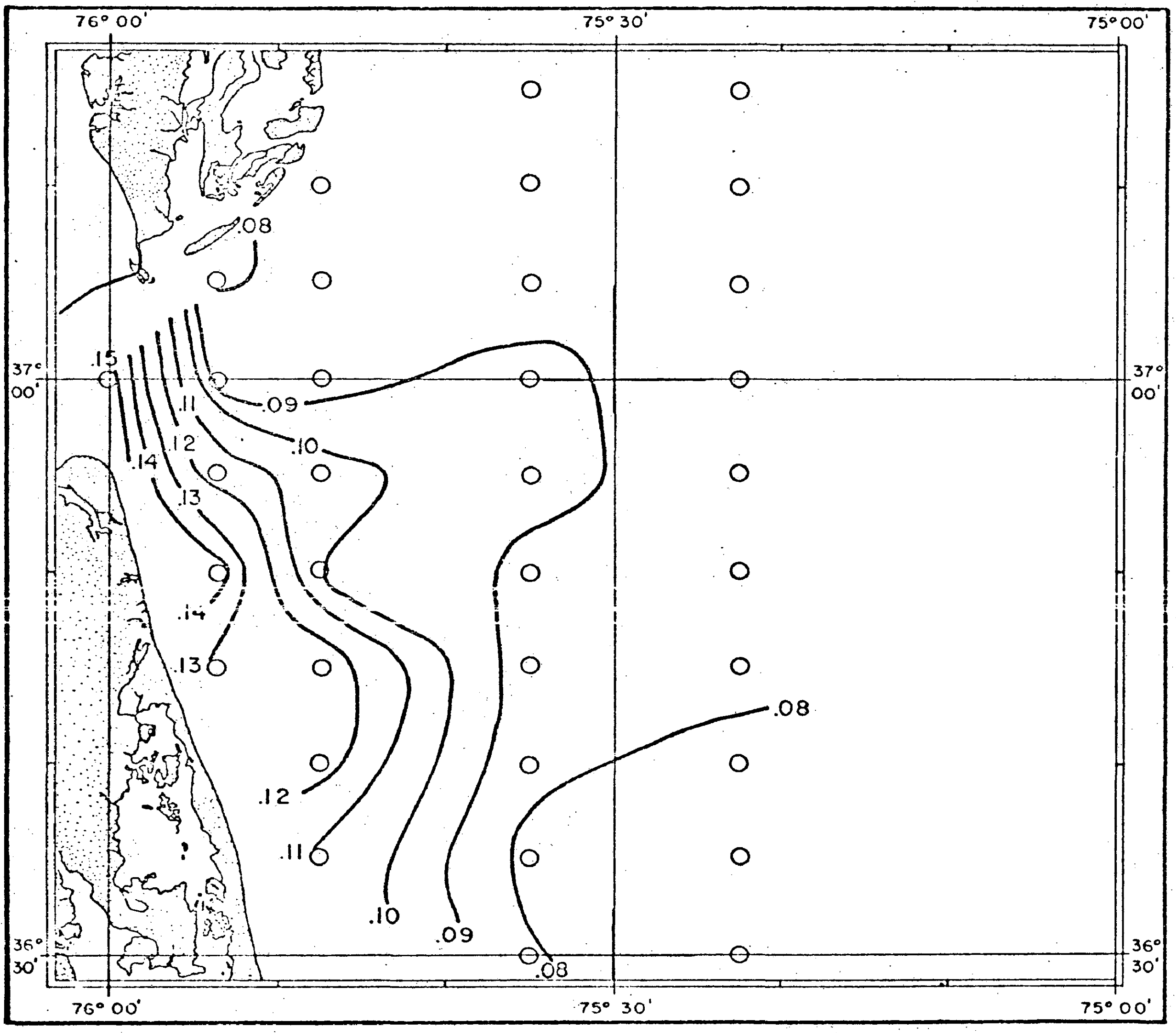

Figure 24. Horizontal distribution of mean fraction of admixed fresh water; Operation Override I; August, 1969.

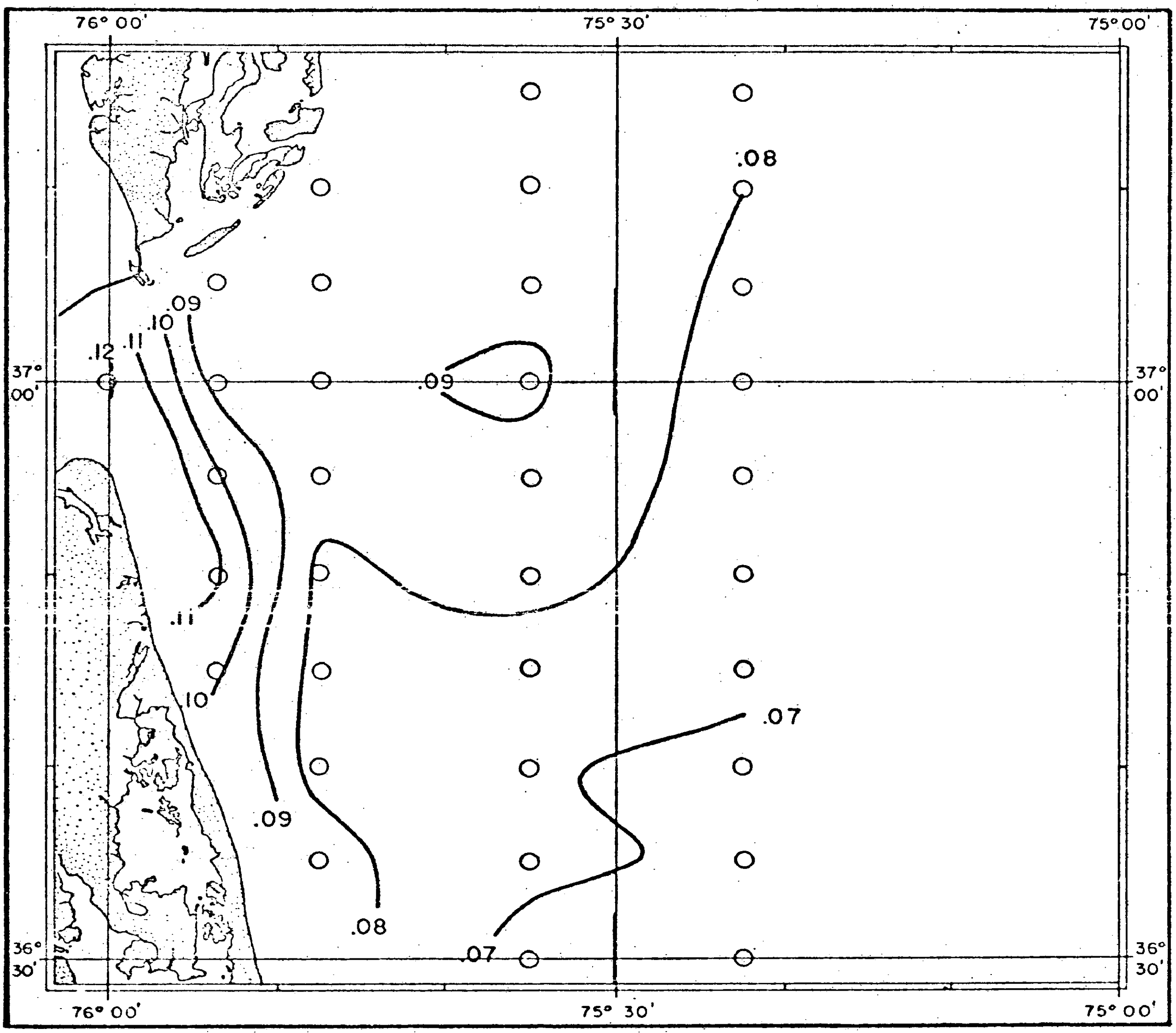

Figure 25. Horizontal distribution of fraction of admixed fresh water at the bottom; Operation Override I; August, 1969.

