THE PHYSICAL OCEANOGRAPHY OF HUMBOLDT BAY

Steven L. Costa
Dept. of Oceanography
Humboldt State University
Arcata, CA 95521
and
Dept. of Oceanography and Ocean Engineering
Florida Institute of Technology
Melbourne, FL 32901

Preface

John Isaacs had a marvelous grasp of the problems involving all aspects of marine science. He was a man who did not ignore the practicalities of life. He was at one time a commercial salmon fisherman in Oregon and ultimately became one of the foremost oceanographers in modern times. This direction to his life's work was spurred partly because the scientific community could not answer his incisive questions about the sea in which he worked. That he recognized the problem at which this symposium is ultimately aimed is demonstrated by the following remarks taken from his introduction to the first volume of the Sea Grant report series:

> "There are great and ever-growing funds of scientific and technical knowledge and understanding of humankind and the planet. One of the most active is the understanding of the sea, of human influence upon it, and of opportunities for human betterment from its resources.
>
> "Knowledge and understanding of the oceans encompass the span between the broadly fundamental and the sharply practical. This wide range of knowledge of the sea clearly possesses great potential for important guidance of the directions of human activities. Yet its influence has been less than its potential. Most legislative and regulatory actions have been little influenced by what is known about the sea and reflect a failure of the research scientist, the public and those in industry and government to communicate.
>
> "This failure of communication between the scientist and the public is not restricted to marine science, of course, but it is common in many fields. It thus becomes vital to develop insight into the complexities of this fundamental and general problem of our times, to engage in thoughtfully designed experiments, and to encourage and nurture ideas that may grow into meaningful bridges of communication across the gulf that now cleaves action from understanding."

IN: Proceedings, Humboldt Bay Symposium, March 26, 1982, Eureka, California

It is this deficiency in communications that this symposium addresses. The fact that the symposium, at least in part, results from work John Isaacs supported and encouraged is appropriate and rewarding.

Introduction

It is the purpose of this paper to briefly outline the major features of physical oceanography of Humboldt Bay. Particular attention is paid to what is known about the bay rather than presenting a compendium of "studies that should be done". Hopefully, this may be of value to those requiring answers or solutions to particular questions and problems. Reference is made to many of the studies and data collection efforts presently available to aid those requiring information based on the best avialable data. A conscious effort is made to avoid the academic "insufficient data" syndrome.

Considerations of the physical oceanography of an estuarine or lagoonal system involve many interactions which tend to be quite complex. It is convenient to artificially segment the discussions into three main areas: the driving forces acting on the system, the processes through which the system responds, and finally the responses of the system to the driving forces. Each of these, and each of the individual topics within these major groupings, must be viewed within the framework of the physical setting, geometric characteristics, and geomorphology of the system.

The scope of this paper is obviously too limited to present every aspect of the bay and the processes affecting it. Only those topics considered of primary importance will be addressed below. Other areas of "secondary" importance will be mentioned where appropriate but a detailed presentation would not add substantially to the purposes of this presentation.

Morphology of the Bay

The general morphological characteristics of Humboldt Bay make it a rather unique estuarine system. It is best described as a multi-basin coastal lagoon with limited freshwater input. The entire bay covers about

(Isaacs/Kerstetter; R/CZ-47)

90 square kilometers at high tide (25 square miles) and about 29 square kilometers at low tide (8 square miles). Approximately 70 percent of the bay consists of tidal mud flats exposed at low water cut by a complex system of channels. Only the Entrance Bay portion of the bay remains constant in surface area over a tidal cycle. Table I details the geometric properties of various portions of the bay. There exists a set of aerial photographs taken in connection with a Sea Grant project at Humboldt State University (HSU) that graphically show the variations in bay area and shoreline at various tidal stands.

Due to the nature of the morphology of the bay it is generally divided into several distinct areas. The nomenclature usually ascribed to the basins and channels is presented in Figure 1. South Bay and Entrance Bay are more-or-less directly connected by a very short channel. Arcata Bay communicates with Entrance Bay by the relatively long North Bay Channel, which bifurcates at the north end. One of these branches splits once more (Eureka Channel) around Woodley Island. The bay is separated from the sea by two long sand spits and is connected to the ocean by the twin-jettied Entrance Channel approximately 1829 meters in length (6000 feet) and 671 meters wide (2200 feet) at the seaward end.

Driving Forces

-Tides-

Humboldt Bay is a tidally driven coastal lagoon, thus one of the major considerations here must be a somewhat detailed summary of the tidal characteristics of the system. This bay is well described as an interconnected series of three distict shallow basins. This compartmentalized nature of the bay results in relatively complex tidal responses. Simple descriptions of the tides will not suffice for many purposes and sophisticated data processing techniques are often required to gain a better understanding of the dynamics of the bay. Such detailed treatment will not be dealt with in this paper, but potential and necessary applications will be pointed out.

This bay is characterized by mixed semi-diurnal tides which generally increase in amplitude with distance away from the entrance. Phase lags correlated with distance from the entrance are also observed. Figure 2 shows typical tidal elevation curves within the bay. Figure 3 illustrates the variations of tidal elevations within the bay. This figure was constructed from recently obtained tidal data and is not taken from the published tide tables, which are only approximations. The corresponding relation with phase (e.g. time of high and low water) is not readily available at this writing. Figure 3 shows the differences in phase as obtained from the NOS tables, but should be viewed as illustrative only and not exact.

A number of tide stations have been occupied in the bay at various times. Much of this data is quite recent (1977-1982). The reference datums and elevations of these stations are shown in Table II. Note that these are final datums as received by the National Ocean Survey (NOS) rather than the preliminary datums previously published (for example by Shapiro Associates). The locations of these stations are shown in Figure 3. Additional tidal data have been recorded by investigators at Humboldt State University in connection with Sea Grant and U.S. Army Corps of Engineers projects.

The noted increase in tidal range at locations in the bay are also reflected in historical data. The tide range appears to have increased through time. This may well be a reflection of the effects of navigation channel improvement in the bay. Deepening these channels decreases the frictional resistance to tidal flows. There is also some evidence of response of mean tide level to changes in sea level during the last 70 years.

-Waves-

The entrance to Humboldt Bay has undergone significant modification during the last century as a result of improvements to the harbor for navigation purposes. Because of the high wave energy climate in the region, waves are one of the major driving forces affecting the entrance and the immediately adjacent interior portions of the bay. Offshore wave data for the region are generally limited to that provided by hindcast techniques. However, such data sets are still of great value in assessing the role of waves in the evolution and operation of the bay entrance.

The Pacific northwest experiences the most severe wave conditions, on an annual basis, in the continental United States. For the California coastline there exist two hindcast data sets. Until a few years ago the only data available for use were those developed by National Marine Consultants for the Army Corps of Engineers. These statistics were based on a three year hindcast analysis (1956-58) of synoptic weather maps. More recently a far more extended data base was constructed for the California Dept. of Navigation and Ocean Development by Meteorology International Incorporated based on the U.S. Navy Fleet Numerical Weather Control singular wave analysis. These data are provided for six deep water stations off the California coast and are based on the 24-year period from 1951-74. At the present time there is an ongoing data collection effort by the State of California and the Army Corps of Engineers to provide a coastal wave data base.

TABLE I. GEOMETRIC CHARACTERISTICS OF HUMBOLDT BAY

	Humboldt Bay	Arcata Bay	South Bay	Entrance Bay	Investigator
Length[1] (miles)	14.1	5.5	3.7	2.5	Thompson, 1971
Width[1] (miles)	4.2	4.2	2.6	2.0	"
Surface Area (mi.^{2})					
@ MHW	24.5	14.2	6.4	2.7	"
@ MLLW	11.3	4.7	2.9	2.6	"
Depth[2] (ft.)	11.4	13.0	5.5	19.8	Univ. of Washington, 1955
Tidal Prism (10^9 ft^3)					
Mean Range	2.44	-	-	-	Johnson, 1972
Spring Range	4.38	-	-	-	O'Brien, 1971
Spring Range	3.51	-	-	-	Johnson, 1972
Spring Range	3.4	1.7	1.0	0.5	Costa, 1980

Entrance Inlet at MSL

Width	2200 ft.	Johnson, 1972
Depth	33.5 ft.	"
Cross Section	51900 ft^2	"

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[1] Maximum

[2] Average

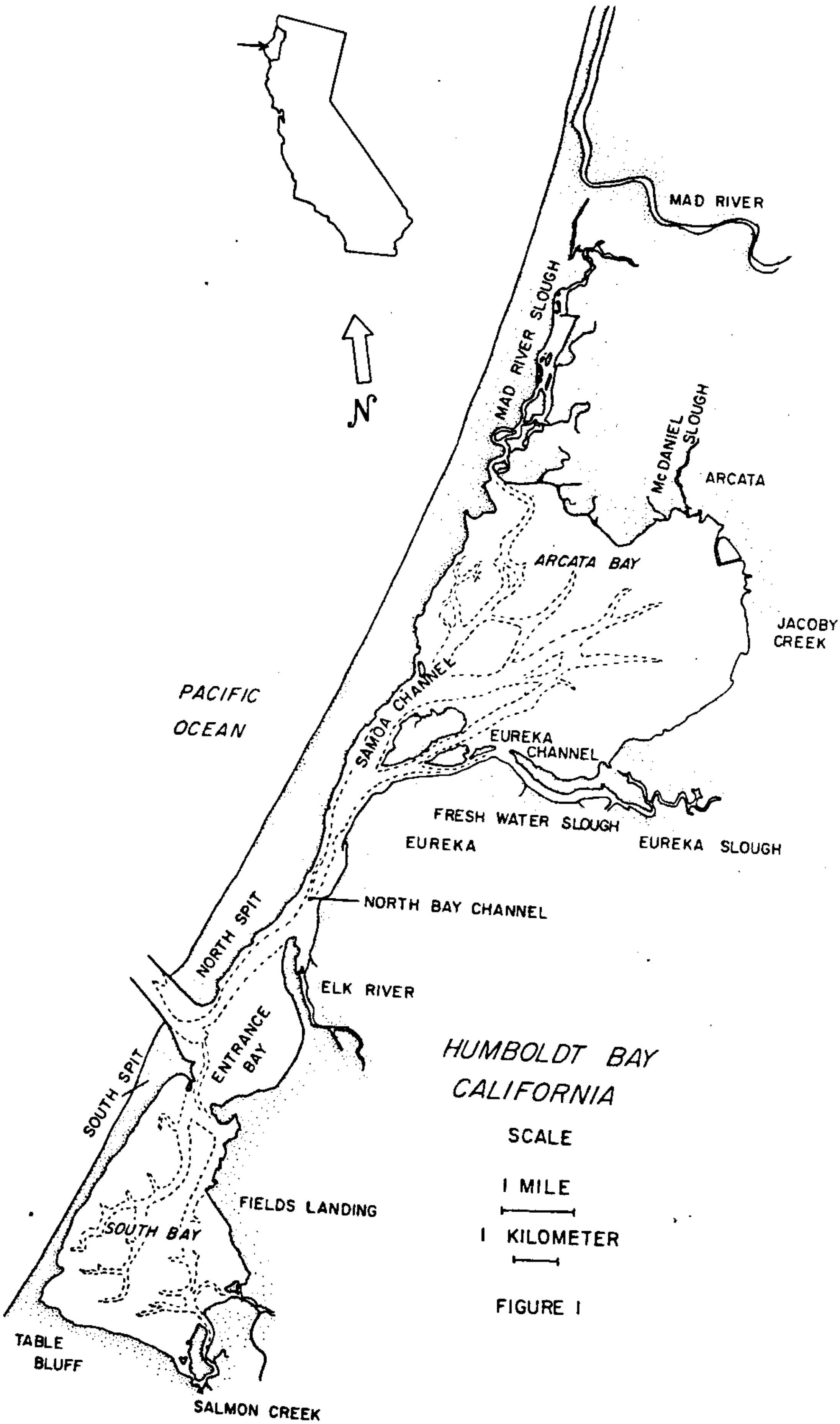
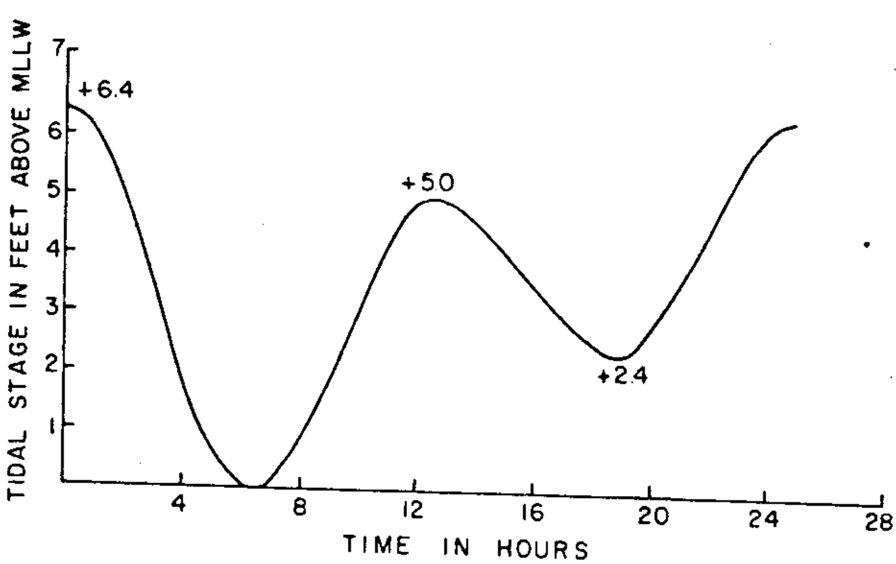
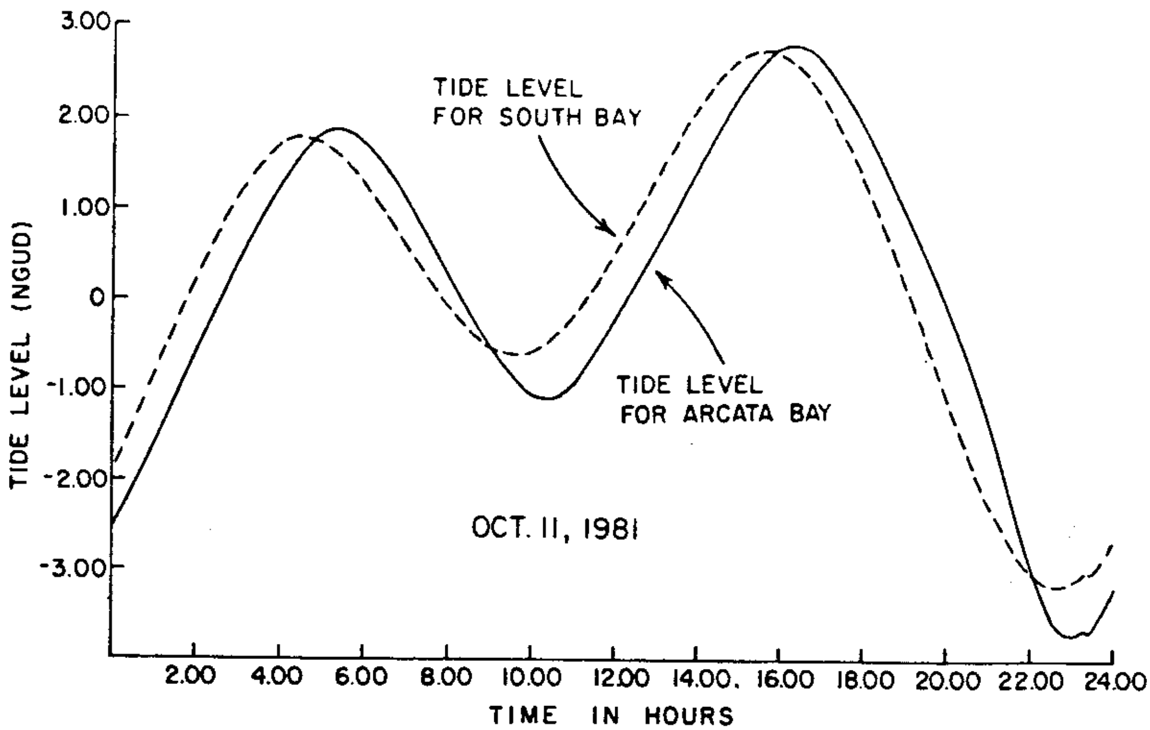

