THE CIRCULATION IN KEEHI LAGOON, OAHU, HAWAII, DURING JULY AND AUGUST, 1968

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ABSTRACT

The data from seven oceanographic field surveys taken during July and August, 1968 in Keehi Lagoon, Oahu, Hawaii, and the results of an analysis of these data are presented in this report. The primary objectives of the work were to determine the volume transports to and from the lagoon and to find the circulation both in the lagoon and in the area adjacent to the entrance.

The surface circulation was found to be strongly dependent upon the prevailing winds. A westward flow of surface water was observed in most areas of the lagoon except during periods of weak winds. The subsurface flow (below 2.5 meters) was strongly dependent upon the bathymetry. This flow was either to or from the lagoon depending on whether a flooding or ebbing tide was in progress. However, on the eastern side of the lagoon, the incoming transport was greater than the outgoing transport, particularly in a dredged ship channel that crosses the lagoon entrance reef. In contrast, the outgoing transport was greater than the incoming transport on the western side of the lagoon. These conditions result in a limited amount of daily flushing of the lagoon from the east to west.

The tide records showed a large number of high amplitude free oscillations of the lagoon surface. The contribution to the circulation from these free oscillations was examined and found to be nominal throughout most of the lagoon, but significant at a few locations in the lagoon. The stratification in the lagoon was also examined and found to be of importance only in the dredged seaplane channels bordering the lagoon and in the area outside and west of the lagoon entrance. Two contributing factors causing the existing stratification are stream runoff from the Moanalua and Kalihi Streams, and warming of the surface water due to surface heat exchange. Most of the warming of the surface water takes place over the large centrally located mud flats in the lagoon. This warm water subsequently flows into the seaplane channels during ebbing tides and later moves westward around Ahua Point.

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I. INTRODUCTION

Keehi Lagoon is located on the southern shore of the island of Oahu, Hawaii, and is adjacent to the city of Honolulu (see Figure 1). The lagoon is approximately triangular in shape with the entrance to the lagoon extending east-west from Sand Island to Ahua Point (see Figure 2). An important feature of the lagoon is its unique bathymetry. This bathymetry is a combination of dredged seaplane channels (approximately 3 meters deep) bordering the lagoon on its three sides, and extensive centrally located shallow mud flats (approximately 1 meter deep). Parallel to the entrance, a line of coral reefs (approximately 2 meters deep) extend completely along the entrance to the lagoon.

The land area surrounding Keehi Lagoon is occupied primarily by industry, commerical agencies and the military. The northwest side of the lagoon borders the Honolulu International Airport. The State of Hawaii is currently considering a proposal to extend the runway system of the airport into the area occupied by the reefs at the entrance of Keehi Lagoon. This consideration has raised two questions. First, how much water is presently being transported around Ahua Point during the daily tidal changes, and, second, what effect will additional bathymetric restrictions have on the circulation and flushing presently found in the lagoon? Prior to answering these two questions, the circulation in the lagoon must be known. The task of describing this circulation was the objective of this work, and it was accomplished while the author was consulting for Tetra Tech, Inc., Pasadena, California.

A literature search soon revealed that no information was available on the circulation in Keehi Lagoon. Therefore, a field program was developed and measurements were taken during July and August, 1968. The field work was limited to two months duration because a need existed for early results at the time this work was initiated. However, the work, though limited in duration, did reveal the basic circulation patterns in the lagoon, along with other interesting results. This report presents the field data and the results that followed from the data analysis.

II. METHOD OF APPROACH

The field work was accomplished on days such that a variety of tidal and meteorological conditions were represented in the data. The circulation and tidal data, along with the results of a hypsographic analysis, were used to estimate the volume of water transported daily to and from Keehi Lagoon and to estimate the flushing rate resulting from this transport. The meteorological data were used to examine the dependence of the circulation on different weather conditions. Numerous and pronounced free oscillations of the lagoon surface were found in the tidal data, therefore, the task of determining the effect of these oscillations on the circulation in the lagoon was later added.

Observations of temperature and salinity were taken to examine the stratification in the lagoon. The station temperature data, along with the meteorological data, and a daily record of surface water temperatures taken at one location, were used to obtain an estimate of the total heat exchanged and the rate of evaporation at the surface of the lagoon. Plots of the temperature and salinity data also aided in verifying the circulation patterns found in the lagoon.

III. OBSERVATIONS

Seven field surveys were conducted between July 19, 1968 and August 5, 1968. A summation of the observations taken during these surveys is given below:

	Measurement	Number	Depth
1.	Surface Floats	53	0 meters
2.	Current Meters (Ekman)	58	0, 2.5, 6 meters
3.	Current Meters (Integrating)	4	2.5 meters
4.	Temperature	82	0, 2.5, 6 meters
5.	Salinity	64	0, 2.5, 6 meters
6.	Meteorological	21	--

Estimates (112) of the wave height, period and direction were also obtained at the even numbered stations during each survey.

The meteorological data included the air temperature, wet bulb temperature, cloud cover, wind velocity, and wind direction. They were obtained for July and August from the United States Weather Bureau Station, Honolulu Air Terminal.

A continuous tidal record for the period from July 18, 1968 to August 16, 1968 was obtained from a tide gauge located on the northwestern side of Keehi Lagoon (see Figure 2, location marked TG).

The instruments used to obtain the field measurements are listed below:

1. Hydroproducts *In Situ* Salinometer - Model RS-5-3 induction salinometer consisting of a twin-toroid transducer and thermistor bead on a fifty-foot cable, and a balance bridge with direct conductivity-to-salinity conversion.
2. Ekman-Merz Current Meters (2) - TSK Model - T.S. Ekman-Merz.
3. Belfort Portable Liquid Level Recorder - No. 5-FW-1, consisting of a cam, float, and balance weight to record liquid levels.
4. Integrating Current Meters (4) - constructed by D. Avery; Department of General Engineering, University of Hawaii; See Avery (1968).
5. Drift Cards (30) - six-inch square, plastic, and numbered consecutively.
6. Wind Speed and Direction Indicator.
7. Wave Staff.

The calibration and field use of each instrument are described in detail in Bathen, 1968, Technical Report 14, University of Hawaii, Hawaii Institute of Marine Biology, Oahu, Hawaii, *A Descriptive Study of the Physical Oceanography of Kaneohe Bay, Oahu, Hawaii*, Section 2-A, pp. 18-22. These descriptions will not be discussed in this report.

IV. RESULTS

Hypsographic Analysis - U.S. Coast and Geodetic Survey Map Numbers 4132 and 4109 were used for the hypsographic analysis. The portion of Map 4132 showing the lagoon was divided into 8.1×10^3 m^2 squares (90 m sides) by a 38 by 76 line grid (see Figure 2). Table 1 following gives a summary of the results of the hypsographic computations, and Figure 3 shows a plot of the results for each line in the grid.

TABLE I - RESULTS OF THE HYPSOGRAPHIC ANALYSIS
(at Mean Sea Level)

Keehi Lagoon Volume = 13.69×10^6 m^3
Area = 5.95×10^6 m^2
Average Depth = 2.3 m

Bottom Area exposed at the lowest observed tide = 43%

Volume exchanged during the maximum observed tidal change (84 cm) = 4.75×10^6 m^3

Volume exchanged during the minimum observed tidal change (5 cm) = 0.24×10^6 m^3

Figure 3 shows the area and volume of Keehi Lagoon as a function of tidal height. The area curve in Figure 3 clearly shows the considerable effect the extensive shallow mud flats have in changing the amount of water surface area in the Lagoon as the tide changes. When the tide dropped lower than 20 cm below an estimated mean sea level (MSL - estimated from 30 days of tidal records), large areas of mud flats became exposed. This had the effect of restricting the flow during low water to the three dredged seaplane runways.

Figure 4 shows the distribution of the areas of 114 vertical cross-sections defined by the hypsographic grid described above. The cross-sectional area of the entrance to the Lagoon (Section A) is approximately 6452 m^2 at MSL. The maximum observed tidal change was 84 cm, which is equivalent to a tidal change of approximately 4.75×10^6 m^3. This tidal change took place over a five hour period; therefore, the average exchange transport was approximately 0.95×10^6 m^3/hour. This transport would correspond to an average current velocity at the lagoon entrance of 4.1 cm/sec.

The increase in the vertical cross-sectional areas shown in Figure 4 (upper diagram) at Cross-Sections e and n is due to the dredged areas found around Stations 7, 9 and 10, and to the dredged channel from Station 26 to Station 28. This suggests that during low water, the greater portion of the transport to and from the lagoon will be restricted to these two areas, one on each side of the lagoon. The areas of the vertical cross-sections parallel to the entrance (lower half of Figure 4) show a uniform decrease proceeding from the entrance toward the Moanalua and Kalihi Streams. This suggests that the subsurface flow from the eastern to the western side of the lagoon may favor a path that remains in the east-west seaplane channel running parallel to the lagoon entrance.

Tides and Oscillations - Continuous tide records were taken from July 18, 1968 to August 16, 1968. During this period, the tides varied from diurnal (July 19, 1968) to semi-diurnal (July 30, 1968) in character. The maximum tidal change observed was 84 cm, during which the water level dropped approximately 13 cm below the level of the shallow mud flats.

A striking feature apparent on all of the tide records, was the large number and amplitude of free oscillations of the lagoon surface. The period of these free oscillations ranged from 12 to 60 minutes, with the amplitudes ranging up to 7 cm. Figure 5 shows two typical tide records taken at Position TG (see Figure 2), illustrating some of these free oscillations. The disturbing forces that initiated these free oscillations probably came from the flooding and ebbing tide and from the rapid flow onto or off of the mud flats during their flood or exposure. In addition, some free oscillations may have been caused by rapid barometric changes or by the release of a wind set-up on one side of the lagoon during the passage of observed summer squalls.

Figure 6 shows a plot of period versus the frequency of occurrence of free oscillations (lower diagram) during the 30 days of observation, and a plot of the observed free oscillation periods as a function of tidal height (upper diagram). Above mean low water, the observed periods of free oscillations ranged from 30 to 48 minutes (see Figure 5, areas marked "A", "C", and "D"), with 48 minutes having the highest frequency of occurrence. At lower low water (when the mud flats are exposed) periods from 19 to 24 minutes were recorded. Since the tide gauge was located on the northwestern side of Keehi Lagoon, it was probably recording the oscillations in the seaplane channel along this air terminal side of the lagoon. This air terminal channel can become an independent bathymetric feature at lower low water. Theoretically, a channel open at both ends, and having the same dimensions as this air terminal channel, would have a uninode free oscillation period of 25.6 minutes. The free oscillations with a period of 24 minutes, generally recorded after the mud flats were exposed (see Figure 5, area marked "B"), were probably such uninode oscillations along the length of this channel. The contribution of a uninode oscillation to the current velocity in the channel can be calculated (Re: Bathen, (1968) Section 3D, p. 41). The oscillation would add or subtract, depending on their phase relationship to the existing currents, a maximum of 3.3 cm/sec to the current velocity found around Station 7.

The theoretical free oscillations for Keehi Lagoon at mean low water and mean high water were calculated for oscillations up to five nodes along the length and width of the lagoon (re: Bathen, 1968). This analysis was undertaken to estimate where and to what extent free oscillations contribute to the current velocities in the lagoon. The results, given in Tables II and III below, suggest that uninode and binode free oscillations along the length and width of the lagoon, account for most of the disturbances recorded in the tidal records. These oscillations would contribute a maximum of 4.1 cm/sec (length oscillations) and 1.6 cm/sec (width oscillations) to the current velocities found around Stations 23, 7 and 2.

