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Authors
Leopold, Luna B
Collins, Laurel
Inbar, Moshe

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IN TIDAL SALT MARSH WETLANDS

Luna B. Leopold, Laurel Collins and Moshe Inbar
Geology and Geophysics
University of California, Berkeley

CALIFORNIA WATER RESOURCES CENTER
University of California, Davis

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CHANNEL AND FLOW RELATIONSHIPS IN TIDAL SALT MARSH WETLANDS

Luna B. Leopold, Laurel Collins, and Moshe Inbar

ABSTRACT

In a natural tidal channel, Tule Slough, in Petaluma Marsh bordering the Petaluma River north of San Pablo Bay, synoptic measurements of stage and velocity were made at seven locations along the 3 mile length of the channel. Stage at each location was tied to a common datum and thus slope of the water surface could be computed. Values of slope were predominantly of the order of .0001 or less but under some tides and in one reach attained a value of .0006 .

As maximum or minimum tide height approached slope became zero but often hovered near zero for long periods of time. With few exceptions slope became zero hours or minutes before velocity reversed direction indicating that an adverse slope is necessary to reduce the water momentum to zero.

Contrary to previously published accounts, none of which had synoptic measurements at several stations, the graph of slope vs time is not sinusoidal but much more closely resembles a flat and long cycloid curve.

The longitudinal profile of the water surface is practically horizontal at maximum tide for the full three miles of channel length. Due to shallowing of the channel upstream at lowest tide the upper reach becomes essentially dry while in the downstream reach the profile is nearly flat. At midtide the water surface slopes in opposite directions at the two ends of the channel length.

The data suggest that there are at least two and possibly more types of tidal channels with respect to the change of width, depth, velocity and discharge along the channel. Tule Slough has few tributaries, has a nearly constant width for most of its length, shallows but little except at its far upstream reach. Therefore the hydraulic geometry relations found in the one channel for which data are available, Wrecked Recorder Slough in Virginia, do not apply. It is here suggested that such a difference would result from the character of the sediment making up the marsh and thus the type of vegetation growing on it. This pickleweed marsh is underlain by very fine clay containing much peat. The clay is derived from San Pablo Bay which is a shallow, large reentrant fed by only two minor rivers and which recieves little or no water or sediment from the Sacramento River.

PURPOSE AND OBJECTIVES

In a natural channel formed and maintained only by tidal flow and without terrestrial addition of inflow, the objective of the study was to measure synoptically the progress of the tidal incursion along the channel by simultaneous measurement of water surface stage and velocity. The synchronous observations at seven locations permitted computation of water surface slope and during midtide periods, the friction factor and bed shear stress. This simple - sounding task is sufficiently formidable that it had not previously been accomplished.

These observations together with channel crosssections allow the hydraulic geometry to be constructed.

A quantitative description of the physical features of both marsh and channel was also planned. Because in the San Francisco Bay area there are a variety of marsh types such as Spartina marshes and pickleweed marshes, it was hoped that describing the hydraulic character of this one the reasons for observed differences would be somewhat more clear.

RELATED RESEARCH

The classic paper by Pillsbury (1956) was based on the unproven assumption that channel width decreases exponentially with distance up the estuary. This together with the assumption that slope varies as a sinusoidal function of time at any location led to an oversimplified picture of the hydraulic nature of the filling and emptying of the tidal prism. His two field examples were given without data. The present research was intended to elaborate on his ideas and provide quantitative support for such elaboration.

Friction factor and bed shear stress have been computed in only one previous investigation (Dyer, 1970) and in that by measurement of vertical velocity profiles but without direct measurement of water surface slope. Our intent was to obtain these quantities by another method and in a much smaller and simpler estuary.

The hydraulic geometry of a tidal channel was determined in only one field example in Virginia, first by Myrick and Leopold (1963) and again in the same channel by Langbein (1963).

Despite a very extensive literature on marshes and tidal estuaries, details of hydraulic action are few and the presentation of actual data quite absent.

METHODS AND PROCEDURES

Tule Slough, a natural channel, drains part of Petaluma Marsh. The latter is one of the few large tracts of marshland in the San Francisco Bay area that is essentially intact or undiked. It is criss-crossed with numerous narrow, shallow ditches constructed earlier in the century for mosquito control but these small features appear not to have changed the physical or hydraulic character of the major channels. Indeed, the planimetsric survey of the marsh made by the US Hydrographic Office in 1865 is nearly identical to the present. This long (3 mile) estuarine channel has remained essentially unchanged for more than a century.

Along the main tidal channel seven staff gages were installed. Three water stage recorders were placed at the mouth, at a midpoint, and at the upper end of Tule Slough.

On several occasions every staff gage was manned for a full working day during which water level was read at five minute intervals.

At each location float measurements of surface velocity were made at time intervals varying from 5 to 10 minutes. Floats consisted of orange peels, easily seen and but little affected by wind. Measurement of time over a reach of 30 feet was made by stop watch.