MAD RIVER
MAD RIVER SLOUGH
McDANIEL SLOUGH
ARCATA
ARCATA BAY
JACOBY CREEK
PACIFIC OCEAN
SAMOA CHANNEL
EUREKA CHANNEL
FRESH WATER SLOUGH
EUREKA
EUREKA SLOUGH
NORTH BAY CHANNEL
NORTH SPIT
ELK RIVER
ENTRANCE BAY
SOUTH SPIT
SOUTH BAY
FIELDS LANDING
TABLE BLUFF
SALMON CREEK
N
HUMBOLDT BAY
CALIFORNIA
SCALE
1 MILE
1 KILOMETER

FIGURE 1



Mean tide curve, South Jetty, Humboldt Bay, CA (after U.S. Army Corps of Engineers, 1976).



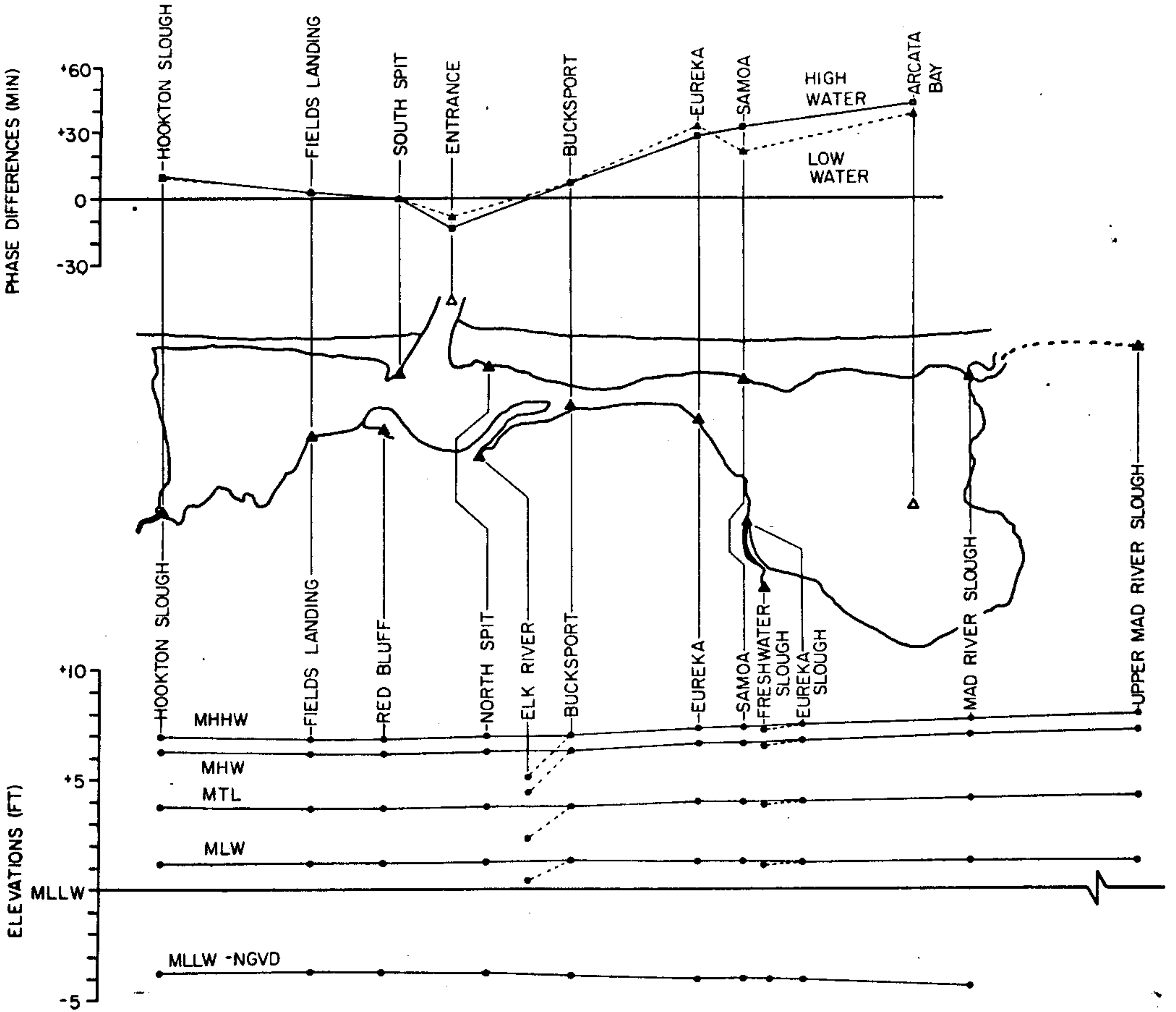
Typical tide curves at the extreme ends of Humboldt Bay, CA (after Costa, Stork, Diebel and Landsteiner, 1981).

FIGURE 2

TABLE II. TIDAL DATUMS AND DATES OF RECENT NOS OCCUPATIONS

Station	Dates	MHHW	MHW	MTL	MLW	MLLW	NGVD	Mean Range	Diurnal Range
Upper Mad River Slough	7/78-1/79	7.93	7.22	4.26	1.30	0.00	N/A	5.92	7.93
Mad River Slough	9/77-2/80	7.75	7.04	4.18	1.32	0.00	-4.30	5.72	7.75
Samoa	4/78-6/79	7.33	6.62	3.95	1.27	0.00	-3.99	5.35	7.33
Eureka Slough	3/78-6/79	7.48	6.76	4.01	1.27	0.00	-4.04	5.49	7.48
Eureka	8/77-2/80	7.32	6.61	3.94	1.28	0.00	-4.02	5.33	7.32
Freshwater Slough	3/78-1/79	7.20	6.49	3.78	1.08	0.00	N/A	5.41	7.20
Bucksport	8/77-2/80	7.00	6.30	3.76	1.28	0.00	-3.85	5.02	7.00
North Spit	8/77-Present	6.93	6.22	3.73	1.25	0.00	-3.72	4.97	6.93
Elk River	9/77	5.10	4.40	2.33	0.39	0.00	N/A	4.01	5.10
Red Bluff	4/78-1/79	6.81	6.12	3.67	1.21	0.00	-3.69	4.91	6.81
Fields Landing	4/78-2/80	6.82	6.12	3.66	1.20	0.00	-3.67	4.92	6.82
Hookton Slough	9/77-6/79	6.94	6.24	3.73	1.22	0.00	-3.71	5.02	6.94

Elevations in feet above MLLW.



Tidal elevations from recent NOS tide station occupations and phase lags from NOS tide tables, Humboldt Bay, CA

FIGURE 3

the primary values of this study will be the ability to verify the previous hindcast data sets. Fortunately, one of the wave stations occupied is directly offshore of Humboldt Bay.

Figure 4 presents annual wave roses constructed from the hindcast data for sea and swell. Figure 5 shows the monthly averages of this data. The predominant swell is seen to be from the northwest. The predominant directions of seas are from the south-southwest and north-northwest. Since the jetties at the entrance to the bay are oriented toward the nothwest, the longer period swell would be expected to have the most direct impact within the entrance and in the interior of Entrance Bay.

The arriving swell is equal to or greater than 1 meter (3.3 feet) in height about 31 percent of the time. Similarly, the seas are 1 meter or higher about 57 percent of the time. It is of particular interest that the combined sea swell data (not shown in the figures) indicate that the combined wave height is 1 meter or greater about 58 percent of the time. High seas and swell often occur at the same time. The coastline experiences incident open ocean swell from winter storms at the same time that locally high seas are generated. The statistics are not such to make the above statements exact, however they do appear to be qualitatively correct.

Examination of the data on a monthly basis shows that the predominant incident swell arrives from a west-northwesterly direction (280-300 degrees) during October through April. This is also the period of the highest and most frequent occurrence of swell. May through August exhibit frequent occurrences of local seas from the north. In the months November through March the seas arrive from the west-southwest. As will be seen later the direction, intensity, and frequency of the waves impinging on the entrance to Humboldt Bay have dramatically affected the evolution of Entrance Bay in recent years.

-Density Differences-

In addition to waves and tides there are other driving forces to be considered. The most obvious of these is the density difference in the water column resulting from fresh water inflow. The drainage area of Humboldt Bay is only about 805 square kilometers (233 square miles). Point source runoff to the bay is via Elk River, Jacoby Creek, FreshwaterEureka Slough, McDaniel Slough, Mad River Slough, and other smaller sloughs and creeks. The total annual fresh water input to the bay is only on the order of the tidal prism. (The tidal prism is the amount of water exchanged between the bay and the ocean over a half tidal cycle.) Therefore, the overall circulation of this bay is dominated by tidally driven flows, modified by the bathemetry and the wind field over the bay. Since the precipitation in the region is strongly seasonal and sporadic (storm event controlled) even during the wet season (November through March), the overall effects of stratification are minimal.

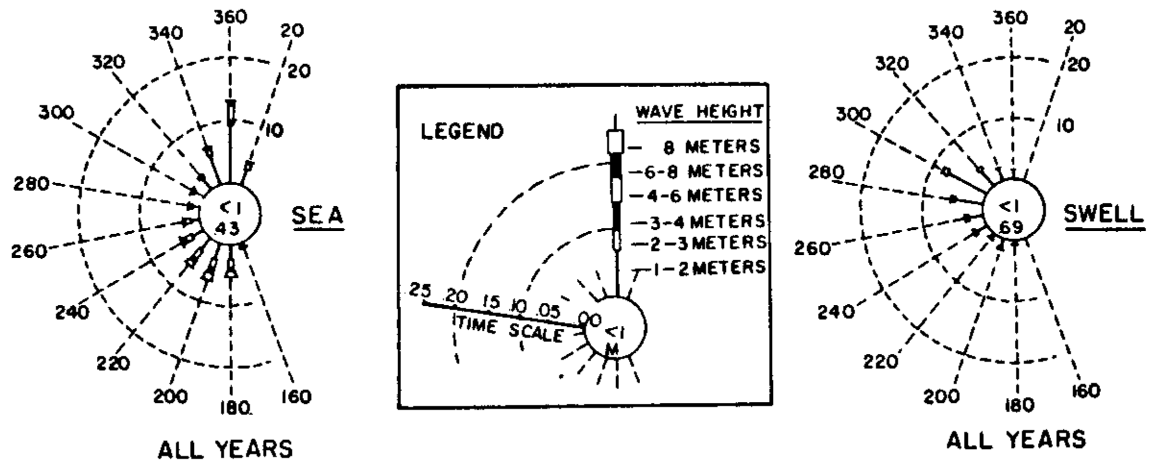
Figure 6 shows the average annual rainfall at Eureka, and to illustrate the event oriented nature of the fresh-water input into the bay, the cumulative rainfall over a particular annual cycle is also shown. Figure 7 shows the response of the salinity distribution of the bay as a whole for a particular year. It is immediately seen that there are seasonal changes in the longitudinal distribution of salinity with season. However, the vertical stratification remains rather insignificant. The bay changes from a completely mixed coastal lagoon system during the dry season to a weak vertically homogeneous estuary in the wet season.

