

HYDROGEOLOGY OF THE PALO ALTO BAYLANDS,
PALO ALTO, CALIFORNIA
WITH EMPHASIS ON THE TIDAL MARSHES

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ABSTRACT

The Palo Alto baylands, located on the southwestern margin of the San Francisco Bay, California, consist of preserved tidal marshes and other areas that have been considerably altered by man since the 19th century. The baylands are flat-lying and have very little local relief.

The 200 feet of sediments below the Palo Alto baylands are flat-lying, unconsolidated and late Quaternary in age. They consist of estuarine clays interfingered with alluvial clay, sand and gravel. This sequence was produced by two major inundations of the sea in the bay area during the last 150,000 years.

Groundwater occurs under pressure in two separate zones. A deep aquifer exists at depths of 150 to 200 feet and is separated from shallow confined aquifers above by a relatively thick sequence of clay deposits. The shallow aquifers exist at depths of 10 to 50 feet and appear to gain water from adjacent aquitards. Near the bay, these shallow aquifers have very high chloride contents.

In the natural tidal marshes the water table commonly stays close to the marsh surface. Steep-sided banks of tidal marsh channels consist of a porous structure which extends 10 to 20 feet away from the channel. The permeable section appears to gradually become shallower away from the channel. However, the majority of the marsh deposits have very low permeabilities. Bay water probably percolates slowly down through the sediments to the shallow aquifers.

Altered tidal marshes, like the Palo Alto Flood Control Basin, have been isolated from tidal fluctuations for several years. The

surface of the flood basin has lowered 3 to 5 feet as a result of the loss of salt marsh deposits. The water table here exists several feet below the surface. The permeabilities of the flood basin sediments appear similar to the low permeabilities common in the natural marsh deposits. Further environmental restorations of areas like the flood basin by re-introduction of tides will hopefully restore the character of the natural tidal marshes.

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INTRODUCTION

Since the mid-1800's the natural tidal marshes of the San Francisco Bay have been drastically altered by the activities of man. Of the 265 km² present in 1850, only 15 km² remain untouched (Atwater and Hedel, 1976). However, an appreciation of these overlooked marshlands has developed in recent years and attempts at preserving untouched tidal marshes and restoring damaged ones have begun. These activities have encouraged many scientific investigations of the biologic and geologic aspects of tidal marshes in the San Francisco Bay.

The purpose of this work is to study the hydrogeologic aspects of the Palo Alto baylands with specific interest in the preserved natural tidal marshes. Also of particular interest are areas in the baylands that are damaged and presently to be restored. All present information on the hydrogeology of the baylands has been gathered and combined with field studies conducted by the writer in order to define the hydrogeologic system. In turn, this information is used to help in analyzing the effects that proposed environmental restorations will make on damaged tidal marshes. One such altered tidal marsh presently to be restored is the Palo Alto Flood Control Basin.

Previous studies of a geologic nature have been carried out by several people. Pestrong (1965) made detailed studies on the development of drainage patterns on tidal marshes in five natural marshes in southwest San Francisco Bay. Sarna (1968) delineated the thickness and areal extent of the recently deposited bay mud in the south San Francisco Bay area from

available well and engineering boring logs. Nichols and Wright (1971) developed a detailed map at a scale of 1:10,000 of the historical margins of the marshlands of 1850 for the entire San Francisco Bay area. Pestrong (1972) also studied sedimentation patterns in the tidal flats of the Cooley Landing marsh at the northern extent of the Palo Alto baylands. His work included an analysis of the distribution of grain sizes in the deposits of the tidal flats and marshes and the process of sedimentation that forms the deposits. Atwater and Hedel (1976) studied the recent deposits of the Palo Alto tidal marshes and interpreted their environments of deposition. In addition, Atwater, Hedel and Helley (1976) described the environments of deposition of the first 200 feet of sediments just north of the Palo Alto baylands area based on samples obtained from borings for the foundation of the Dumbarton Bridge. Their studies also included the history of sea level rise and vertical crustal movements of the last 10,000 years. Finally, several engineering borings have been made and described by various consultants such as Cooper, Clark and Associates and Woodward-Clyde Consultants. A large part of this work was done in support of foundation investigation studies.

