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AN INVESTIGATION OF POSSIBLE CAUSES OF THE SO-CALLED "SNEAKER WAVE" AT TOMALES BAY, CALIFORNIA

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INTRODUCTION

Tomales Bay opens into the Pacific Ocean at the southern end of Bodega Bay, approximately 35 miles north of the Golden Gate (see Figure 1). The bay is long and narrow, extending approximately 12 miles along the line of the San Andreas Fault but never much over a mile in width. The bay is bordered on one side by the Point Reyes National Seashore, now a portion of the Golden Gate National Recreation Area. Because of its proximity to the San Francisco metropolitan area, the Bay is a major recreational resource and a popular boating and fishing site.

In spite of its popularity, however, the mouth of Tomales Bay can be treacherous. Reports of dangerous conditions originate with the earliest European explorers. Juan Francisco de la Bodega y Quadra, one of the first European navigators to enter the bay, anchored for the night of October 4, 1775, somewhere near Sand Point. According to the journal of his pilot, Francisco Antonio Maurelle (see Edwards, 1964), ". . . at two in the morning the other tide began to flow, and on encountering the sea in a very strong current it began to kick up in such a remarkable manner that at four in the morning the seas broke against each other so violently that some that pounded us covered us from stem to stern. One of them set adrift our canoe, which we had tied alongside, and made splinters of it.

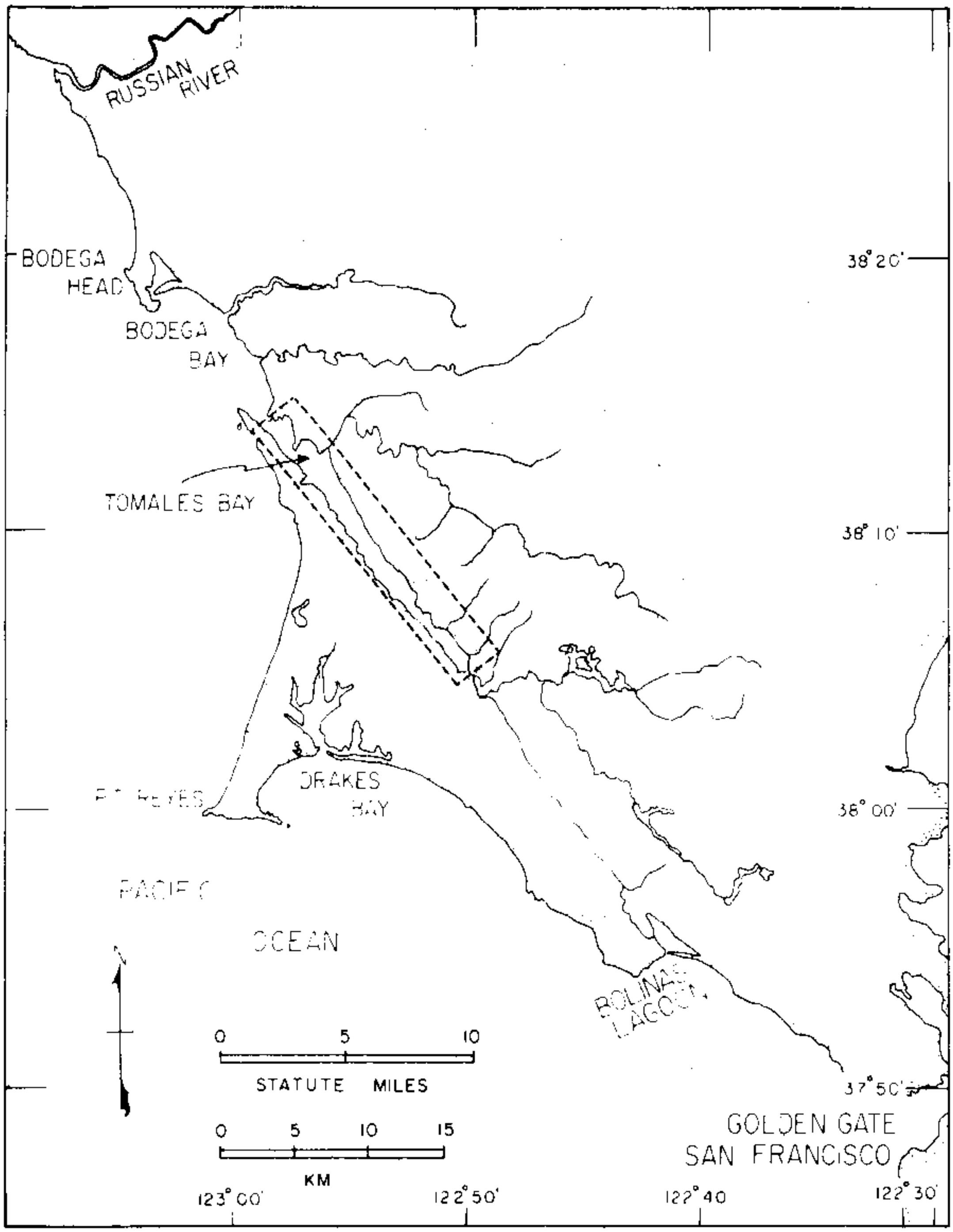

Figure 1 Location of Tomales Bay, Central California
(Map from Daetwyler, 1966)

"Since the mouth is not sufficiently wide to accommodate the waters, the flood and ebb tides enter and leave through it with considerable force, so that they meet with the waves outside when there is a bit of weather along the coast to agitate them, and the waves break in front of the entrance. . ."

In the years since 1775 the peculiar conditions at the mouth of Tomales Bay have been responsible for the deaths of a substantial number of boaters. Figure 2 shows the locations of 7 fatal accidents which occurred in the period 1963-1972. Often boaters who have survived the accidents describe their experience as having been struck by a large, unexpected breaking wave, which seems to have formed from a previously calm sea. Thus the phenomenon has come to be known as the "sneaker wave," a name connoting a degree of mysticism. At several points around the bay the California Department of Navigation and Ocean Development has posted a sign reading as follows:

"ATTENTION BOATMEN--

Don't be misled by calm water near the entrance to Tomales Bay. Dangerous "Sneaker Waves" can develop rapidly, particularly at times of falling tide, ebb-current and adverse wind."

Explanations for the cause of the "sneaker wave" cover a wide range. The writers have been told, for instance, that "when the sun and the moon are on the same side their attraction is stronger and

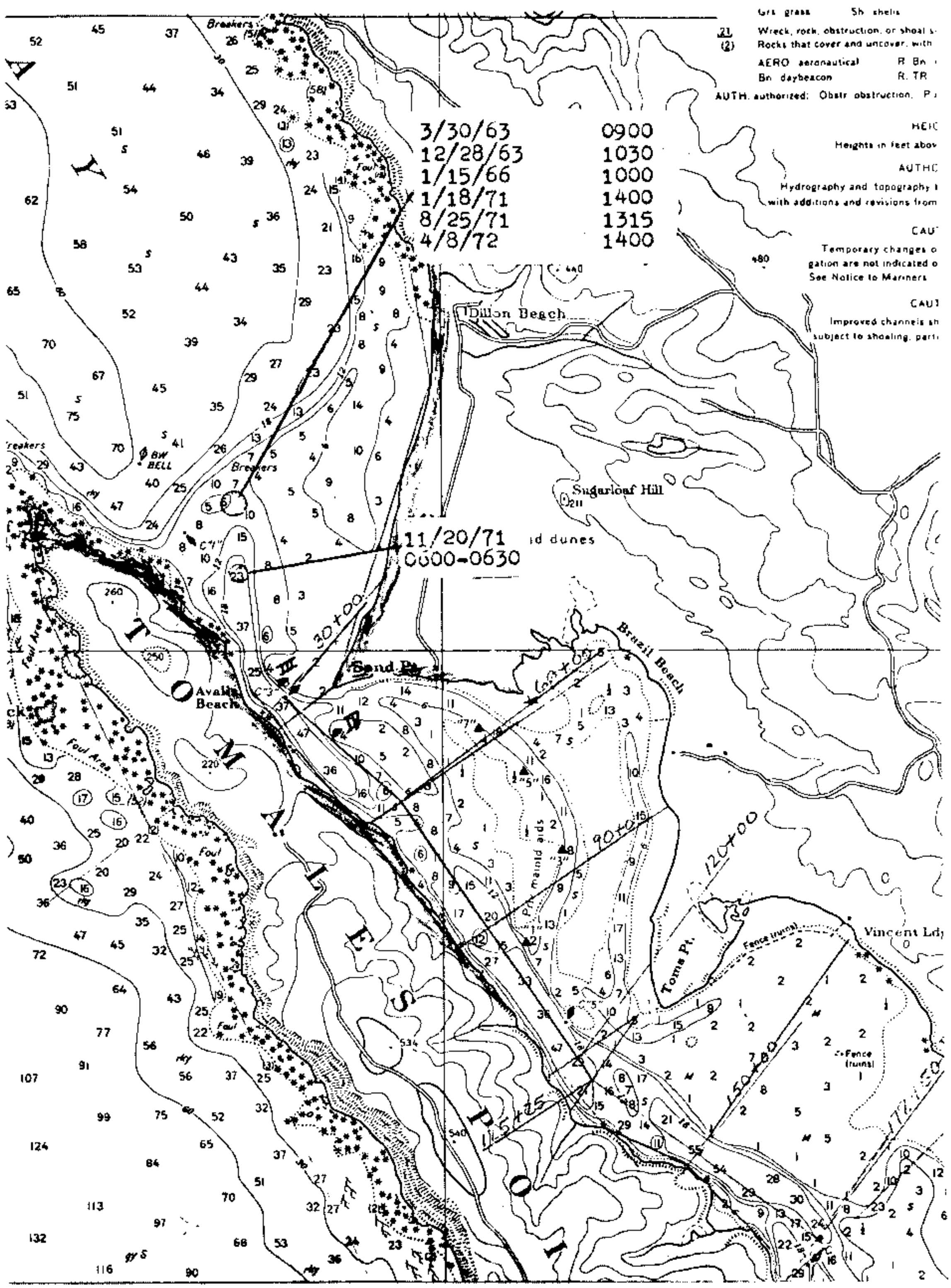

Figure 2 Locations of 7 fatal accidents at the mouth of Tomales Bay

they cause parts of the water to leap upward." Similar unscientific explanations are not uncommon; many boaters who are not well familiar with the bay seem to have seen the signs, heard the stories, and come away with visions of an unpredictable and terrifying phenomenon which lies in wait at the mouth of the bay.