TABLE II - FREE OSCILLATIONS ALONG THE LENGTH OF THE LAGOON AT MEAN SEA LEVEL (SEE FIGURE 2, PARALLEL TO THE ENTRANCE)

Node	Period (minutes)	Maximum Current Velocity (cm/sec)	Location of Maximum Velocity (see Section A)
1	53.6	3.1	Station k (midway between Sand Island and Ahua Point)
2	25.6	1.9	Station f (on the western side of the lagoon entrance)
3	18.8	2.2	Station k (midway between Sand Island and Ahua Point)
4	14.3	3.4	Stations i, p (just west of the center of the lagoon entrance, and in the entrance channel)
5	11.3	4.1	Stations l, p (just east of the center of the lagoon entrance, and in the entrance channel)

TABLE III - FREE OSCILLATIONS ALONG THE WIDTH OF THE LAGOON AT MEAN SEA LEVEL (SEE FIGURE 2, ORTHOGONAL TO THE ENTRANCE)

Node	Period (minutes)	Maximum Current Velocity (cm/sec)	Location of Maximum Velocity (see Section B)
1	36.3	1.4	Station h (in the channel on the northeast side of the lagoon)
2	15.6	1.0	Station l (where the Moanalua and Kalihi Streams enter the lagoon)
3	10.7	0.9	Station b (on the reefs just in from the lagoon entrance)
4	7.5	1.3	Station a (on the reefs at the lagoon entrance)
5	5.8	1.6	Station a (on the reefs at the lagoon entrance)

Circulation - The primary emphasis of the seven field surveys was to find the circulation patterns in Keehi Lagoon, and to find the amount of water flowing to and from the lagoon during the tidal changes. The results of the circulation observations are shown in Figures 7 through 11. Measurements were taken during rapidly flooding and ebbing tides, during which the rate of tidal change was as great as 11.4 cm/hr.

A. Flooding Tides - The surface float and current-meter station data taken during flooding tides are shown in Figures 7 and 8. These data were taken both during a period of low wind velocities (1 to 3 knots) and during a period of normal trade winds (030°-070°, 5 to 16 knots). The results show that, during a flooding tide, surface water (1 to 1.5 meters deep) crossed the reef southeast of Ahua Point and entered Keehi Lagoon from this area around Stations 20 and 22. This surface water flowed northeast in the air terminal channel toward Stations 9 and 10 during periods of weak wind velocities. A large portion of surface water also entered the lagoon by flowing over the main central portion of the entrance reef (Station 24) and by passing through the break in the reef caused by the deep entrance channel (Station 26). A small portion of surface water also entered the lagoon over the reefs just west of Sand Island. This water flowed into the seaplane channel running along the northeast shoreline of the lagoon from Station 27 to Station 28.

As the wind increased to normal trade wind velocities or greater, the surface water on the western side of the lagoon flowed southwest out of the lagoon, around Ahua Point, and remained confined shoreward of the offshore reef line. This confinement close to shore was due to the opposing onshore transport of water across the reefs (Stations 17, 21 and 20) during the flooding tide. During trade winds, the surface water entering on the eastern side of the lagoon was diverted westward around the entrance reef (Station 24) until it joined the surface flow of water leaving the lagoon on the western side.

At 2.5 meters depth, water was observed entering the lagoon even under the influence of opposing trade winds. Figure 8 indicates that most of this subsurface incoming transport entered through the dredged ship channel on the eastern side of the lagoon. The flow on the western side of the lagoon at 2.5 meters depth, west of Ahua Point and shoreward of the entrance reefs (Stations 13, 14 and 15), was either toward the shoreline (during weak winds) or westward along the shoreline (during strong winds). During weak winds the subsurface flow in this deep area (6 meters) around Stations 13, 14 and 15 was slowly eastward; substantially different than the direction of flow in the surface layer. As the trade wind velocity increased, the direction of this subsurface flow was more toward the shore, but again, its direction differed noticeably from the westward surface flow.

The currents observed at the surface during flooding tides ranged from 20.7 cm/sec to 4.5 cm/sec. As discussed, these surface currents were directed both to and from the lagoon; their direction depending strongly upon the wind velocity and direction. At 2.5 meters depth, however, the current was observed flowing only into the lagoon during flooding tides, with velocities ranging from 12.0 cm/sec to 2.0 cm/sec. At 6 meters depth outside and west of the lagoon, the observed currents ranged from 4.2 cm/sec to 2.8 cm/sec with the direction generally being opposite to the prevailing surface flow.

B. Ebbing Tides - Figures 9 and 10 show the data taken during ebbing tides. These data were obtained during periods of normal trade wind velocities (5-12 knots) and high trade wind velocities (18-24 knots). During all of the ebbing tides observed, a strong flow of surface water (1 to 1.5 meters deep) was found leaving the lagoon (Station 11), moving southwest around Ahua Point, and continuing westward outside of the lagoon. During normal trade winds, the westward flow of water past Ahua Point (Stations 21 and 17) remained inside the offshore reef until it passed Kumumau Point (Station 15). However, during strong trade winds, the flow was observed moving offshore through breaks in the reef from Stations 20 to 16. During ebbing tides the surface water from the northern portion of the lagoon and from the eastern side of the lagoon also moved westward toward Ahua Point. It was during a period of strong trade winds and ebbing tide (July 22, 1968) that the westward flow of water in the air terminal channel (past Station 6) reached a maximum of 29.1 cm/sec. The surface flow velocities during ebbing tides ranged from 29.1 cm/sec to 9.1 cm/sec, while the flow direction was essentially southwest throughout the lagoon.

At the 2.5 meters depth, the flow during ebbing tides was westward, with velocities ranging from 21.6 cm/sec to 2.4 cm/sec. This flow across the lagoon was directed toward Ahua Point by the air terminal channel (Station 31 to Station 9) and the entrance reef channel (Station 28 to Station 10). Outside the lagoon, the flow at 2.5 meters was also westward, moving along the entrance reef from Station 25 to Station 18.

Some deviations from a westward flow were observed close to the shoreline at Ahua Point. In the deep (9.1 meters) small basin west of Ahua Point, the flow at 6 meters was found to be either eastward or shoreward. In all observations, the flow was moving in a substantially different direction than either the surface flow or the flow at 2.5 meters depth. However, this deep eastward flow was weak, with current velocities ranging from 3.9 cm/sec to 2.6 cm/sec.

C. General - Figure 11 shows results of the integrating current-meter measurements taken at 2.5 meters depth. The integrating current-meter consists of a freely rotating film holder, held directionally stationary with a magnet. The film and holder are immersed in an oil bath beneath a plumb bob painted with a drop of radium. The instrument, with floatation, is anchored subsurface, and records obtained from its two layers of film after an appropriate amount of time has elapsed. Each diagram in Figure 11 shows the two film records obtained at each location. These records show the distribution of the current velocities and directions that were recorded continuously for eighteen days. The outer solid line in each diagram represents an integration of all the velocities and directions at each location during the eighteen day period, while the inner dashed line (second film layer) shows the prevalent current velocities and directions.

The integrating current-meter results further verify that during a flooding tide, the flow over the reefs off of Ahua Point on the western side of Keehi Lagoon (Diagram at position B) was directed shoreward. The subsurface flow that entered the western side of the lagoon (Diagram at position A) was divided into two branches, one flowing past Station 9 into the air terminal channel, and one past Station 10 into the entrance reef channel. The diagram at position A also indicates water was transported southwest, past Stations 9 and 10. The inner dashed line of this diagram does show that the prevailing transport past Station 11 was to the southwest. This was the water that left Keehi Lagoon and flowed southwest around Ahua Point during the ebbing tides. The diagram at position C shows both a net southwest transport, and a weak subsurface shoreward and eastward flow existing to the west of Ahua Point.

The diagram at position B indicates that water entered and left Keehi Lagoon through the break in the reef south of Ahua Point

(Station 20). The inner diagram indicates that some water flows southeast through the break in the offshore reef, but that there is a net flow of water from the offshore reef toward Ahua Point (slightly toward Station 11). The southeast flow leaving the lagoon at this break in the entrance reef was not found during any of the other current observations. Possibly the bathymetry in the immediate area of this position was responsible for the southeast direction of flow, because further offshore of the reef (Station 19) the flow was observed moving southwest.

The diagram at position D shows that the flow direction in the deep ship channel on the eastern side of the lagoon was primarily north-south. The outer solid line does show the tendency of the water entering the lagoon to turn westward once inside of the entrance reef. In particular, the entire diagram shows a greater transport of water into than out of the lagoon. This diagram also shows the strongest recorded current velocity of 32 cm/sec. This was water that entered the lagoon and flowed north in the deep ship channel from Station 26 to Station 28. The four integrating current-meter diagrams in Figure 11 show current velocities ranging from 32 cm/sec to 5 cm/sec. These values agree well with the surface float and Ekman-Merz current-meter observations previously discussed.

Surface Heat Exchange - Stratification can be an important factor in restricting the amount of vertical mixing present in inshore waters. This stratification can be caused by a number of factors such as a low salinity runoff from streams, or the development of a warm surface layer due to heating of the water at the surface. An analysis of the net surface heat exchange was completed so that an evaluation could be made of the role of surface heating in altering the temperature of the lagoon.

The total heat exchanged at the surface of the lagoon was computed, using the meteorological and surface water temperature data. The method of computation used is discussed in detail in Bathen (1968), Section 3G, pp. 79-85. An area weighted mean of the sea surface temperatures observed during each of the seven field surveys was compared with the daily surface temperatures recorded at the tide gauge location. These comparisons provided the basis for estimating a mean daily surface water temperature of the lagoon, during the days when no field survey data was available. A computation was then performed for each daily set of meteorological and surface water temperature data. The results for all days were then averaged. These mean results are given below in Table IV. The mean of values for July and August from Kaneohe Bay, Oahu, Hawaii (Bathen, 1968; pp. 149-151) are also given to enable comparison with another inshore area with similar bathymetric features.

TABLE IV. RESULTS OF THE SURFACE HEAT EXCHANGE COMPUTATIONS

Mean Values for July and August, 1968		Keehi Lagoon	Kaneohe Bay
Temperature of the Surface Water	=	28.3°C	27.6°C
Wet Bulb Temperature	=	20.1°C	20.1°C
Wind Velocity	=	13.0 kts	9.9 kts
Cloud Cover	=	80.0%	55.9%
Evaporation	=	19.1 cm/mo	18.9 cm/mo

The computations for the surface heat exchange gave the following results:

		Keehi Lagoon	Kaneohe Bay
Humidity	=	48.3%	60.0%
Incoming Radiation	=	+ 423 cal/cm^2/day	+ 464 cal/cm^2/day
Back Radiation	=	- 132 cal/cm^2/day	- 124 cal/cm^2/day
Heat of Evaporation	=	- 389 cal/cm^2/day	- 307 cal/cm^2/day
Sensible Heat	=	+ 17 cal/cm^2/day	- 3 cal/cm^2/day
TOTAL HEAT EXCHANGED	=	- 81 cal/cm^2/day	+ 30 cal/cm^2/day

The above results show that during the period of observations there was a mean loss of heat from the surface of Keehi Lagoon. This contrasts with Kaneohe Bay. The bay normally gains heat during an equivalent period in July and August. There are a number of reasons why the results from Keehi Lagoon (on the leeward side of Oahu) differed from past results from Kaneohe Bay (on the windward side of Oahu). First, the incoming radiation for the lagoon was attenuated more due to the high cloud cover during late July and early August. Normally the cloud cover on the lee (Keehi) side of the island is less than the windward (Kaneohe) side (see U.S. Department of Commerce 1954, 1962). Second, the back radiation from the lagoon was slightly higher due to the higher seawater temperatures and to a large difference between the temperature of the air and the temperature of the water. Third, the evaporative heat loss was high in Keehi Lagoon due to an above normal average wind velocity for the period of the study. In addition, the lower humidity made the difference in specific humidity between the sea surface and the air greater. Last, the sensible heat exchanged at the surface was greater in Keehi Lagoon due to the greater difference between the temperature of the air and the temperature of the water and to the higher wind velocities. All of the above factors resulted in a mean heat loss from the surface of the lagoon during July and August, 1968. Considering the cloud cover and wind velocity generally found on each side of the island, one would expect a slightly higher surface heat gain in Keehi Lagoon, and therefore, slightly higher water temperatures. The mean temperature in the lagoon for July and and August, 1968 was higher than the Bay. However, daily mean temperatures in Keehi Lagoon did decline during this period due to a series of summer squalls in late July.