The occurrence and movement of subsurface water in the baylands has been described by Sokol (1964). He discussed the hydrogeology of the San Francisquito drainage and alluvial cone and briefly described the pressure zone of the cone. Subsurface water in the Palo Alto baylands area has been described in more detail by the Santa Clara Valley Water District in two reports by Jenks and Adamson (1973 and 1974), consulting sanitary and civil engineers, who were reporting on a project for water reclamation and ground water recharge for the city of Palo Alto. Many

regional reports by the California Department of Water Resources (1967, 1968, 1973 and 1975) include brief descriptions of the subsurface water in the Palo Alto baylands region.

GEOGRAPHIC SETTING

The Palo Alto baylands is located on the southwestern margin of San Francisco Bay about thirty-five miles southeast of San Francisco, California (fig. 1). The crossing of $37^{\circ} 27'$ north latitude and $122^{\circ} 7'$ west longitude is close to the center of the area. The area covers approximately 1900 acres and is bordered by the city of East Palo Alto on the northwest, the city of Mountain View on the southeast, San Francisco Bay on the northeast and U.S. Highway 101 on the southwest (fig. 2). All land except a few tracts are incorporated in the city of Palo Alto.

The climate is that of ocean-moderated conditions. The mean temperatures in January and July are 47°F and 66°F , respectively, with a yearly mean of 57°F (Jenks and Adamson, 1973). An average of about nine days a year have highs of 90°F or over, while about fourteen days a year have minimum temperatures below 32°F . Average yearly rainfall is fourteen inches with close to seven inches falling in January and February. Only .3% of the yearly rainfall occurs in the period from June to August. Prevailing winds are generally from the northwest. In the summer an afternoon sea breeze typically follows a calm morning and early afternoon.

The general topography of the Palo Alto baylands is flat lowlands with local relief of only a few feet. The area is located in the bay plain physiographic province bordered on the west by the San Francisquito cone and San Jose plain (fig. 1). The baylands region generally slopes northeasterly toward San Francisco Bay, but a majority of the land surface has been altered by the activities of man which have interrupted the continuous