Considering the seasonal nature and limited extent of this input, many of the generalizations concerning classical estuarine behavior will not suffice. On the average, Humboldt Bay has the appearance of an unstratified coastal lagoon. Overall it might appear that the effects of fresh water input can be ignored. Further consideration, however, shows that at localized places throughout the bay the effects of such input can be extremely important. These localized effects, particularly on processes involving sedimentation rates and patterns, nutrient influx, and productivity, can be of importance to large areas within the bay. One such localized area where density stratifications are important will be examined as an example.

-Wind-

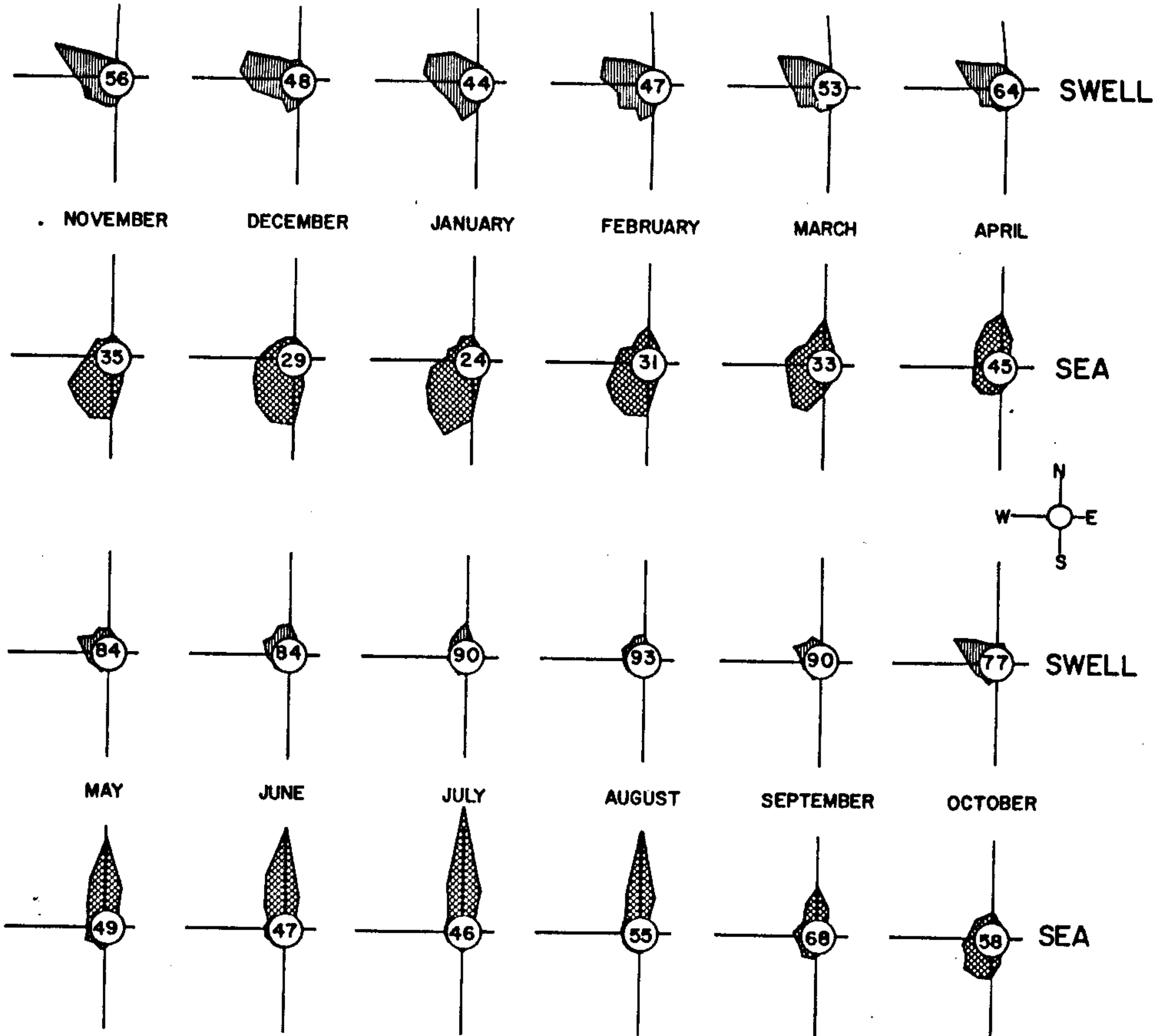
The nature of Humboldt Bay also admits wind as a major driving force. Approximately 70 percent of the bay consists of very shallow areas, much of which is generally exposed at lower low water. The effects of wind blowing across these areas can be significant in a number of ways. The surface currents in the shallower portions of the bay can be influenced by the wind, despite the overall dominance of the tidal action in the bay. There are particular reaches in the bay with a fetch (the distance over water which the wind blows) long enough to allow the formation of locally generated waves two to three feet high, especially during southerly or southwesterly storms. The action of the wind can be quite important in redistributing dissolved and suspended material within the bay. Unprotected bank erosion, particularly on the remaining salt marsh areas is greatly enhanced by the combination of varying water level and wind induced wave action.

The winds in the vicinity of Humboldt Bay have seasonal characteristics very much like the wave data presented above. Figure 8 presents an example of a wind rose for the area. Table III is an example of the



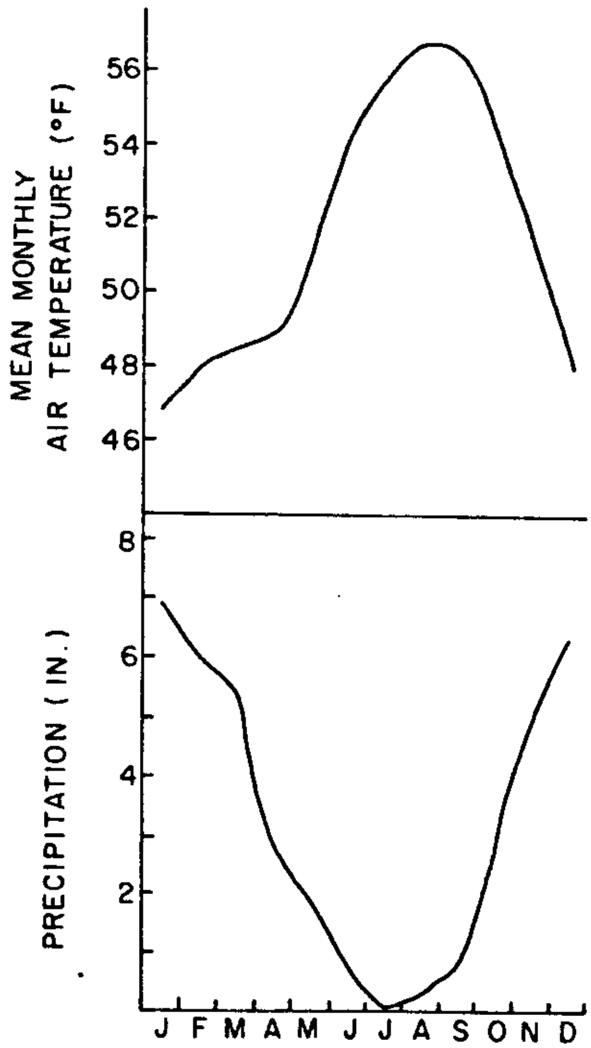
Annual hindcast wave roses for offshore sea and swell (after Meteorology International, 1977).

FIGURE 4



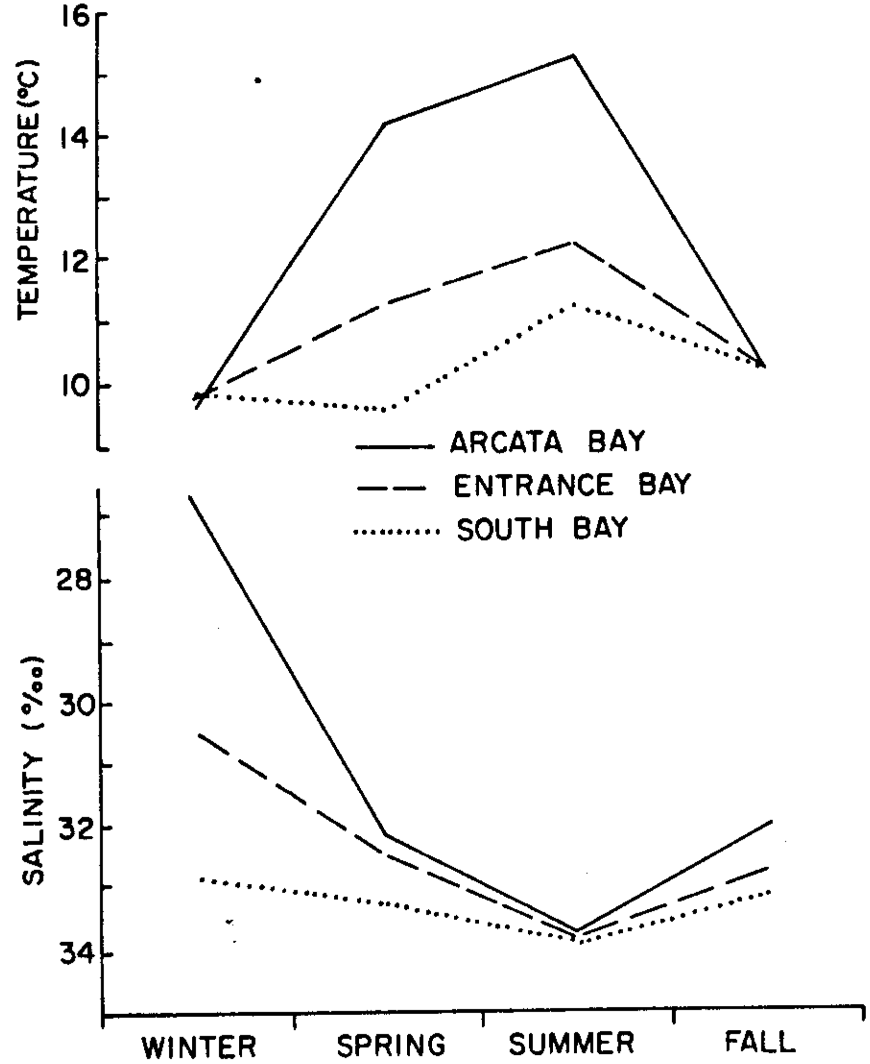
Relative frequency of arrival directions for hindcast deep water sea and swell. Circled numbers indicate percent frequency that waves are less than 1.0 meter. (Data from Meteorology International, Inc, 1977)

FIGURE 5

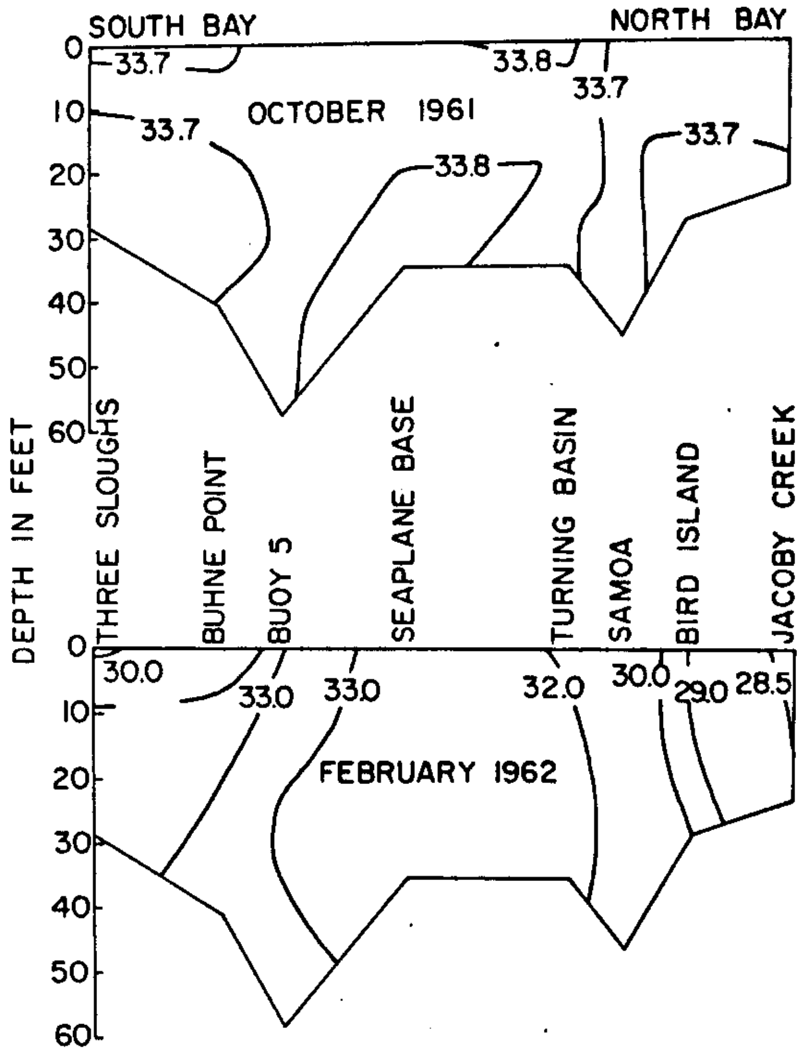


Seasonal cycles of air temperature and precipitation, Eureka, CA (U.S. Dept. of Commerce, 1963).