Applying the heat exchange computations to just the data from the central shallow mud flats gave a mean total heat exchange of +21 cal/cm^2/day. This is comparable to a diurnal water temperature increase of approximately 0.3°C for a mean water depth of 71 cm on the mud flats. As stated previously, the water on the mud flats leaves during an ebbing tide, flows into the seaplane channels and subsequently flows out of the lagoon. As will be noted in the following Section, warm water that left the central mud flats, remained on the surface and cooled as much as 1.0°C in passing around Ahua Point during an ebbing tide. Thus surface heating (or cooling) of the water passing over the central mud flats does influence stratification in Keehi Lagoon, particularly on the western side of the lagoon and in the area west of Ahua Point.

Distribution of Temperature and Salinity - Figures 12-15 show the temperature and salinity observed in Keehi Lagoon and in the areas adjacent to and west of Ahua Point during flooding and ebbing tides. These maps were obtained by plotting the field data, corrected for instrument calibration, and drawing isopleths for 0 and 2.5 meters depth.

Figures 12 and 13 show the distribution of temperature and salinity during a flooding tide. The Figures indicate a flow of water from 0 to 2.5 meters entering the lagoon through the dredged ship channel on the east side of the lagoon. Some incoming flow over the central portion of the entrance reef (around Station 23) is also suggested by the pattern of isopleths. The temperature and salinity data from the small deep basin west of Ahua Point show a three layer density stratification, 0-2 meters, 2-6 meters, and below 6 meters. The combination of water flowing southwest from the lagoon, the previously discussed slow eastward deep flow (below 6 meters) observed in the basin, plus the addition of fresh water from a drainage canal and outfall at Ahua Point, is probably responsible for the varying water character and stratification found in this area. Warm water (28.2°C) from the mud flats (Station 4) was followed around Ahua Point using surface floats on July 22, 1968. This water cooled 1°C during the four hour period of observations. During July and August, 1968, the difference between the surface water temperature minus the bottom water temperature west of Ahua Point (Station 14) varied from +0.1°C (July 23, 1968, ebbing tide) to -0.9°C (July 25, 1968, flooding tide).

Some stratification due to runoff was found in Keehi Lagoon around the mouths of the Moanalua and Kalihi Streams. The result of low salinity water entering the lagoon from the Moanalua and Kalihi Streams is apparent in Figure 13, around Stations 31 and 32. The low salinity water from this area later moved slowly along the western side of the lagoon when the tide ebbed. At the observed velocity of 9.7 cm/sec (Figure 10, Station 31) this water would take approximately 13 hours to reach Ahua Point. Therefore, it takes more than a single tidal change to leave the lagoon. Earlier we noted that all surface water in the lagoon tends to move toward the western side of the lagoon during a flooding or ebbing tide when trade winds are blowing. This is probably why the salinity of the water at the surface all along the western side of the lagoon was less than along the eastern side during both flooding and ebbing tides.

Figures 14 and 15 show the temperature and salinity distribution during an ebbing tide. Figure 14 indicates that the slightly warmer water found on the large centrally located mud flat moves toward Ahua Point (Station 11). This water later leaves the lagoon and flows around Ahua Point. Once around the Point, the character of the water begins to vary substantially due to the following: west of Ahua Point, along the shoreline, low salinity cooler water accumulates. This cooler water is probably the result of outflow from both an outfall at Ahua Point and from a drainage canal located approximately 500 meters further west of the Point along the shoreline. Some of this cooler water mixes with that portion of the water leaving the lagoon that remains close to the shoreline. Density computations, using the July 23rd data of Figures 14 and 15, show that the density of the shoreward portion of this cool surface water is less than the subsurface water, and it therefore remained on the surface, close to the shoreline. Cool water close to the shoreline was observed moving slowly eastward around Ahua Point. When this weak eastward flow met the westward flow of water leaving the east-west entrance reef channel (from Station 28 to Station 11), a pattern of eddies developed off Ahua Point. Two large eddies, approximately 300 meters diameter, one centered 600 meters east, and the other 400 meters west of Ahua Point, were very apparent during the field survey on July 31, 1968. When the flooding tide was strong and the trade winds weak, this eddy pattern continued after the ebbing tide and moved eastward around Ahua Point approximately 600 to 800 meters into Keehi Lagoon.

Comparing Figures 13 and 15 shows that the water southeast of the entrance reef (Station 25) was noticeably less saline on July 25th. This was probably due to the rainstorm that occurred on July 24th over Mamala Bay. Figure 15 indicates that some of the warm water originating on the mud flats also flowed south across entrance reef channel, and continued on to the entrance reef (Station 23). The cooler, low salinity water entering the lagoon (Station 32) from the Moanalua and Kalihi Streams meets the warmer lagoon water around Stations 30, 31 and 32. On July 23, 1968, this cool stream inflow apparently divided at Station 31 in the process of flowing toward the lagoon entrance during an ebbing tide (see Figure 9). The isopleths in Figure 14, however, suggest a majority of this stream inflow proceeds along the western side of the lagoon.

V. CONCLUSIONS

The duration of this survey was very short. Thus the observed range of oceanographic conditions that were present both in Keehi Lagoon and in the area south and west of Ahua Point were probably limited in comparison with the annual range of conditions present at these locations. Though some observations were taken during a period of weak southerly winds, observations during strong Kona (southerly) wind conditions are absent. However, a few general conclusions can still be made about the circulation, transports and flushing in the lagoon. The results of the hypsographic analysis and the current observations suggest that during trade wind conditions, a larger portion (55%) of the volume of water transported into the lagoon during a flooding tide enters on the eastern side. At high water, as the mud flats and entrance reefs become flooded, the incoming flow increases over the entire entrance reef. The amount of incoming surface flow entering on the western side is strongly dependent upon the wind. The deep incoming flow on this side of the lagoon is normally weak, and increases only when the trade wind velocity is weak. The subsurface incoming currents (below 2.5 meters) on the eastern side were observed to be two to three times greater than the deep incoming currents on the western side of the lagoon.

The current velocities observed during ebbing tides suggest that a larger portion of the volume of water that had been added to the lagoon during the flooding tide leaves on the west side by flowing around Ahua Point (Stations 9, 10 and 11). This southwest flow of water from the lagoon and around Ahua Point continues either toward Kumumau Point (Station 15) or leaves through breaks in the entrance reef (Stations 16 and 18). The choice is dependent upon the direction and velocity of the wind. The current velocities that were observed throughout the lagoon during the maximum tidal drop (84 cm) indicate that approximately 65% of this tidal volume left the lagoon by flowing around Ahua Point (Station 11). Therefore, approximately 3.1×10^6 m^3 of water must have passed through the 962 m^2 cross-section, drawn from Ahua Point through Station 11, during a 6 1/2 hour period. This is equivalent to an average current velocity of 13.8 cm/sec past Station 11. This value agrees reasonably well with the current velocities measured at Station 11 (13.5 to 19.9 cm/sec) during ebbing tides.

Flushing of Keehi Lagoon is accomplished each day by the incoming and outgoing water supplied by the tidal change. The incoming water during a flooding tide, mixes with the water already in the lagoon, and then leaves later during the ebbing tide. The amount of this mixing is undetermined. However, at the maximum tidal change observed (84 cm) a substantial amount of water (35%) was added to the total volume of the lagoon. Also note that there is a moderate amount of east to west flushing of the lagoon each day during the daily tide changes. This is due to the tendency of water in the lagoon to favor a westward flow. Approximately 20% of the total volume of water that enters the east side of the lagoon each day, crosses the lagoon and leaves on the western side. This flushing has probably aided the capacity of the lagoon in accepting the effluents presently being added along the shoreline.

The results of this study show the circulation around Ahua Point can be very active. This is the general area proposed for the Honolulu Air Terminal Runway Extension. The results of the hypsographic analysis has indicated that the currents off Ahua Point, even during the absence of wind, would be expected to range from 4 cm/sec to 14 cm/sec due to the tidal transports to and from Keehi Lagoon. Construction of a taxiway leading from the shoreline, anywhere between Ahua Point to Kumumau Point, to a proposed runway on the entrance reef (from Station 16 to Station 20) will substantially constrict the flow of water from Keehi Lagoon. Any construction of this nature must consider the flow of approximately 2×10^6 to 4×10^6 m^3 passing Ahua Point, particularly during the ebbing tide.

Though a substantial net flow of water passes Ahua Point each tidal change, the combined effects of stratification in the area west of Ahua Point, diurnal heating of the water prior to flowing past the Point, and varying wind conditions, can cause the circulation pattern at the Point to vary considerably. During July and August, 1968, this pattern varied from a consistent flow around the Point during moderate or strong trade winds, to a variable eddy pattern found predominantly during periods of weak winds. The seasonal variation, however, may be greater than that observed in July and August.

VI. FIGURE CAPTIONS

Figure 1	Location of Keehi Lagoon, Oahu, Hawaii
Figure 2	Reference Map
Figure 3	Area and Volume of Keehi Lagoon inside Section A (Figure 2) as a Function of Tidal Height
Figure 4	Area of 35 Vertical Cross-Sections Parallel and Orthogonal to the Entrance of Keehi Lagoon at Mean Sea Level
Figure 5	Typical Tide Records showing Recorded Free Oscillation of the Lagoon Surface
Figure 6	Free Oscillation Period as a Function of Tidal Height and Frequency of Occurrence of Observed Free Oscillations
Figure 7	Surface Float Data for Flooding Tides
Figure 8	Current Meter Data for Flooding Tides
Figure 9	Surface Float Data for Ebbing Tides
Figure 10	Current Meter Data for Ebbing Tides
Figure 11	Integrating Current Meter Data
Figure 12	Temperature Distribution - Flooding Tide
Figure 13	Salinity Distribution - Flooding Tide
Figure 14	Temperature Distribution - Ebbing Tide
Figure 15	Salinity Distribution - Ebbing Tide