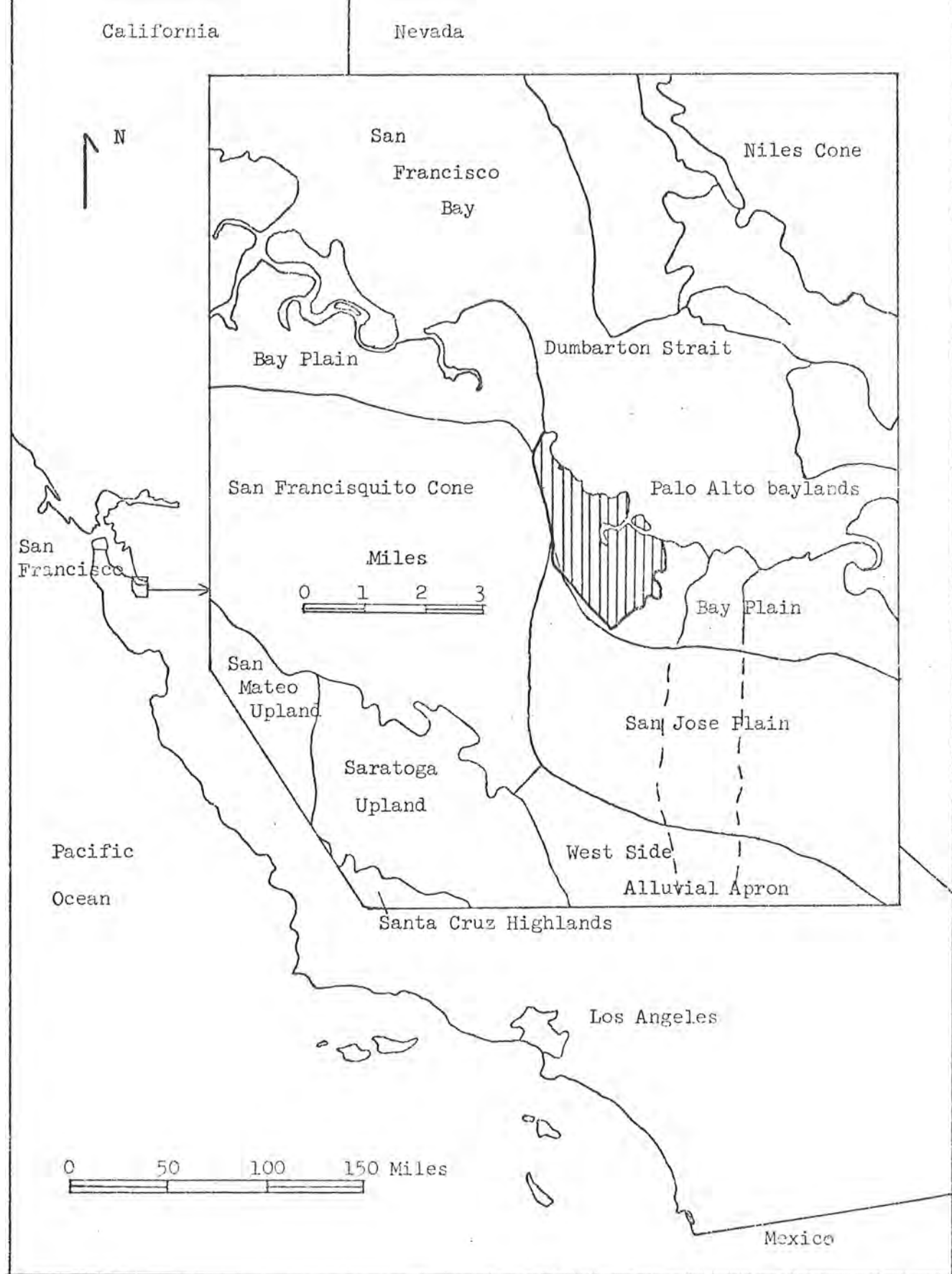


Figure 1. Location of the Palo Alto baylands, Palo Alto, California. Inset shows regional physiographic provinces.