FIGURE 6



Seasonal cycles of temperature and salinity (after Shapiro Associates, 1980).



Salinity distribution in the channels of Humboldt Bay (after Skeesick, 1963).

FIGURE 7

seasonal variations in wind speeds and also presents the maximum winds that have been observed in the past.

-Other Driving Forces-

The phenomena mentioned above are considered by the author to be the most important of the myriad driving forces operating on this bay. Without doubt, many other such forces can be identified and play a role in the behavior and response of the bay. These include solar heating, variations in cloud cover, a host of anthropogenic influences, and so on. Other individuals, depending on their particular interests may consider any of these others of "primary" importance. The particular forcing functions chosen here do however, represent the minimum set that must be considered to construct the physical framework, within which, the bay operates. In this sense, they are given the appellation of "primary".

The influence of man is, of course, an important and often overriding force on this and most other estuarine systems. The ways in which such influence interacts with the natural forces at work add an additional degree of complexity to the analysis. Some of the more important affects are considered in a separate section of this paper.

Processes

The process through which the driving forces act to produce the resultant responses of the bay are of the most critical interest to the scientist and engineer. An understanding of the underlying physics of these processes allows an understanding of the ultimate behavior of the system. More importantly, such understanding allows the prediction of how the bay will respond to changes induced by both natural evolution and man's activities. Such predictions are absolutely required to engage in wise management of the natural resources of the bay, particularly in view of the competing and often conflicting interests of various segments of the population.

Unfortunately, a complete description of these processes, even if they were well understood, is well beyond the scope of this paper. A few examples of the importance of efforts to provide an understanding must suffice here.

The ability to predict tides and tidal currents needs no justification to anyone at all familiar with the marine and coastal environment. The tides are generated by the gravitational attraction of the sun and moon and the characteristics of their positions with respect to the Earth. But since there are literally scores of astronomical factors, as well as the geographic features of the planet, to be considered , the prediction of what the tides will be at any point in the future becomes extremely difficult. Simply to predict the astronomical component of the tides requires sophisticated mathematical treatment. Fortunately, our ability to do this is presently well developed and published tide tables are available worldwide.

A "tidal epoch" is approximately 19 years in length. Therefore, accurate predictions of the tides require 19 years of past data. Most people familar with Humboldt Bay have recognized significant deviations from the published tide tables. Some of these are due to meteorological effects that cannot be forecast. However, there is another element in tidal predictions in the bay which is not generally recognized. The published tide tables are based on a rather short record of tidal observations at South Spit taken in the early 1900's (see Table II) and then tied into Crescent City to the north. It is not unexpected that the present day tide tables leave something to be desired. The National Ocean Survey currently occupies a tide station on North Spit, and the data collected from this station should eventually be available to allow more precise tidal predictions in the bay.

The prediction of waves is a much more statistical effort; that is, we can only determine what will happen on the average. Even this is a difficult process. It is often of more interest to be able to predict how a particular wave climate will affect coastlines and coastal structures. An excellent example of this is the ability to determine the rate at which waves on the adjacent beaches will move sand along those beaches and into the entrance of the bay. In addition we would like to know under what conditions the sand will bypass the entrance and when it will actually enter the entrance channel and degrade the depth available for navigation.

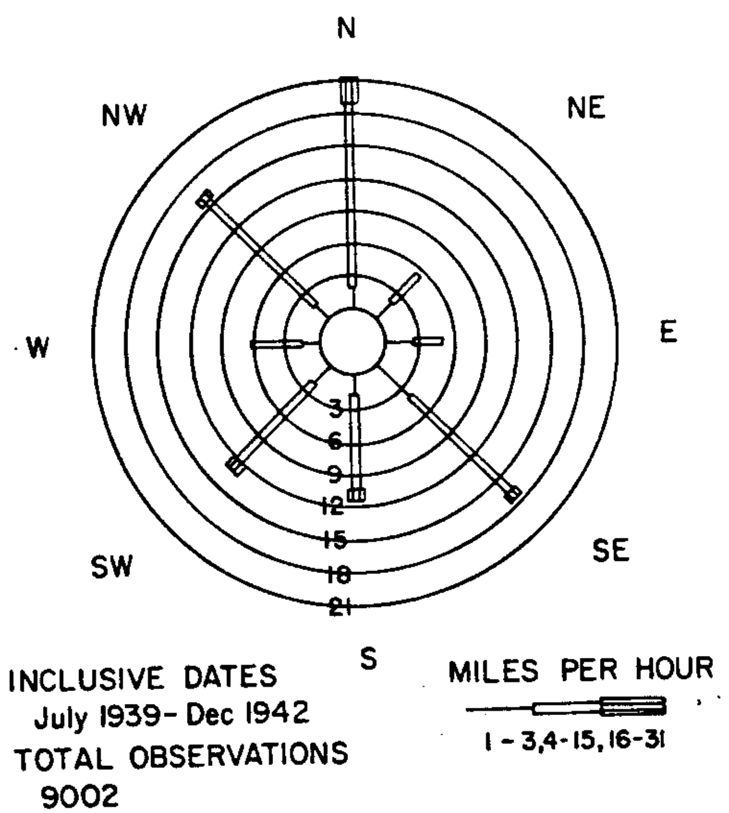
This is a particularly difficult problem for Humboldt Bay. There exist few estimates, and even fewer good ones, as to how much sand is transported along the beaches. Recent work has indicated that the Humboldt littoral cell is somewhat different than the classical situations that are well studied (e.g. southern California). The seasonal nature of the waves incident on the coast, the amount of sand introduced by the nearby rivers, the identifiable sinks and transport paths of this material, and a host of other factors must be considered.

The process by which fresh water input to an estuary are better understood than the role of waves discussed above. Again, however, Humboldt Bay is somewhat unique and does not fit any of the classical schemes of analysis very well. We do find that this process can be adequately described under the correct assumptions based on actual observations within the bay to a good degree. The problems in this area are more of inadequate observations than those of inadequate theory.

TABLE III. MONTHLY AVERAGE AND MAXIMUM WINDS

Month	Mean Wind Speed (mph)	Prevailing Direction	Maximum Wind Speed (mph)	Maximum Wind Speed Direction
January	6.9	SE	54	S
February	7.2	SE	48	SW
March	7.6	N	48	SW
April	8.0	N	49	N
May	7.9	N	40	NW
June	7.4	N	39	NW
July	6.8	N	35	N
August	5.8	NW	34	N
September	5.5	N	44	N
October	5.6	N	56	SW
November	6.0	SE	43	S
December	6.4	SE	56	S
Annual	6.8	N	56	SW
Length of Record (yrs)	54	54	67	67

(from U.S. Department of Commerce, 1977)



Hourly average surface winds (MPH), percentage frequency of occurrence (after U.S. Army Corps of Engineers, 1956).

FIGURE 8

The comments in the above paragraph generally apply to each of the other processes that may be of primary or secondary importance in the bay. Each estuarine system is unique, generalizations are dangerous, and experience with the individual system is invaluable.

Responses

-Current Patterns-

Of most direct interest to the non-academic community are the results obtained once the data on the driving forces is analysed to the point where descriptive and predictive output is obtained. Again, the scope of this paper limits the discussion here to a few main topics of general interest. Concentration will be focused on recent developments in the understanding of how Humboldt Bay operates as a natural system.

The overall current pattern has been the subject of a number of investigations. Figure 9 illustrates the general ebb and flood patterns. It is obvious that flood and ebb dominant regions exist throughout the bay. These features of the circulation are very important when attempts are made to predict the distribution and ultimate fate of dissolved and suspended substances within the bay.

There have been a number of studies of detailed circulations at localized places within the bay. At first thought it might seem inconsequential to consider differences (i.e. net currents) that are only on the order of centimeters per sec when the major flows are on the order of meters per sec. However, the following example should adequately demonstrate the critical nature of some of these small scale features.

Recent investigations have reinforced the hypothesis of a net circulation within Entrance Bay that is described in Figure 10. One of the most stiking features of this circulation is the ability of water exiting North Bay Channel to work around the eastern shore of Entrance Bay and enter South Bay. This means that activies in the northern parts of Humboldt Bay can affect the water masses of the extreme southern part of the bay.

To further investigate this phenomenon a number of drifter and streamer studies were accomplished that show two important aspects of this circulation. There is a fairly well defined location at the southern end of North Bay Channel that determines which water masses might be expected to follow a trajectory that will result in their introduction into South Bay. Water from further north than this point is subject to mixing laterally across the entire channel and only relative predictions as to its fate can be made. Some of these drifter paths are shown in Figure 11.

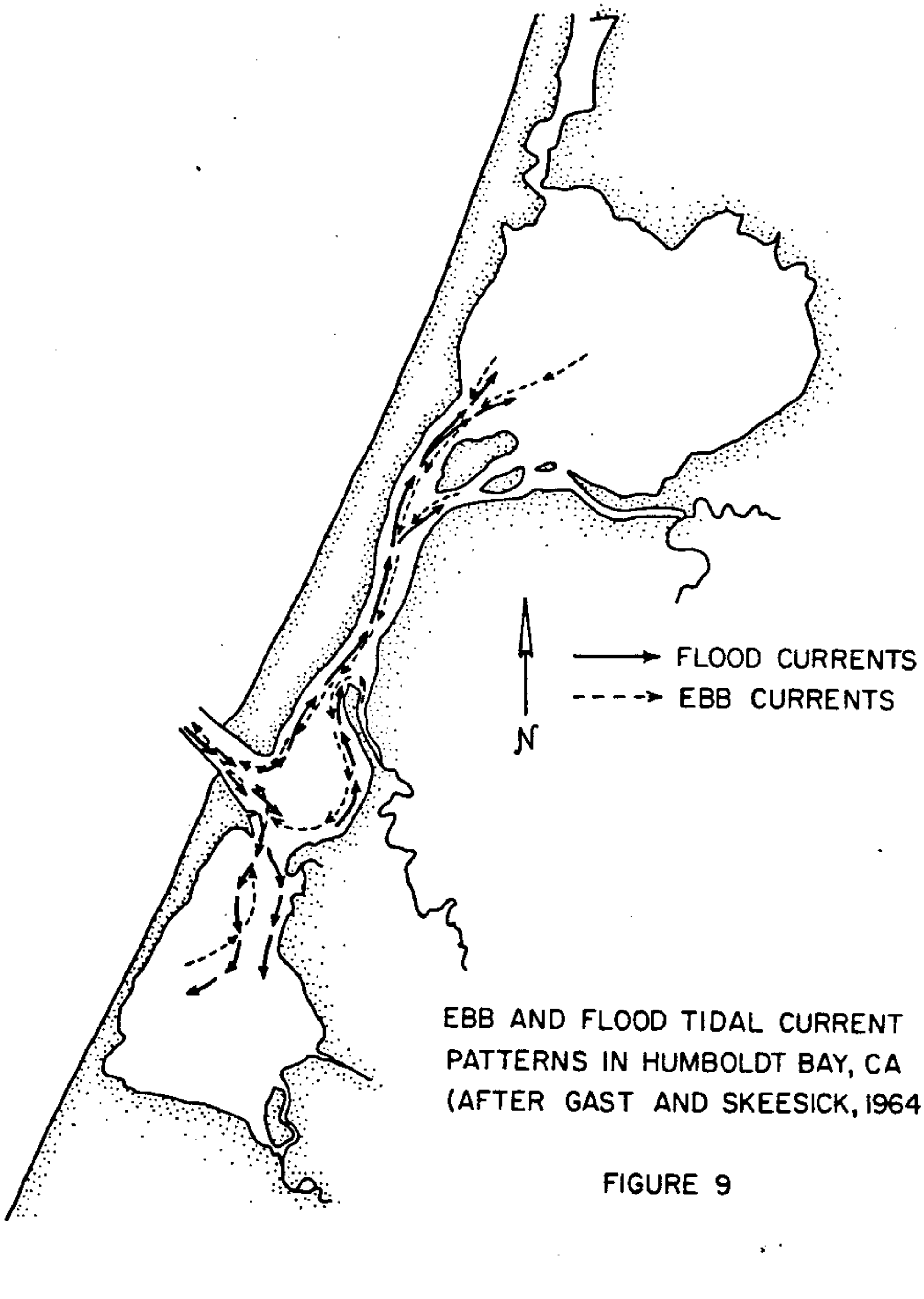
Anchored streamers placed across the entrance to South Bay have indicated that the inflow to this basin from Entrance Bay begins on the eastern side of the channel while an ebb current still exists on the western side of the channel. The timing of this flow appears to be a fairly well defined function of tidal range. The phenomenon is a result of the larger mass of water ebbing from Arcata Bay but being impeded by the long narrow North Bay Channel. The above situation has been observed and documented, but at this time the quantitative importance of the flow pattern can only be guessed at.

-Longshore Transport-

The transport of sand along the beaches adjacent to the entrance to the bay is of critical importance to the viability and operation of Humboldt Bay as a port. It is this material that forms the outer bar and inner shoal at the entrance. This is also the material that finds its way into the navigation channel and limits the available depth. Thus, it is of some interest to determine how the material moves along the beaches.