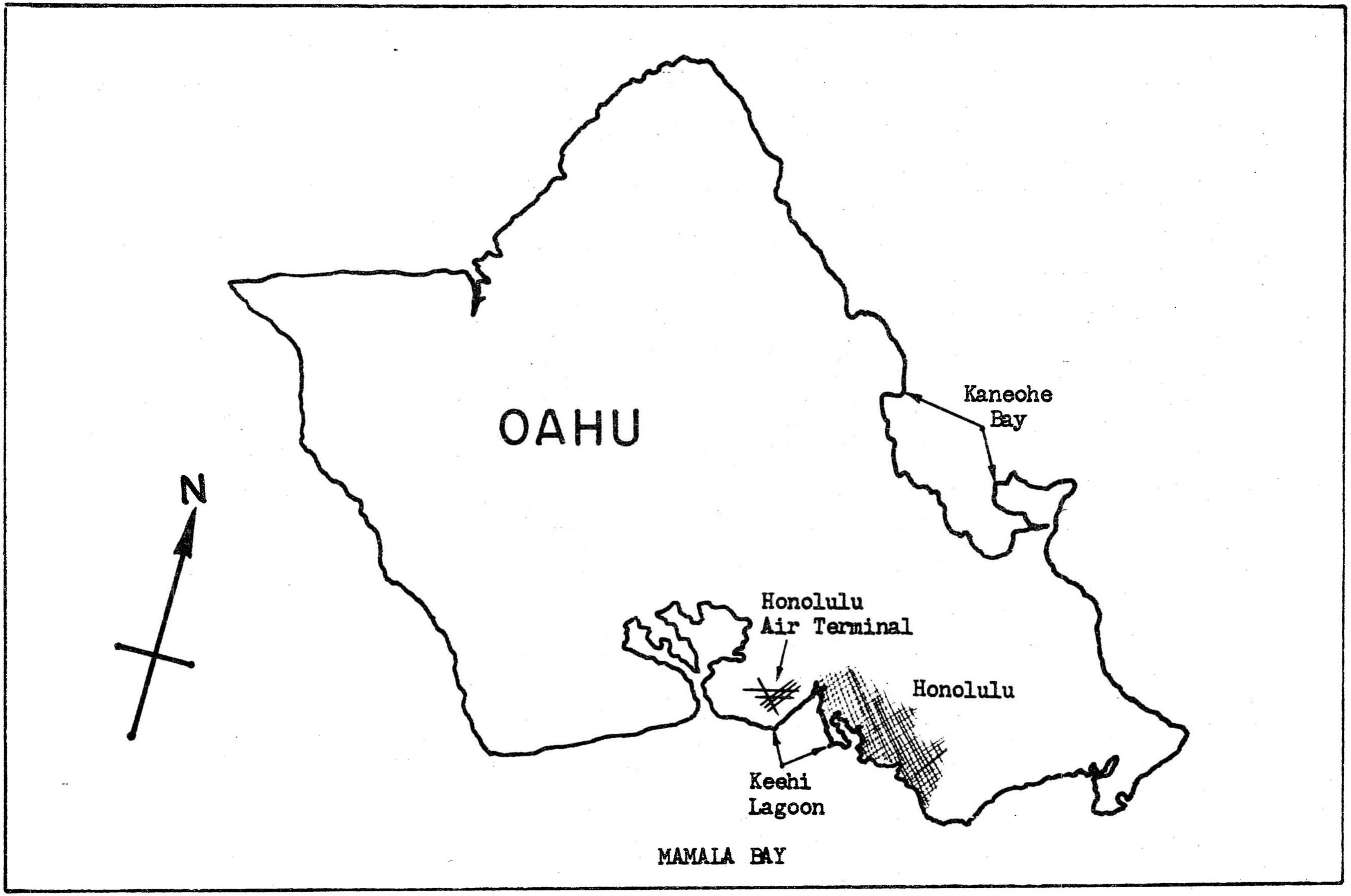


Figure 1 Location of Keehi
Lagoon, Oahu, Hawaii.

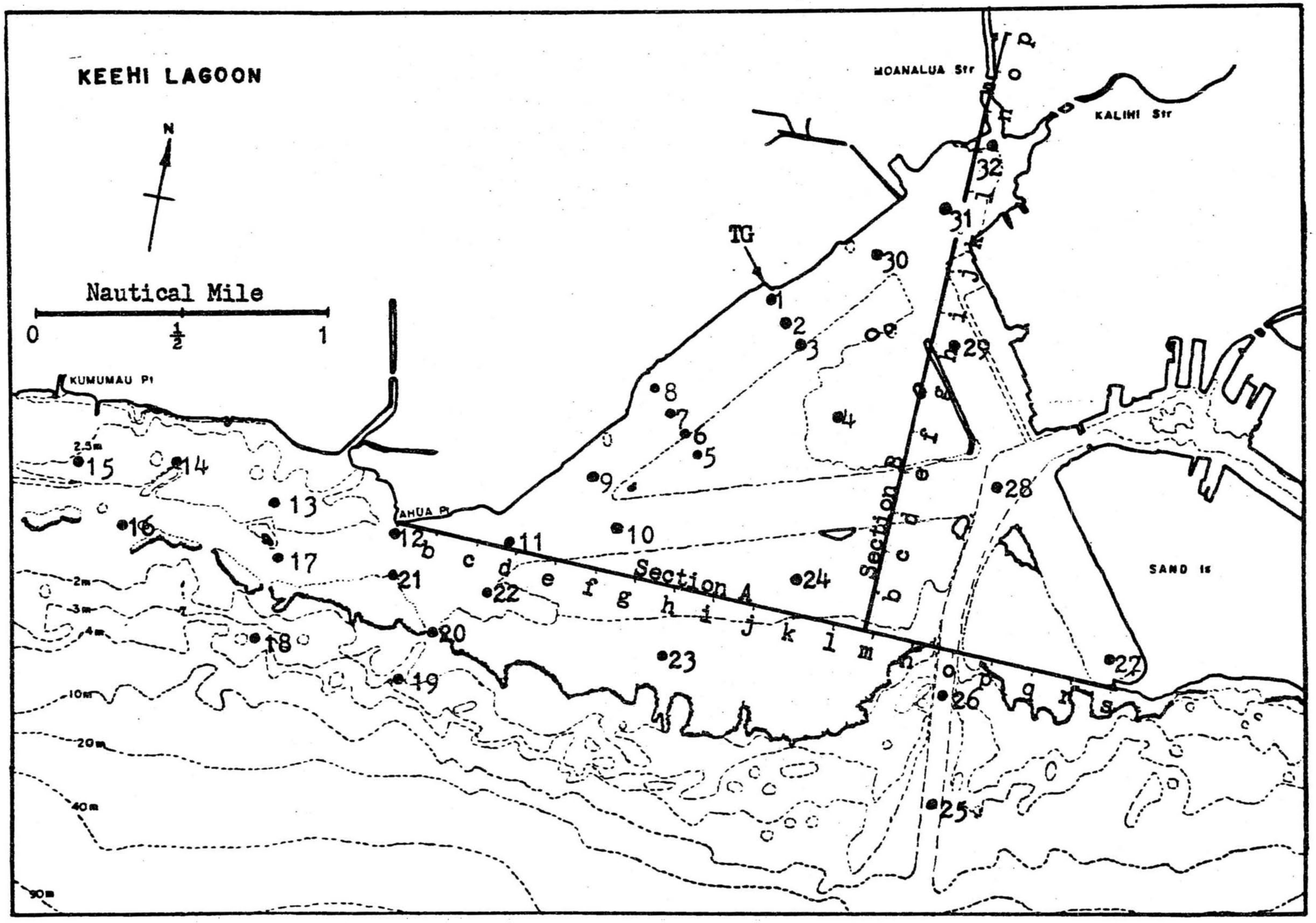
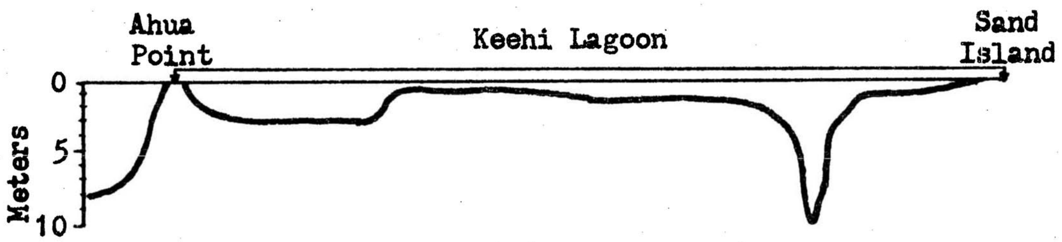


Figure 2 Reference Map. The figure shows the location of the two sections used for a hypsographic analysis plus the locations selected for the 32 stations and the tide gage (TG).



Section A (See Figure 2)
Crosssection of the lagoon entrance

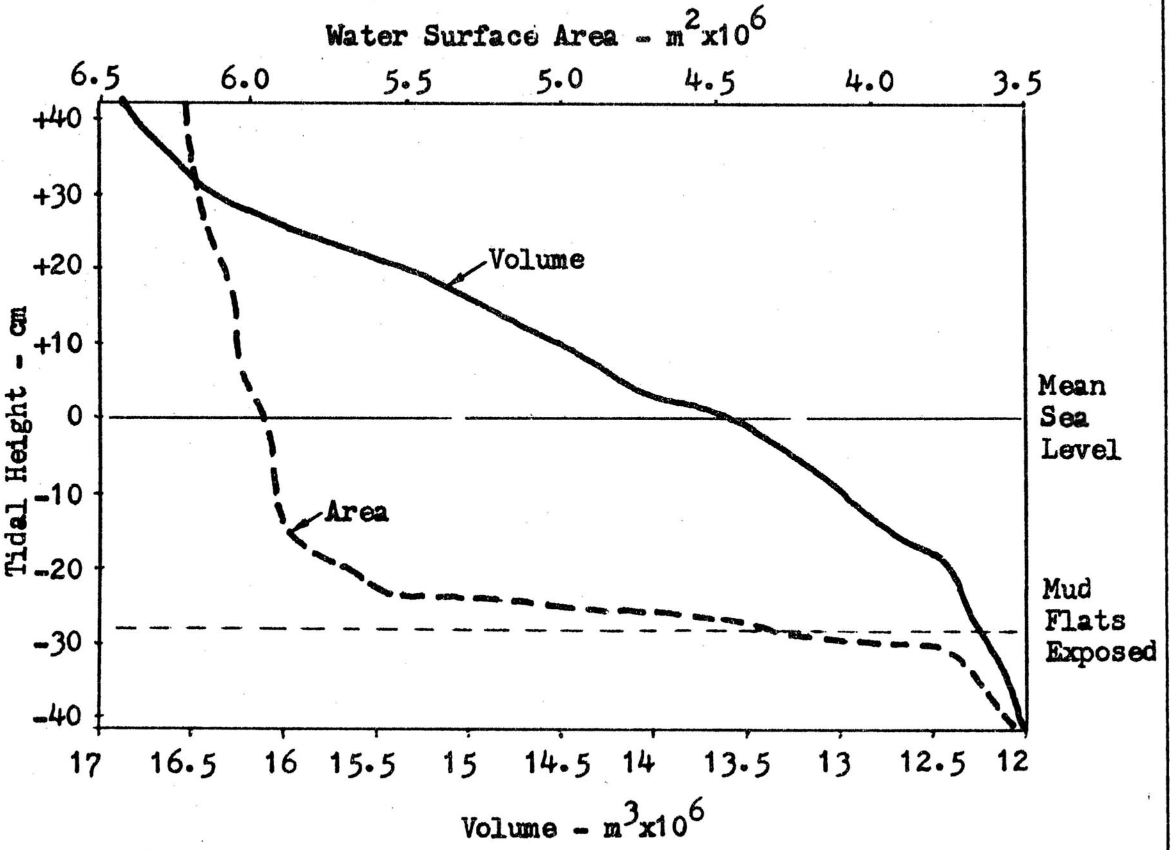
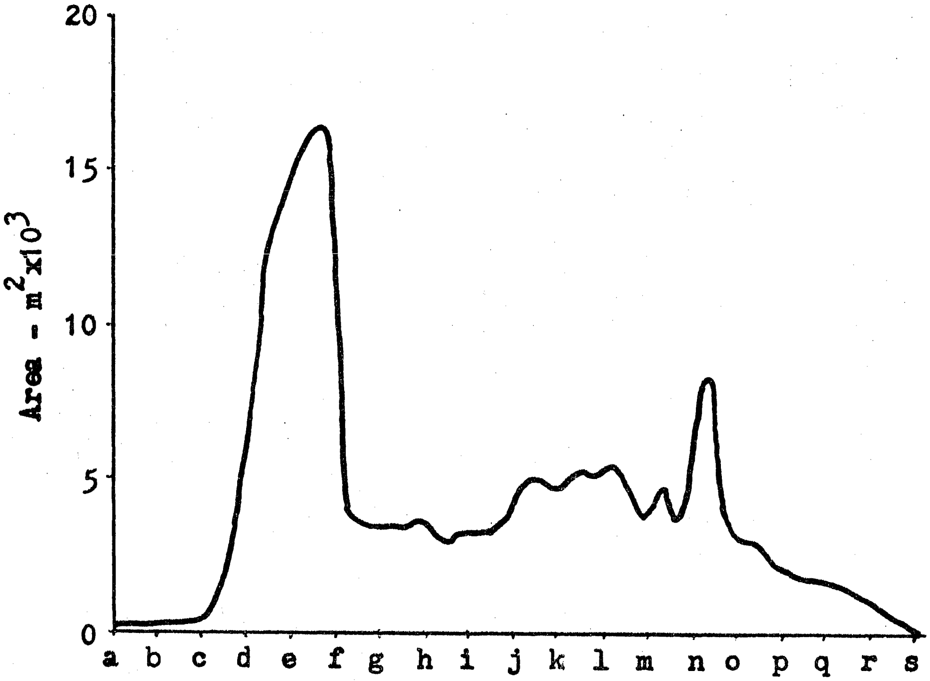
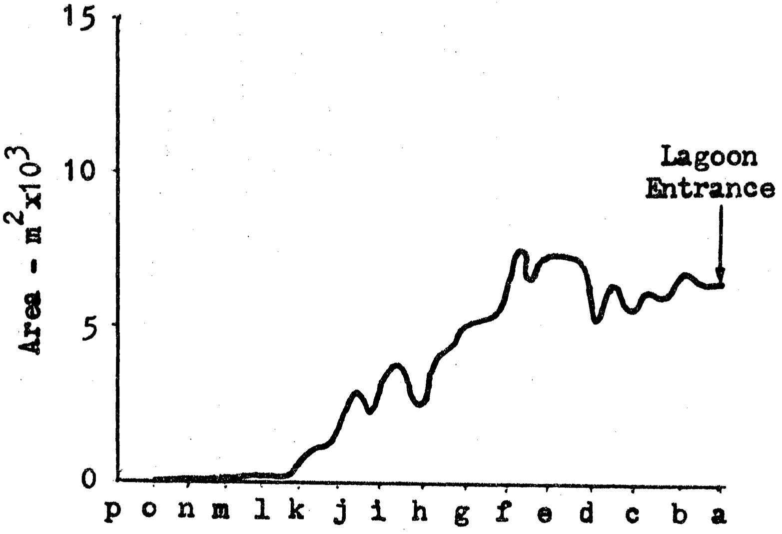