Local residents, on the other hand, have much more prosaic explanations for the many accidents. The best fishing in the area is usually over the bar which lies off Sand Point, so this is where the fishermen prefer to fish. According to one local resident when asked about the sneaker wave, "There's no such thing. When the tide is running out the water depth at the bar drops. The waves that have been rolling in all along start to steepen; eventually a large one comes in and breaks. If the fishermen are still out there sitting over the bar, chances are good that they'll get dumped."

In January 1973, the University of California was asked to undertake a laboratory study of the "sneaker wave" phenomenon, to determine whether the occurrence of the wave could be related sufficiently well to tidal and oceanic conditions so that a warning system could be devised. Studies in the laboratory were inconclusive, and the project was subsequently extended to include observations of tidal currents, depths of flow, and wave conditions in the field. This report gives the results of the studies; first we review briefly the work carried out in the laboratory, then we give the results of the field observations, and finally we give an analysis of what we believe to be the "sneaker wave" phenomenon and make recommendations concerning revision of the material distributed by the Department of Navigation and Ocean Development.

POSSIBLE CAUSES OF THE WAVE

Although a large number of accidents have occurred at the mouth of Tomales Bay, many are not reported and the number that are are insufficient to permit statistically valid correlations with time of day, phase or height of tide, swell, wind, or other factors. Thus the only feasible approach is to hypothesize causes that fit some of the known descriptions and to test as many of those hypotheses as possible. The empirical description is of a wave that appears unexpectedly, sometimes in reasonably calm weather. The wave is reported to be as much as 12 feet high, and usually to be followed by others. A train of three waves is often mentioned. Descriptions of this sort appear in accident reports filed with the State of California, but it must be remembered that they come from survivors who often had little boating experience.

It is possible that a wave similar to those described could be caused by any of the following:

1. Formation of a short-term tidal bore, caused by the ebb flow running against a rising tide in Bodega Bay;

2. Formation of antidunes on the channel bottom, resulting in "sand waves" which form on the water surface and break against the flow;

3. Arrival of freak ocean waves generated a long distance away, which might break upon arrival over the offshore bar;

4. Seiching in Bodega Bay, which would cause the water depth over the offshore bar to fluctuate and cause intermittent breaking of ocean swell; or

5. Steepening of the ocean swell over the offshore bar because of the opposing tidal flow during ebb.

This study was originally conceived as an investigation into the likelihood of formation of a tidal bore. When that seemed unlikely, the possibilities of seiching and of steepening because of tidal outflow were investigated. Neither the formation of anti-dunes nor the arrival of freak ocean waves could be studied in the laboratory, and no indication of either cause was observed during the field studies.

The following sections report our observations concerning the three causes which were studied.

LABORATORY EXPERIMENTS

Tidal Model Studies: - Aerial photographs occasionally show the presence of a line of white water stretching completely across the mouth of Tomales Bay and having the appearance of a tidal bore. Tidal bores normally form in estuaries where there is a large riverine outflow and a large range of tide; for instance, a bore frequently traveled up the Colorado River from the Sea of Cortez until the river discharge was reduced by the construction of Hoover Dam and various water diversion projects. It seemed possible that the outflow from Tomales Bay, running against the rise of tide in Bodega Bay, might be sufficient to cause a sudden short term formation of a bore. A distorted Froude-scale model was constructed in a small tidal basin in the hydraulics laboratory of the University of California. The model represented the tidal prism of Tomales Bay, the geometry of the mouth, and the tides in Bodega Bay. Typical and extreme tidal conditions were studied, but at no time was the formation of a tidal bore observed. It was concluded that the "sneaker wave" phenomenon cannot be explained as a short term or even an incipient tidal bore.

Current-induced Wave Steepening Studies: - It is well known that an adverse current causes an incoming wave to steepen and possibly to break. Carr (1950), for instance, shows by a simple linear theory that a uniform adverse current velocity of $C_o/4$, where C_o is the deep water wave velocity, will cause all incoming waves over a flat bottom to steepen and break. While the geometry at Tomales Bay is too complex to permit application of any simple theory, it is clear that the ebb current is sufficient to cause waves to steepen over the bar.

To get some idea of the effect of wave steepening, a model of the constricted section of the mouth of the bay was made in which the ebb current and the approaching waves could be simulated. An undistorted model at a scale ratio of 300:1 was constructed using the bathymetry obtained during the June 1974 field survey (see the following section, "Field Observations"). The extent of the model was approximately from station 4 to station 6 of the survey, as described in the next section. The model was constructed inside a recirculating flume so that any desired current could be maintained, and a paddle board wave generator was installed in one end of the flume. Four wave gages were installed: one in "deep water" near the paddle board, and one each at stations 6, 5 and 4 of the survey. Continuous gage readings were recorded on a four channel strip chart recorder. Recordings were made for prototype wave heights of 0, 6, 8, 10, and 12 feet, with each size wave subject to prototype currents of 0, 2, 4, 6, and 8 ft/sec. A typical set of results, for a prototype wave height of 8 ft., is shown in figure 3. The ebb current causes substantial wave steepening; for instance, an 8 ft/sec outflow causes approximately a four-fold steepening of the wave at station 6.

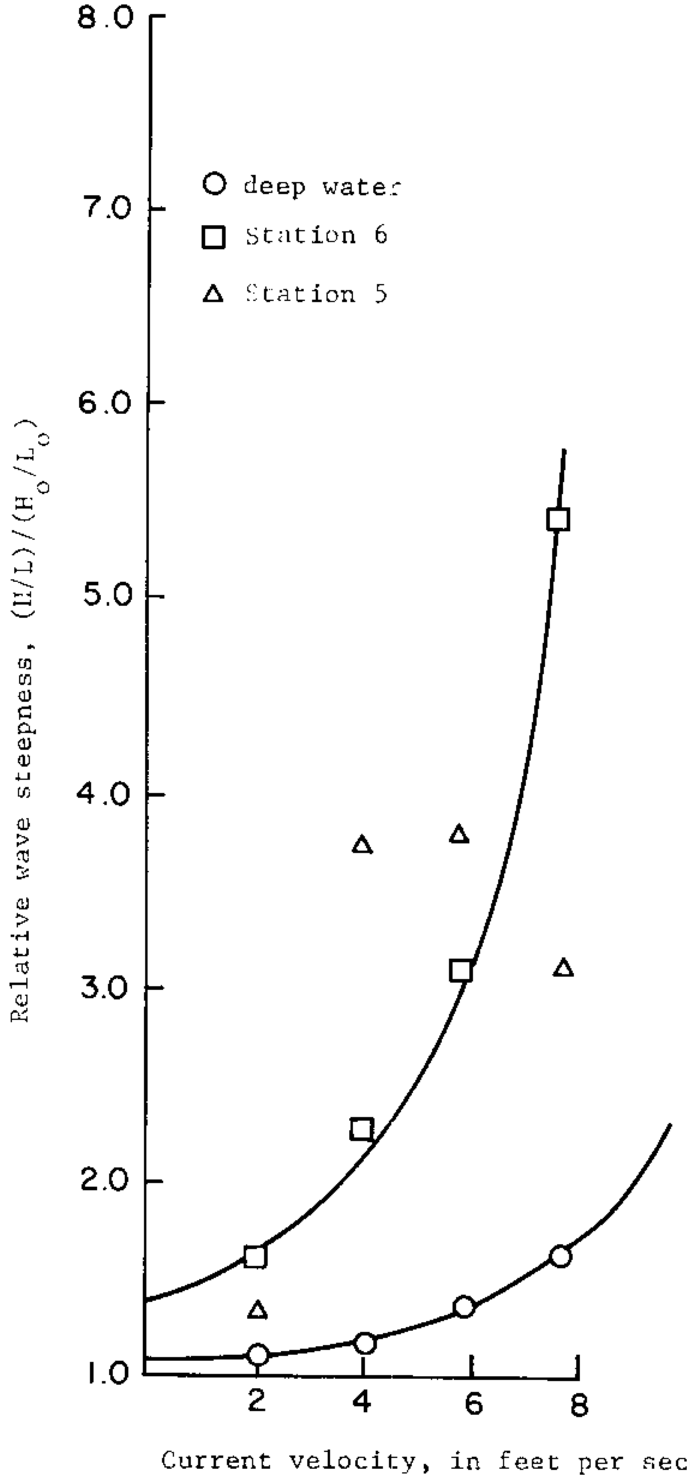

Figure 3 Increase of wave steepness as a function of outflow current velocity, for 8-foot waves

The results of this study cannot be applied directly to Tomales Bay because in the bay the concern is primarily with current-induced breaking of waves over the offshore bar. To reproduce the bar in the laboratory model would have required a much bigger laboratory basin than was available. Nevertheless, it is possible to extrapolate the results of the model to conclude that a 6 to 8 ft/sec ebb current, which is common at the mouth of Tomales Bay, will be a significant factor in causing waves to break over the bar.

FIELD OBSERVATIONS

Detailed observations of currents and bathymetry at the mouth of the bay were taken during the periods June 23-29 and September 15-19, 1974. In January, 1975, a tide gage was installed in Bodega Bay to study the possibility of seiching in the bay. In addition, a number of day-long visits were made to Tomales Point to observe and photograph wave and current patterns.

Bathymetry: - Prior to commencing the studies a traverse was run along the East shore of the Point Tomales peninsula to establish 7 control points. At each control point sights were established to provide cross sections perpendicular to the average bearing of the channel, as shown in figure 4. Two types of bathymetric data were compiled: 1) during each period of field work data were taken at each of the survey stations once, and 2) at station 5 data were taken concurrently with velocity measurements. Depths were measured by a boat mounted depth sounder while a boat was driven across each cross section; distances to the boat from the shore were established by a two-transit triangulation, as shown in figure 5.