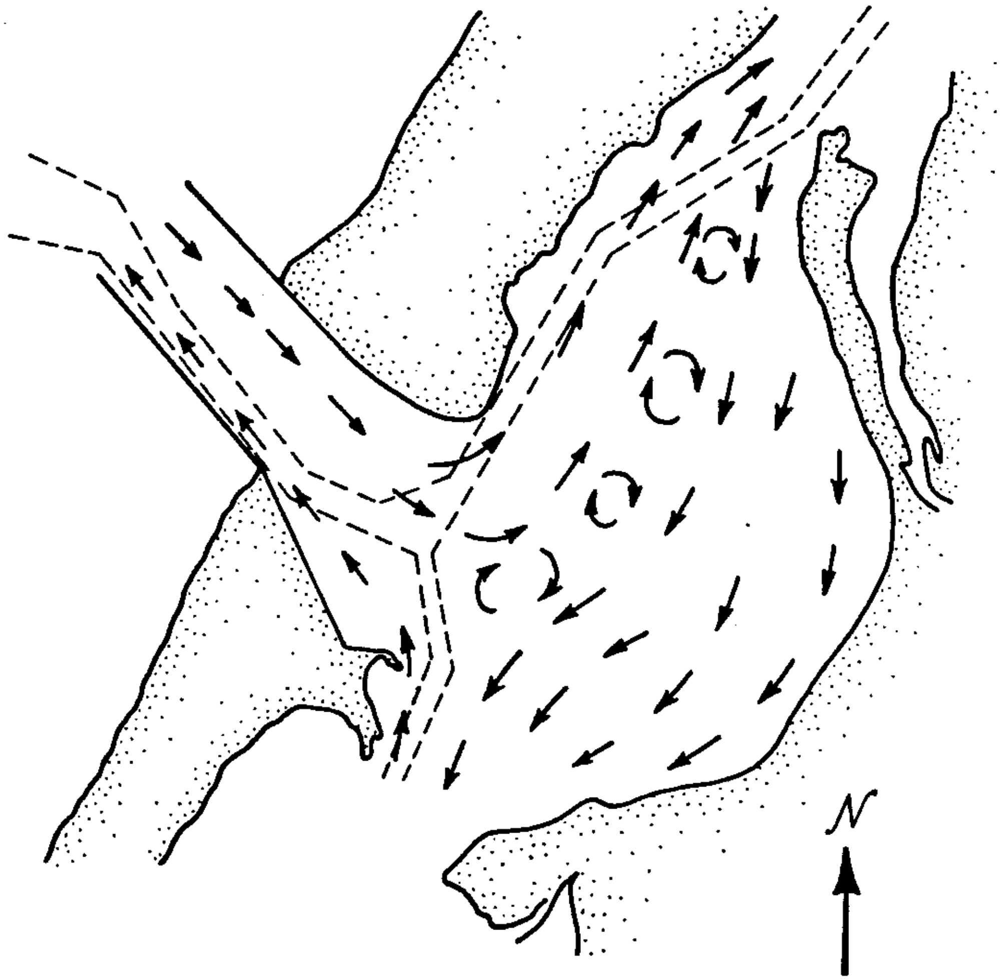
In the past it has always been assumed that the net (average) annual longshore transport of sand was from north to south at about 380 thousand cubic meters per year (500 thousand cubic yards per year). The estimates of the amount of sand delivered to the northern beaches do not support this assumption. The evidence, in fact, shows that the Eel River to the south is the main supply of sand to the Humboldt beaches. (Since most of this material is delivered during times of very high river discharge, this raises some important questions about damming and diversion of Eel River water that have not been adequately addressed.) It appears that the transport of sand in the winter is from south to north, driven by the high locally generated seas that exist at this time(Figure 12). A return flow to the south prevails in the summer but at a smaller rate of transport and in a narrower surf zone. The cyclic migrations of the mouth of the Mad River and a similar type of behavior shown for the mouth of the bay before jetty construction support this idea.

During the winter months, with a wide surf zone dominated by steep waves, a portion of the material is trapped in the entrance and bar channels to the bay. During the milder summer conditions the majority of the material bypasses the bay entrance by means of movement over the outer bar. The extensive dune fields of North Spit appear to be an important sink of beach sand. The relative sizes of North and South spit appear to be a consequence of the seasonal nature of the driving forces (waves) rather than directly indicative of the direction of sediment transport. The tentative conclusion from examination of all of the data is that the net transport is from south to north and at a rate equal to or greater than that previously assumed for this region.



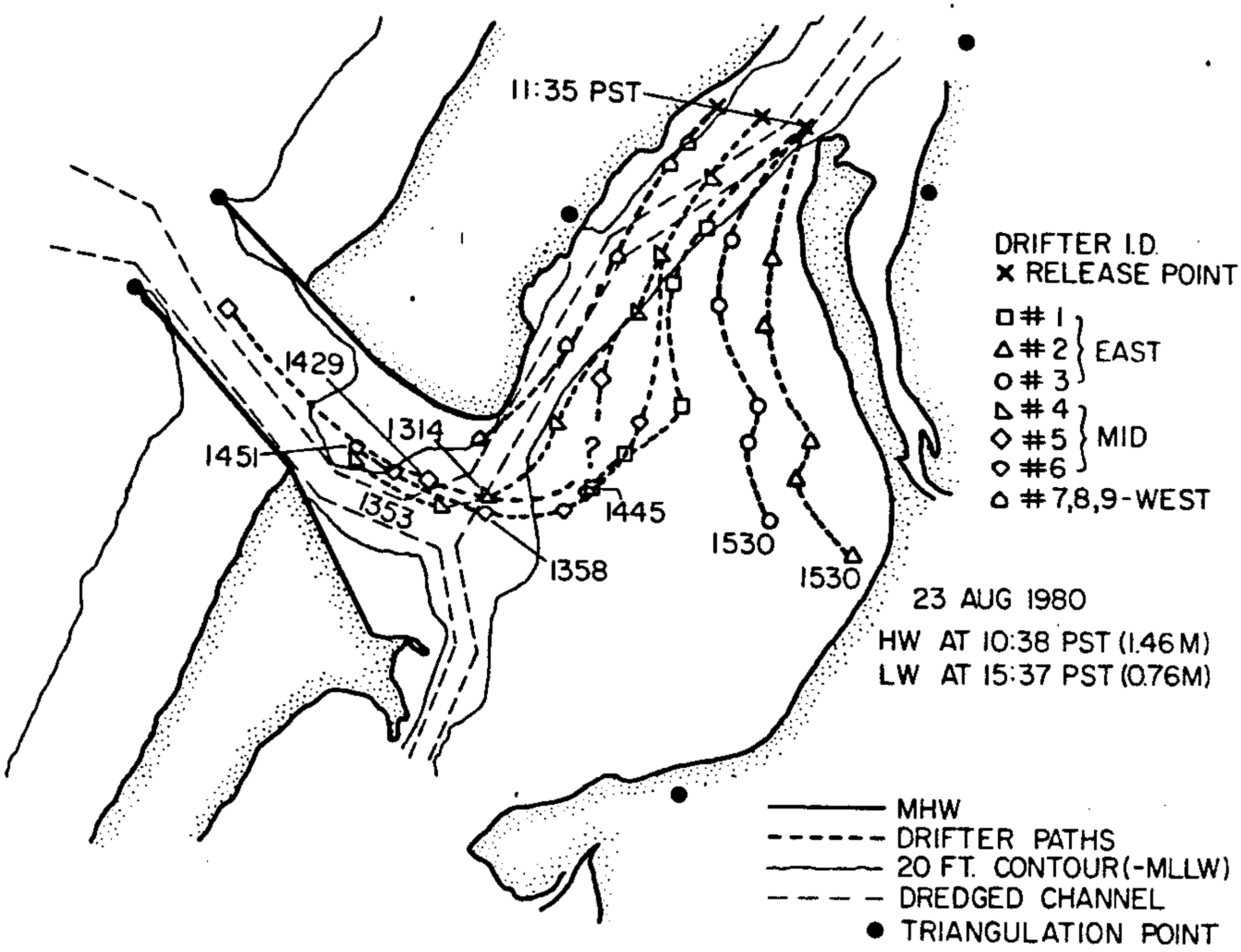
EBB AND FLOOD TIDAL CURRENT PATTERNS IN HUMBOLDT BAY, CA (AFTER GAST AND SKEESICK, 1964).

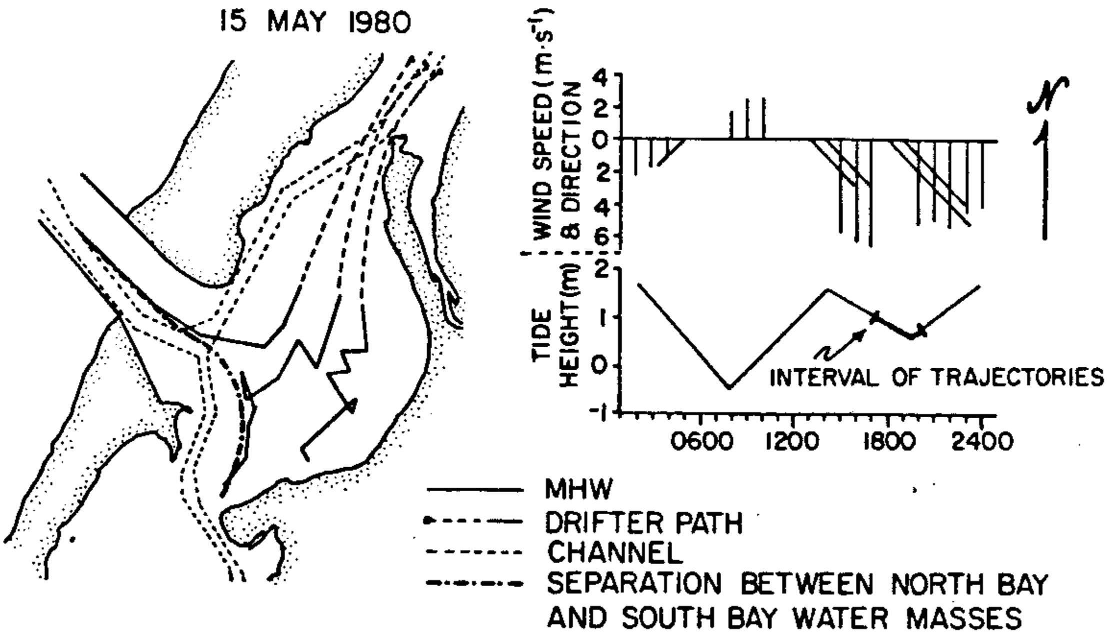
FIGURE 9



HYPOTHETICAL NET CIRCULATION IN ENTRANCE BAY
(AFTER EBBESMEYER ET AL, 1980)

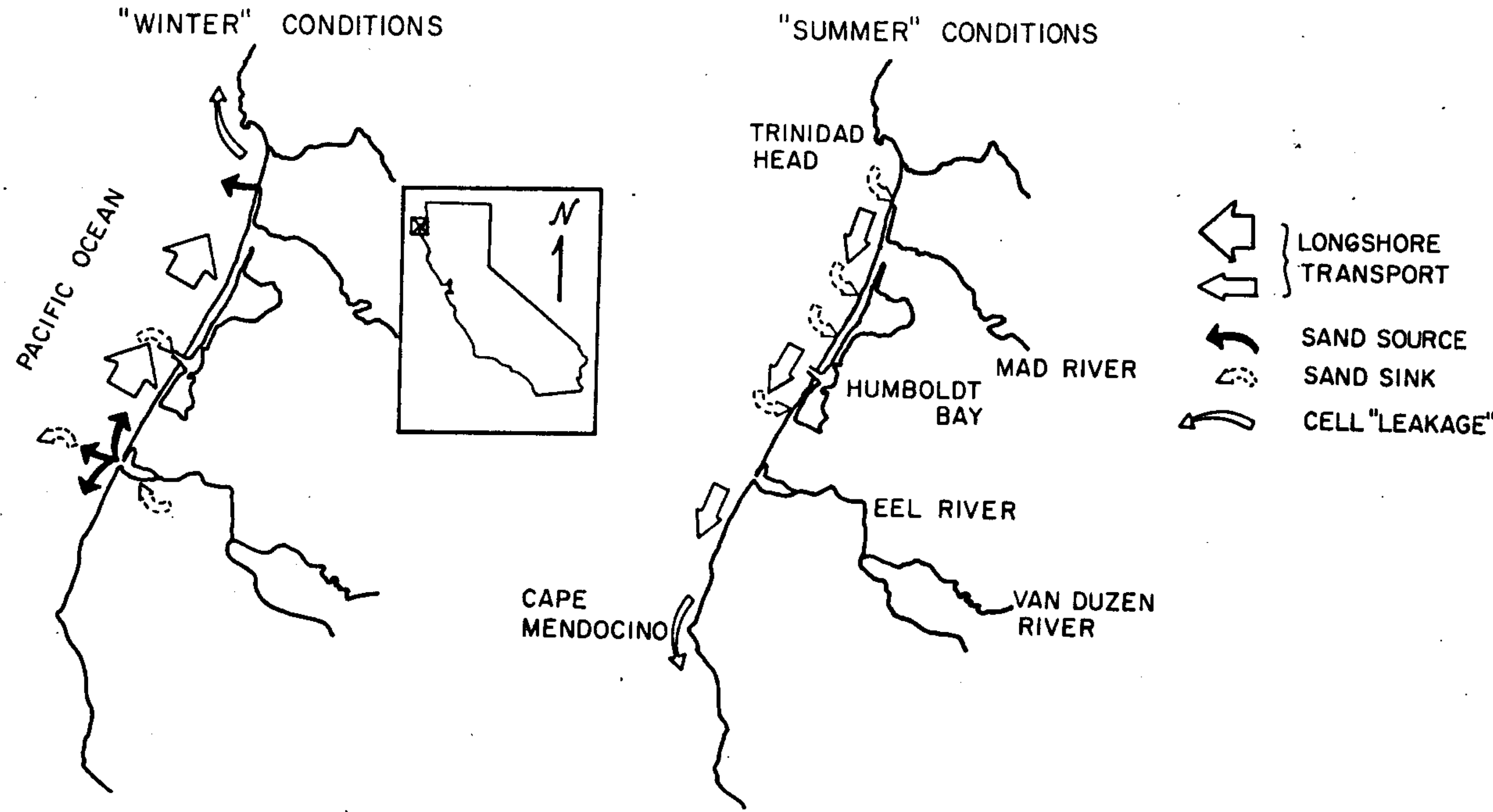
FIGURE 10





EBB CURRENT DRIFTER TRAJECTORIES
IN ENTRANCE BAY, HUMBOLDT BAY, CA
(23 AUG FROM DIEBEL & COSTA, 15 MAY FROM EBBESMEYER, ET AL)

FIGURE 11



HYPOTHETICAL OPERATION OF THE HUMBOLDT LITTORAL CELL

FIGURE 12

-Wave Patterns in Entrance Bay-

The incident ocean waves impinging on the coast at the entrance to the bay, of course, provide energy to the interior of the bay. This is naturally limited to the Entrance Bay region. Figure 13 is a diagram, gleaned from aerial photographs, of the wave patterns introduced. Note that the Entrance Channel acts as something of a filter to the ocean waves arriving at the coast. The depth of the channel and over the bar prohibits waves of more than a certain height from entering the bay. In a similar manner this also limits the periods of the waves that are to be found in Entrance Bay. For a rather wide range of incident ocean waves one finds a much more compact range of waves.