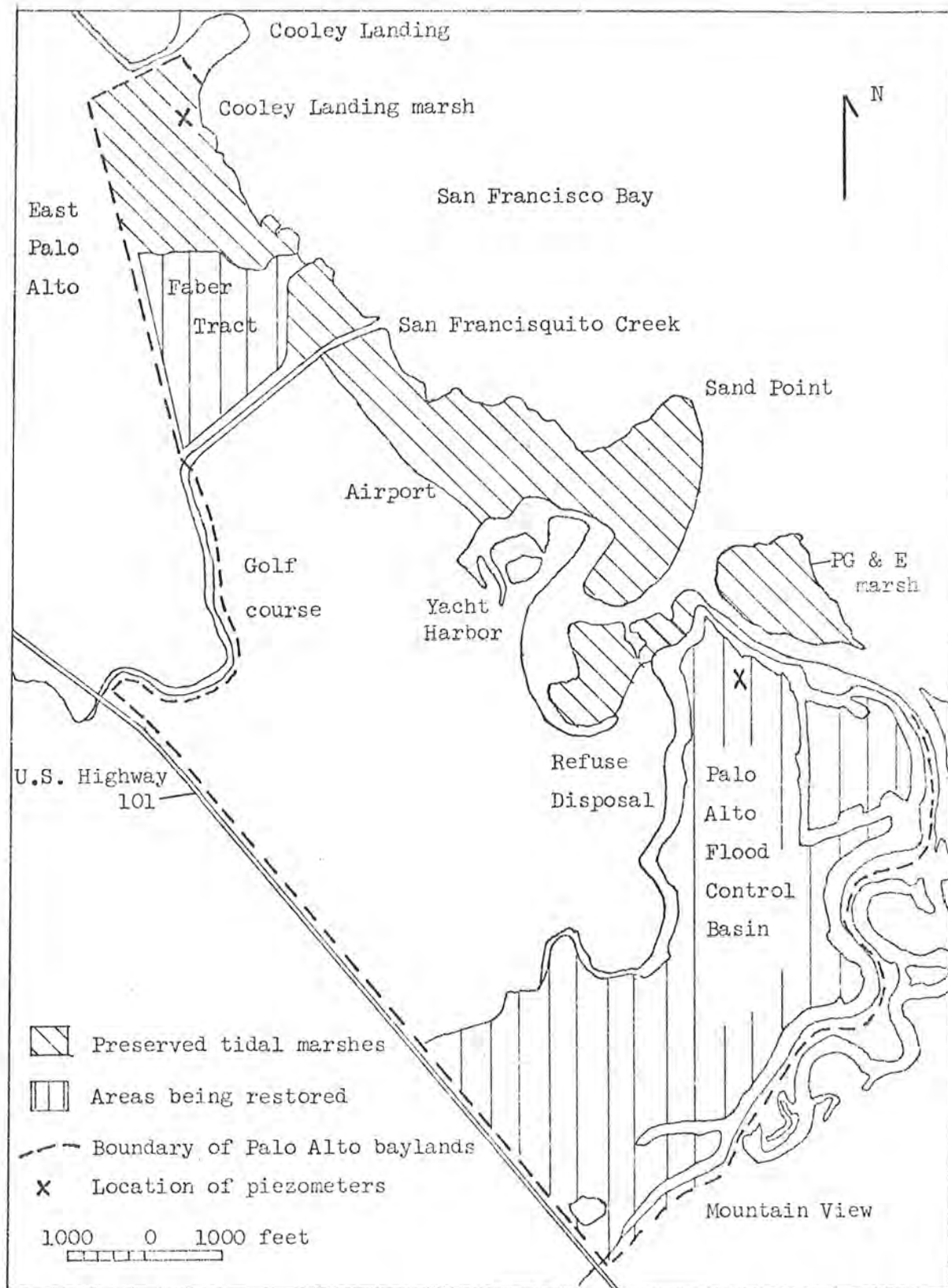


Figure 2. General features of the Palo Alto baylands.

natural land gradient to the bay. Historically, the area was thoroughly covered by tidal marshlands containing an intricate network of channels which became shallower and narrower away from the bay (fig. 3). Today, about ten to fifteen percent of the Palo Alto baylands still consists of these natural marshlands. The remainder of the baylands is being restored (Palo Alto Flood Control Basin and Faber tract), used for recreational purposes (golf course, yacht harbor, and municipal airport) or for private businesses and waste disposal (fig. 2). Man's activities have included filling of the land surface and building construction resulting in the destruction of natural marshland vegetation and modification or total removal of natural tidal channels.

This study is concerned with the hydrogeology of all of the Palo Alto baylands, but the study of the near surface hydrogeology was only concerned with approximately forty percent of the baylands. Specifically, this portion includes all the natural marshes and the Palo Alto Flood Control Basin which is currently under plans of being environmentally restored. Detailed field experiments were conducted in two specific locations in these areas: one in the northeast part of the Cooley Landing marsh, the other in the northern part of the Palo Alto Flood Control Basin (fig. 2). Further geographic descriptions of these field areas are included in the section on the near surface hydrogeology.