The depths observed at station 5 are shown in figures 6 through 8. The purpose of taking a number of observations throughout the tidal cycle was to see if there might be large movements of sand and short term changes in bathymetry. None were observed. Comparison of data at all the stations between June and September also showed

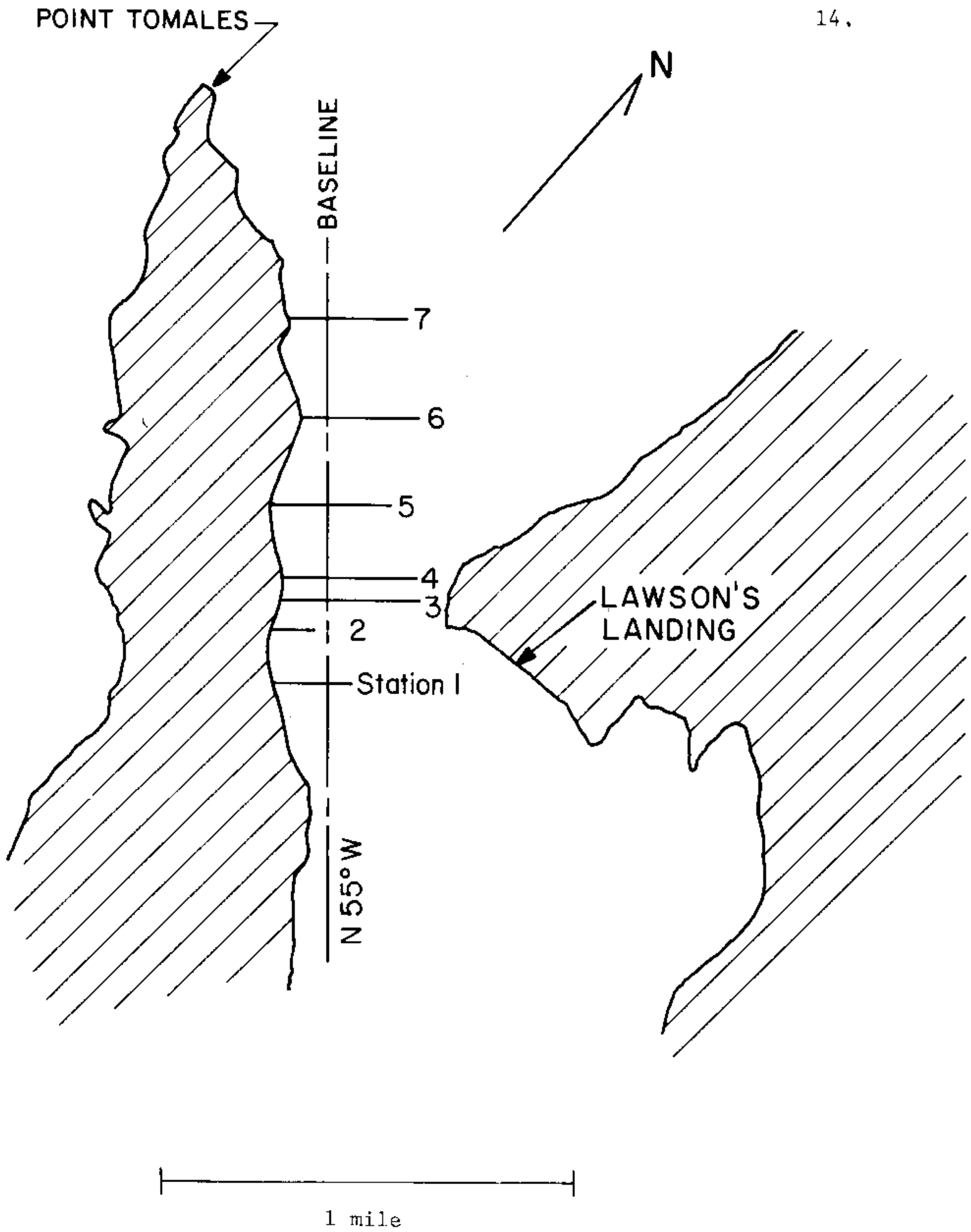

Figure 4 Location map for stations, adopted from U.S. Geological Survey, Tomales, California, 7.5' Quadrangle