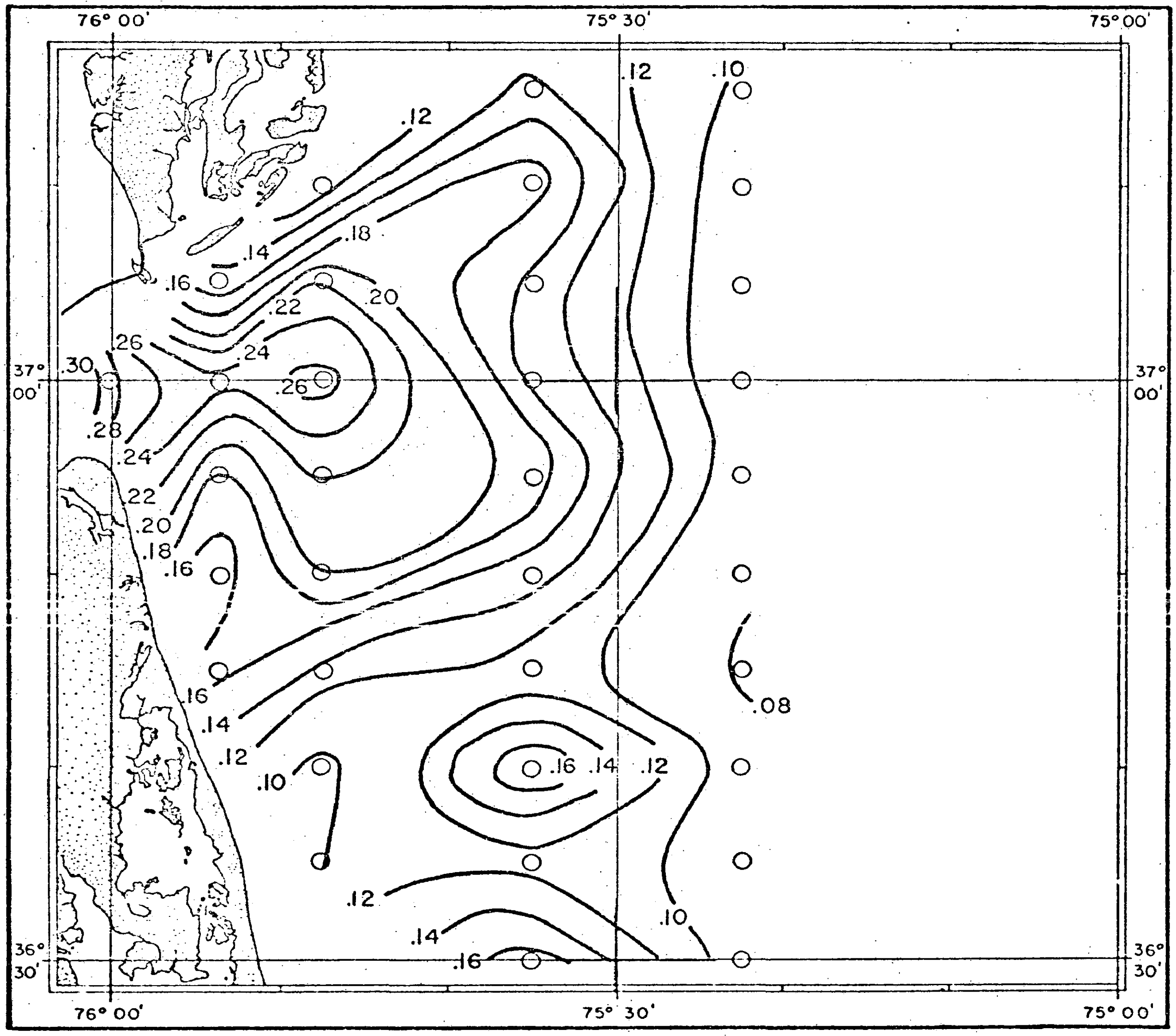

Figure 26. Horizontal distribution of fraction of admixed fresh water at the surface; Operation Override II; September, 1969.

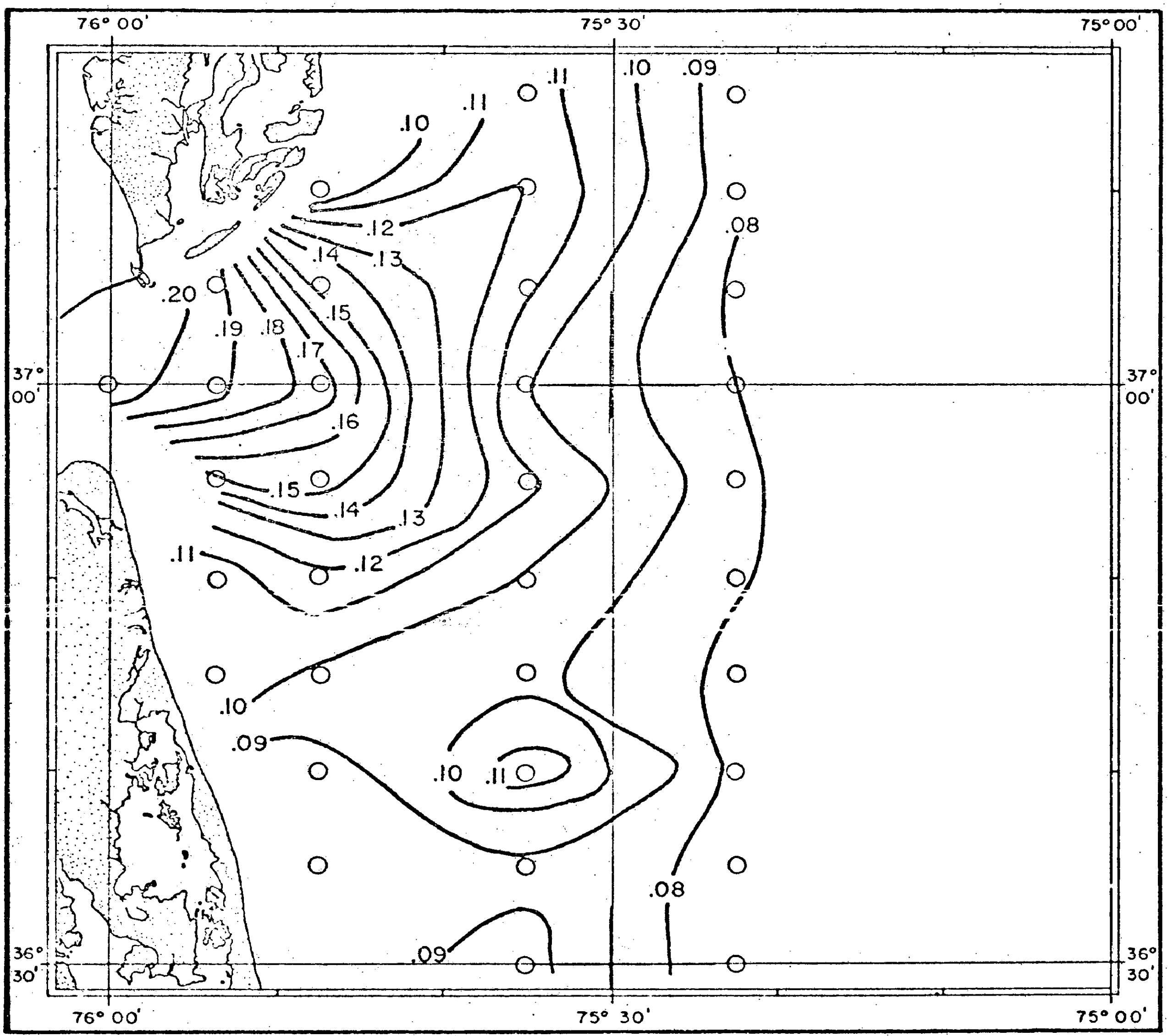

Figure 27. Horizontal distribution of mean fraction of admixed fresh water; Operation Override II; September, 1969.