There is obviously a great deal of information on a diagram such as Figure 13. A few of the more important points are described here. Note that the region near Point Humboldt is a dividing line between waves tending to transport material either south toward King Salmon or north toward Elk River. Most of the wave energy entering the bay is seen to act to transport material to the north, and has provided the mechanism for building Elk River Spit. However, a significant amount of energy is still available for transport to the south. This has been dramatically demonstrated by the recent erosional events along the King Salmon shore line. Another point of interest is the reflected component of wave energy from the eastern shoreline toward back across the bay to North Spit. This has contributed to some serious shoreline erosion at this location which, at first glance, would appear to be well sheltered from wave attack.

There is another, until recently unrecognized, wave driven phenomena in Entrance Bay of considerable theoretical and practical interest. There exists a mechanism by which energy provided by incident ocean waves with periods in the range of 6 to 20 seconds drives a much longer period oscillation within this basin with periods of from 1 to 6 minutes. This is a sloshing or seiching of the water in the basin with amplitudes on the order of a foot. Such action has been recorded and documented by a group of graduate students from HSU. Figure 14 shows records of this occurrence. The figure shows the frequency at which ocean wave energy as recorded offshore is approaching the coast and the frequency bands in which the wave energy within the bay was recorded. Both the filtering action on wave period and the presence of the longer period seiche is easily seen from information presented in the figure.

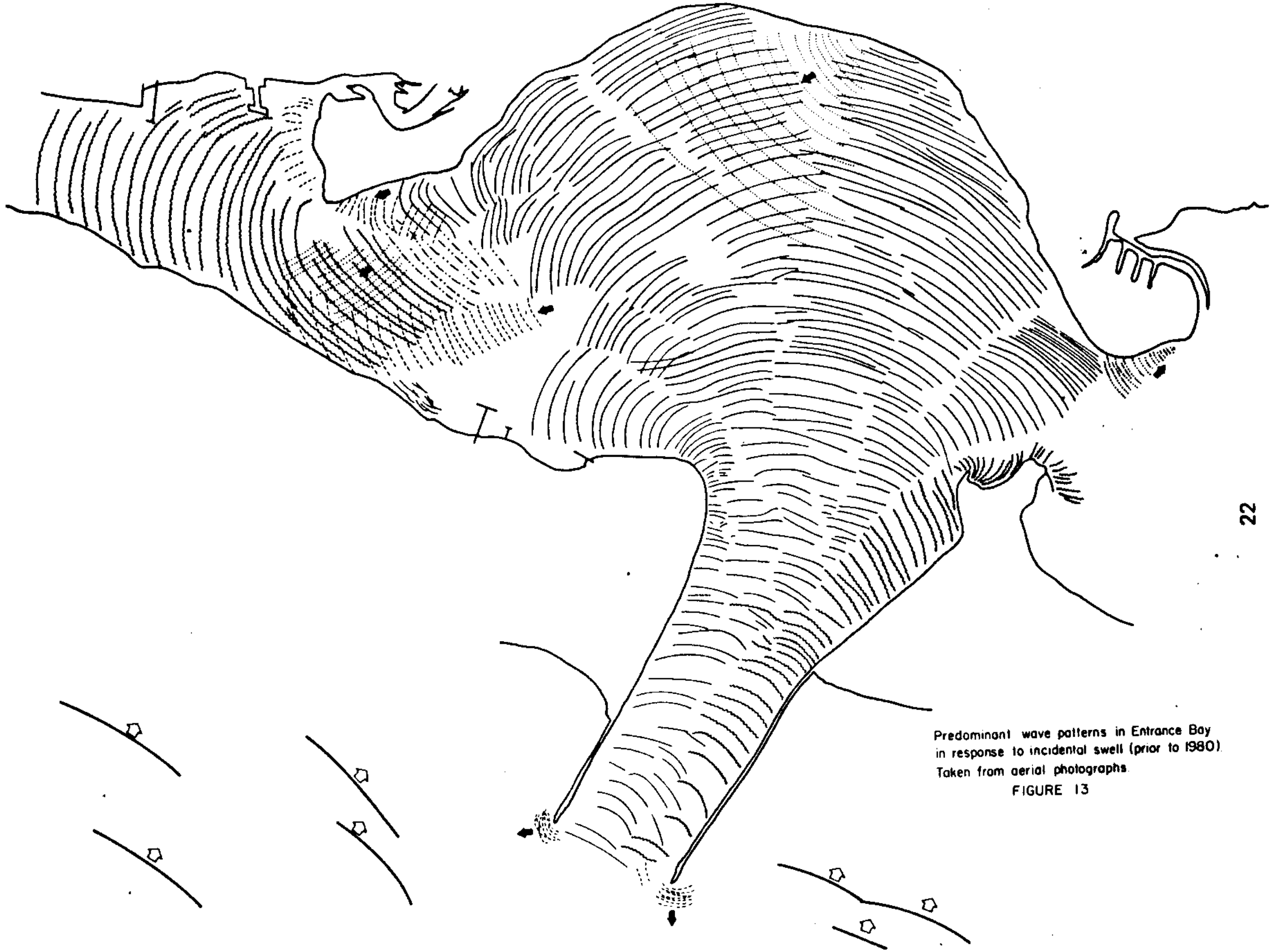
-Seasonal Transients-

Localized effects of event oriented fresh water input into the bay can be of importance as mentioned earlier. Under the author's direction, students at HSU have investigated one such area. A number of stations were occupied in Mad River Slough during the rainy season (Figure 15). One set of data were collected after approximately two weeks of no rain. Another set of data were collected just after a period of heavy rain fall. It was found that following an infusion of fresh water this arm of the bay sequentially displays the entire range of classical estuarine types. Initially it behaves as a highly stratified salt wedge type, becomes partially mixed, then vertically homogeneous, and without further input of water takes on the coastal lagoon nature of the bay as a whole.

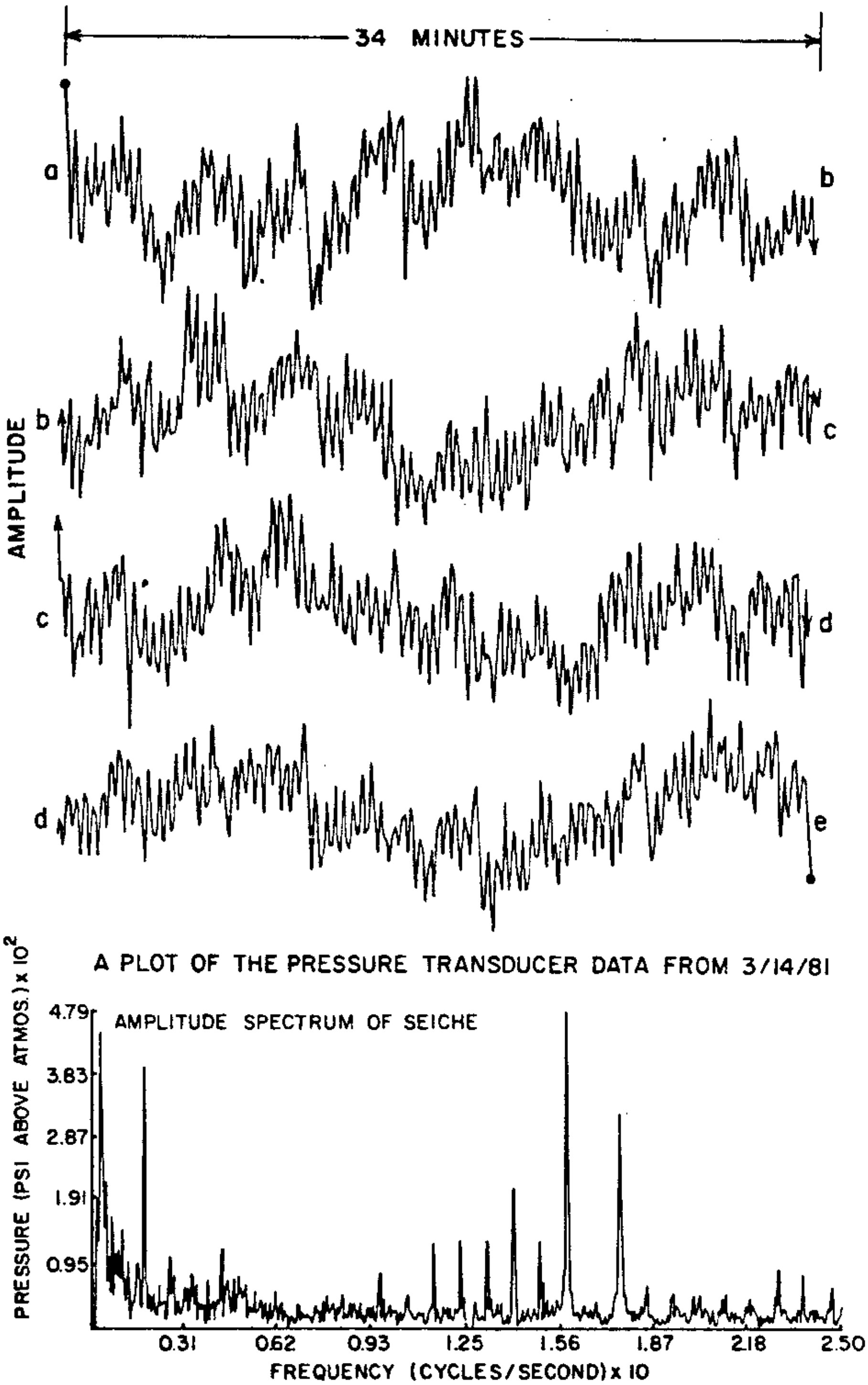
This description is oversimplified, especially as the timing and intensity of rainfall modifies this progression. But it does indicate that the material washed from the adjoining pasture land is not released into the main body of the bay immediately. The transient nature of the slough allows the dissolved and suspended matter to be released into the bay over an extended period of time. This is demonstrated by the salinity history of the bay over an annual cycle as recorded by other investigators at Humboldt State University's Oceanography Department. Figure 16 illustrates such a cycle.

Flushing times in the bay as a whole have been variously estimated from 7 to 40 tidal cycles. Part of the reason for the wide range in estimates is due to the complex nature of the bay and the interests of the various investigators. Displacement calculations have demonstrated that it is possible for a water parcel to travel from the bay entrance to the extreme northern part of Arcata Bay during a tidal half cycle of sufficient range. Thus it is possible for marine water to travel to any part of the bay on a single tidal cycle, with the converse also being true. Obviously, the dispersion and mixing processes are being ignored here for simplicity. There is some evidence that the bay is compartmentalized into distinct water masses that mix relatively slowly. Any estimate of flushing times must be viewed with extreme caution.

One of the most difficult points to address when estimating flushing times are the seasonal transients of the type discussed above. The author estimates the complete flushing time of Mad River Slough to be about 85 tidal cycles when the stratification cycle mentioned above is considered. Arcata Bay may have a flushing time much less than this alone, but the long term infusion of material from the adjacent sloughs during the rainy season would make any such calculation about the basin as a whole rather meaningless. That is the small sloughs would continue to feed dissolved material introduced by runoff into Arcata Bay on every tidal cycle long after the basin would have eliminated such material if it had been directly input all at one time.