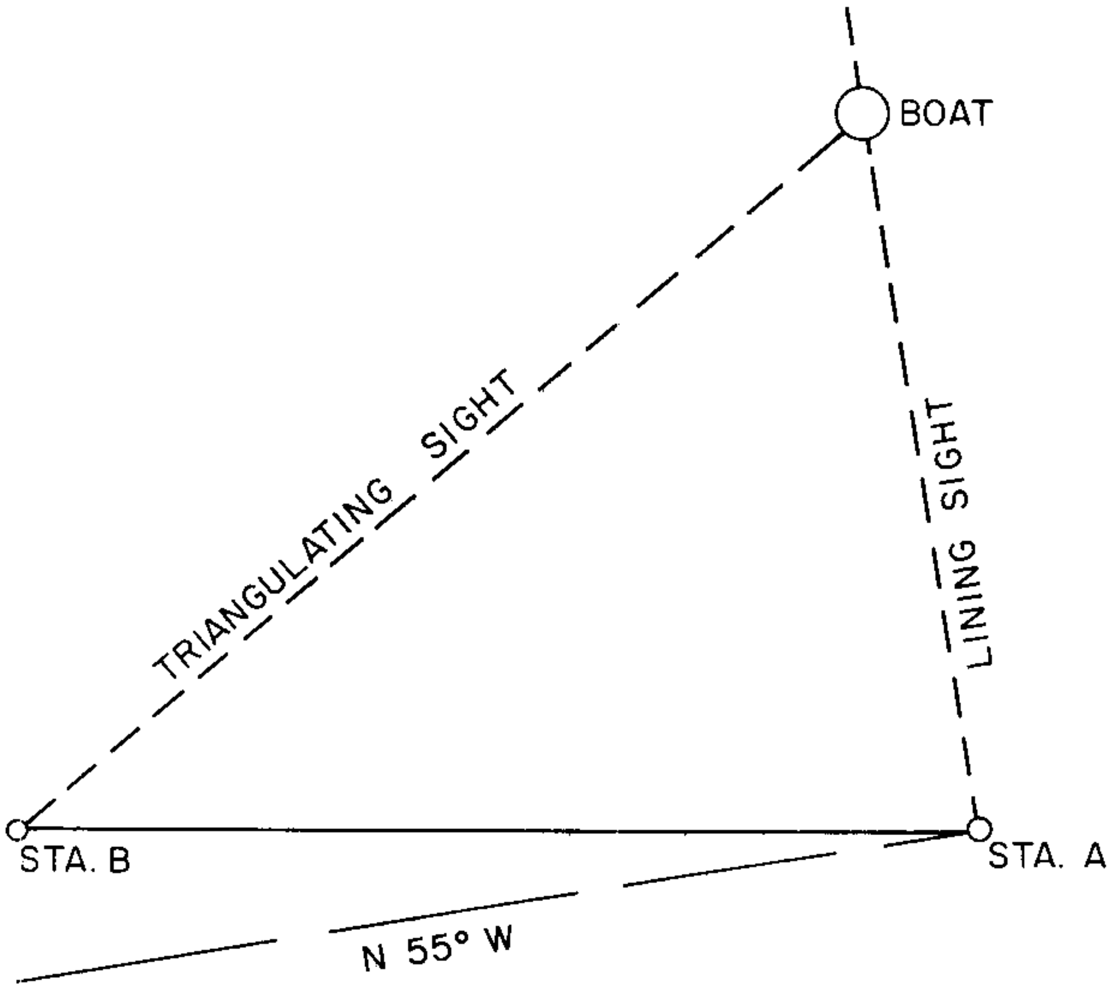

Figure 5 Method used to triangulate distances from boat to shore

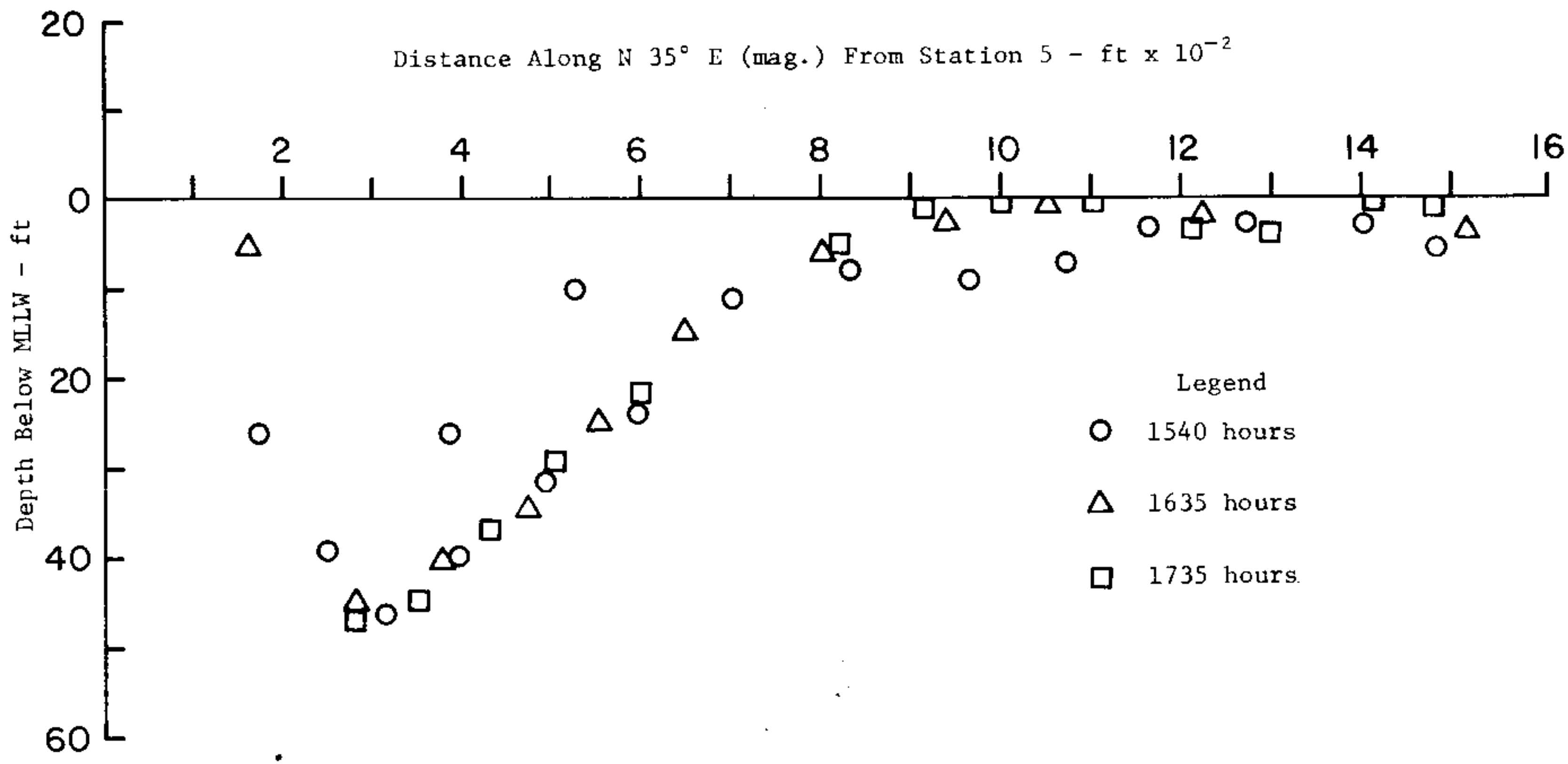

Figure 6 Variation of Depth with Time at Station 5, Flood Tide, June 26, 1974

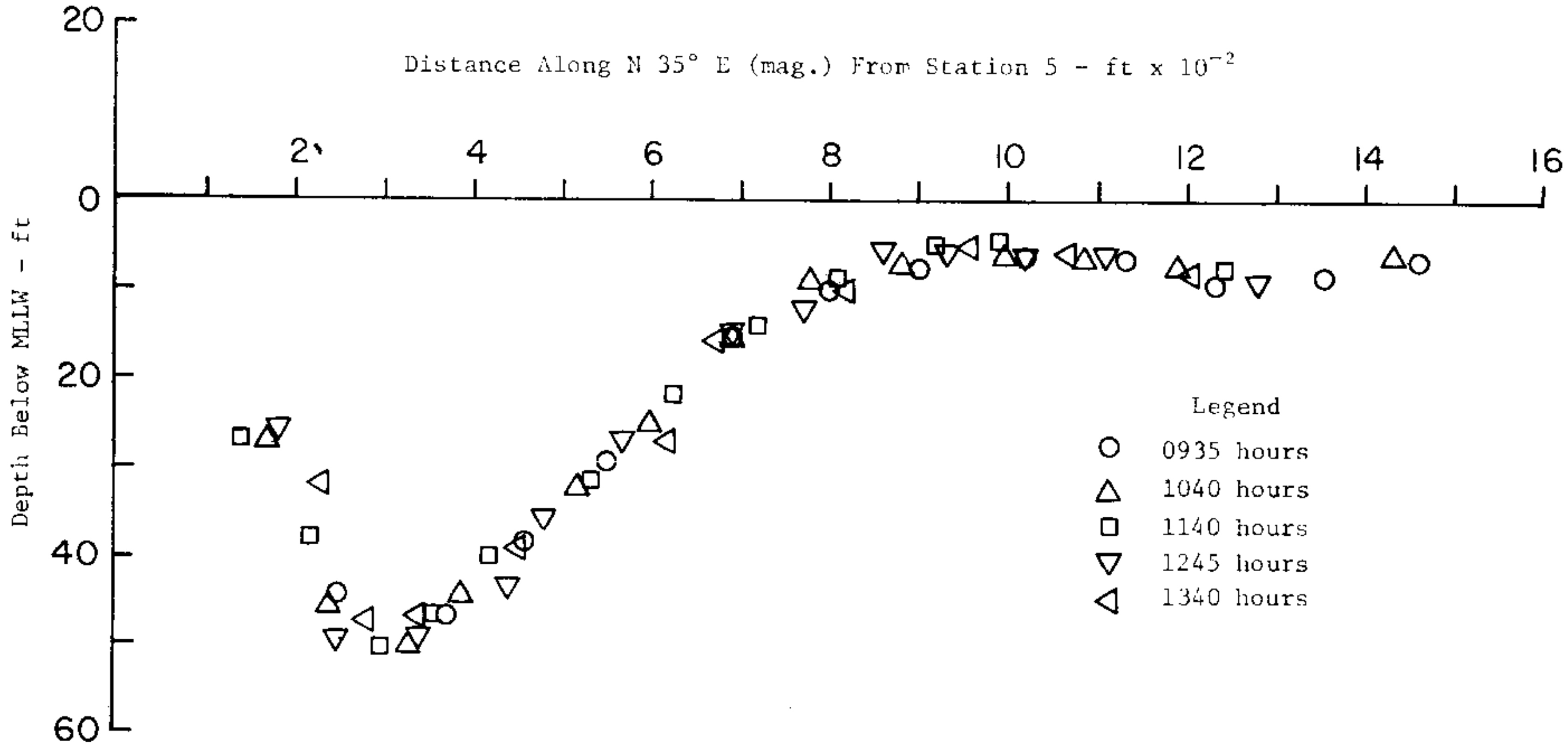

Figure 7 Variation of Depth with Time at Station 5, Ebb Tide, June 28, 1974

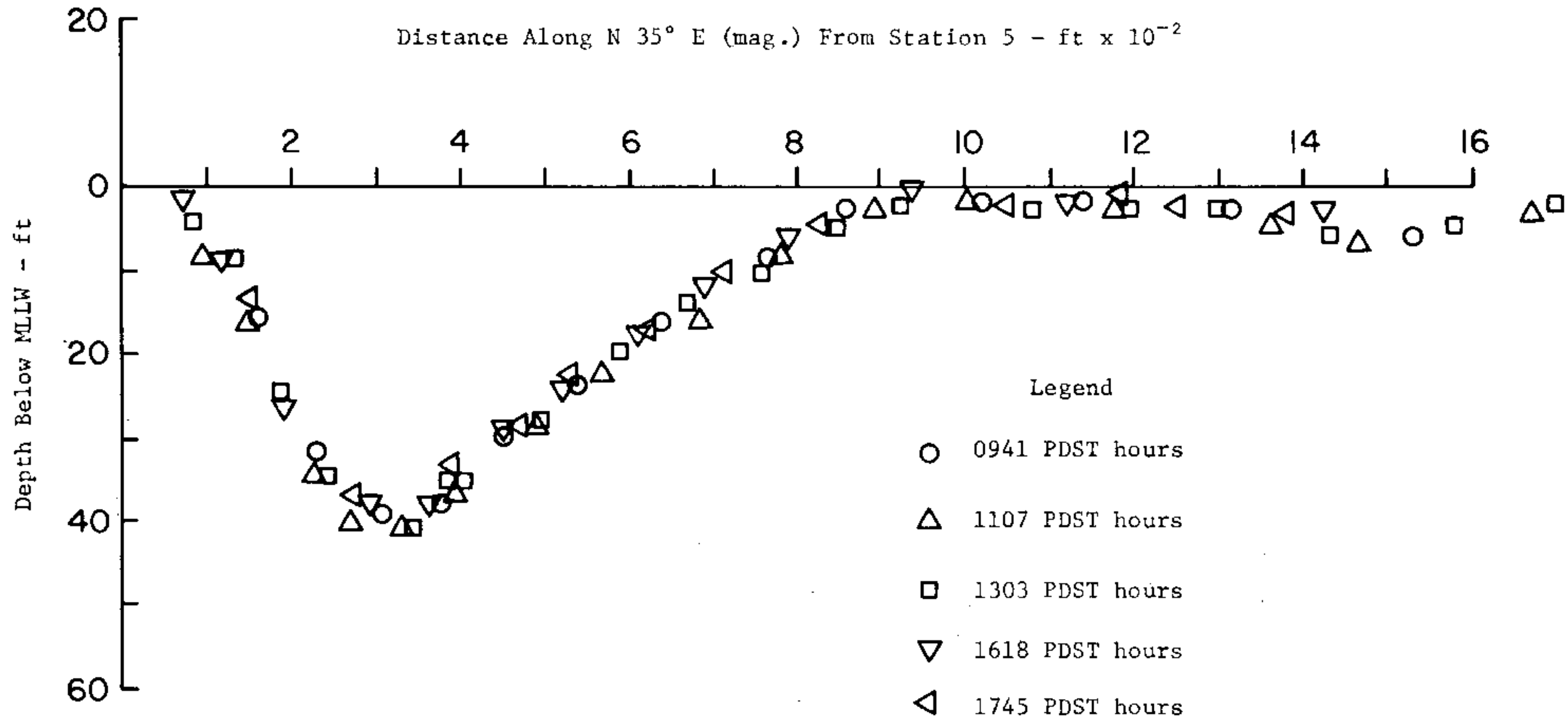

Figure 8 Variation of Depth with Time Flood and Ebb Tide, September 18, 1974

very little change. We conclude that tidal motion alone is not capable of moving large amounts of sediment near the mouth of the bay, since the bathymetry was similar in a period of weak tides in June and a period of strong tides in September. This observation probably explains the lack of formation of antidunes (sand waves; see Kennedy, 1963); antidunes can form when the Froude Number of the flow exceeds 0.8, as it often does at the mouth of the bay, but they require a large amount of sediment transport.

Velocities: - Surface velocities were measured by dropping drogues and observing the time required for the drogues to float 300 ft. between two parallel lines established perpendicular to the channel axis between stations 5 and 6. Drogues were dropped at three points across the channel: at the deepest part of the channel, and to the east and west of this point. Initially these "drop points" were established by marking with buoys, but in most cases the currents were too strong to keep the buoys in position. The approximate locations of the buoys are shown in figures 9 and 10.

Observed velocities under a number of tidal conditions are shown in figures 11 through 16. Analysis of the data (figure 17) showed that the average velocity can be expressed as a linear function of the rate of change of tidal elevation.