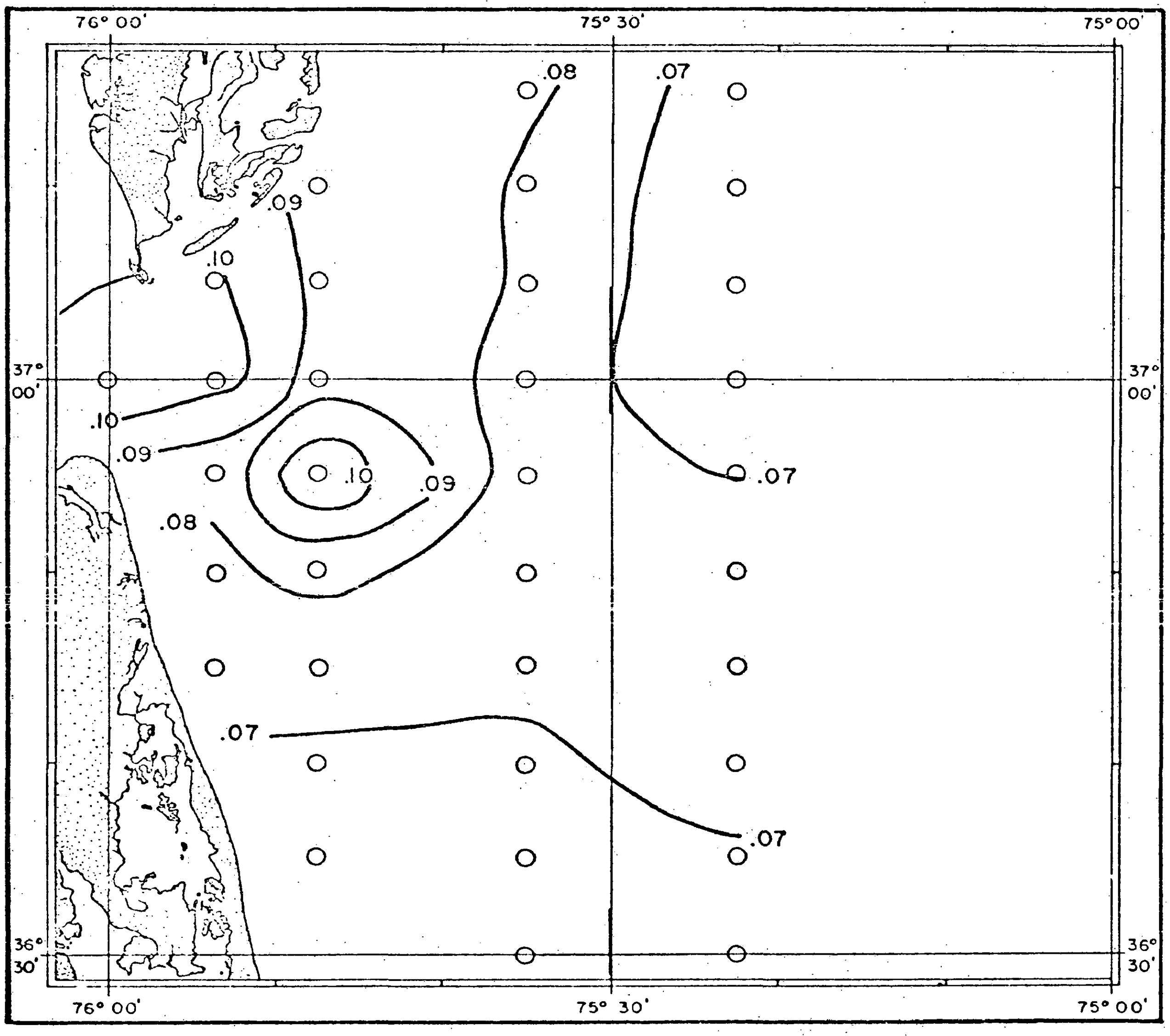

Figure 28. Horizontal distribution of fraction of admixed fresh water at the bottom; Operation Override II; September, 1969.

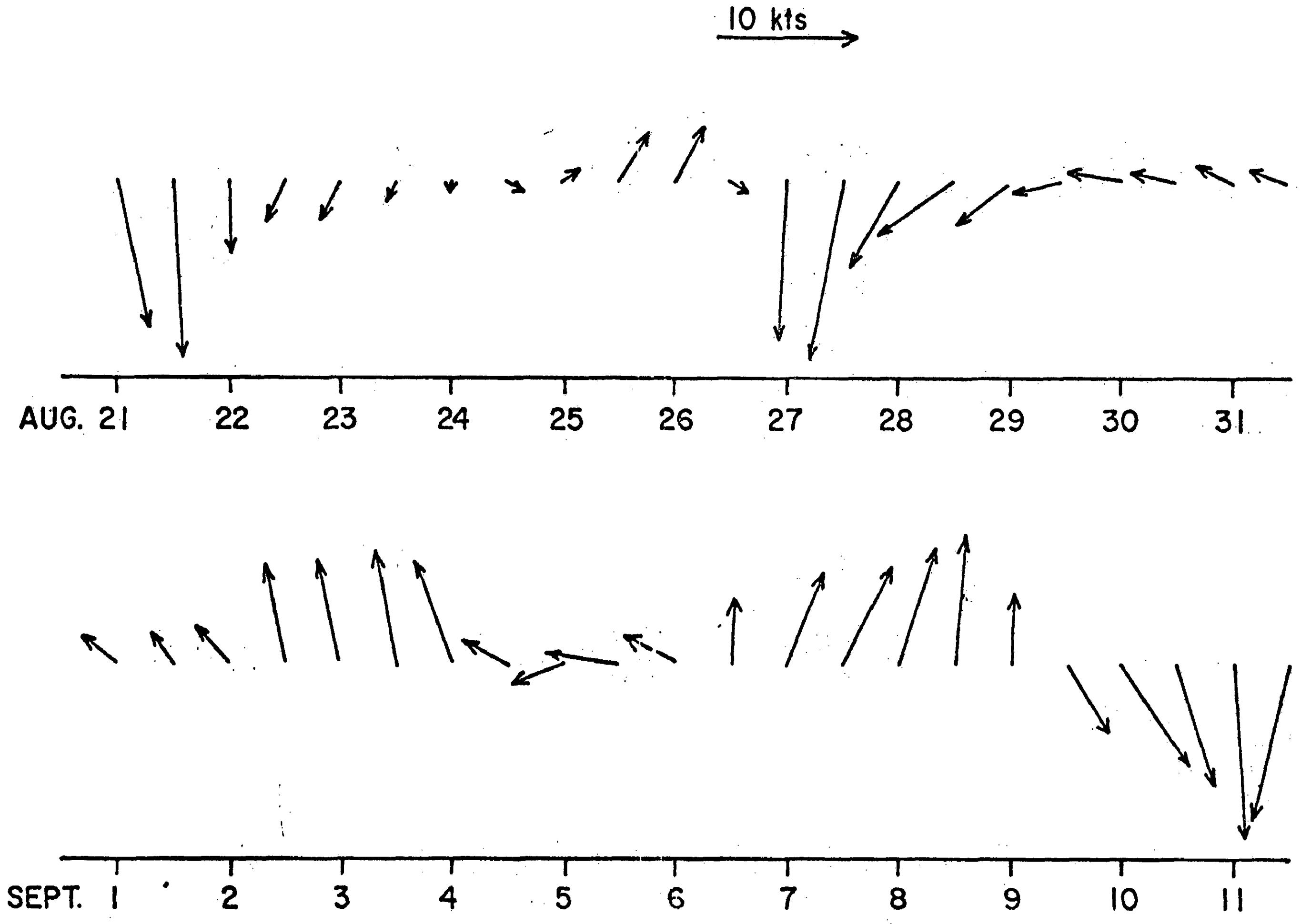

Figure 29. Running 24 hour resultant wind values; Norfolk, Va.