Figure 3 Area and Volume of Keehi Lagoon Inside of Section A (See Figure 2) as a Function of Tidal Height.



Cross-section - Length
(See Figure 2, Section A)



Cross-section - Width
(See Figure 2, Section B)

Figure 4 Area of 35 Vertical Cross-Sections Parallel and Orthogonal to the Entrance of Keehi Lagoon at Mean Sea Level.

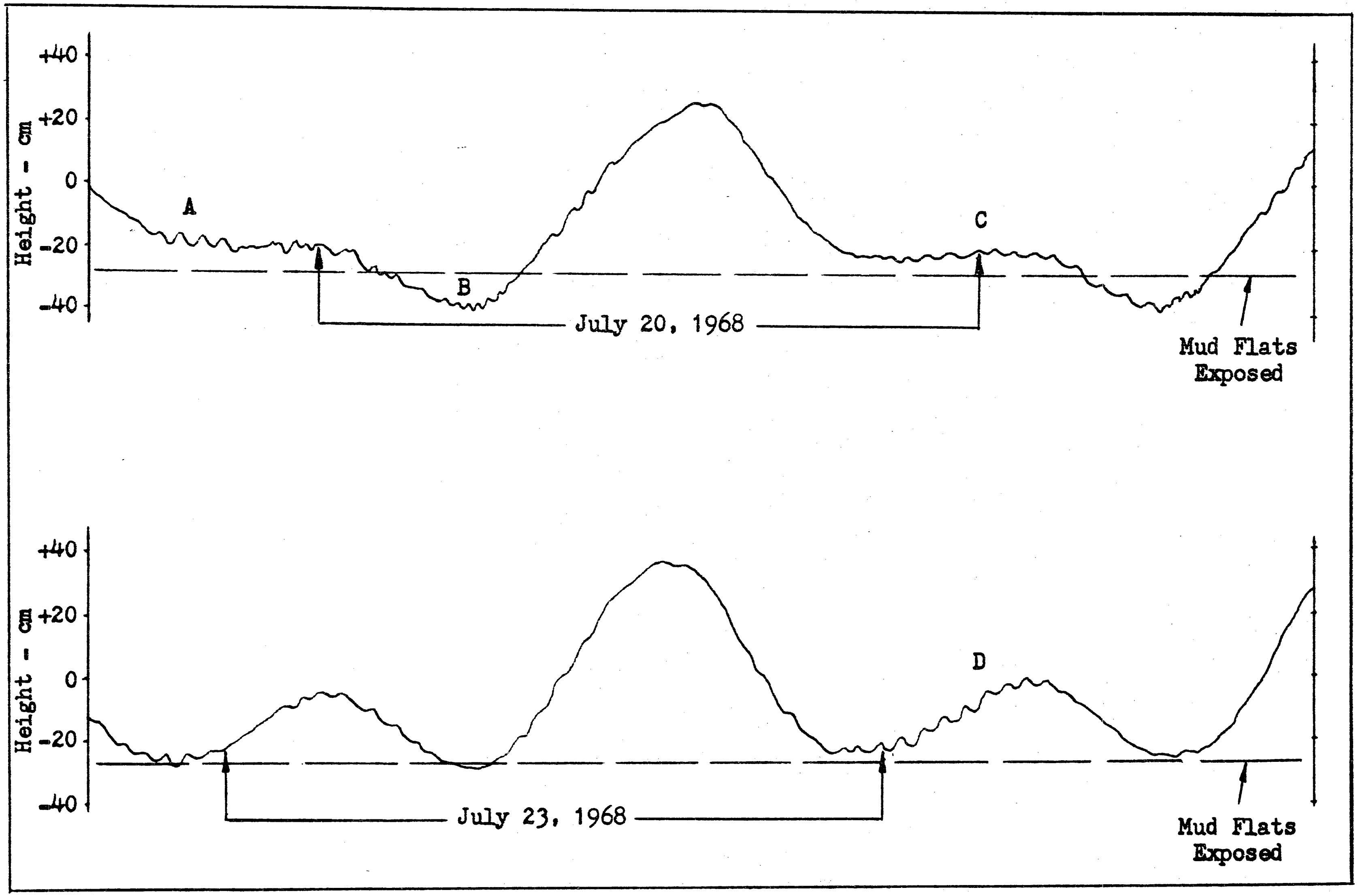


Figure 5 Typical Tide Records Showing Recorded Free Oscillations of the Lagoon Surface (Portions of the Record Labeled A to D). Estimated M.S.L. (from 30 dats of tidal records) is height = 0cm.

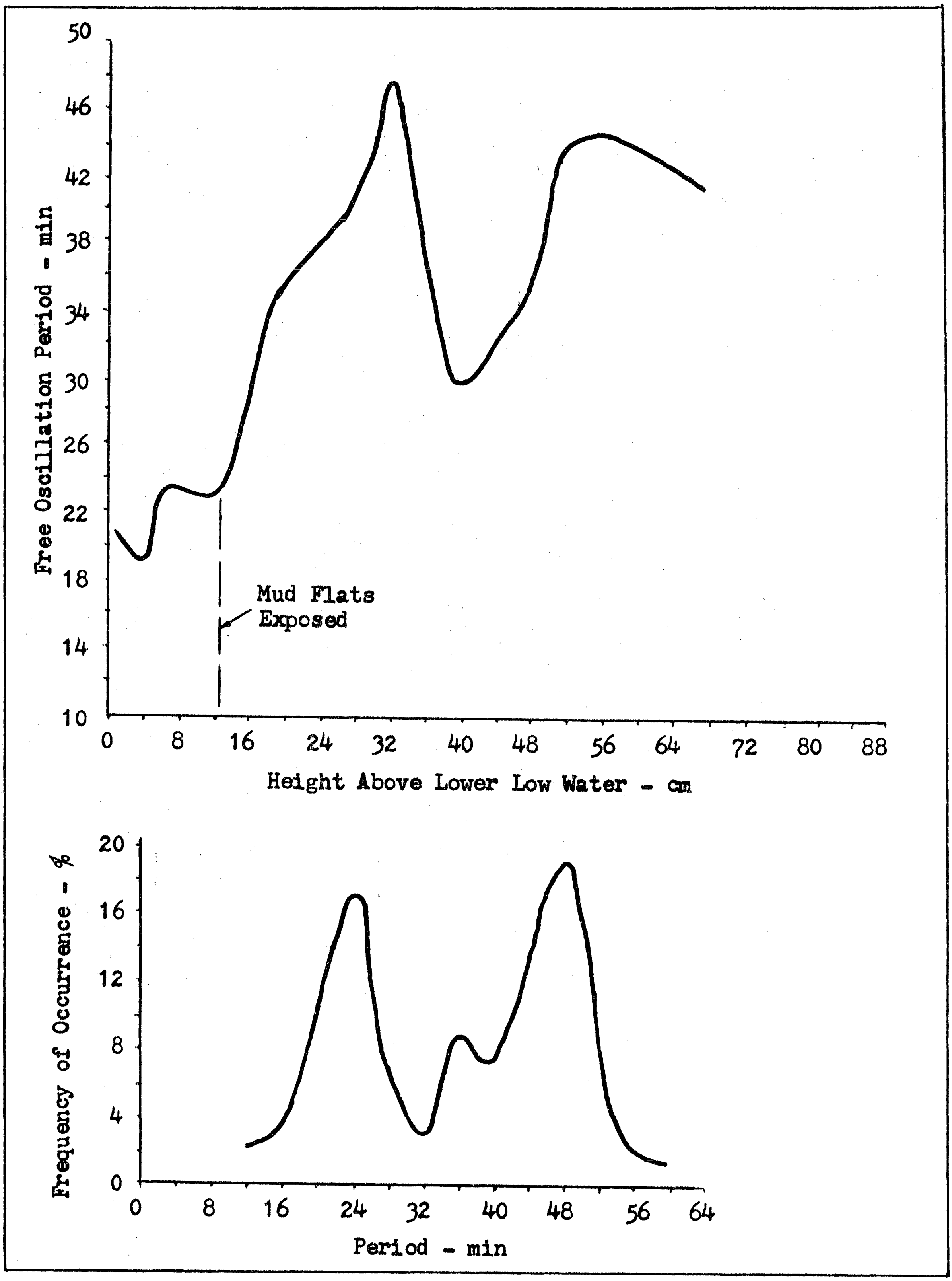


Figure 6 Free Oscillation Period as a Function of Tidal Height (Top) and Frequency of Occurrence of Observed Free Oscillations (Bottom).