Seiching in Bodega Bay: - Bodega Bay may be regarded as a nearly closed basin because of the line of shallow depths running from Bodega Head to Tomales Point. Under some conditions a longi-

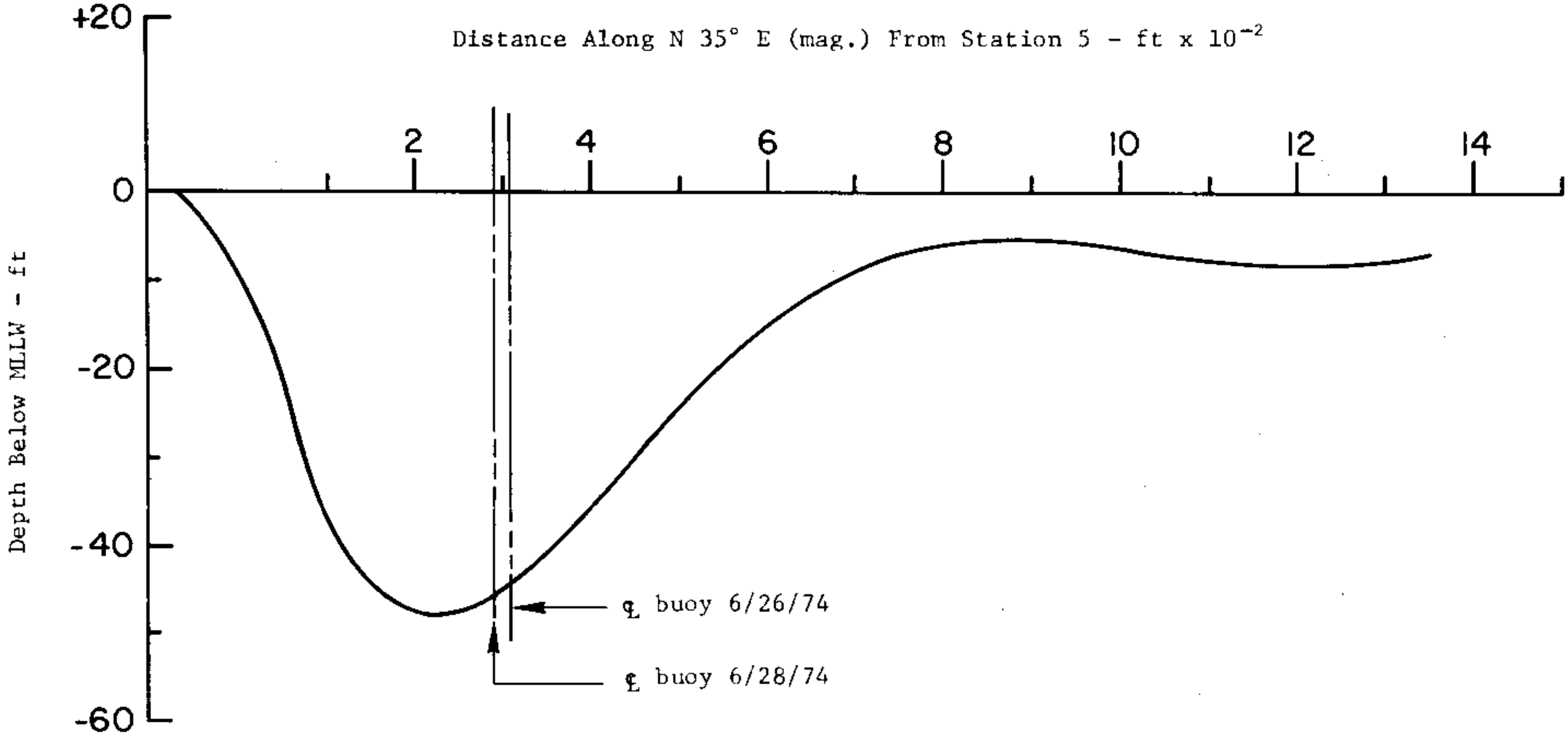

Figure 9 Reference for Channel Velocity Data, Flood Tide, June 26, 1974

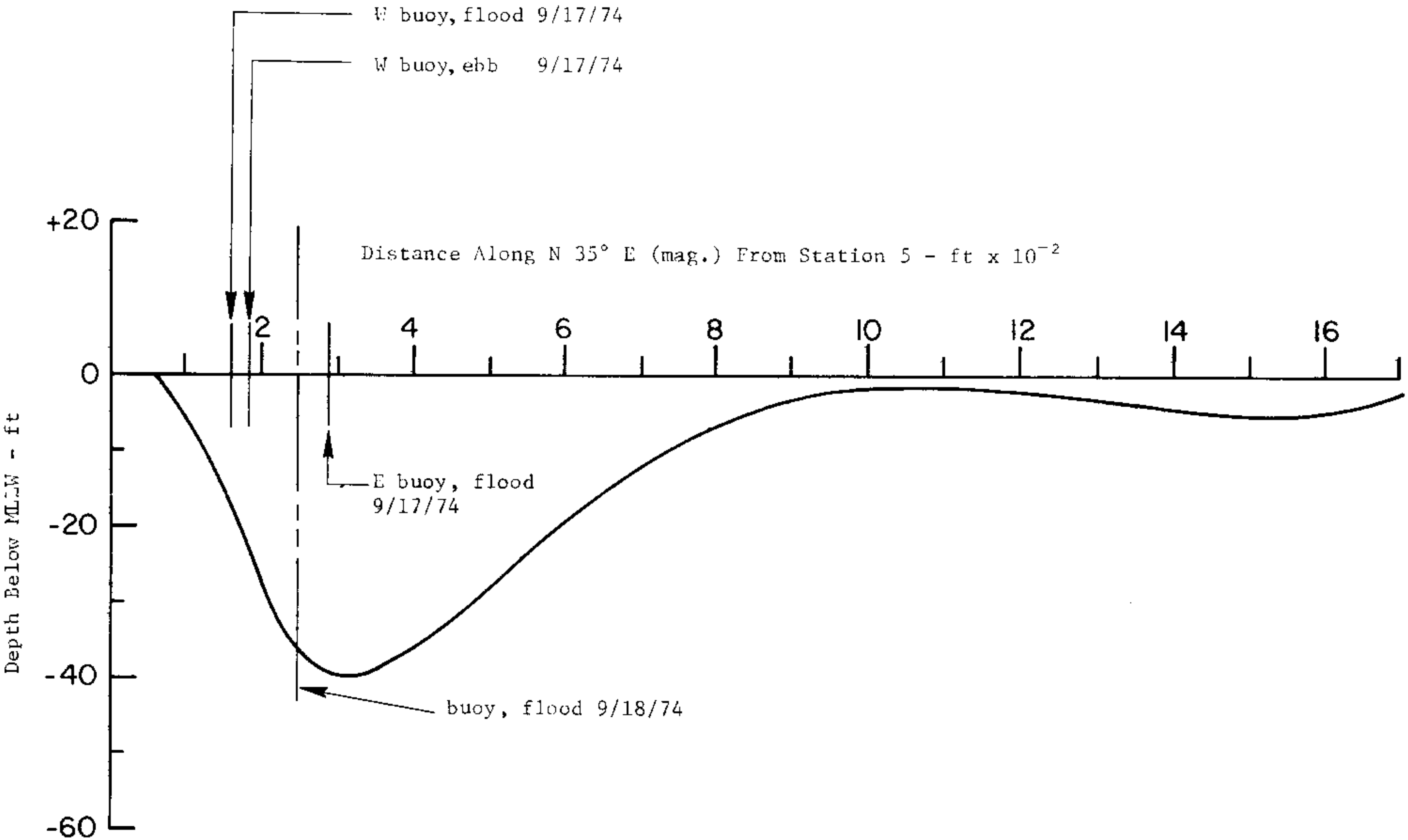

Figure 10 Reference for Channel Velocity Data, Flood Tide, June 28, 1974

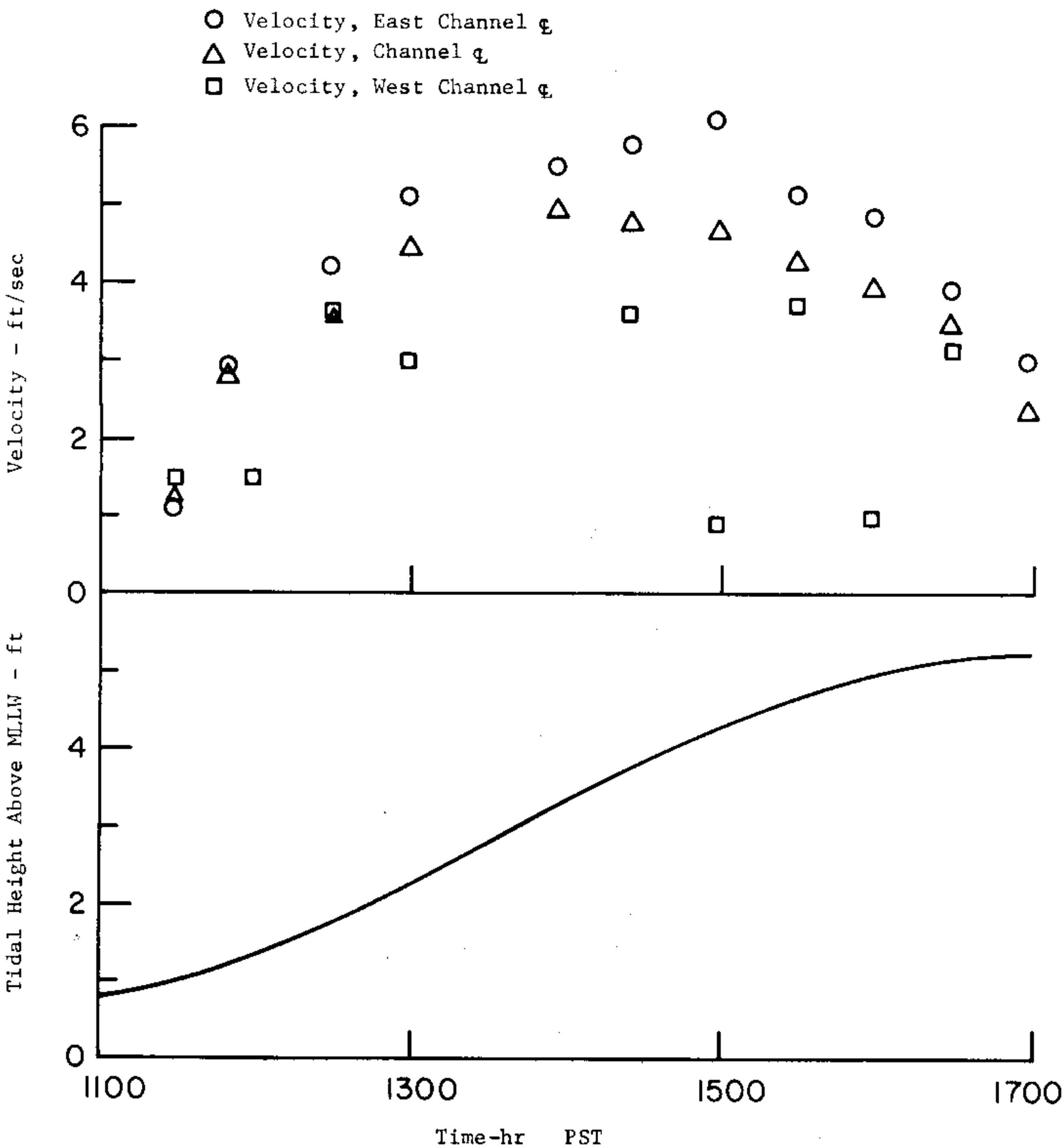

Figure 11 Variation of Tidal Height and Channel Velocity with Time
Flood Tide, June 26, 1974