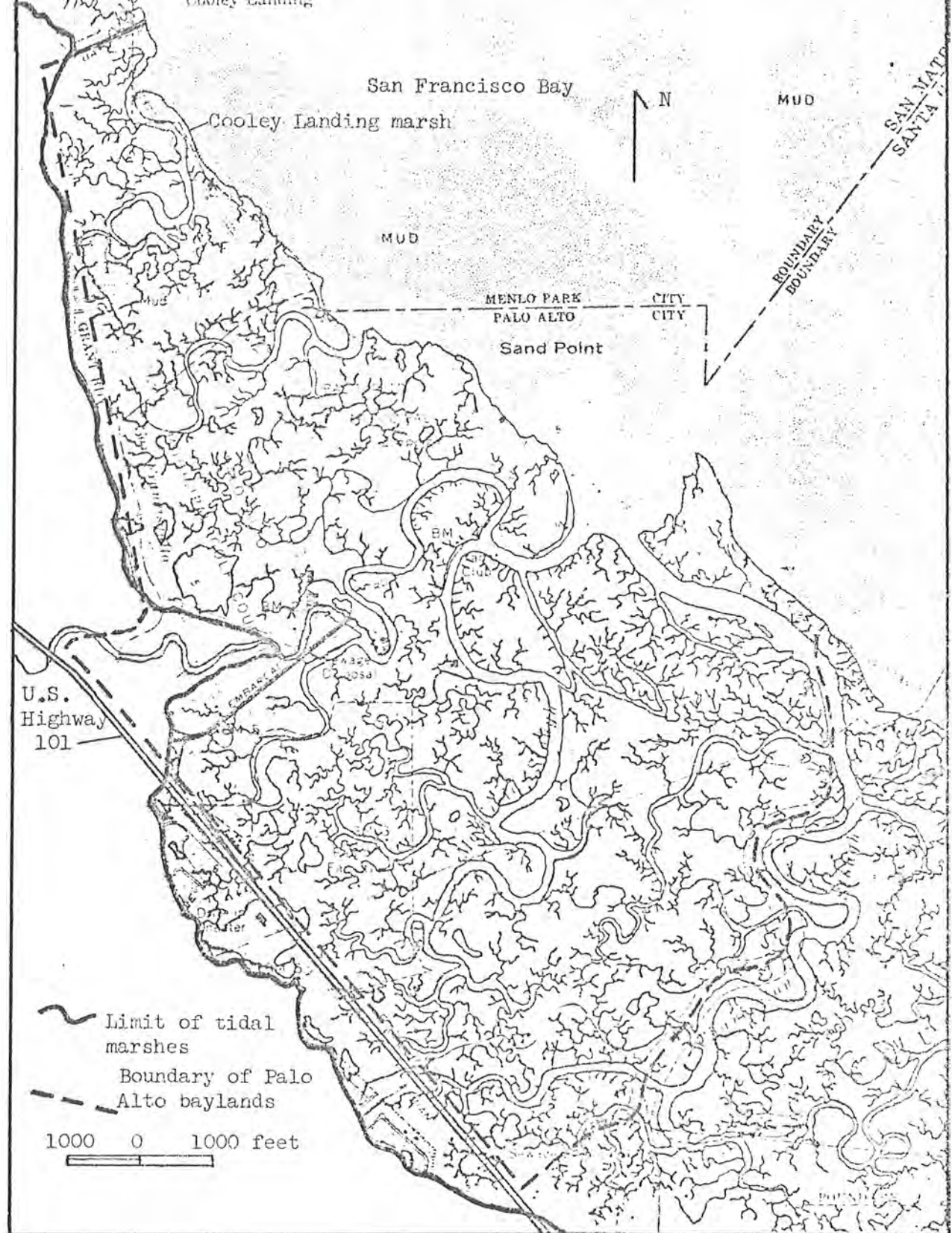


Figure 3. Historic extent of natural tidal marshlands in Palo Alto baylands area. Compiled by Nichols and Wright (1971).