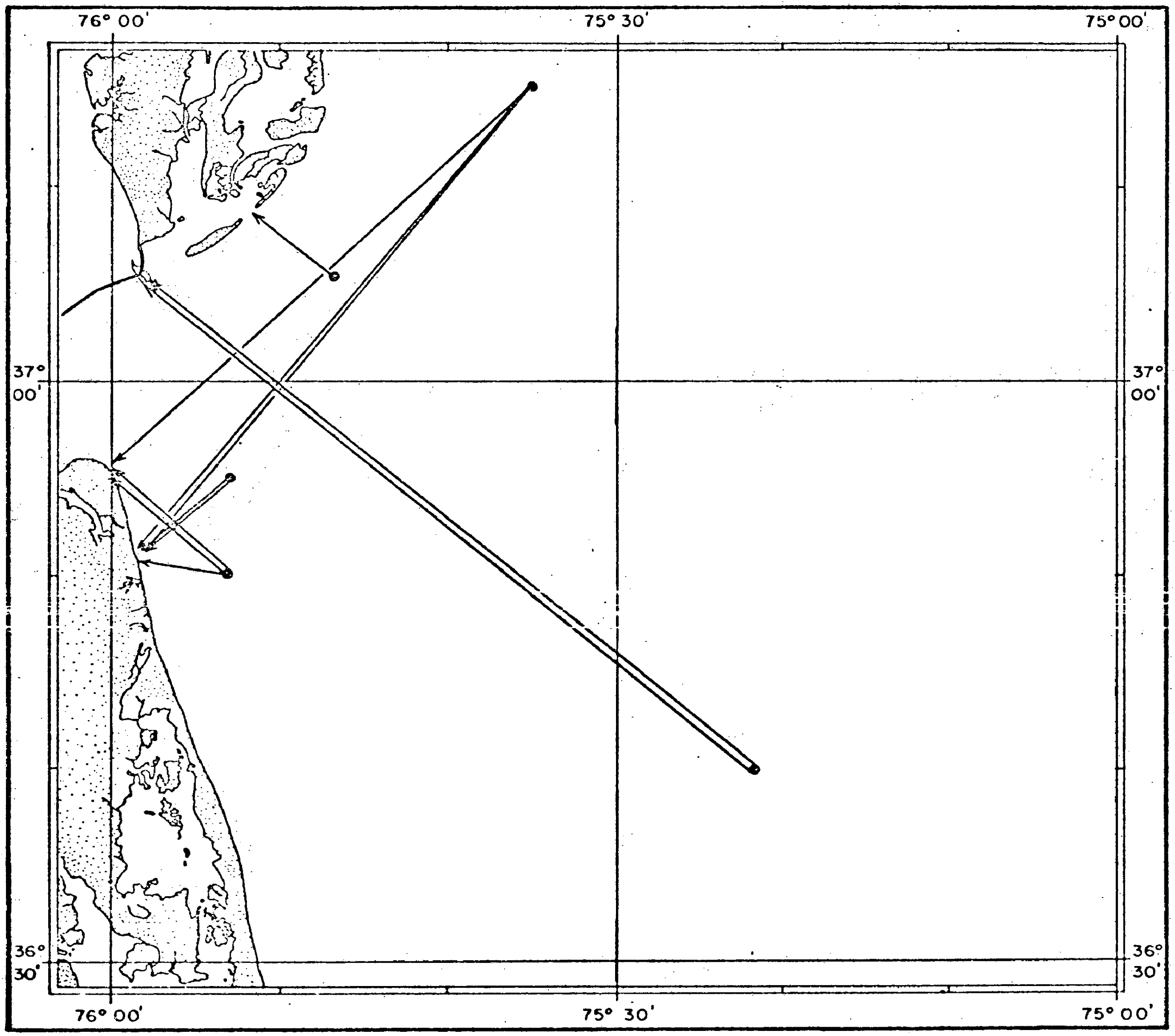

Figure 30. Results of bottom drifter recoveries made within twenty days of release.

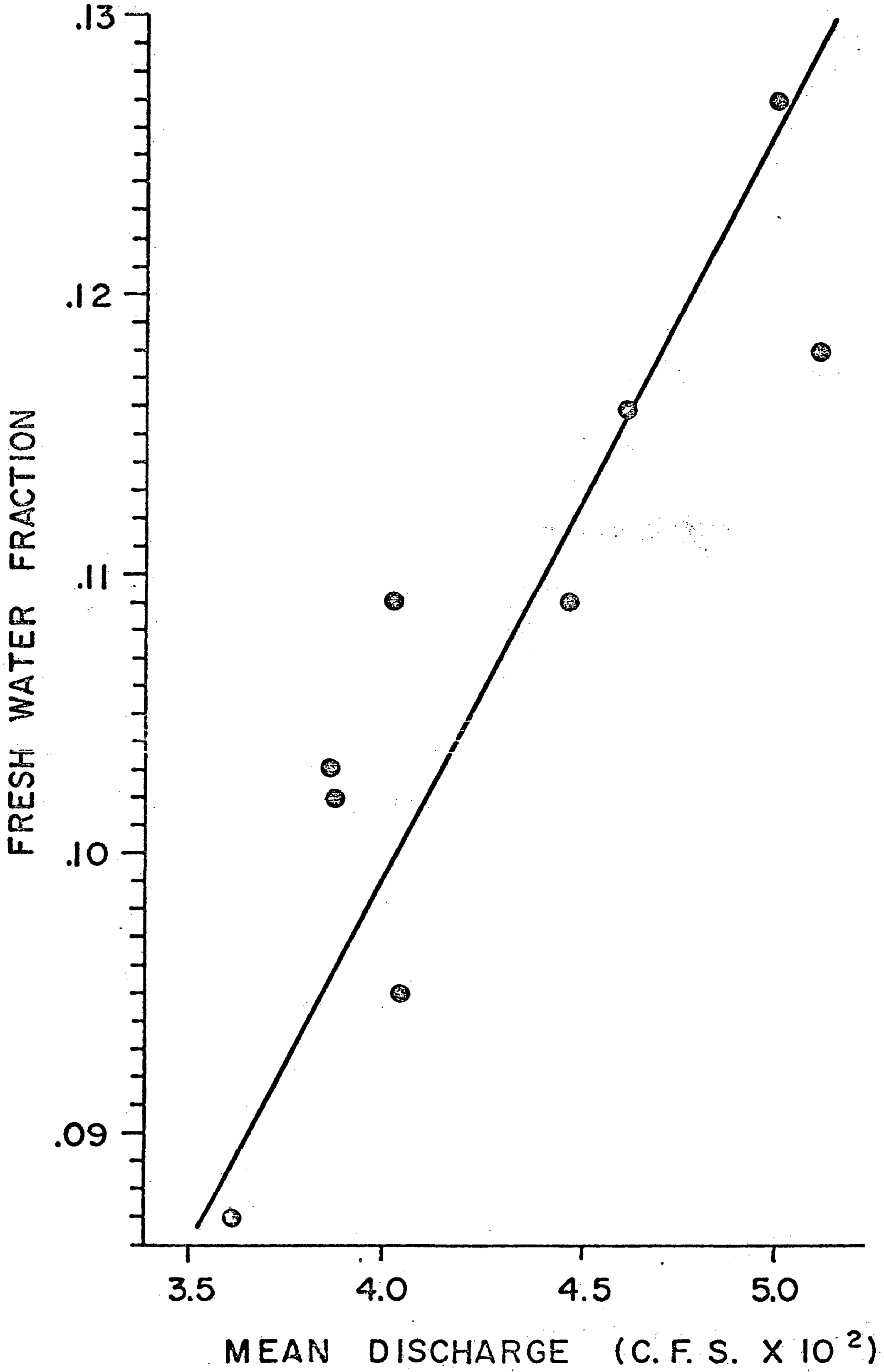

Figure 31. Plot of fraction of admixed fresh water in study area versus mean discharge from the Chesapeake Bay for preceding twelve months.