A critical aspect of this procedure was to establish by levelling the elevation of the zero gage height at each gage plate, all tied to a common datum. The datum chosen was arbitrarily the elevation of a bench mark near the Mouth gage given a value of 100.00 meters or 328.06 feet. On the figures and in the tables elevations are usually shown as in the range of 21 to 28, the 300 being ommitted. On this datum the marsh surface is essentially level at 28.0 feet.

Because the difference in water surface elevation between any pair of gages was in the range of 0.01 to 0.10 feet, it was necessary to assure the maximum error of the levelling survey to be less than 0.01 feet. This was achieved by closing each survey loop at least once and in some case several times. The unstable nature of the marsh surface and its high clay content made surveying a major task and also led to settlement of two of the bench marks with time, an error that needed continual rechecking to correct.

At the beginning of the study an aerial photographic survey was made under contract; so excellent, high resolution, large scale photos were available. These were used to measure areas served by each channel or tributary and to measure distances.

Some vertical velocity profiles were run to obtain a picture of the velocity structure of the flow at different places and times.

Any tilt of a staff gage from the vertical will cause the gage height reading to be too large. This error can be larger than that due to surveying by an order of magnitude. The tilt of every gage plate was measured and for three with appreciable tilt, every gage height reading was corrected for the angle of tilt.

PRINCIPAL FINDINGS

Open and unvegetated ponds are a distinctive feature of this marsh. The edges of these ponds are at a slightly higher elevation than the marsh nearby. They are served by subterranean channels that seem to connect them to the headward tip of the nearest minor tributary channels. Not all marshes in the Bay area have these ponds and their function and history are not understood. Some have not changed since the 19th century survey, some have dried up, and some new ones have formed. These ponds are one of the attributes of a pickleweed marsh and probably have some unknown relation to the unusual channel characteristics observed.

Figure 1 is a planimetric map of Tule Slough showing the location of the observation stations where gage height and velocity were measured. Water stage recorders were installed at three stations, Mouth, Mid (Midstream), and Head (upper or most upstream gage).

Note that there appears to be a small number of tributaries considering the 3 mile length of the main channel. For most of the length, the shape of the meander curves changes but little. Upstream of gage E the meander loops quickly become very small. This change is also reflected in the crosssections of the channel as can be seen in Figure 2. One might expect from the assumptions made by Pillsbury and from the characteristics of Wrecked Recorder Slough of Virginia that width would decrease gradually and systematically upstream but that is not seen in this marsh. Even depth does not decrease in a systematic way for it remains rather constant until upstream of gage E. Rather the impression drawn from the crosssections is a random variation about a uniform width and depth until upstream of gage E.

An important difference is in the vegetation.This, a pickleweed marsh,is overflowed at high tide by only a few tenths of a foot whereas the Virginia marsh was consistently overflowed by a foot or more of depth, and the Spartina vegetation no doubt reflects this fact. The range of stage is also very different. Tule Slough has a range of stage much larger than the 2.5 feet range experienced at Wrecked Recorder Marsh. The range of stage at three places on Tule Slough and that at Golden Gate is shown below for the period of observation in spring 1984.

	Percent of time equal or more than				
	5%	30%	50%	70%	95%
Golden Gate					
High	6.2	5.5	5.1	4.7	3.7
Low	3.3	2.1	0.5	0.1	-1.0
gage Head					
High	6.0	5.5	5.1	4.6	3.6
Low	2.5	1.9	1.2	1.2	1.1
gage Mid					
High	5.6	5.1	4.9	4.4	3.1
Low	2.0	1.4	0.5	0.3	0.0
gage Mouth					
High	6.1	5.7	5.4	5.2	4.5
Low	2.4	1.5	1.0	0.7	0.8

Stage in feet for several locations during the period March 8 - 29, 1984

The median range of tidal stage in feet during the period March 8-29, 1984 was 4.5 at Mouth, 3.9 at Mid and 3.9 at Head gage.

The channels have a somewhat smaller width-depth ratio than terrestrial channels of similar size. The bank material is clay, viscous, soft, often jelly-like. The top of channel banks is tightly bound by roots of pickleweed and in a few places, Spartina or bachrus. These banks tend to slough in arcuate blocks that slide into the channel with little rotation. Thus the channel banks tend to be scalloped in many places and it also leads to the non-uniform change of width and depth in the upstream direction. Yet the overall plan of the channel is smoothly curving in meanders that approximate the theoretical sine-generated curve.

Note on the crosssections in Figure 2 that the sloughed areas give very shallow edges to the channel when water is near or at marsh level. These shallow edges carry little discharge and give a false impression of greater channel width than is important to the carrying of water flow. Therefore the effective width, eliminating these edges has been used in the computation of crossectional area and discharge. In the tables this is indicated by the adjective "adjusted" or simply "adj".