GEOLOGY

In a hydrogeologic study such as this, it is necessary to describe in detail the geology of the area because it controls the flow and occurrence of water. In addition, an understanding of the processes that have developed particular geologic conditions allows accurate extrapolation of hydrogeologic conditions where not many data have been collected. Therefore details of the geology accumulated from various logs are presented along with the conclusions of recent studies on the geology of the Palo Alto baylands.

REGIONAL SETTING

The Palo Alto baylands is located in a region that has been tectonically active for several million years. Northwest-southeast trending structures have developed with long parallel mountain ranges and valleys. The Santa Cruz Mountains and the Diablo Range lie to the southwest and northeast of the Santa Clara Valley, respectively, and are composed of Jurassic, Cretaceous and Cenozoic marine rocks with some ultramafic rocks of Mesozoic age. The Santa Clara Valley is the result of a combination of downwarping and faulting and during the Quaternary has accumulated an aggregate thickness of 1000 to 1500 feet of continental sands, silts and clays interrupted by fairly thick sequences of marine clays (California Department of W. R. Bull., 1967).

STRATIGRAPHY

The first 200 feet of sediments below the Palo Alto baylands were considered in analyzing the hydrogeology of the area. These sediments

are flat-lying, unconsolidated and late Quaternary in age. Sea level fluctuations in the last 150,000 years have produced an interfingering of alluvial and estuarine sediments.

Sediments from 60 to 200 Feet Below the Surface

The deposits from 200 to 60 feet below the surface were studied by use of available well logs in the Palo Alto baylands area. The sequence is dominated by firm gray silty clay which contains a few minor lenses of sand and gravel. At depths of about 150 to 200 feet the sediments are predominantly mixtures of sand and gravel. The density of well logs in the area is too low to enable tracing of these coarse deposits which are highly variable in thickness.

Sediments from 60 Feet Below the Surface to the Bay Mud

In order to describe the sediments of the first 60 feet below the baylands in as much detail as possible approximately 70 engineering boring logs and 30 well logs were accumulated. From these logs a fence diagram was constructed (fig. 4) by placing the geologic descriptions on the diagram and connecting together units of similar grain size. Figure 5 shows the location of the fence diagram and the logs. It must be kept in mind that the logs, especially the well logs, are variable in quality and the same material may be described differently by two drillers. Also, in some areas there are few logs available and here interpolations of units were not made since the sediments are highly variable laterally. Fortunately the writer has some feeling for the character of these deposits since he observed 35 shallow borings to depths of 7 to 10 feet and four borings to a depth of 32 feet.