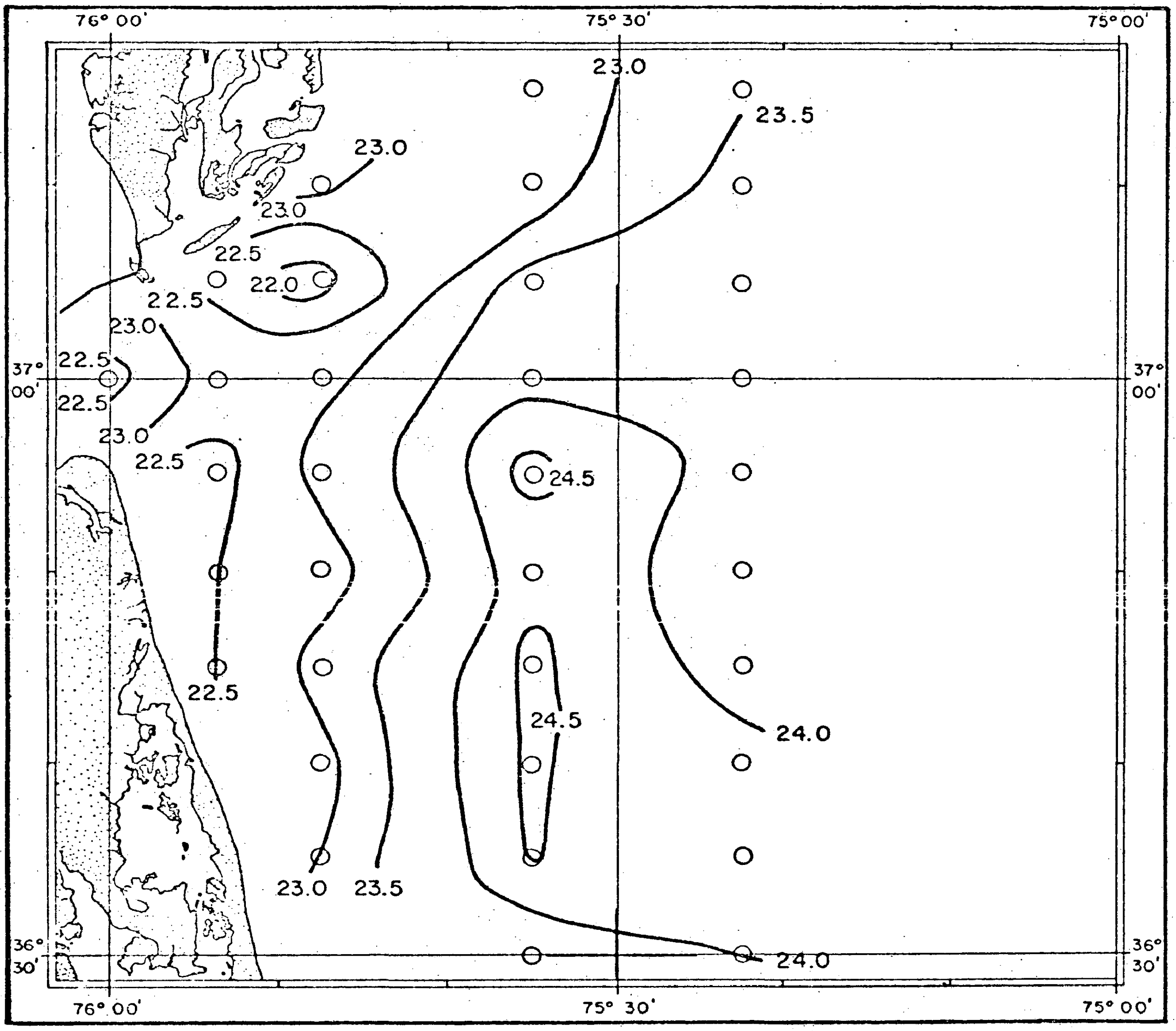

Figure 32. Distribution of surface isotherms; Operation Override II; August, 1969.

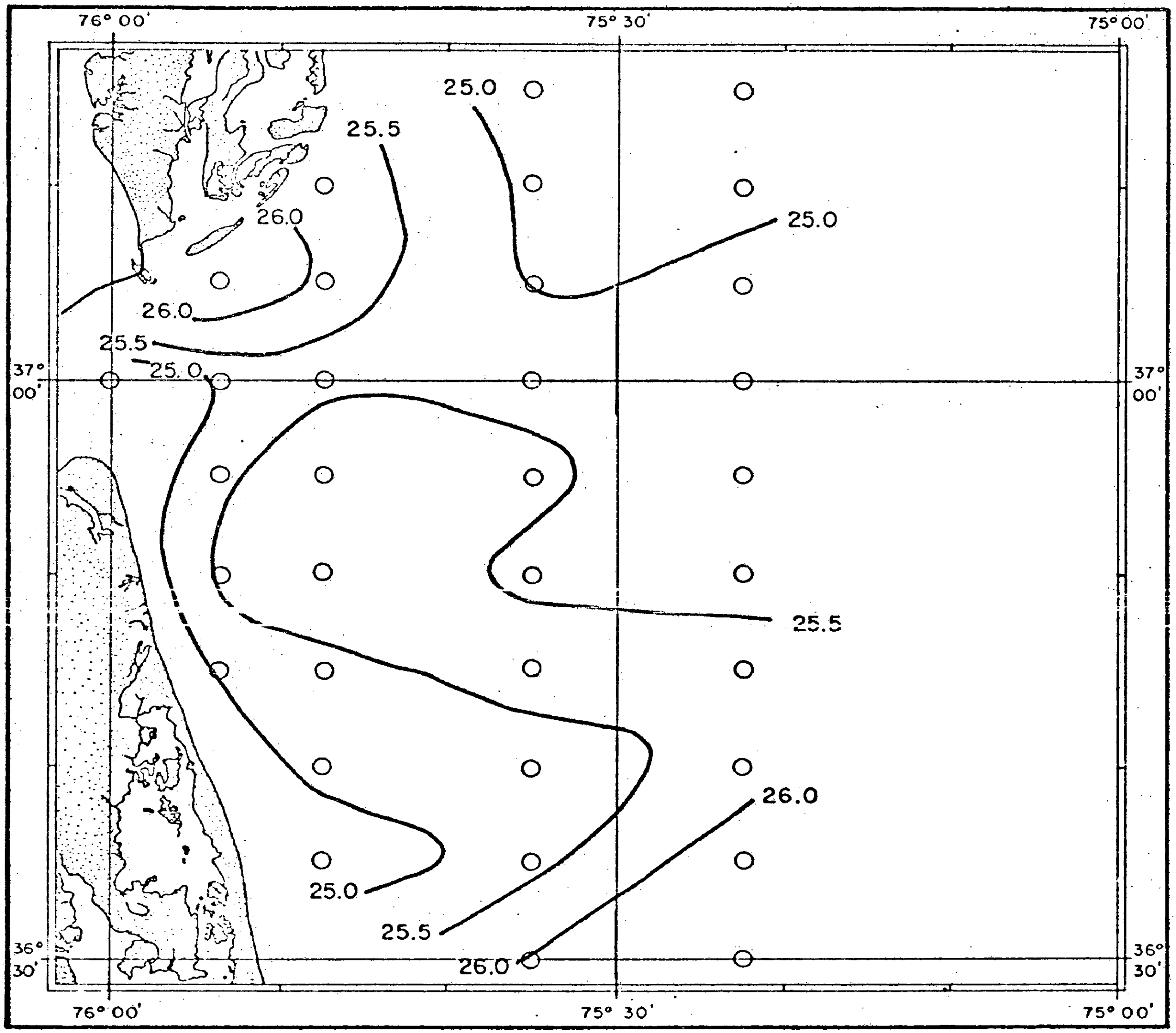

Figure 33. Distribution of surface isotherms; Operation Override II; September, 1969.