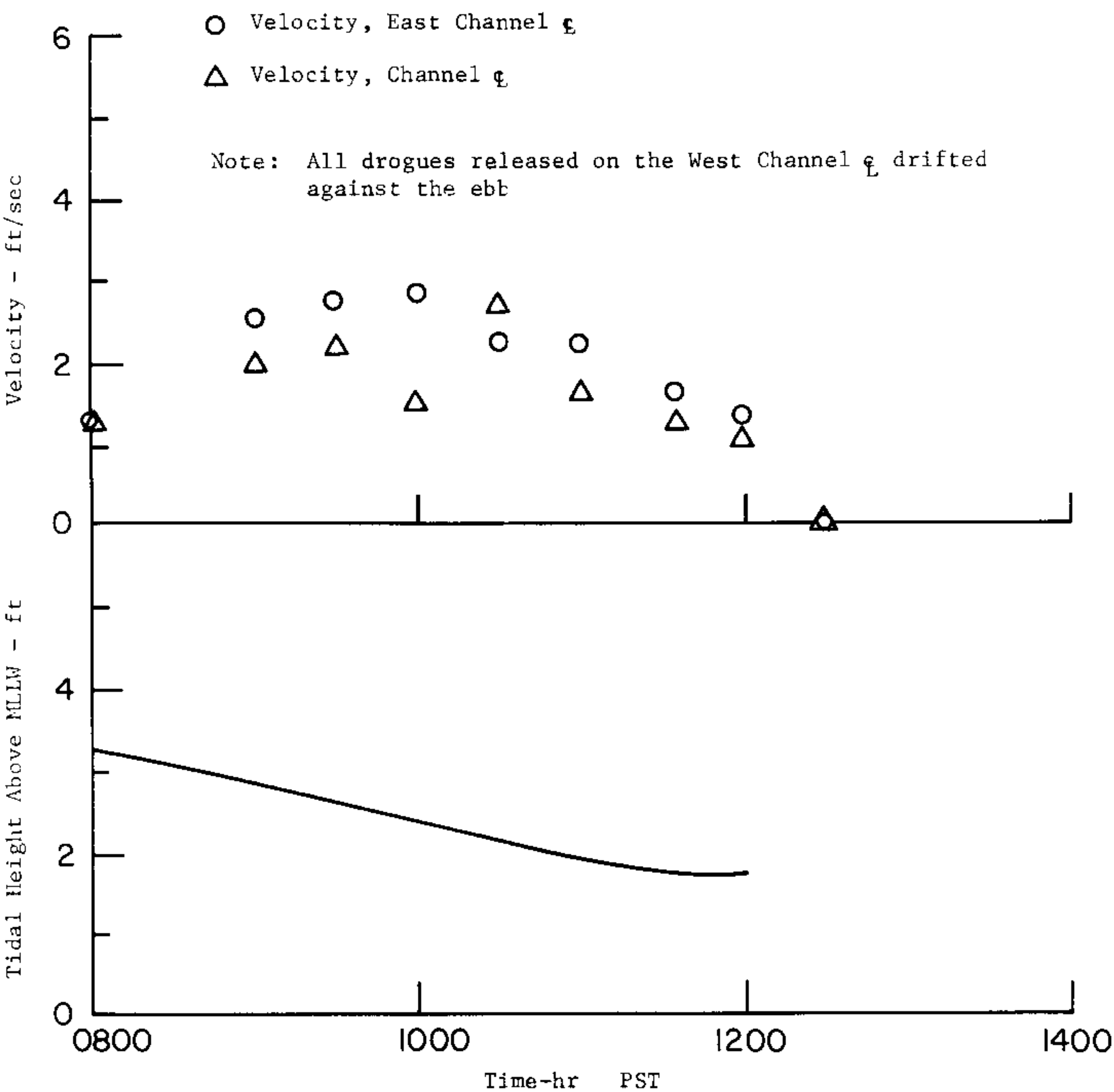

Figure 12 Variation of Tidal Height and Channel Velocity with Time
Ebb Tide, June 28, 1974

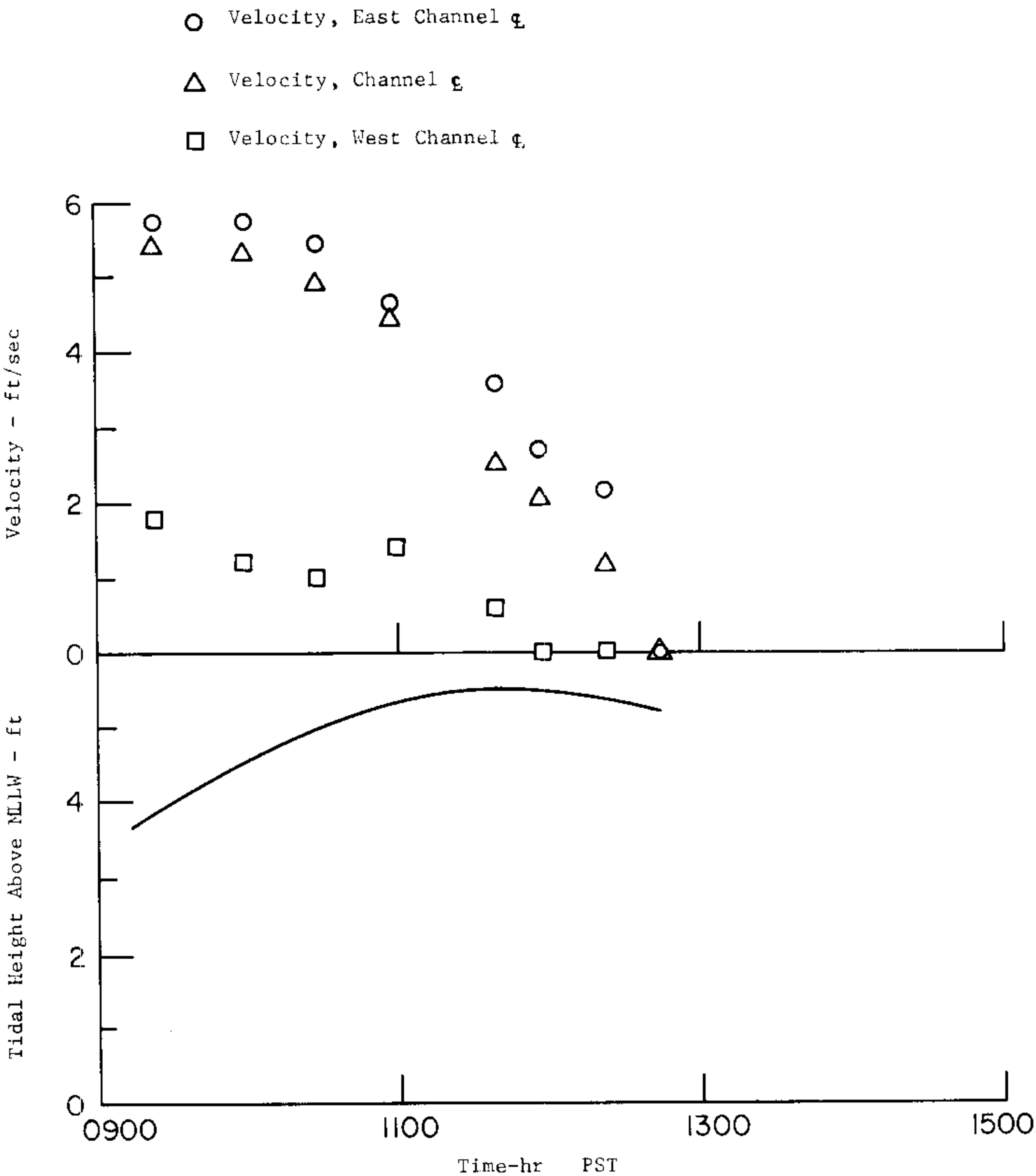

Figure 13 Variation of Tidal Height and Channel Velocity with Time
Flood Tide, September 17, 1974