Velocity as a function of time for each station is shown on Figure 3 which includes two different days to provide an impression of a full tidal cycle. The two days had different tidal range yet the magnitude of the velocities is similar. As can be seen in this example the ebb tide has appreciably larger velocity than the flood tide. This was observed on most days of observation and at most stations.

The velocity at Head and Mouth was smaller than at most intermediate stations, a fact well-explained by the values of slope as will be seen. Water surface slope is larger in the central reach than at either the head or mouth. Velocity passes through zero later than the time of maximum or minimum gage height in every cycle observed. This lag was 1 - 2 hours for both dates shown on Figure 3. The time of zero velocity moves progresively along the channel at a nearly uniform rate. As an example on April 22, the point of zero velocity travelled upstream at 4000 feet per hour (1.11 ft/sec).

The field observations were of surface velocity. Vertical profiles of velocity, as in terrestrial rivers, were not always satisfactory but for overall computations of discharge, the results suggested that mean velocity can be approximated by a value of 0.8 times the measured surface velocity. All discharge values tabulated and used in this report are so computed.

At most stations on most tides surface velocity was close to 1.0 feet per second. As can be seen for April 22 (Figure 3), velocity gradually decreases with time as low tide or as high tide approaches. This again can be seen to be the result of gradually changing slope.

It is the measurement of slope the makes the present data unique. Especially in the most downstream 3000 feet between gages Mouth and C, values of slope are so small that the differences in elevation approach the precision of the measurements, for example a difference of 0.02 feet in 1000 feet, so for these very low values the true value is not known. Yet the pattern is clear. The slope on the central reach of channel changes through time but not in a sinusoidal fashion as previously surmised (Figure 4).

Furthermore, slope varies greatly among pairs of stations. In the central reach it can attain a value of nearly 0.0006 whereas at the mouth reach it may never get larger than 0.00005 .

The data can be used to describe how the tidal prism is filled through time (Figure 5) and drained through time (Figure 6) by those plots of the longitudinal profile of the water surface at one hour intervals. Data are available to present much more detail, as close as 10 minute intervals, but the progression is adequately shown in these two figures.

In Figure 5, showing change from flood to ebb on March 17, the observations begin at 1100 hours when the slope is nearly uniform in the upstream direction (slope designated negative). It steepens upstream between gages D and E. By 1200 hr the slope is uniform for the full 14000 feet of channel. By 1400 hr the water surface is essentially flat at its maximum elevation, closely coinciding with the level of the marsh surface. An hour later the water at Head gage has changed but little and at all gages downstream the level has sharply fallen so the slope is more or less uniform in the positive direction. At 1600 hr and even more at 1650 hr the downstream reach has steepened but the water at all 7 gages has fallen more or less uniformily, about 3/4 foot per hour.

Compare this with Figure 6, a day when the tide goes from ebb through a minimum to a flood tide. From 0800 hr to 1100 hr the graph repeats the later hours of Figure 5 but shows that from 1100hr to 1500 hr the slope in the lower 2000 feet (gages C to Mouth) remains small and constant even though the water surface continues to fall.

Suddenly at 1600 hr the downstream 4000 feet has reversed its slope which is now negative while the upstream 10000 feet still has a positive slope. At this time the water surface is shaped like a flat V. At 1700 hr all reaches have a negative slope, the central portion being steeper than either end of the profile.

Especially interesting on this date is the fact that the level at the Head gage approaches its lowest point near 1200 hr and stays near that level for nearly four hours while downstream gages continue to have a falling level the lowest of which is 2 feet below the lowest level attained at Head gage.

Hydraulic geometry

The well known equations relating discharge to width, depth, and velocity have been shown to apply to the tidal estuary case but the exponents differ from those for rivers. However, data are available for only two examples. This pickleweed marsh has planimetric characteristics that suggest it does not agree with these previous cases, especially owing to the small number of tributaries and the nearly constant width for long reaches. Indeed, when the data were organized, the exponents were quite different for the downstream direction.

For Tule Slough the width exponent b is 0.36, the depth exponent f is 0.18, and the velocity exponent m is 0.43 . This means that compared with the marsh in Virginia, width changes little along the channel, velocity is far from constant but increases rapidly with discharge.

So few cases are available for study that the explanation of the differences can only be conjectural. Even so, a very tentative hypothesis is put forward.

Tule Slough derives its water and sediment from the shallow,large, and often muddy San Pablo Bay. This bay is not served or much affected by the water coming from the Sacramento River into San Francisco Bay proper. Rather it is fed by only two small tributaries, Napa and Petaluma Rivers. These must deliver only very fine sediment for all the northern part of San Pablo Bay is muddy and so shallow that dredged channels are necessary even to get small boats up the channels of the Napa and Petaluma.