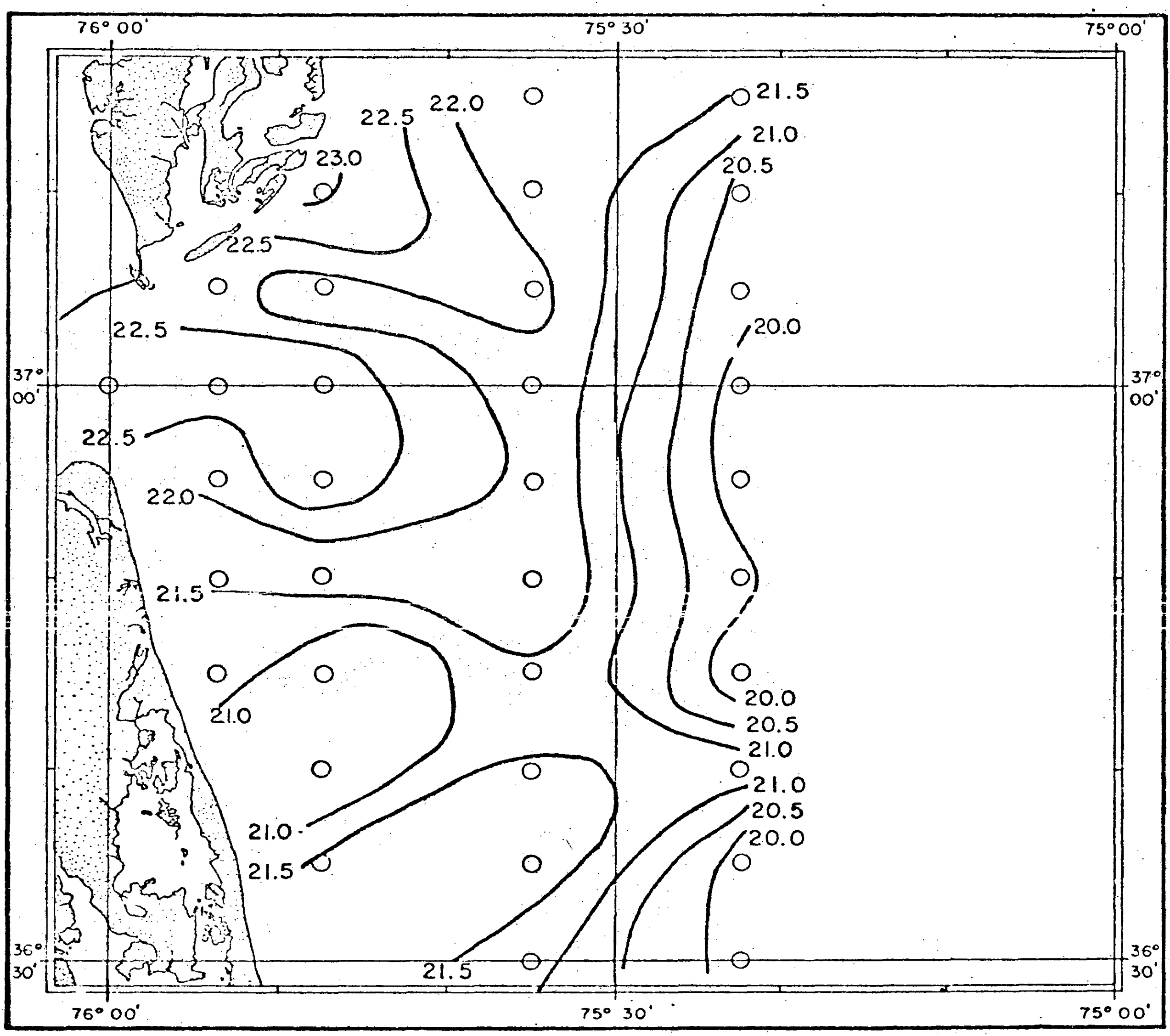

Figure 34. Horizontal distribution of mean temperature (excluding surface observations); Operation Override I; August, 1969.

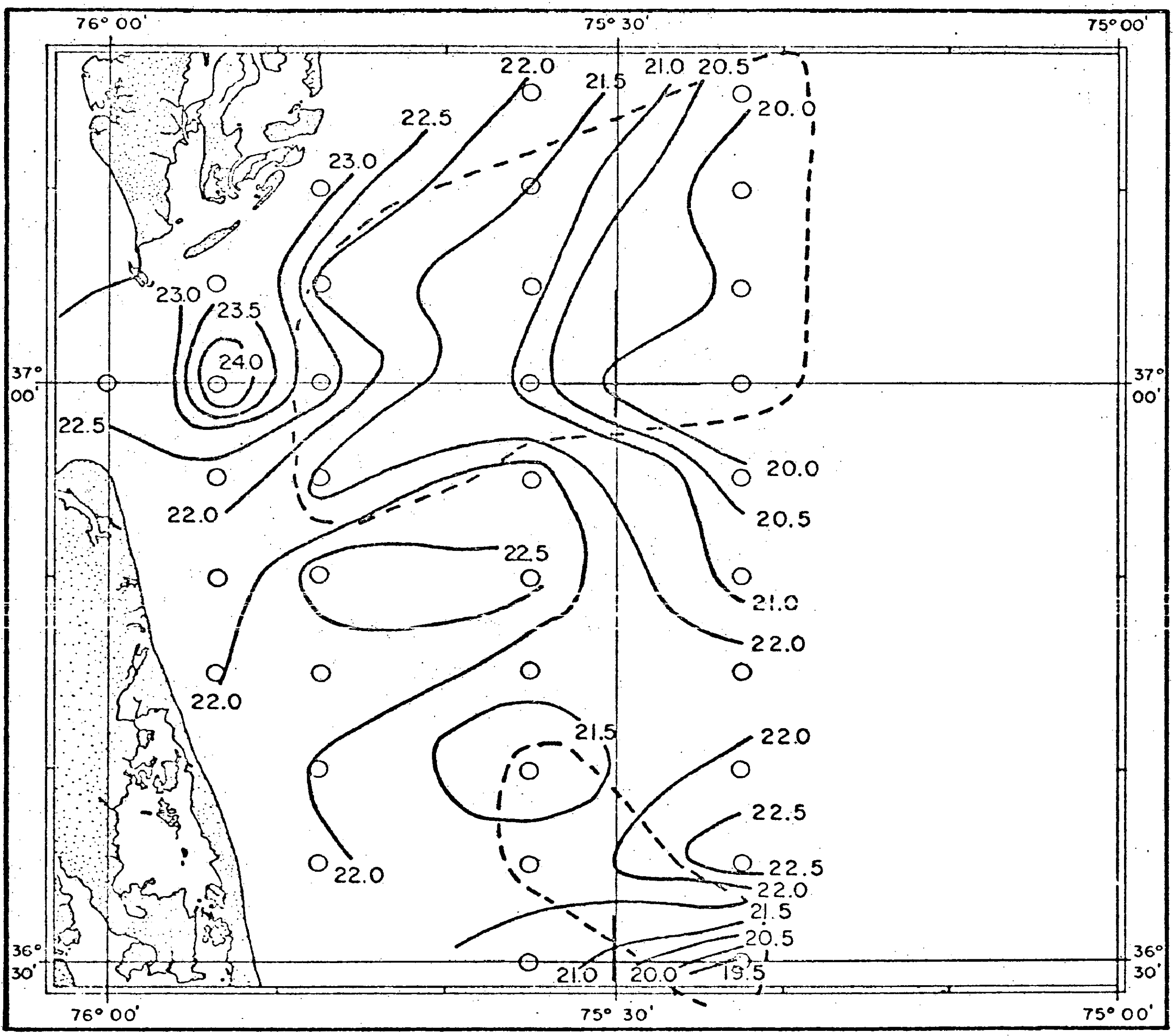

Figure 35. Horizontal distribution of mean temperature (excluding surface observations); Operation Override II; September, 1969.