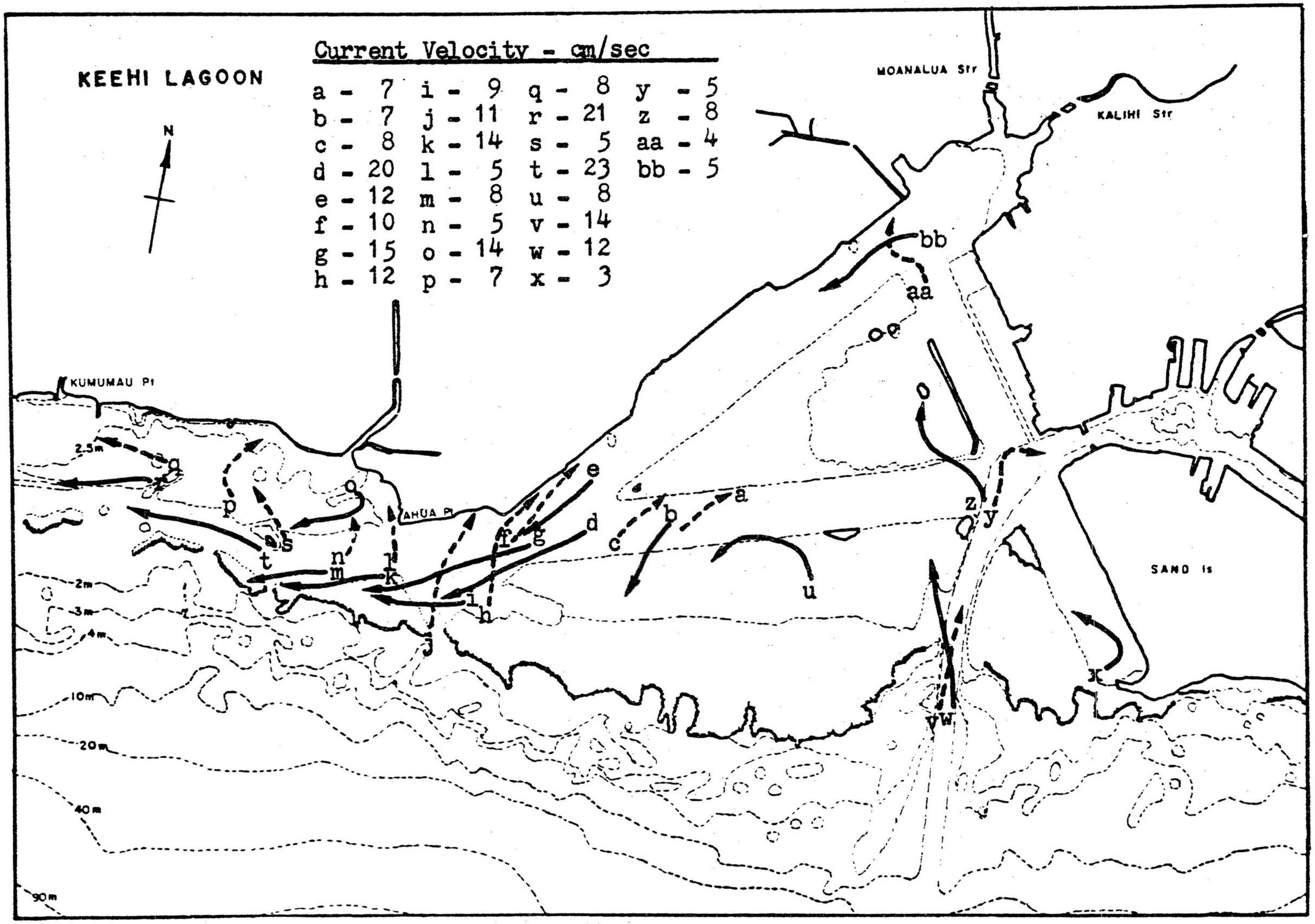


Figure 7 Surface Float Data for Flooding Tides. Average velocities are given for the duration each float was in the water. The dotted paths were observed on July 26, 1968; the remainder were observed on July 27, 1968. Winds: July 26 = 170°, 1-3 kts; July 27 = 35°, 5-12 kts.

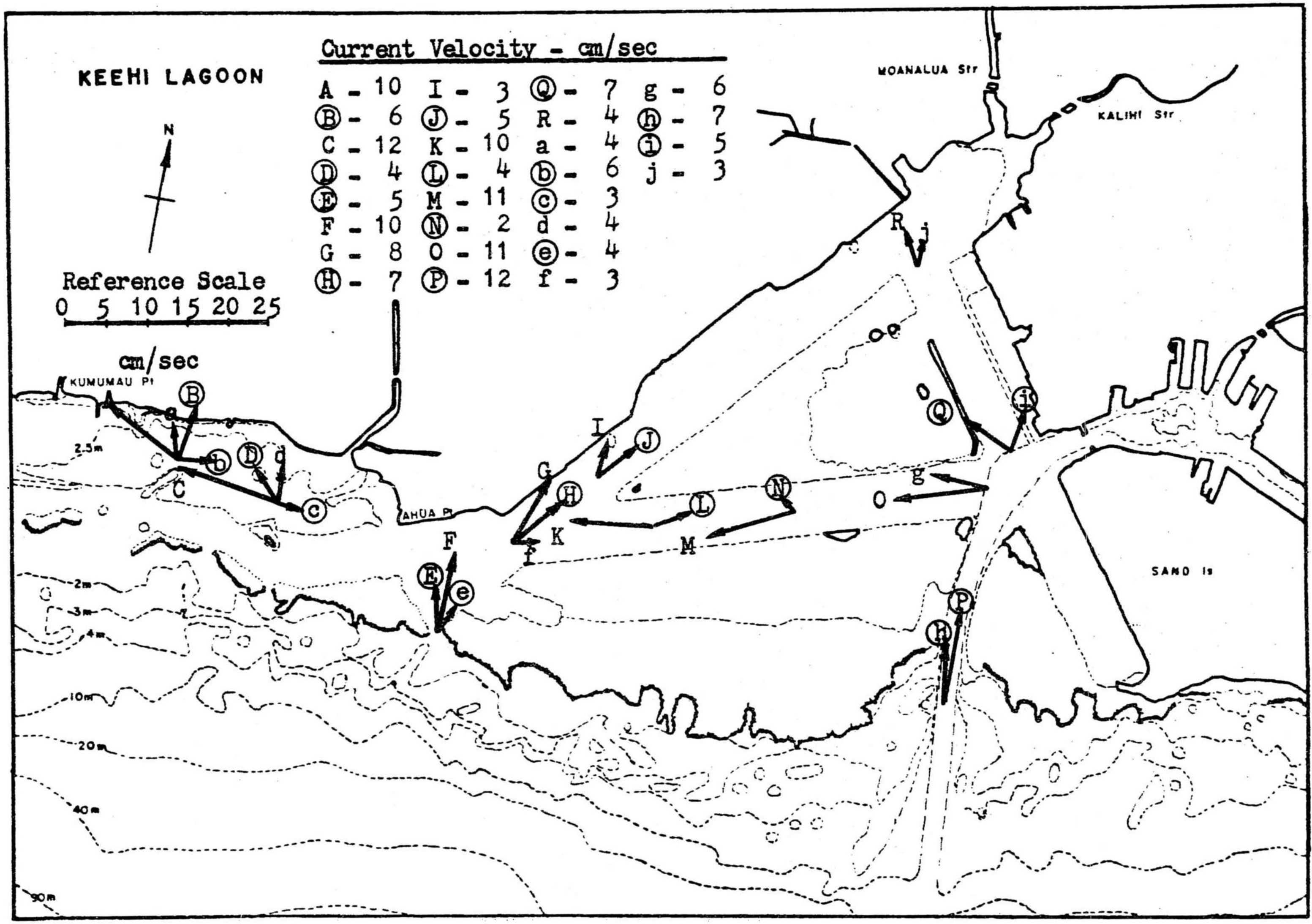


Figure 8 Current Meter Data for Flooding Tides. Stations A to R = 0-2.5 m; Stations a to j = 2.5-6 m. The observations circled were taken on July 26, 1968; the remaining observations were taken on July 27, 1968. Winds: July 26= 170°, 1-3 kts; July 27= 35°, 5-12 kts.

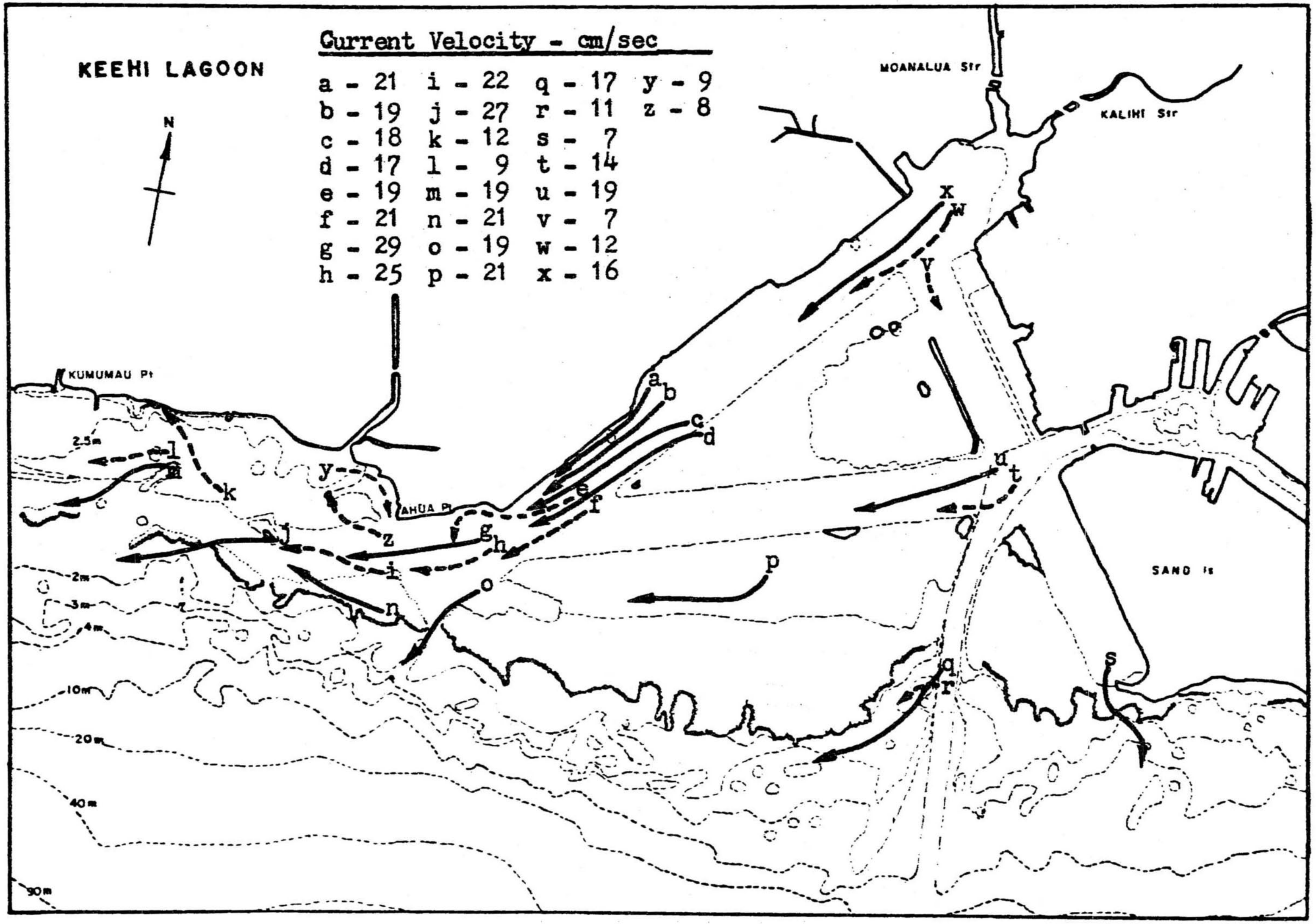


Figure 9 Surface Float Data for Ebbing Tides. Average velocities are given for the duration each float was in the water. The dotted paths were observed on July 31, 1968; the remainder were observed on July 22, 1968. Winds: July 22 = 55°, 18-24 kts; July 31 = 60°, 5-12 kts.