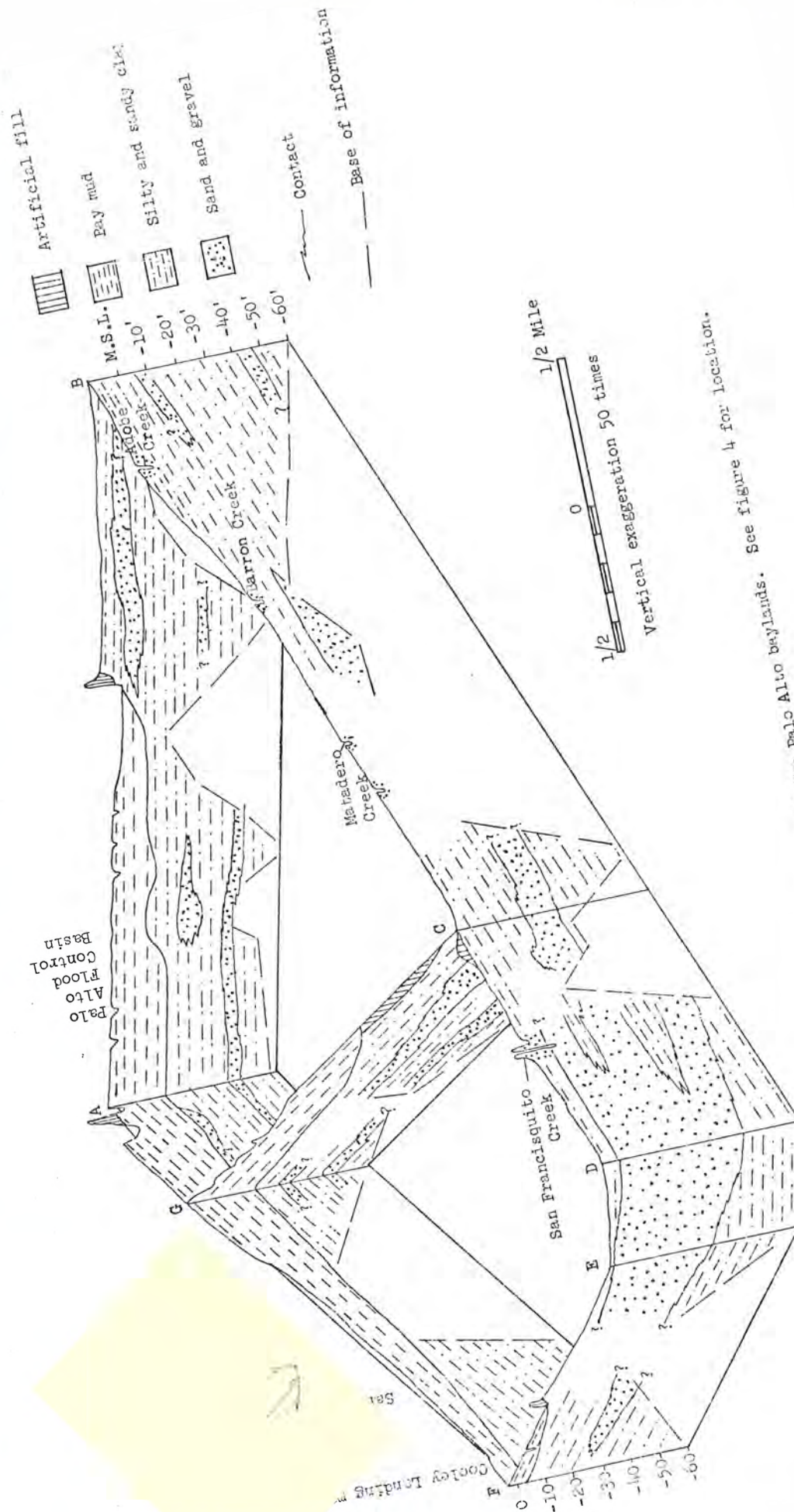


Figure 4. Fence diagram of the Palo Alto baylands. See figure 4 for location.