This fine clay is carried up the small tidal sloughs and forms bank and bed of them. Overflows deposit the clay on the marsh surface to such an extent that high tide usually does not cover the marsh and when it does the overflow depth is only about 0.1 feet. Natural levees near the channels attest the tendency for upbuilding. On such a surface Spartina is uncommon and pickleweed dominates. The clay content leads to bank sloughing and irregularity. This bank sloughing also leads to a larger width-depth ratio than seen in the channels of Spartina marshes.

The high clay content also leads to development of underground channels and for unknown reasons, to open ponds.

In some manner these characteristics are associated with a lack of tributaries and those that exist meet the main channel as hanging valleys. All these lead to an unexpected hydraulic geometry.

Though lacking in the necessary mechanics, the present study suggests that there are at least two different kinds of marshes each having special sets of interrelated characteristics, physical, hydraulic, vegetational, and sedimentological.

PUBLICATIONS

None are as yet published.

In process: Water surface slope, channel character and velocity in a small estuary: Leopold et al.

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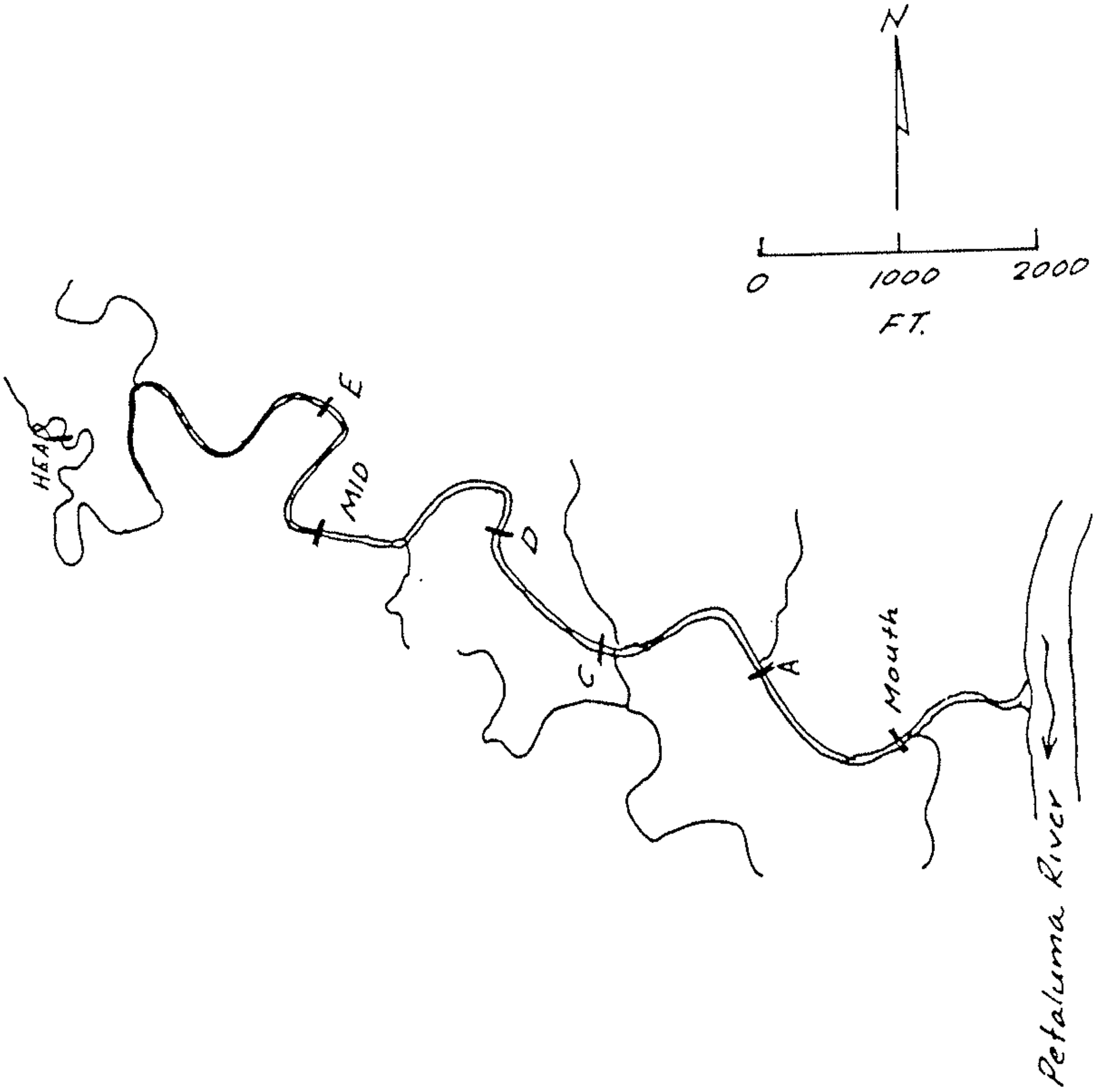
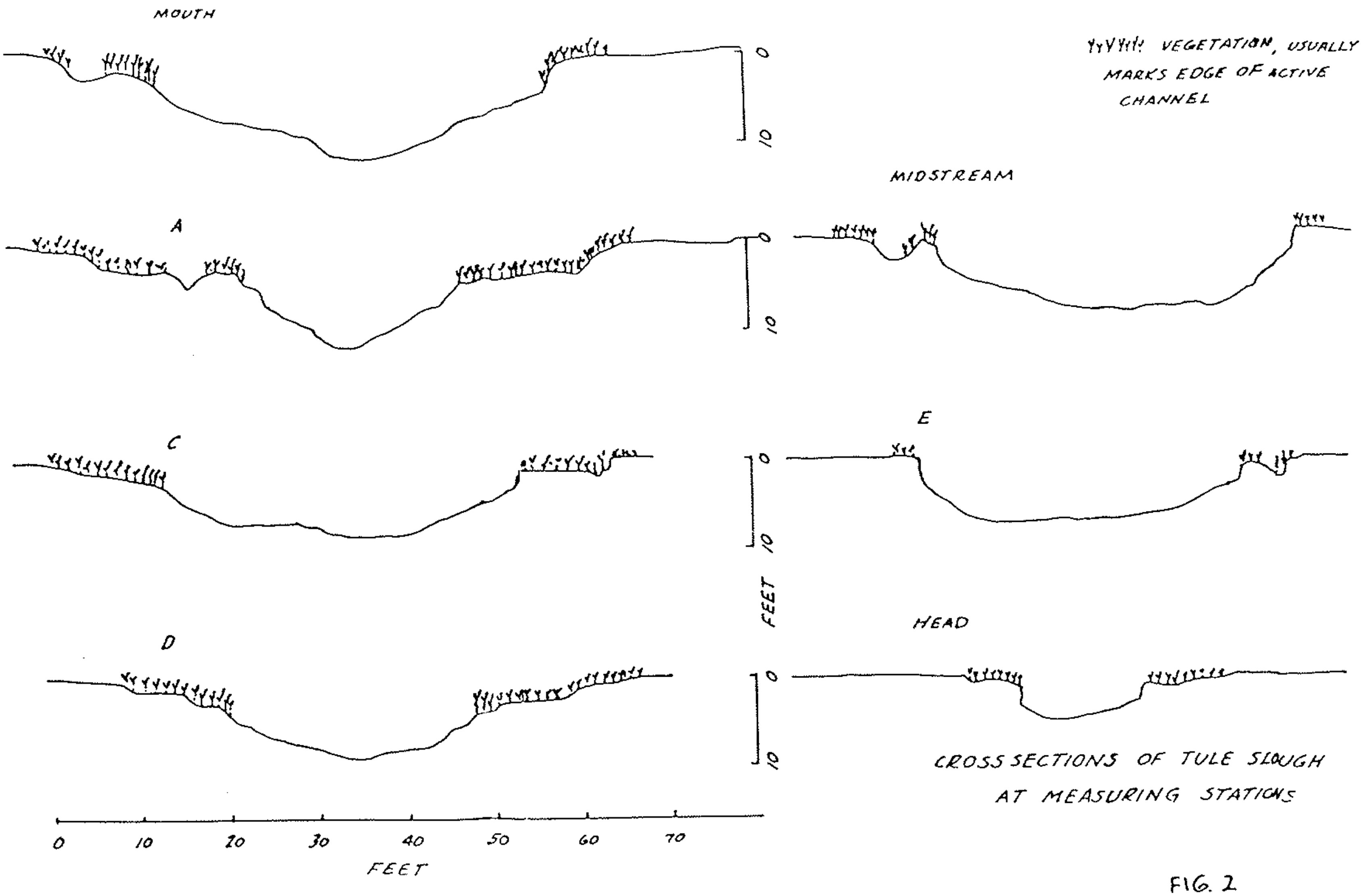