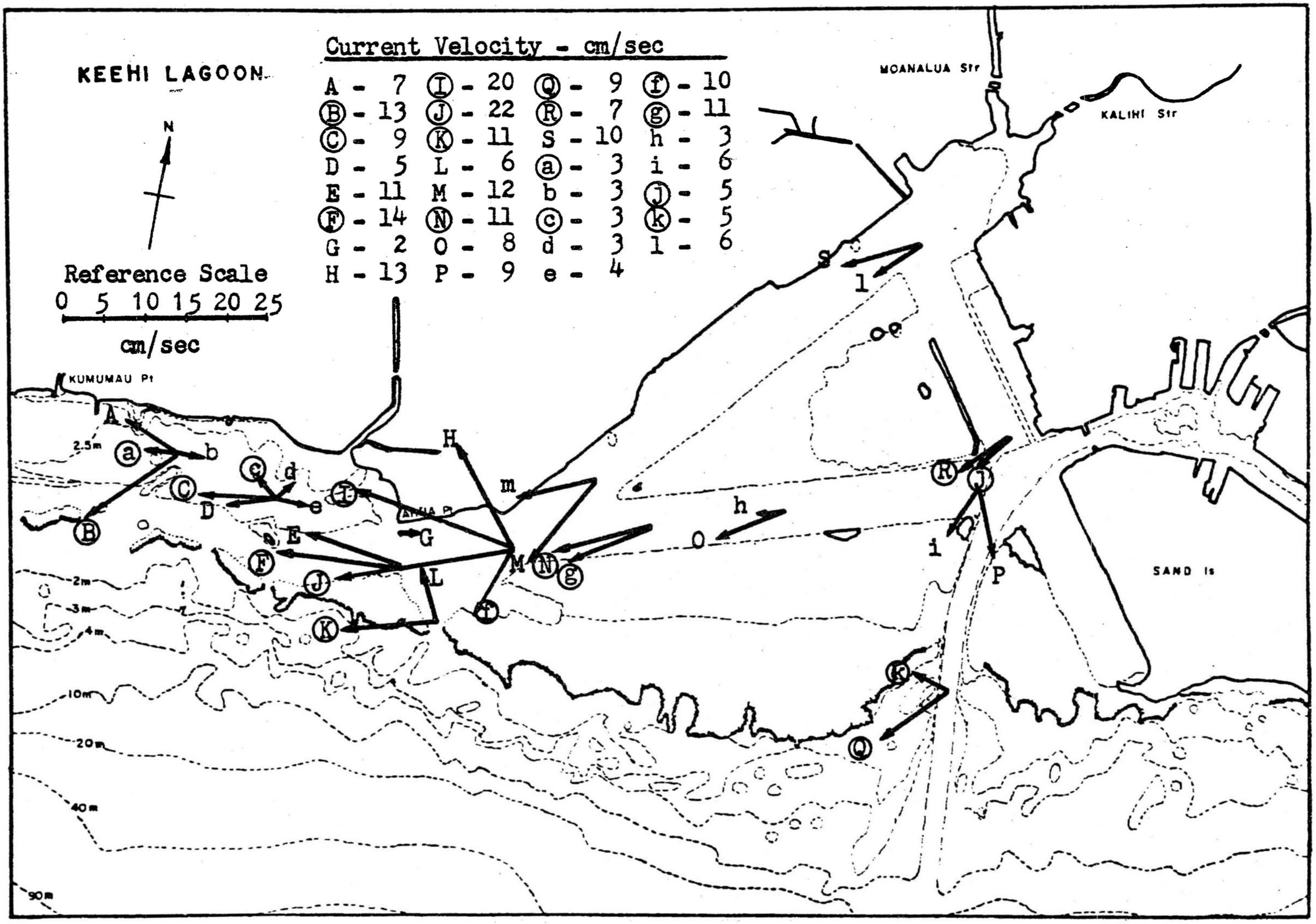


Figure 10 Current Meter Data for Ebbing Tides. Stations A to S = 0-2.5 m; Stations a to l = 2.5-6 m. The observations circled were taken on July 22, 1968; the remaining observations were taken on July 31, 1968. Winds: July 22= 55°, 18-24 kts; July 31= 60°, 5-12 kts.

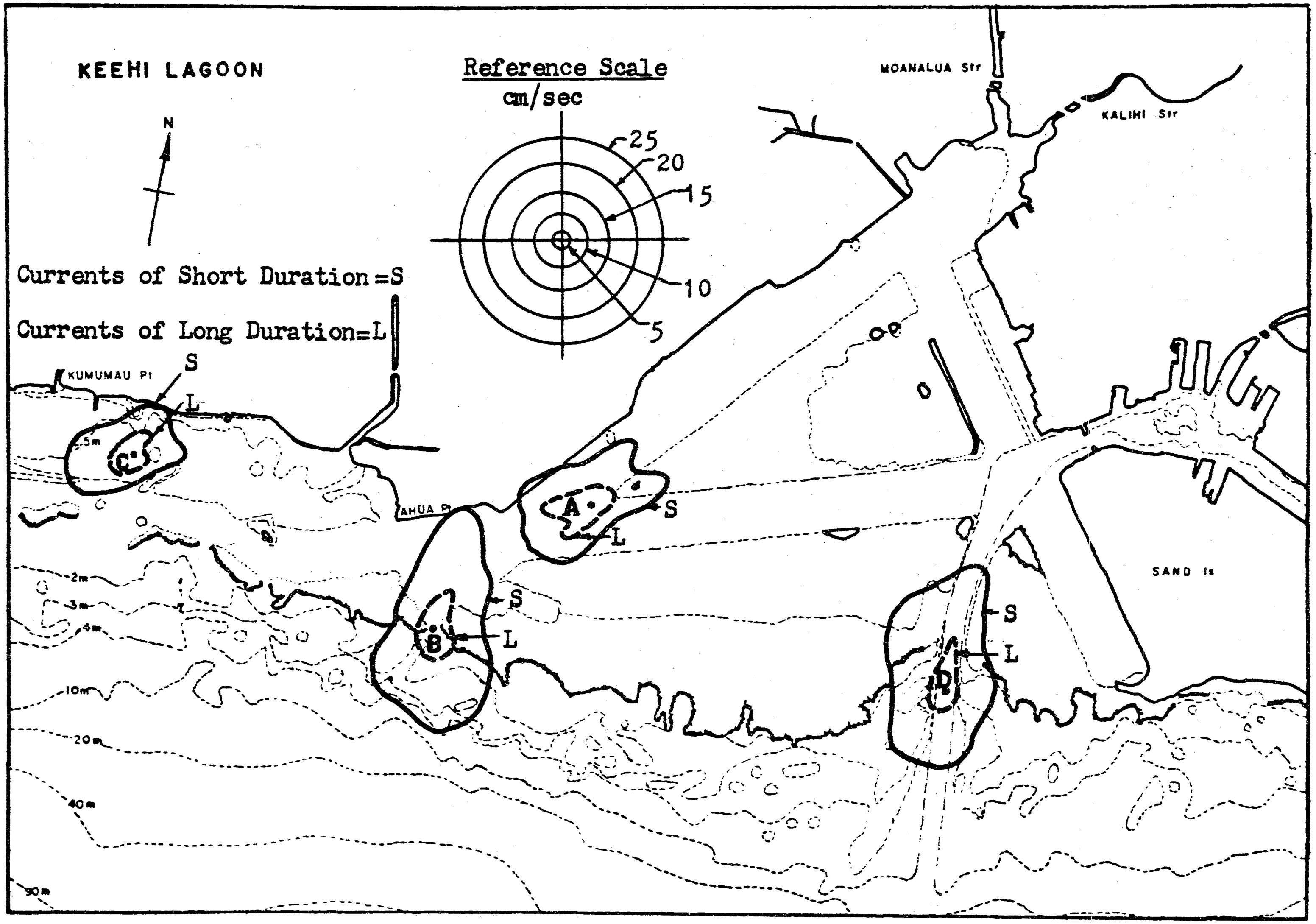


Figure 11 Integrating Current Meter Data. Each diagram shows the currents of short and long duration recorded at each location from July 19 to August 5, 1968 (2.5 m depth).

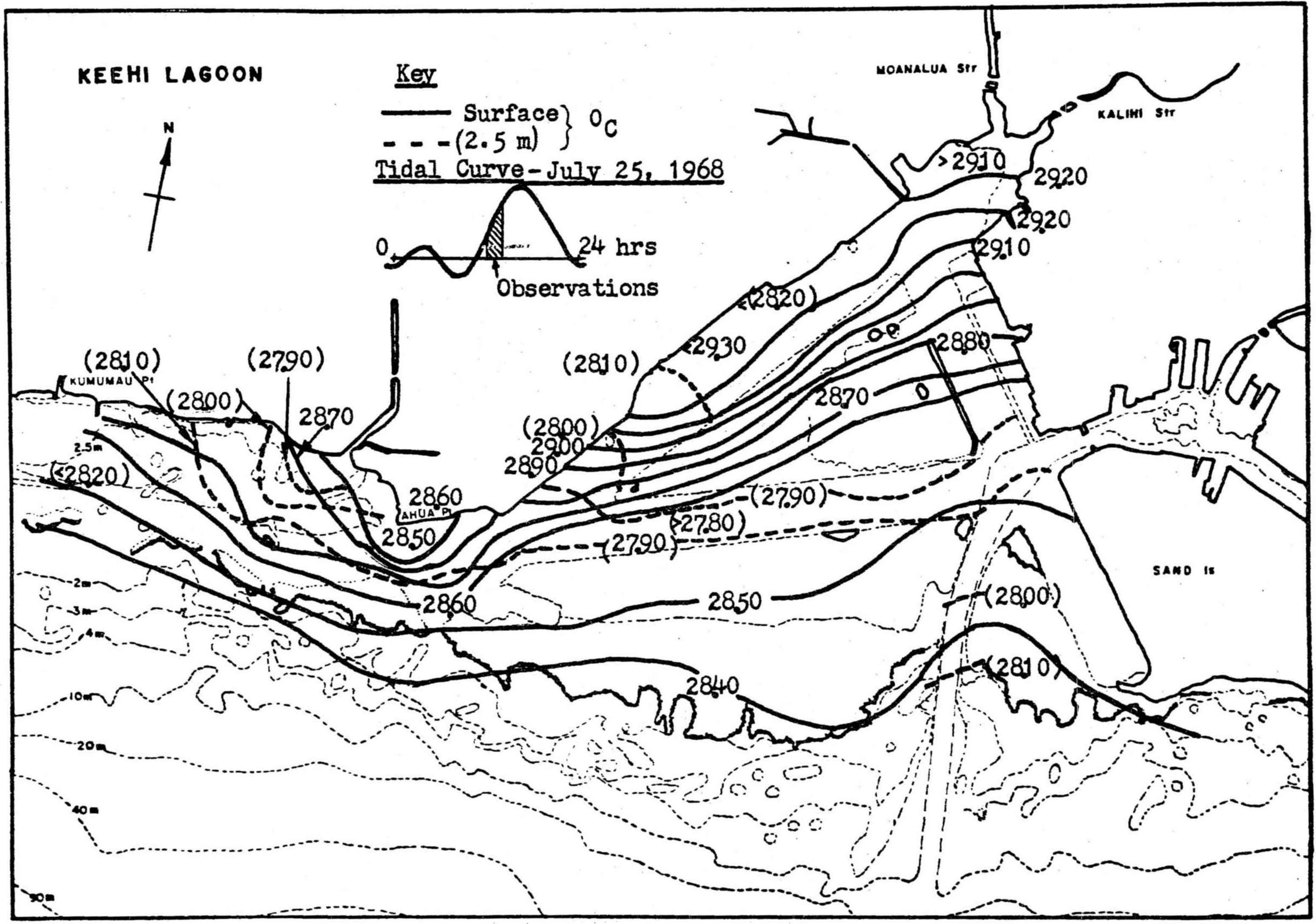


Figure 12 Temperature Distribution - Flooding Tide. The key identifies the contours for the surface and 2.5 m depth and shows the tidal curve for the day of observations.