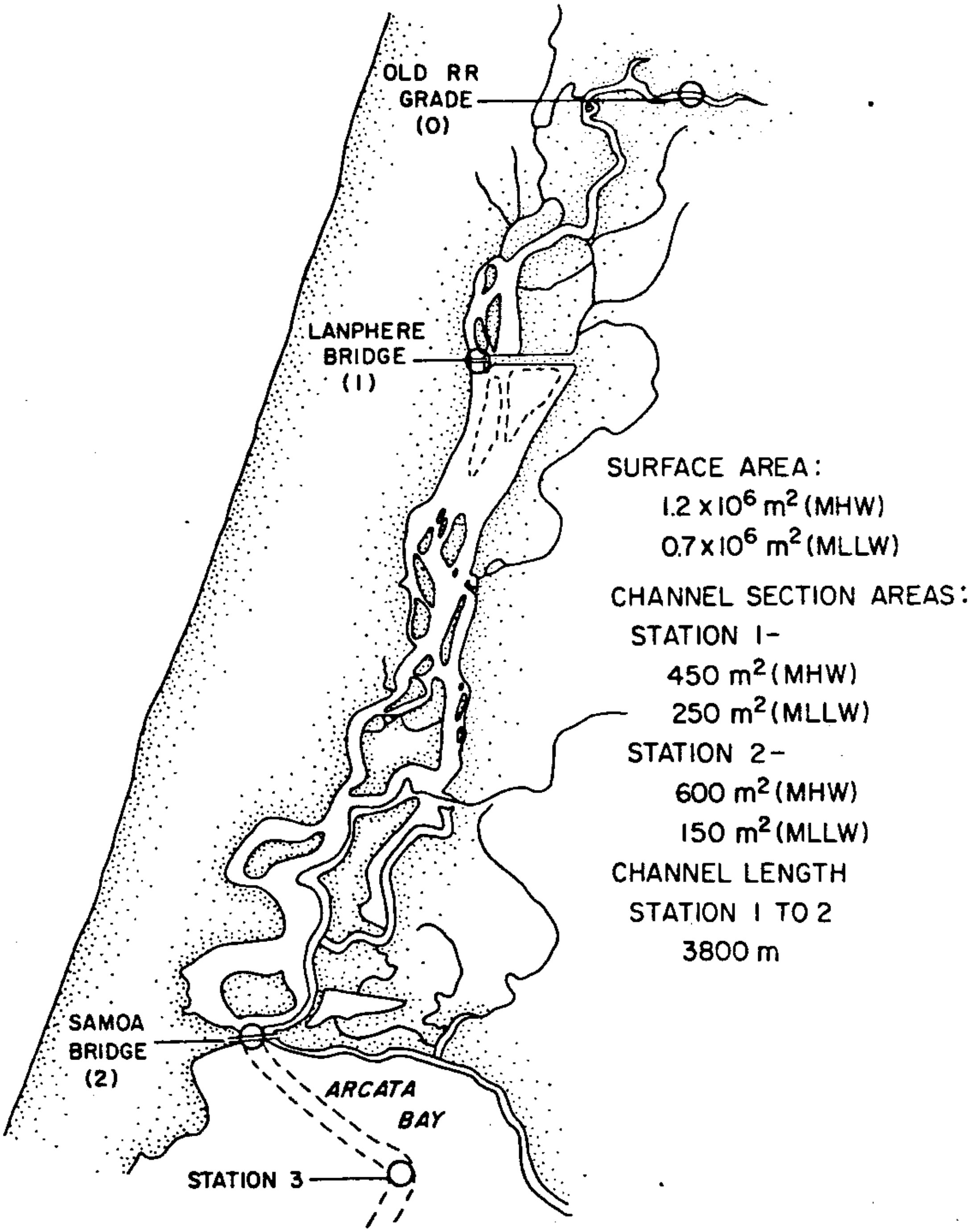
Predominant wave patterns in Entrance Bay
in response to incidental swell (prior to 1980).
Taken from aerial photographs.
FIGURE 13



FAST FOURIER TRANSFORM OF SEICHE DATA FROM 3/14/81

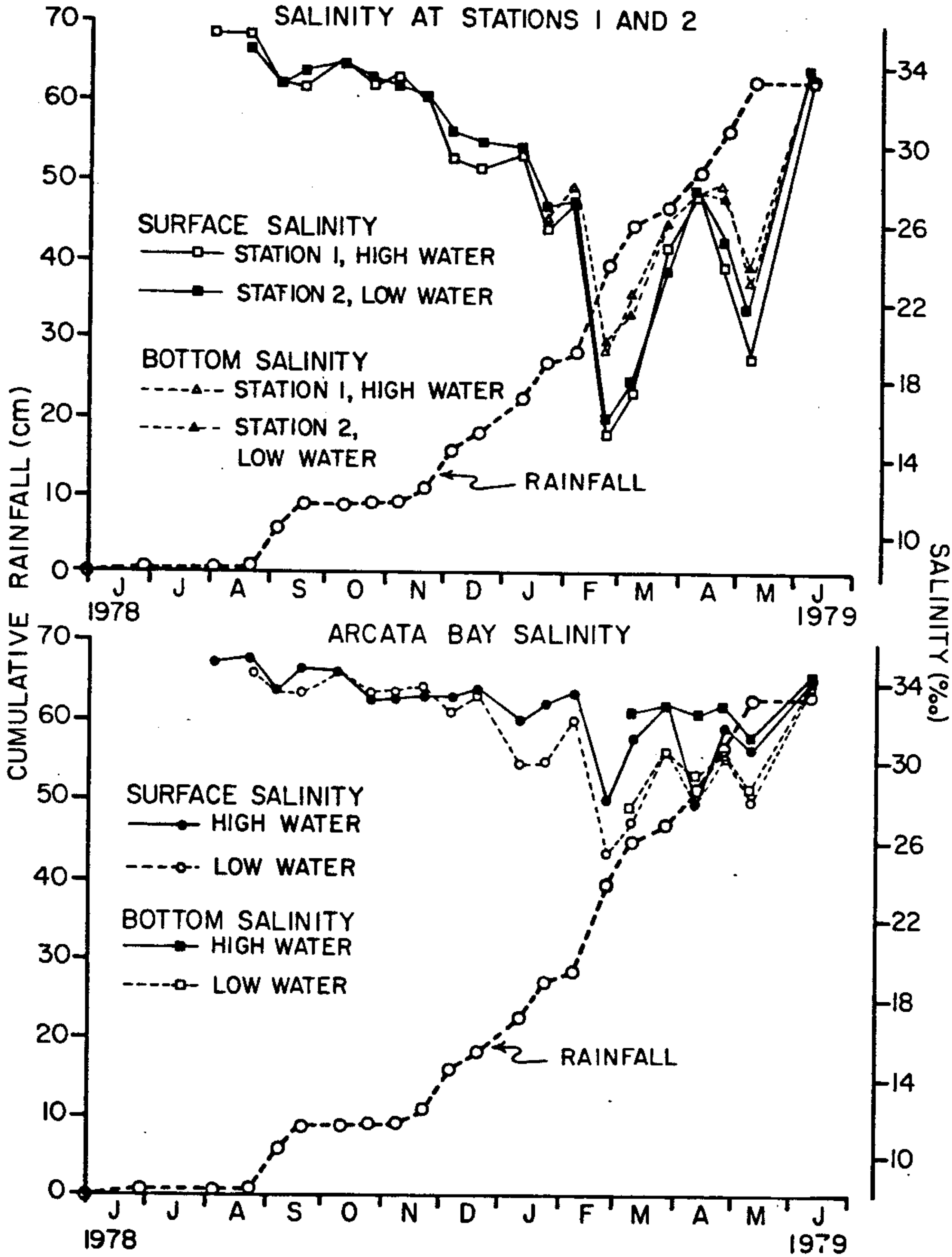
Record showing seiche in Entrance Bay (after Hathaway and Landsteiner, 1982).

FIGURE 14



STATION LOCATIONS IN MAD RIVER SLOUGH (AFTER COSTA, 1981).

FIGURE 15



SEASONAL SALINITY IN MAD RIVER SLOUGH AND ARCATA BAY IN RESPONSE TO RAINFALL (DATA FROM MELVIN AND PEQUEGNAT)

FIGURE 16

-Response to Wind-

The response of the bay to wind is as yet essentially unstudied. It is possible to predict the characteristics of wind wave generation within the bay using standard engineering practices. This requires only the wind direction, intensity, and duration. The effects of wind on circulation and sediment redistribution are as yet undocumented. The author believes that this is the next logical step to be addressed in the overall study of the oceanography of the bay.

The recent prototype data collection program by the Army Corps of Engineers has provided the data to begin such a study. Synoptic current, tide, and wind data at locations throughout the bay were collected by investigators at Humboldt State University. Once these data are reduced and processed it will be possible to significantly extend our knowledge of the bay in a number of areas. The aspects of wind driven circulation superimposed on tidally driven flows are of particular interest. The stations at which data on current speed and direction, temperature, salinity, wind speed and direction, and tidal elevation will soon be available are shown in Table IV.

Effects of Navigation Improvements

The Entrence Bay portion of Humboldt Bay has been in a state of rapid evolution for many decades. Since the initial navigation improvements at the entrance to the bay in the late 1800's the changes observed in Entrance Bay have been dramatic. There is little doubt that the orientation of the jetties and the subsequent deepening of the navigation channel have been responsible for both the rate and direction of the evolution of Entrance Bay. There is no apparent reason to suspect that the recent erosion in the Buhne Point area is not closely linked to the overall changes in Entrance Bay in the past.

The premise that the navigational improvements to the Entrance Channel are the causitive factors in the processes within this portion of the bay is based on a simple observation. Examination of available charts of the location shows that prior to any improvements to the bay the entrance channel appears to have been fixed in its general location but its orientation was extremely variable. An example is shown in Figure 17. The interior of the bay was well protected from incident waves by extensive breaker flats on the seaward side of the entrance. There was no mechanism for focusing waves through the channel and into Entrance Bay. The wave energy that did enter the bay was greatly reduced by the presence of these breaker flats.

Construction of the jetties fixed the orientatation of the Entrance Channel. Furthermore, since the channel was made narrower than its natural state, the currents tended to scour it to a much greater depth. This is graphically displayed in Figure 18. These changes had the effect of focusing wave energy and allowing more energy into the bay. The extensive breaker flats disappeared and in their place the infamous outer bar was formed. Although this bar does absorb some incident wave energy its main effect is to actually focus incident wave energy, particularly the northwest swell, at the seaward end of the jetties. This has the effect of increasing the amount of energy entering the bay.

The complexities and interactions inherent in the effects of the navigation improvements on the features of Entrance Bay are readily seen by consideration of selected examples. The development of Elk River Spit did not become apparent until the early 1930's. Throughout the next ten to fifteen years the spit grew rapidly. Since there was no obvious growth of this spit until 40-50 years after the initial navigation improvements, this could be taken to indicate that the two events are unrelated. However, closer examination of historical charts shows that there existed an eastward channel, up to 30 feet deep in some places, that had to be completely filled before material was available to build the spit. Figure 18 illustrates the evolution and filling of this channel by following changes in the 18 foot depth contour.

Figure 19 illustrates the extent of the changes in the bathymetry of the southern part of Entrance Bay. This figure shows a number of historic profiles at the locations shown. The erosion of the shoreline in the Buhne Point region has been an ongoing process for many years until halted by the construction of rock revetments along most of the eastern shore of Entrance Bay. The recent erosion at King Salmon is simply an extension of the patterns shown here.

Afterword

The preceding discussions have attempted to give an overview of the physical oceanogrphy of Humboldt Bay. What is known about the bay, rather than what is yet to be investigated, was stressed. The presentation was brief by necessity, and incomplete in many details. The author aknowledges his bias toward the particular aspects of the bay of personal interest.

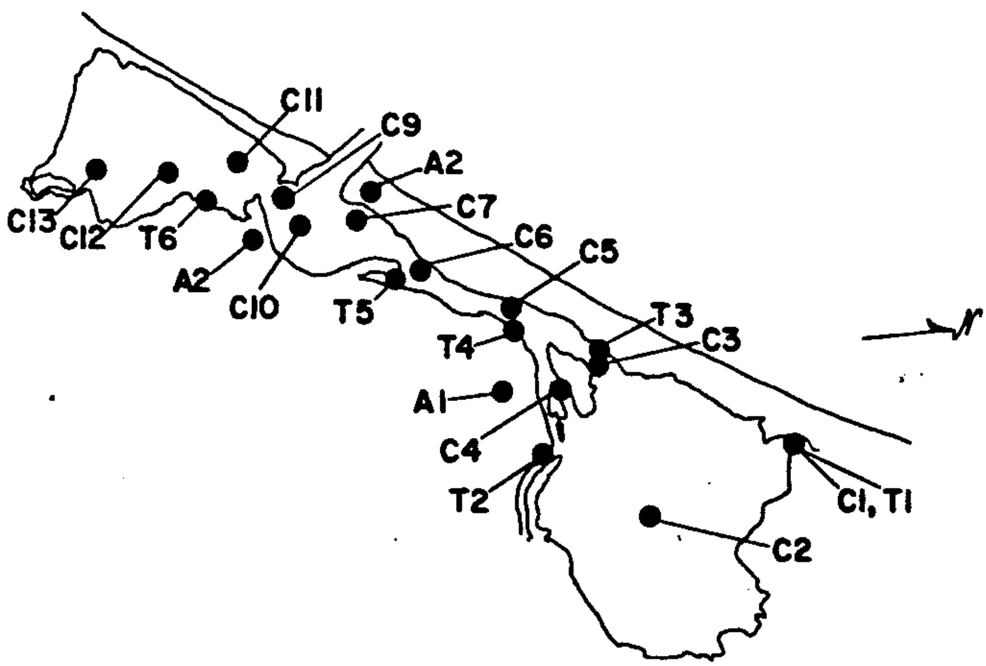
It is customary to present a list of references used. In this case the list would be more extensive than the presentation. The author acknowledges all those investigators who have contributed to the body of knowledge about the bay, but defers a formal list of references. The reader can consult the previously published bibliographies and literature surveys on the bay and adjacent regions for more information. Ap-