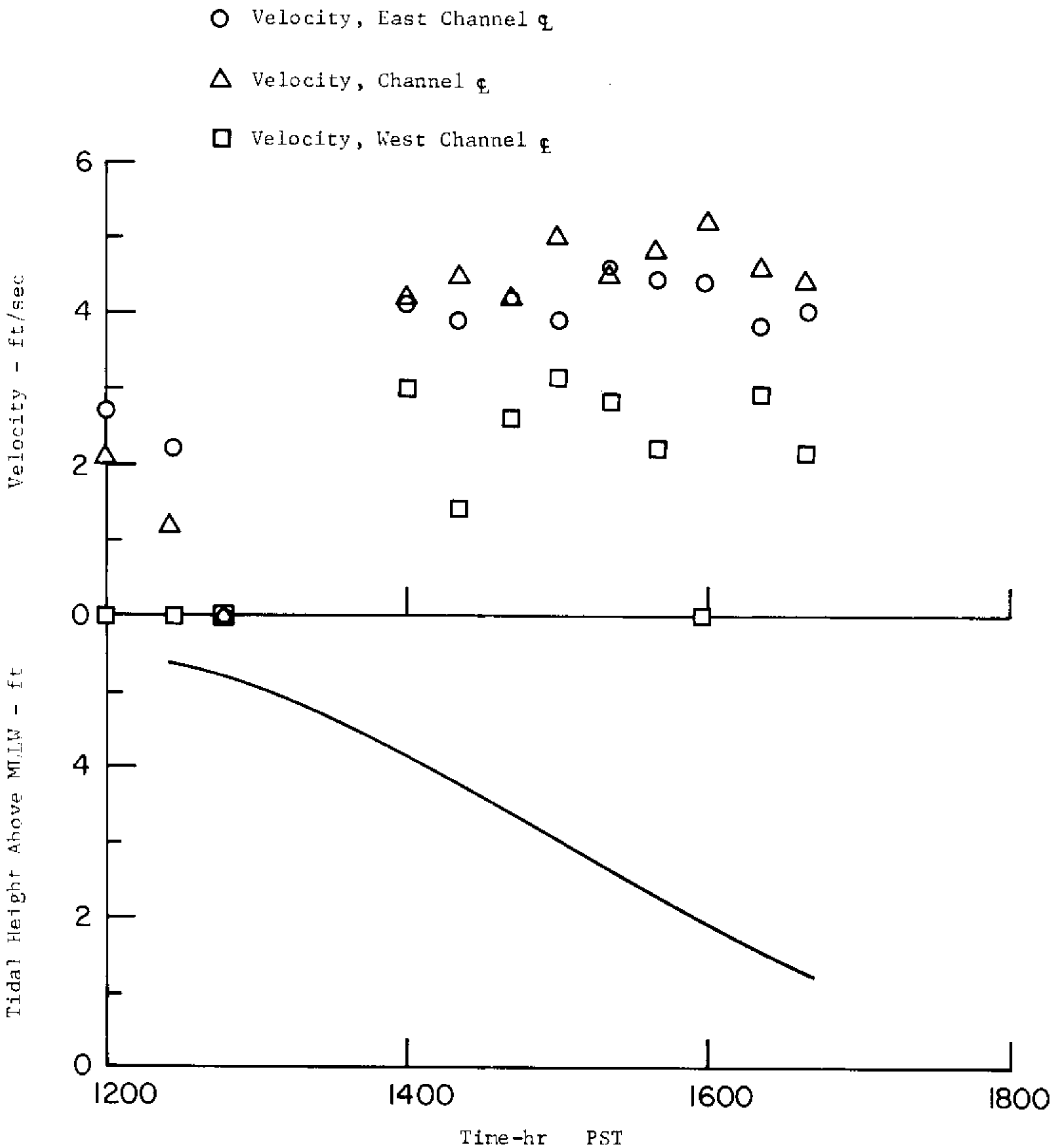

Figure 14 Variation of Tidal Height and Channel Velocity with Time
Ebb Tide, September 17, 1974

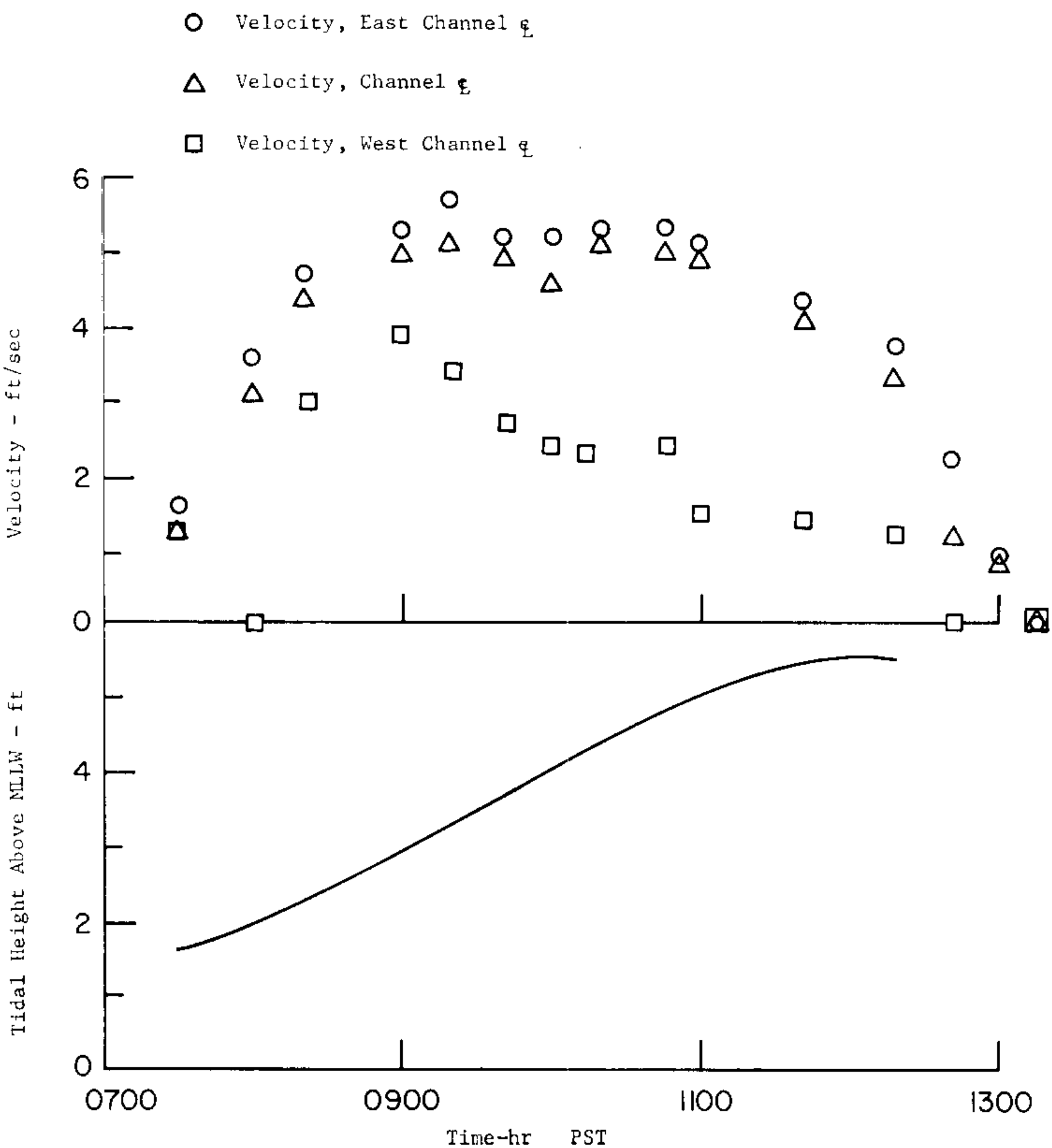

Figure 15 Variation of Tidal Height and Channel Velocity with Time
Flood Tide, September 18, 1974

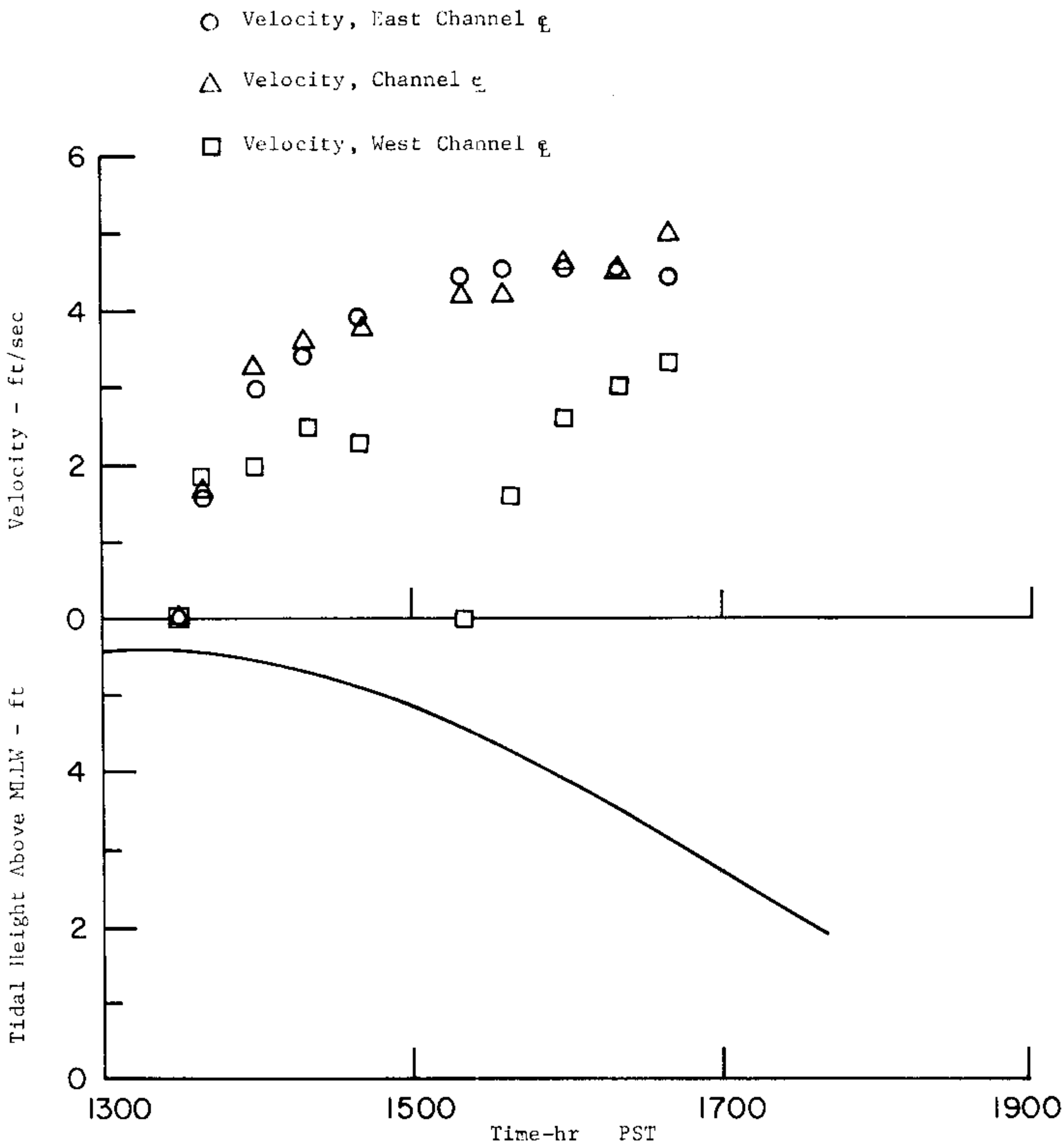

Figure 16 Variation of Tidal Height and Channel Velocity with Time
Ebb Tide, September 18, 1974