LOCATION OF MEASUREMENT
STATIONS, TULE SLOUGH
PETALUMA MARSH

FIG 1

LBL 7/84



CROSS SECTIONS OF TULE SLOUGH AT MEASURING STATIONS

FIG. 2

LBL 7/84

SURFACE VELOCITY THROUGH A TIDAL CYCLE

A COMBINATION OF TWO DIFFERENT DAYS

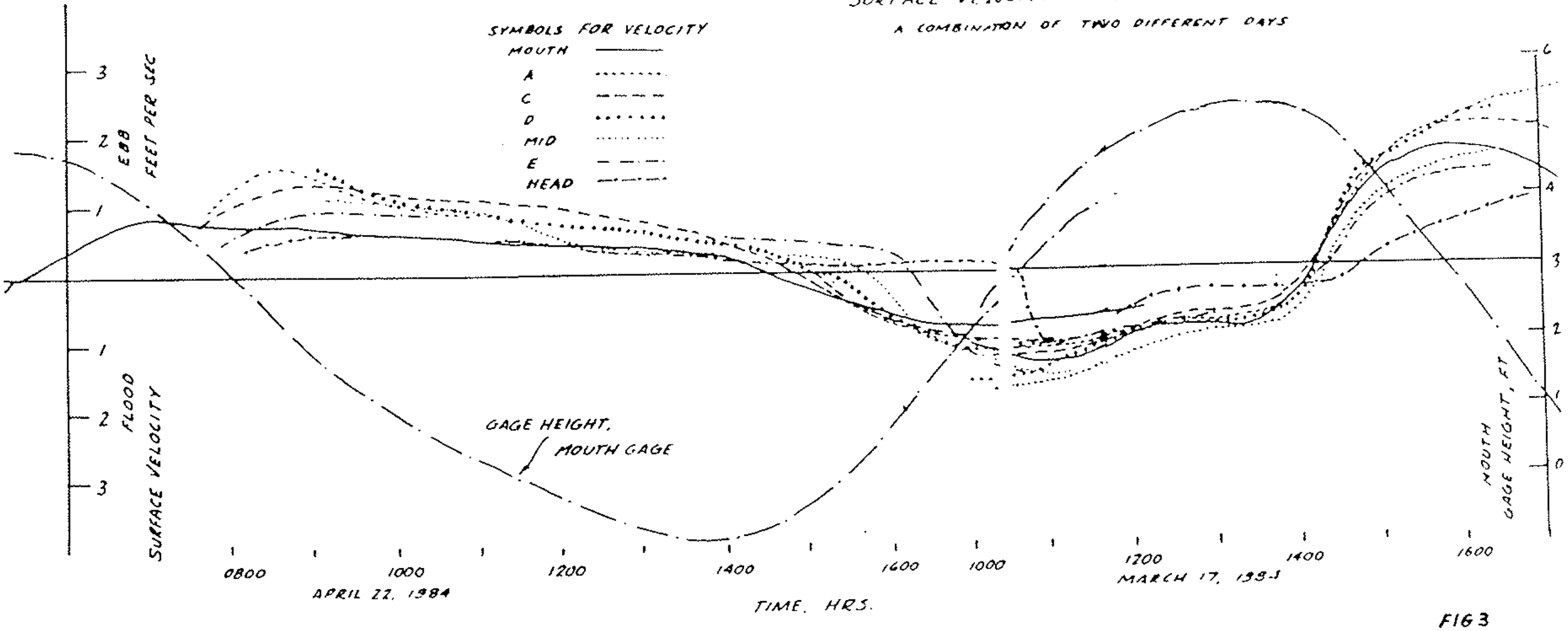
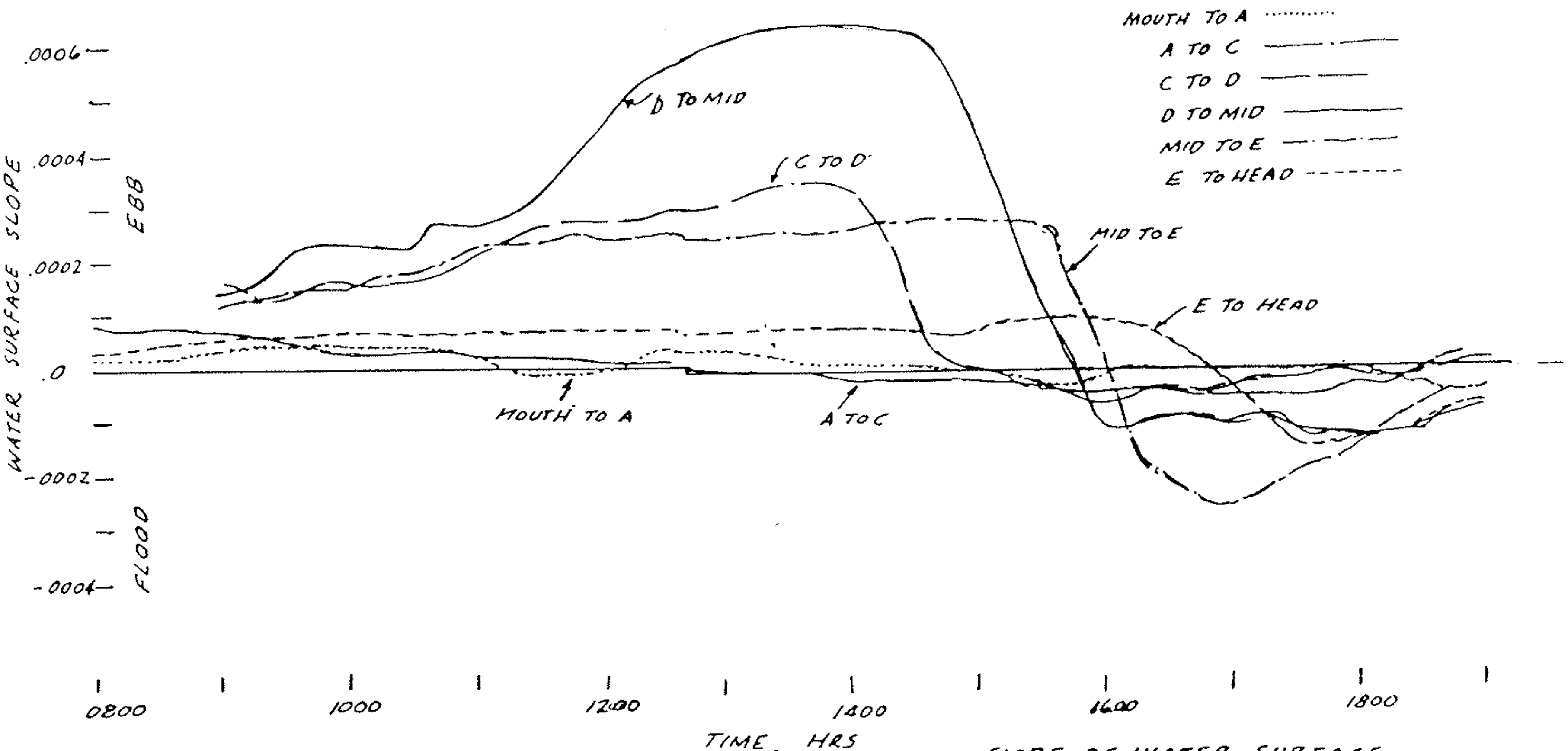