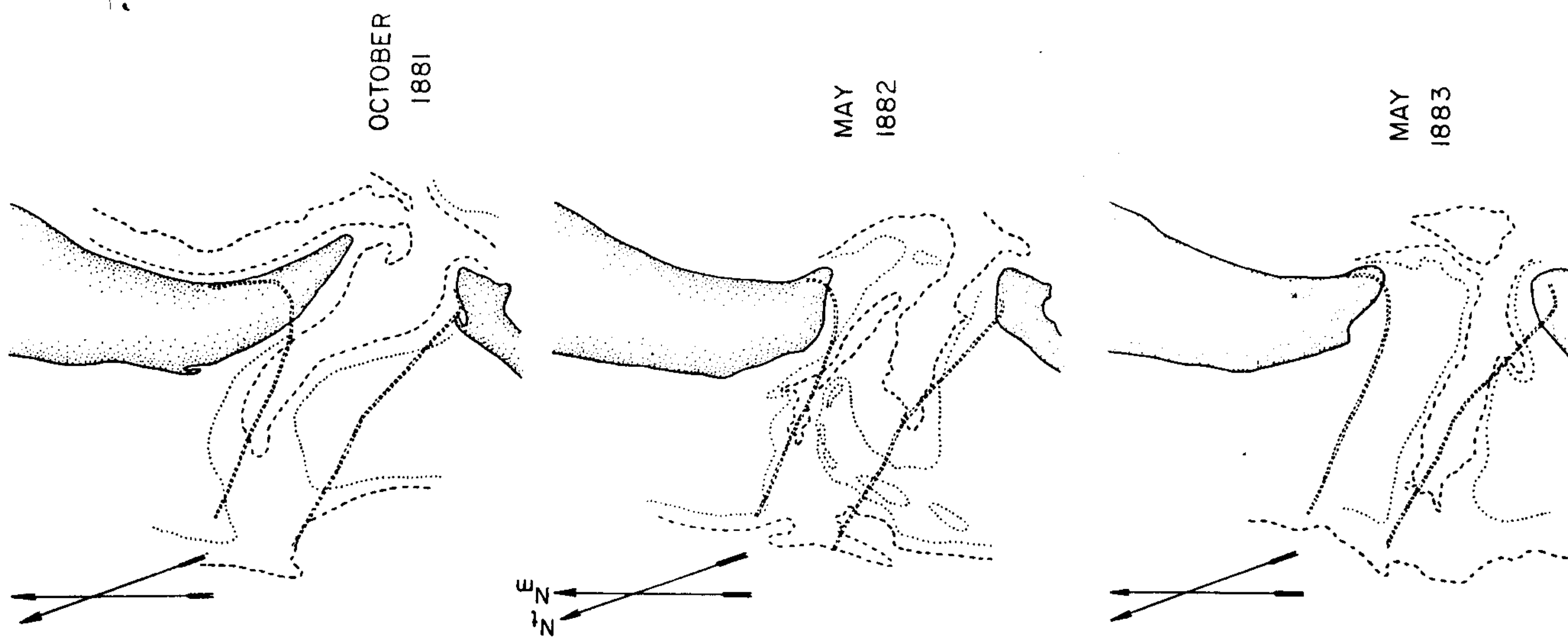
TABLE IV. PROTOTYPE DATA COLLECTION STATIONS

Station	Station Description	Station Type	Longitude	Latitude
	Multi-Meters			
C1	Mad River Slough	S	124 08'56"	40 51'55"
C2	Mid Arcata Bay	B	124 08'04"	40 49'55"
C3	Samoa Channel	S	124 10'41"	40 48'52"
C4	Woodley-Gunther Channel	B	124 09'39"	40 48'48"
C5	North Channel - Eureka	B	124 11'21"	40 47'48"
C6	North Channel - Bucksport	B	124 12' 0"	40 46'28"
C7	North Spit (Coast Guard)	S	124 13'18"	40 45'29"
C8	Entrance Channel	*	124 13'50"	40 45'18"
C9	South Spit	S	124 13'24"	40 44'56"
C10	Entrance Bay	B	124 12'54"	40 45'01"
C11	Southport Channel	B	124 13'43"	40 44'14"
C12	Fields Landing	S	124 13'28"	40 43'20"
C13	Hookton Channel	B	124 13'30"	40 42'21"
	Tide Gages			
T1	Mad River Slough		124 08'56"	40 51'55"
T2	Eureka Slough		124 08'31"	40 48'25"
T3	Samoa Channel (LP dock)		124 10'45"	40 49'04"
T4	North Channel - Eureka		124 11'11"	40 47'44"
T5	Elk River Slough		124 11'44"	40 46'21"
T6	Fields Landing		124 13'21"	40 43'25"
	Anemometers			
A1	Weather Service		124 09'46"	40 48'10"
A2	Coast Guard Station		124 13'00"	40 46'01"
A3	PG&E		124 12'39"	40 44'30"

Multi-Meters: salinity, temperature, turbidity, current speed and direction

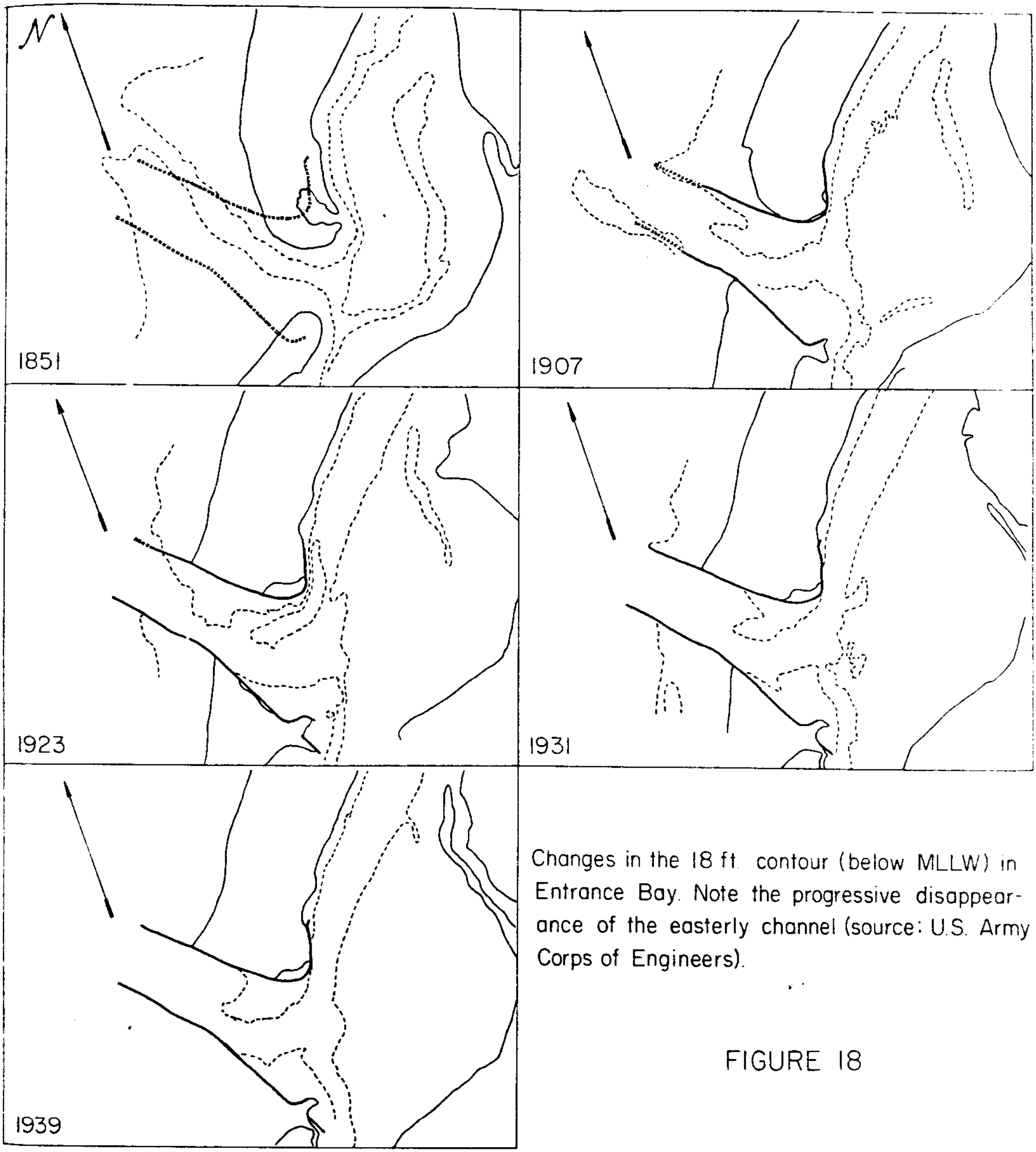
* = station not occupied, B = buoy station, S = standoff station (nav aid)





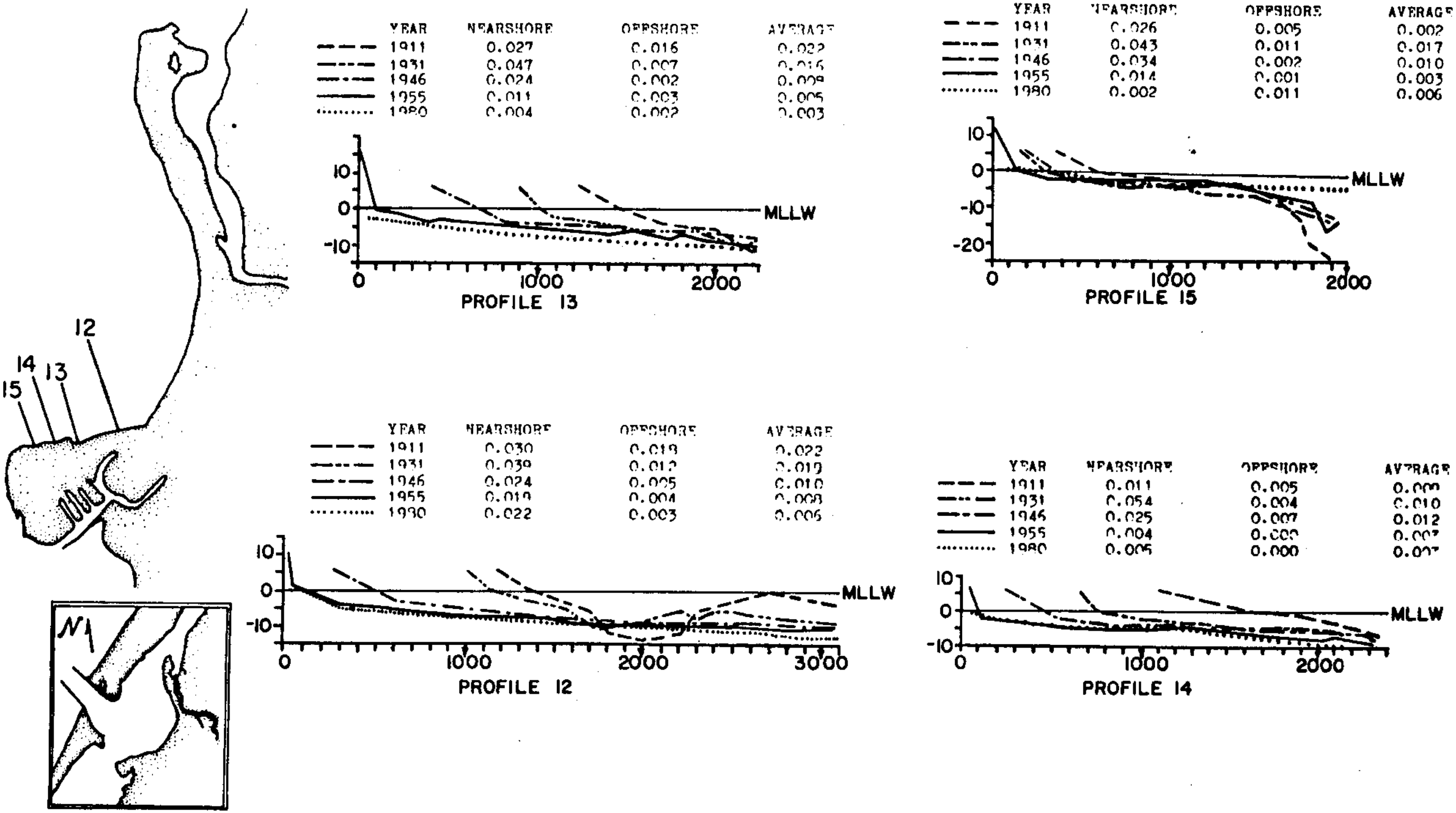
Examples of the entrance and "breaker flats" before jetty construction
(source: U.S. Army Corps of Engineers) .... MLLW: _____ -18(MLLW)
============= position of jetties as they appear presently

FIGURE 17



Changes in the 18 ft. contour (below MLLW) in Entrance Bay. Note the progressive disappearance of the easterly channel (source: U.S. Army Corps of Engineers).

FIGURE 18



Historic profiles from Entrance Bay showing change in profile slopes (after 1956 Beach Erosion Control Report, Corps of Engineers, San Francisco Dist.)

FIGURE 19

propriate credits are given for each of the figures and tables presented in the text.

Acknowledgements

Many people and agencies are responsible for contributions to the increasing knowledge of Humboldt Bay. An exhaustive list would violate the space limitations of these proceedings. The risk of unintentional omissions is also forbidding. However, of particular note is the San Francisco District, Corps. of Engineers current data collection program, and the past support by NOAA, National Sea Grant College Program, Dept. of Commerce, under Grant 04 8 M01 189 and the State Resources Agency, Project RCZ-47 through the California Sea Grant College.

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