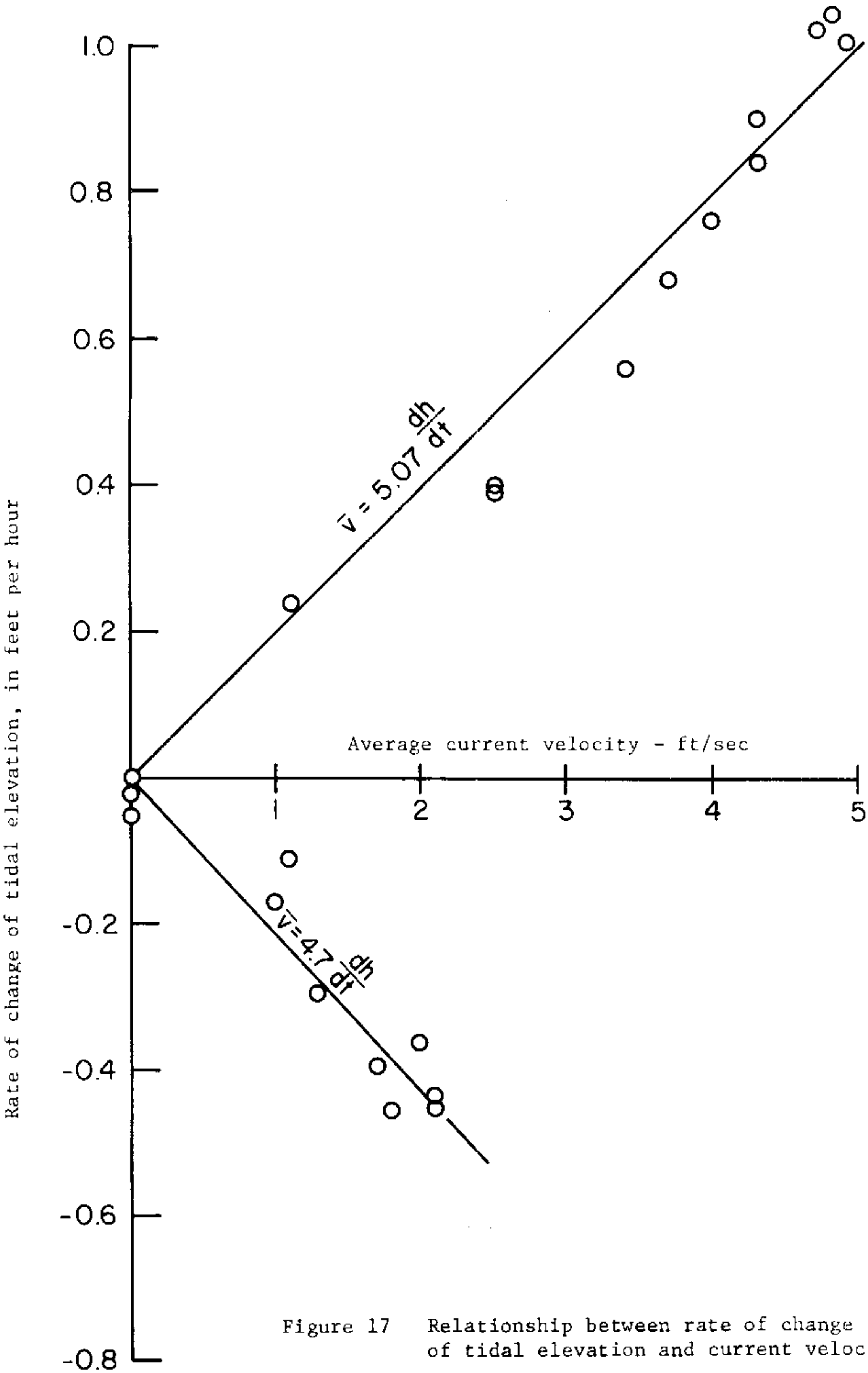

Figure 17 Relationship between rate of change of tidal elevation and current velocity

tudinal seich may possibly form in Bodega Bay. If the seich were of sufficient amplitude, it might produce intermittent breaking of waves over the Tomales Bar, as the water depth over the bar would alternate from shallow to deep. To study this possibility a Stevens Tide Gage (model F) was mounted on the eastern jetty, just inside the channel entrance to Bodega Harbor, for a period of 4 days, from January 28 to January 31. The unit was mounted in a stilling well tuned to eliminate wave periods less than 2 minutes. As the fundamental period of Bodega Bay is approximately 12 minutes, any longitudinal seich should have been recorded. During the 4-day period of record it was not possible to identify any seich motion in Bodega Bay. This result is not considered to be conclusive, since funds were not available to continue the study or improve the instrumentation; it seems likely that a seich will often be present in Bodega Bay, but perhaps not of sufficient magnitude to affect the breaking of waves.

Other Observations: - Several one-day trips were made to Tomales Point to observe conditions qualitatively during periods of particularly large tidal range. The following observations were made:

1. When the tidal range exceeds approximately 5 feet the ebb flow velocity is sufficient to produce critical flow at the mouth of the bay. The flow becomes critical approximately one and a half hours after high tide. The occurrence of critical flow is marked by

the sudden appearance of choppy, standing waves. These waves have a wavelength considerably shorter than the usual ocean swell and a height which we estimate to be of the order of one to two feet. They occasionally break upstream, and sometimes move slightly upstream before breaking. Figure 18 shows critical flow waves observed on February 5, 1974, when the tidal range exceeded 6 ft.

The critical flow waves are not sufficiently large to represent much danger to boaters. They do form very suddenly, however; we have observed the water surface change from perfectly calm to very choppy within 5 minutes. The waves are stationary with respect to the shore, but the current through the waves is deceptively high, probably on the order of 7 to 8 ft/sec. It seems likely that boaters are sometimes caught in this current without realizing its strength, and the sudden appearance of waves where the water had previously been calm might lead to panic.

2. The ebb tide flows as a jet, with nearly constant velocity, from the mouth out over the bar. On one occasion we observed a boater whose engine failed while entering the mouth during a strong outflow. The boat was carried directly towards the bar and would have been carried into the breakers had not the engine been restarted in time.

3. Ocean swell as little as one foot in height will break over the bar during a strong tidal outflow. On October 15, 1974, the wind was calm all day, the ocean swell as observed at the tip of Tomales Point appeared to be less than one foot in height, skies

Figure 18 Standing waves at the mouth of Tomales Bay. The current is estimated to be 7 to 8 ft/sec from right to left, and the wave crests are stationary.

were clear and the temperature above 70°F. In short, it was as perfect a day as probably ever occurs along this coast. Looking out over the bar at high tide the ocean surface appeared absolutely smooth. Nevertheless, two hours after high tide a wave broke over the bar with sufficient force to have swamped a small boat. Following the first breaker waves continued to break for the remainder of the period of tidal outflow.

4. Off Dillon Beach, but inside the bar, there is one area in which we frequently observed waves breaking with their crests perpendicular to shore. We could not identify the cause of these breakers, but they were seen under a variety of tide and wind conditions. They did not appear to be large, but coming from an unexpected angle they might occasionally spill a small boat.

5. Several times we noticed boaters dragging their anchors while fishing near the bar in a strong tidal flow. It seems likely that boaters are sometimes dragged over the bar unknowingly.

CONCLUSIONS AND RECOMMENDATIONS

In our opinion there is no such thing as a mysterious "sneaker wave" at the mouth of Tomales Bay. On the contrary, conditions are reasonably predictable, and the boater who understands the nature of the currents and exercises due caution runs no unusual risk. There is, however, a combination of waves and currents of sufficient complexity to give rise to the legend of a "sneaker wave," and there is very great danger to the uninformed boater.

Specifically, the dangers which exist at the mouth include the following:

1. The velocity of the ebb current can be deceptively high. Although the water surface may be calm inside the mouth, and there may be no indication of a current, the velocity of the flow may exceed 7 ft/sec. It is possible for a boat to be swept out of the mouth into potentially dangerous conditions before the operator realizes what he is caught in.

2. Frequently the ocean swell will not break over the bar during high slack tide, and the bar will appear to be a safe place to fish. The same swell will break, however, when acted on by the adverse current of the ebb tide. The exact time of occurrence of the first breaker cannot be predicted, and the breaker is likely to be a great surprise to any boaters in its vicinity. Consequently the bar is an extremely dangerous place to be during a falling tide.

3. Associated with the high velocity of the ebb flow there is an area of short, very choppy waves near the mouth which are formed by the flow becoming hydraulically critical. Just upstream of the critical conditions the water surface is usually very calm. The rapid change in conditions may add to the danger, especially if the unwary boater tries to turn around to avoid the choppy section and is carried into it broadside by the current.

In addition to the above dangers, which are specifically tide related, there are of course all of the usual dangers of a rough coast. Undoubtedly many of the accidents in this area have had nothing to do with the currents, but are simply the result of the folly of inexperienced boaters in boats too small and waves too big. About this type of accident there is nothing our study can say.

In response to the number of accidents, the California Department of Navigation and Ocean Development has taken two actions: the posting of signs already mentioned and the recent publication of a brochure, "Boating safety hints for Tomales Bay" (DNOD 6-74). The description given in the brochure is similar to the findings in this report with the following exceptions:

1. The brochure emphasizes that breakers occur mostly because of the drop in water level near low tide. Our observations are that breakers are likely to occur as soon as the ebb tide becomes strong, and this happens when the tide is still near its high.

2. The signs and the brochure emphasize the importance of adverse winds. While adverse winds no doubt increase the danger of breakers, they are not necessary. Unexpected breakers can occur when the wind is calm, and are then perhaps more dangerous because they are less expected.

In other respects we find the brochure to be an accurate and well written account of the dangers.

Recommendations: -

1. The section of the brochure entitled "Cause of the 'Sneaker Wave'" should be changed to read as follows:

"Breakers in the shallow area round the entrance to Tomales Bay (Bar) result from the drop in water level after high tide and the outrush of water during the ebb. Because of these factors, ocean swells turn into breakers when they reach the bar, just as they do when they reach a shoreline.

The formation of the Sneaker Wave is dependent upon the water depth, the size of the swell, and the speed of the ebb current. Sneaker Waves should always be expected during an ebb tide if the tidal drop exceeds five feet, even when the ocean swell is imperceptible."

2. The brochure should be distributed as widely as possible. A copy should be displayed in a permanent glass case at all locations where signs are presently installed.

3. Other than their scare value, the presently installed signs give little useful information. They should be revised, and a more explicit sign posted above the brochure. Probably the most useful message that could be given to the novice boater, in large letters, is the one contained in the brochure, "Before the tide starts going out...be on your way in."

4. Installation of a sophisticated warning system based on measurements of wind, waves, and tide is not possible at this time. Such a system, say for instance a siren which would blow at the beginning of ebb tide, could conceivably be installed, but it would probably do little good because the exact swell and tide conditions for the occurrence of the first breaker cannot be predicted, and a siren which sometimes blows at the wrong times is likely to be worse than no siren at all. It might be possible, however, to install a buoy mounted sign in the water just inside Sand Point to warn of deceptively fast ebb currents. With sufficient imagination one might even install a current meter with a needle large enough to be read by passing boaters. The unusualness of such an installation might of itself emphasize the dangers, but whether the number of accidents would be reduced, we cannot say.

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