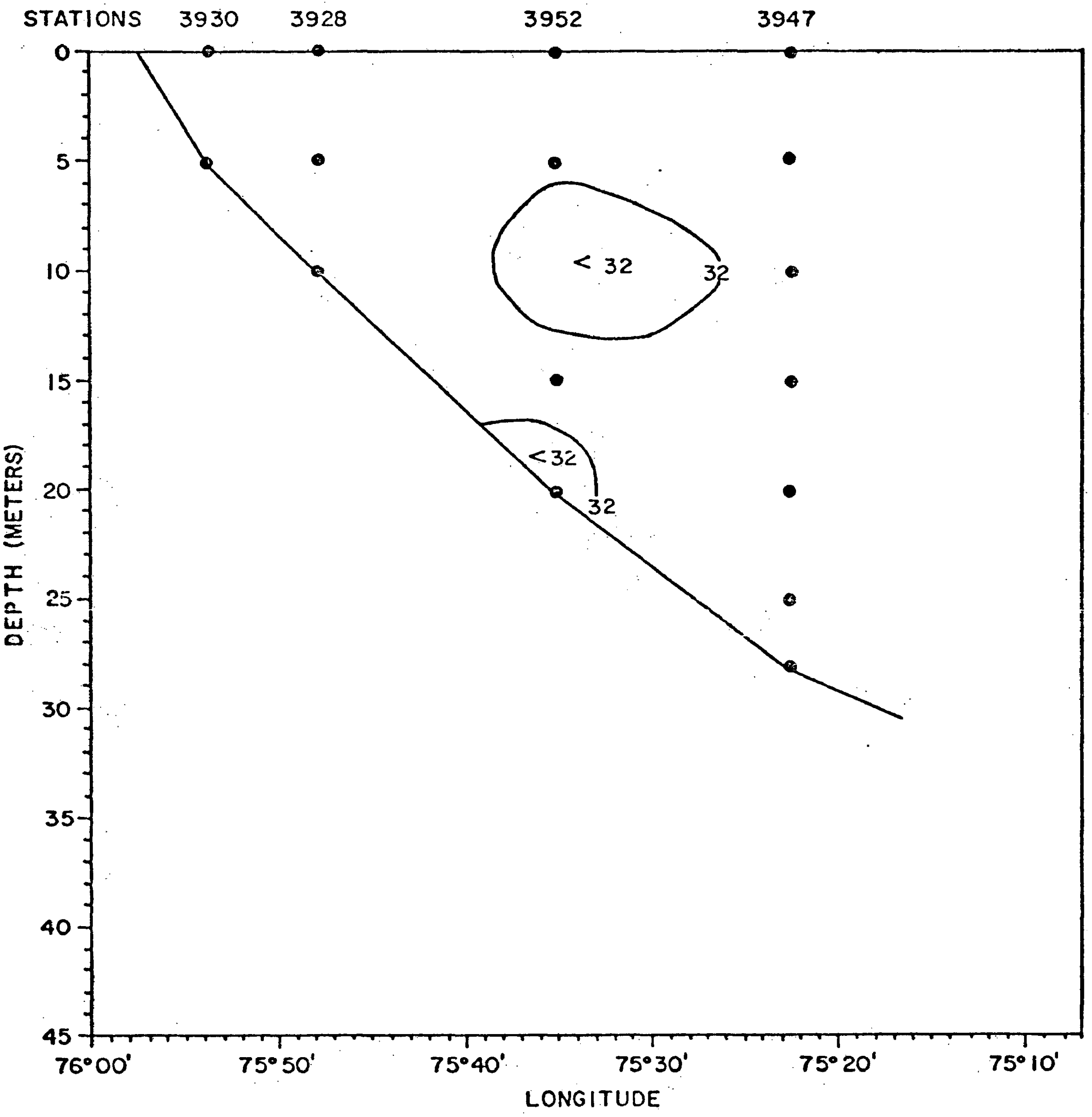

Figure 36. East-west oriented salinity section along 37°05'N; Operation Override I; August, 1969.

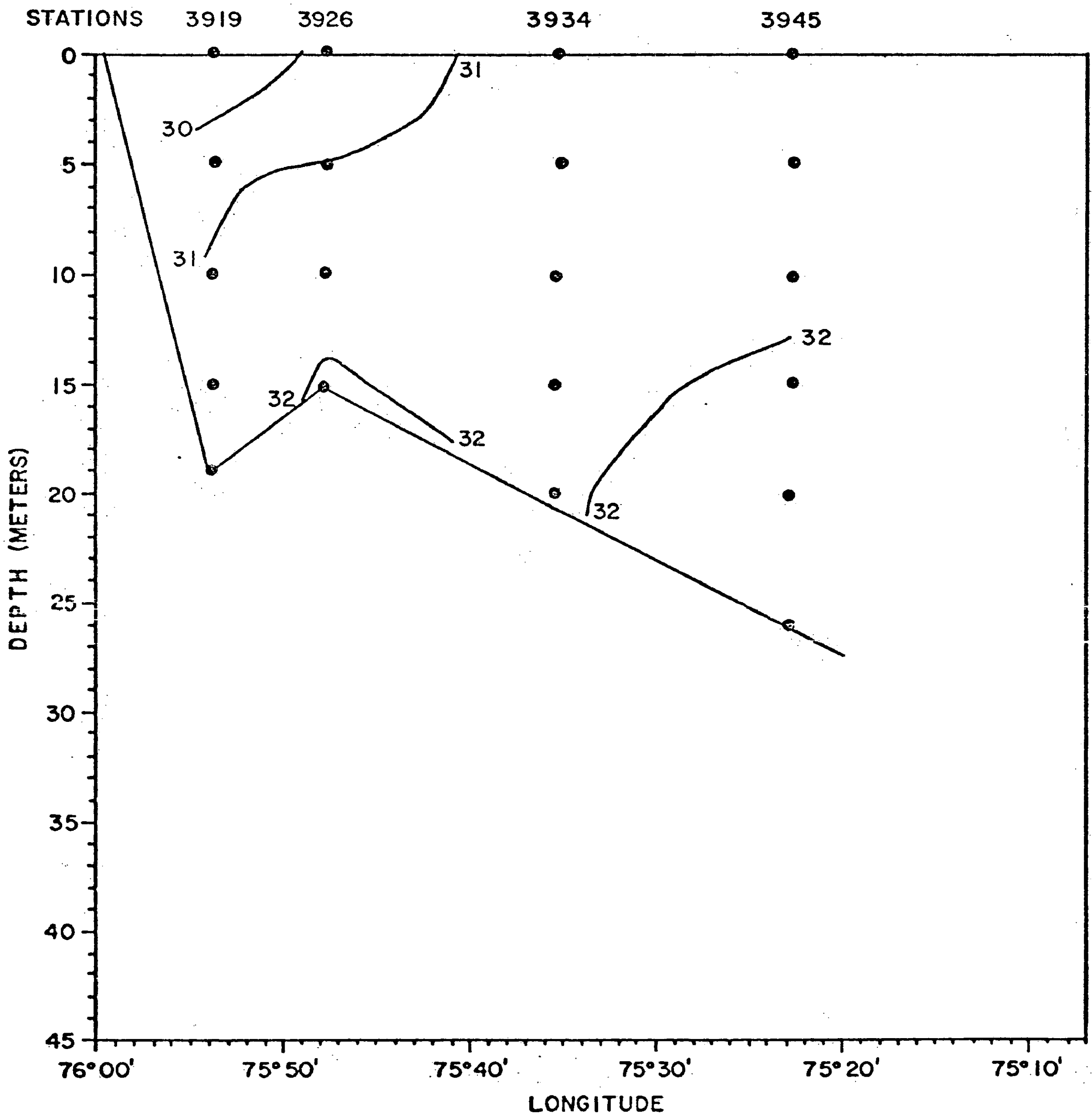

Figure 37. East-west oriented salinity section along 36°55'N; Operation Override I; August, 1969.