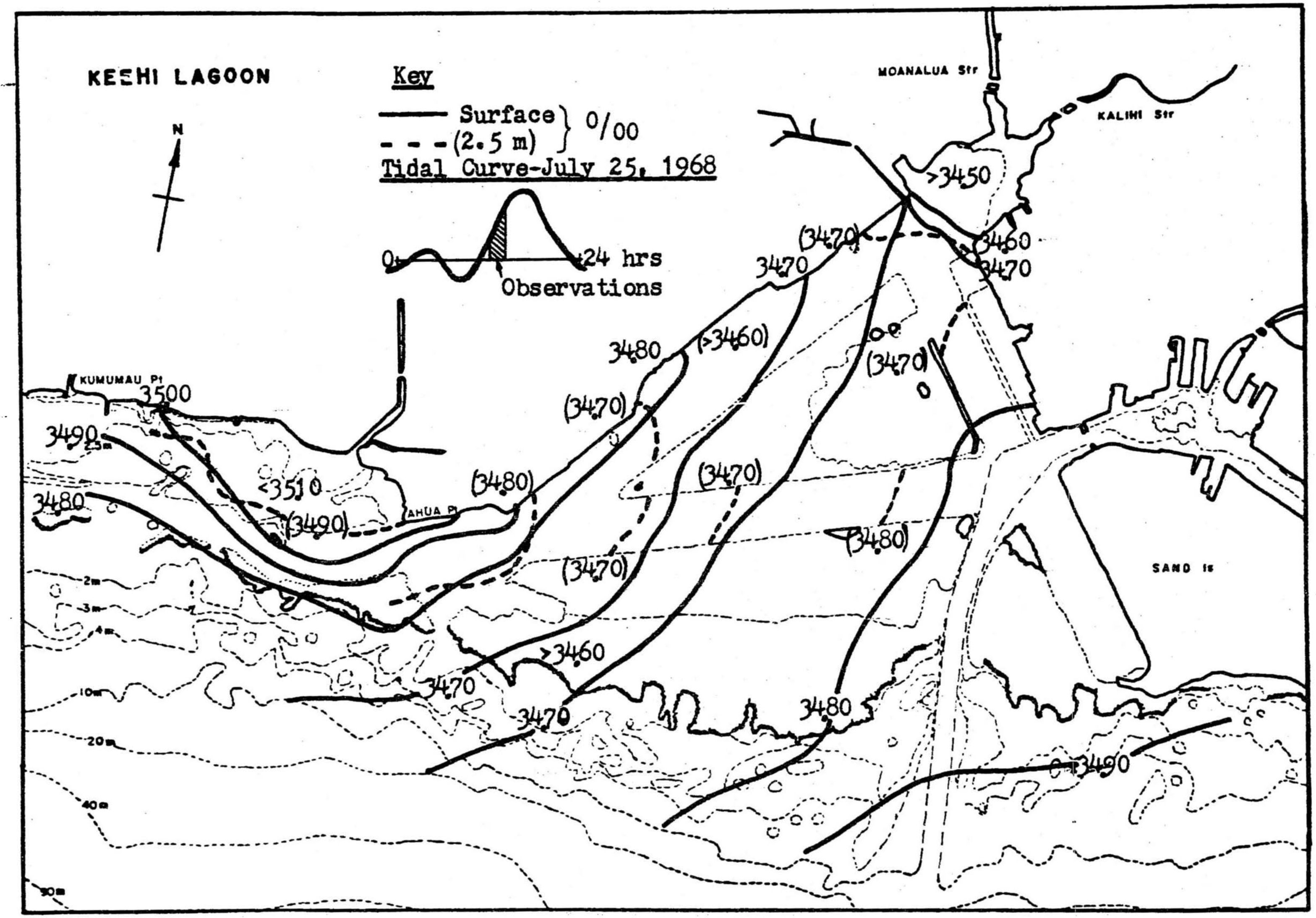


Figure 13 Salinity Distribution - Flooding Tide. The key identifies the contours for the surface and 2.5 m depth and shows the tidal curve for the day of observations.

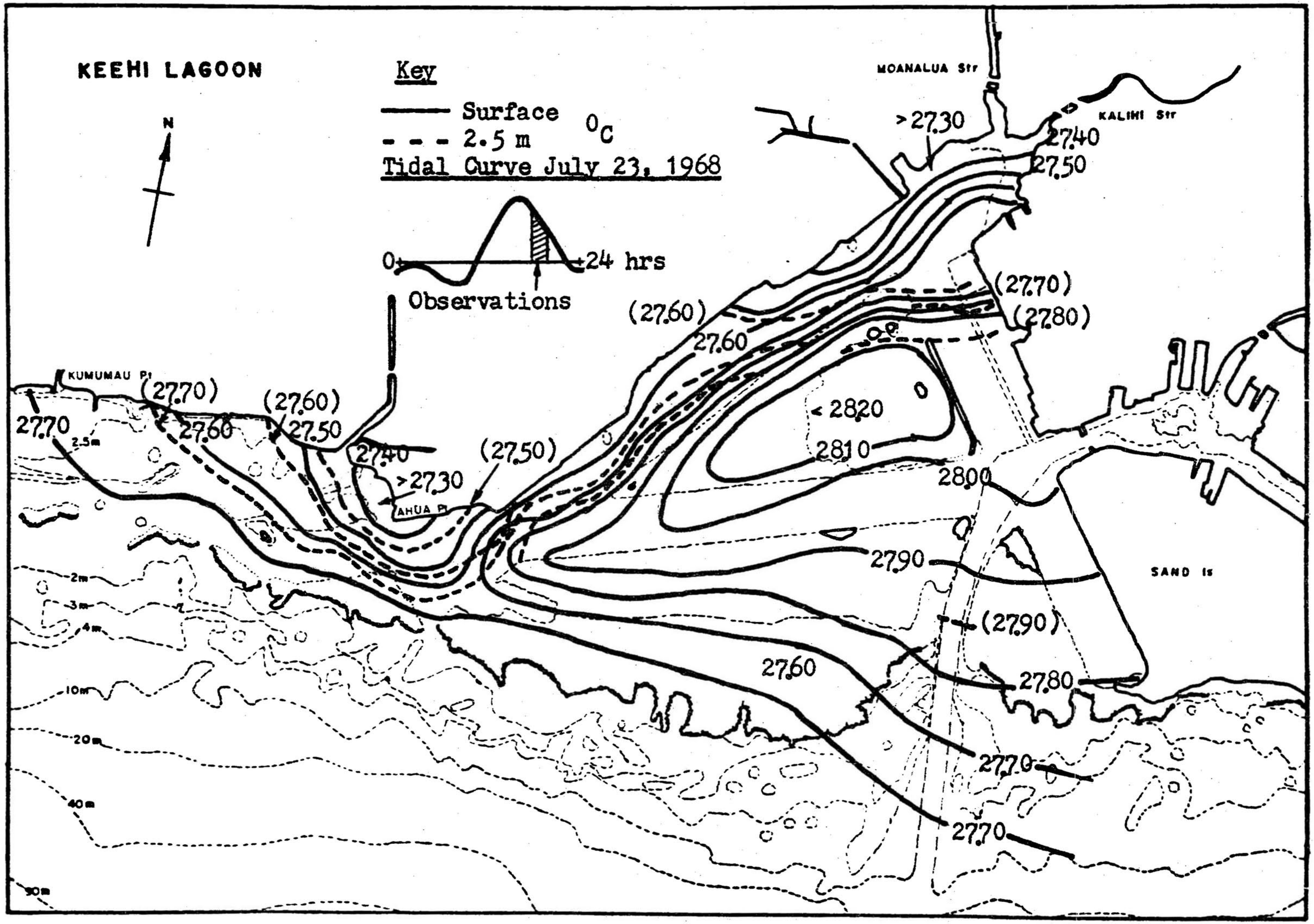


Figure 14 Temperature Distribution - Ebbing Tide. The key identifies the contours for the surface and 2.5 m depth and shows the tidal curve for the day of observations.

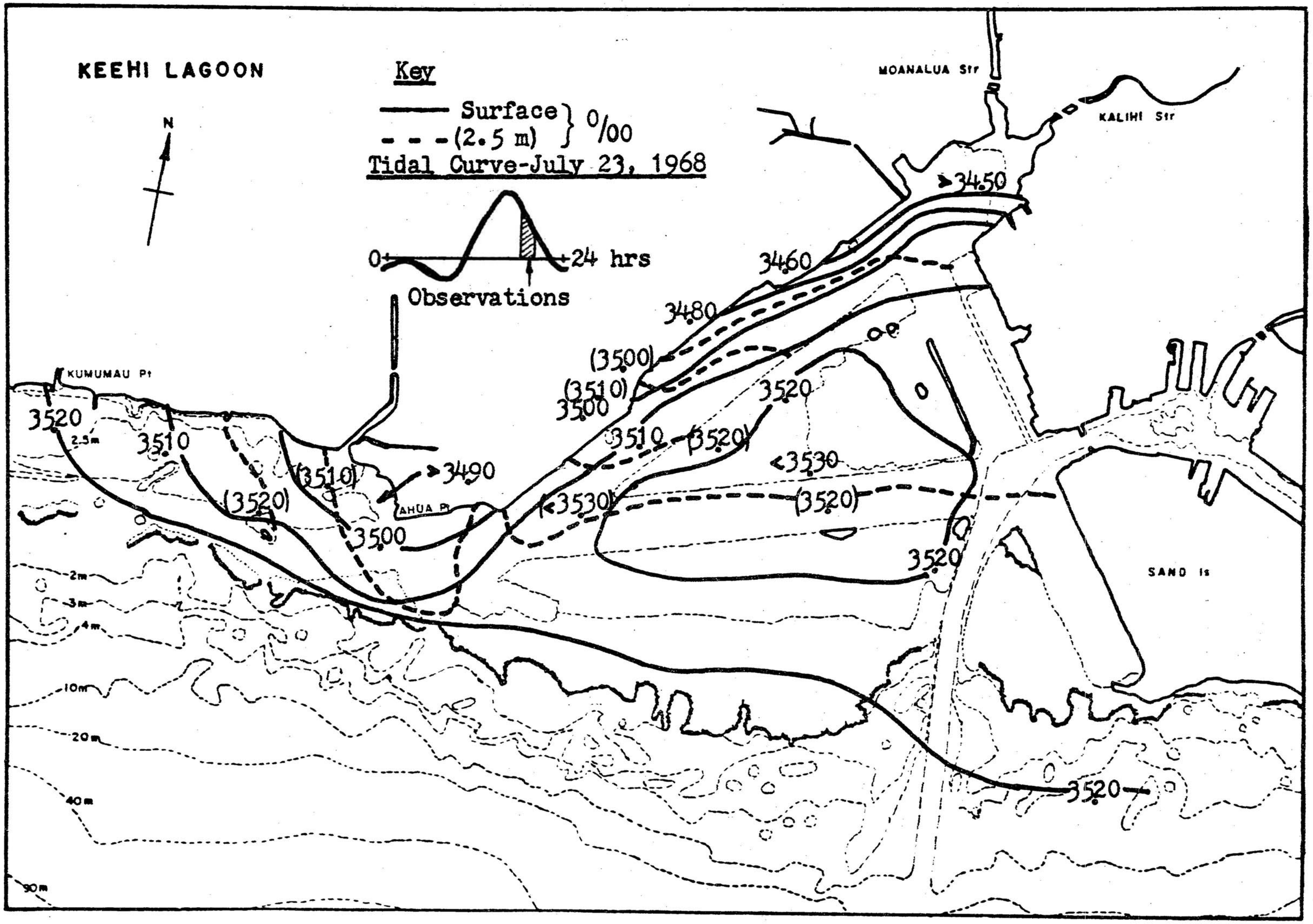


Figure 15 Salinity Distribution - Ebbing Tide. The key identifies the contours for the surface and 2.5 m depth and shows the tidal curve for the day of observations.

VII. BIBLIOGRAPHY

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