FIG 3

[illegible]



SLOPE OF WATER SURFACE
THROUGH TIME
APRIL 22, 1984

FIG 4

LBL 7/84

WATER SURFACE PROFILES AT ONE HOUR INTERVALS
MARCH 17, 1984

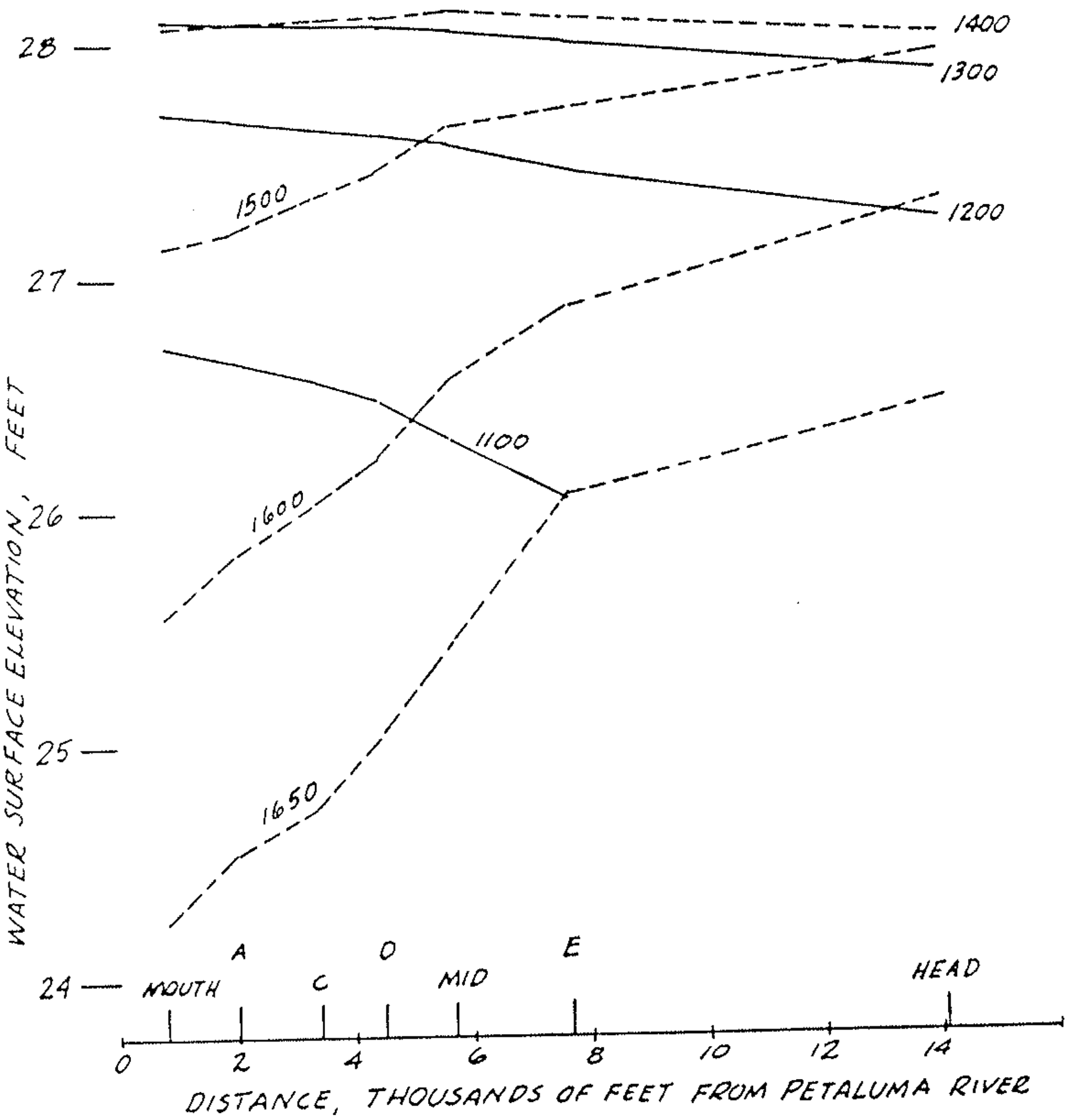


FIG. 5

LBL 7/84

WATER SURFACE PROFILES AT ONE HOUR INTERVALS
APRIL 22, 1984

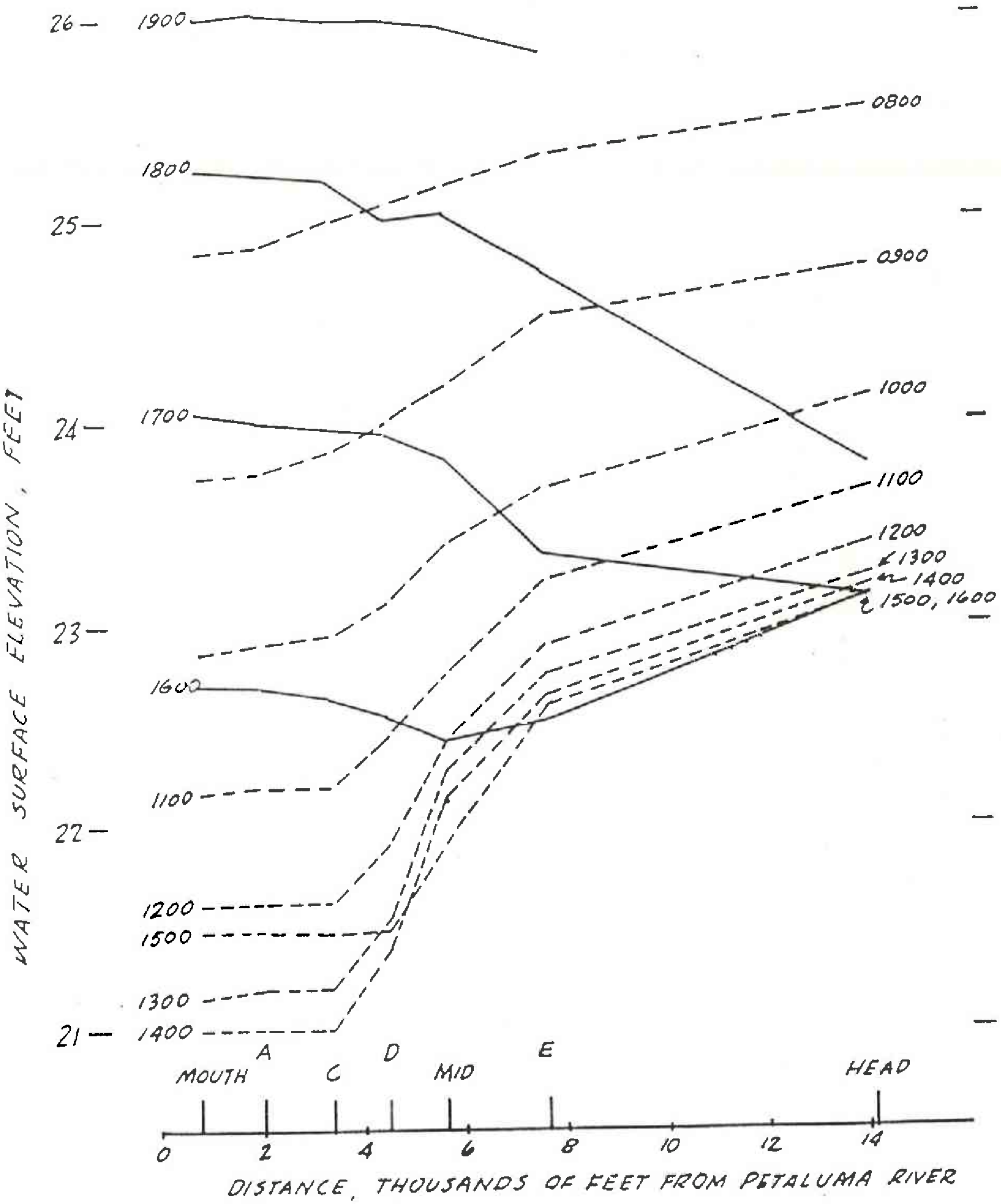


FIG. 6