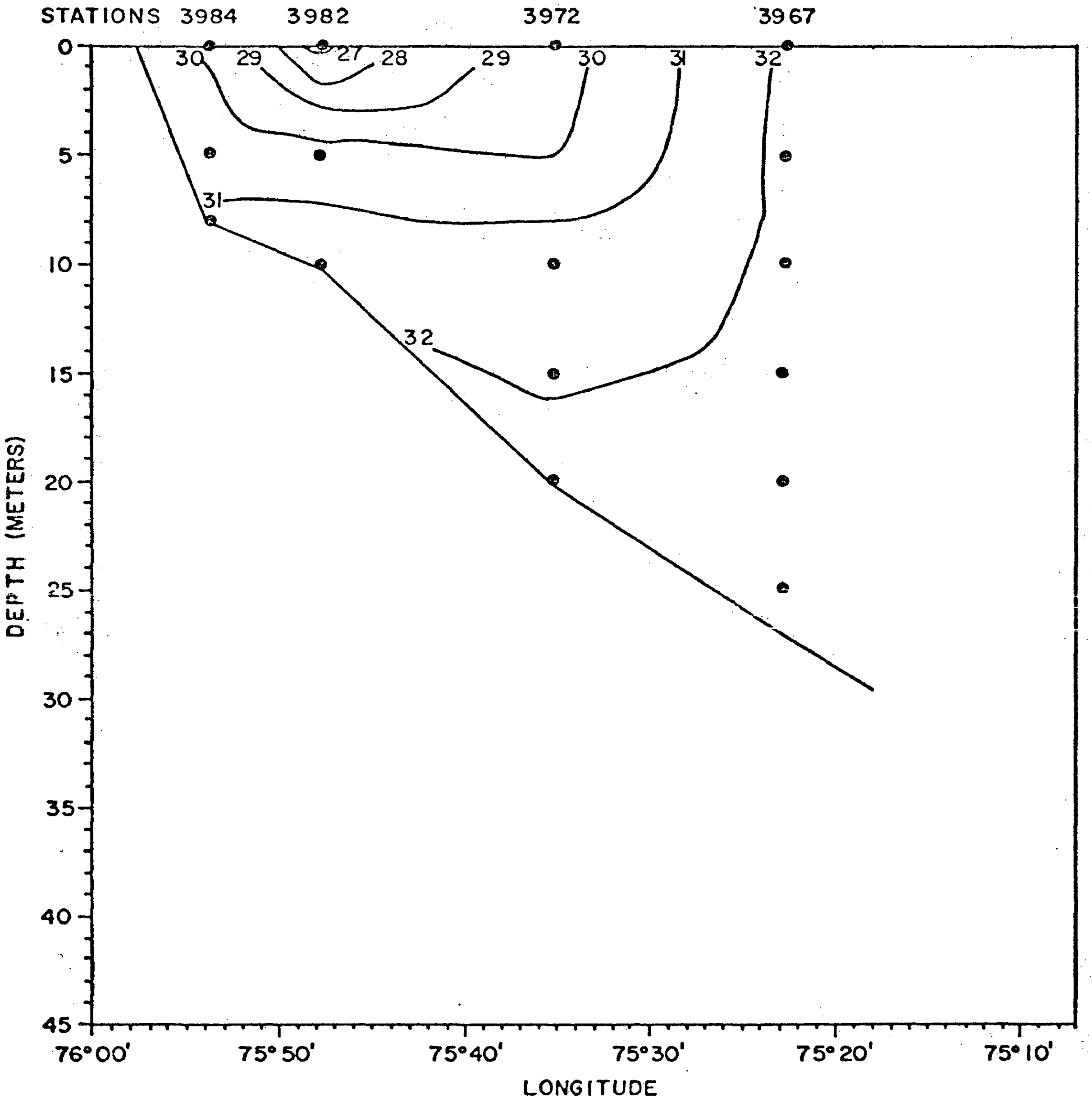

Figure 38. East-west oriented salinity section along 37°05'N; Operation Override II; September, 1969.

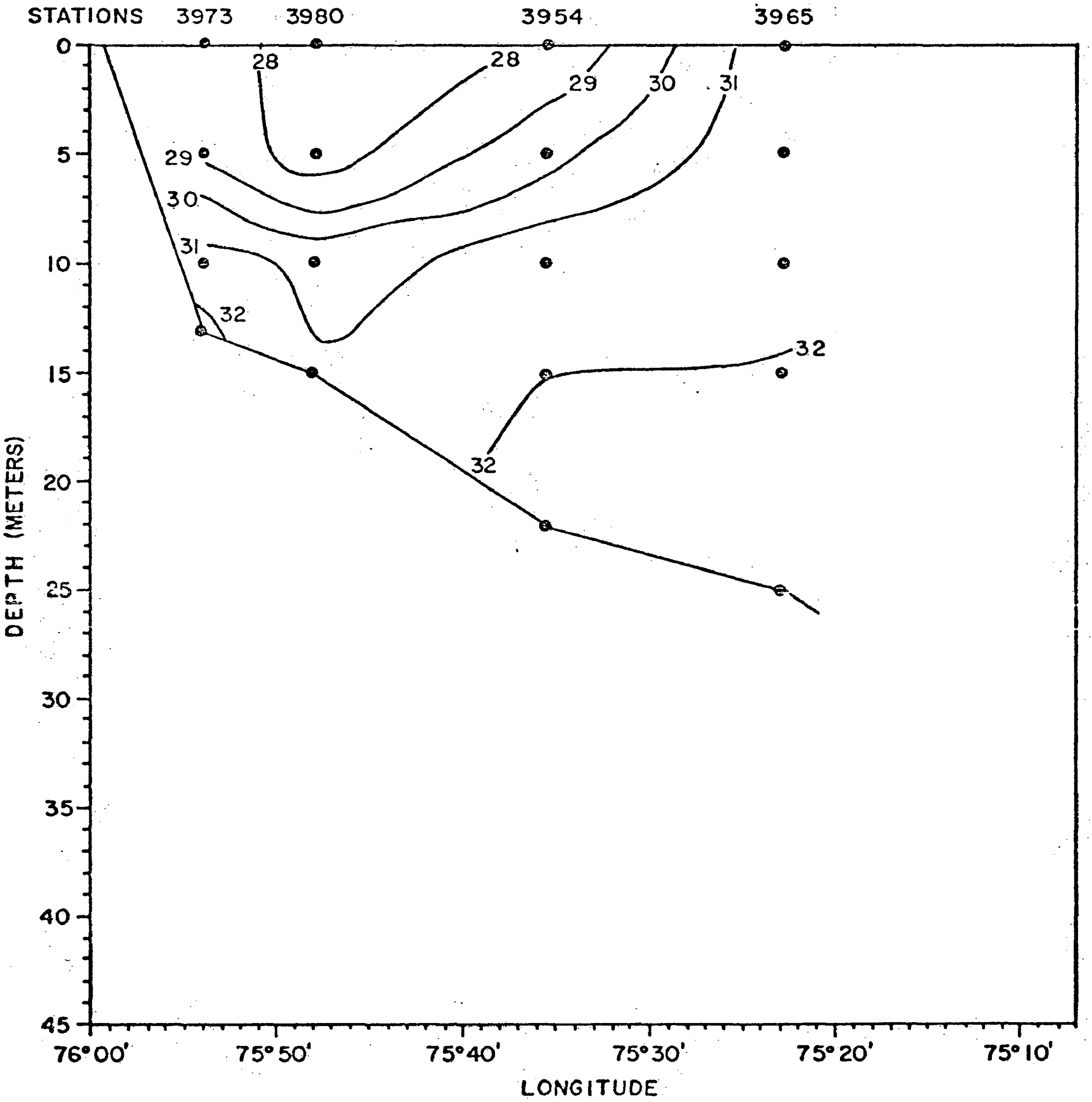

Figure 39. East-west oriented salinity section along 36°55'N; Operation Override II; September, 1969.

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