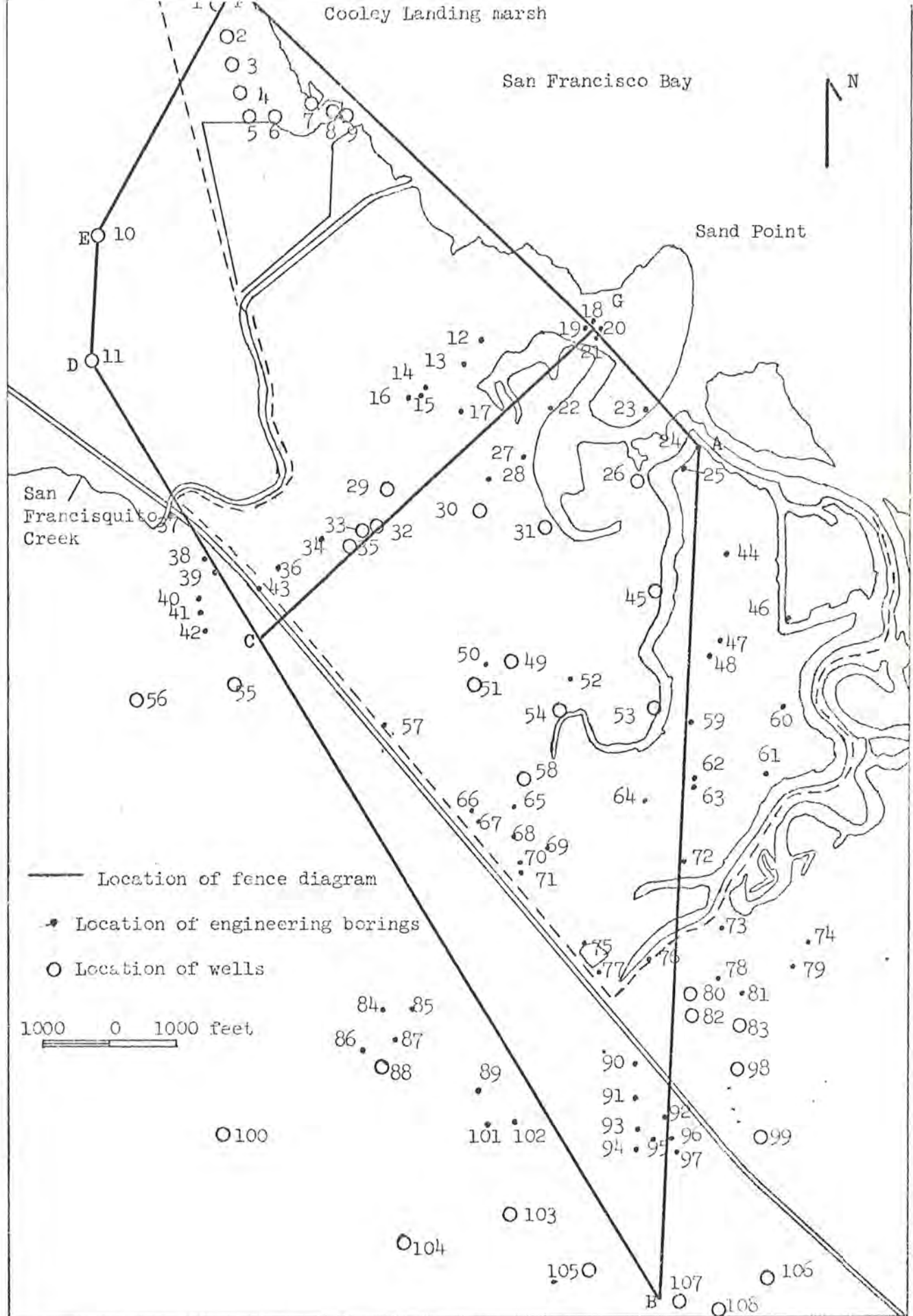


Figure 5. Location of fence diagram and well and engineering logs. Source of logs is given in appendix A.

On figure 4 two members are outlined below the bay mud and artificial fill. These members correspond to a general grouping of clay on the one hand and sand and gravel on the other. The clay member is mostly silty and often becomes sandy next to coarser deposits. Minor lenses of gravel and sand of about a foot thick occur throughout this member. The color of these silty clays is commonly described as gray, brown, yellow and tan. In some places, especially just below the bay mud, the silty clay is described as greenish-brown. These silty clays are predominantly firm to stiff and are fairly dense.

The other member delineated on the fence diagram consists of loose to dense coarse-grained deposits consisting mainly of sand and gravel with some silt. These deposits are moderately to poorly sorted and usually contain a small percentage of clay which evidently gives them their brown to gray color. The gravel has been observed by the writer to be well rounded, flat and as much as two inches in its longest dimension. The sand is of all sizes from fine to coarse. No detailed information is available to interpret trends in grain size distribution.

The firm silty and sandy clay member and sand and gravel member are complexly interfingering and variable in areal extent and thickness. Two beds of the sand and gravel deposits can be traced for some distance in the central part of the area. Section G-C in figure 5 shows the beds at a depth of 45 and 25 feet each varying from about 5 to 10 feet in thickness. The bed at 45 feet continues in section G-A, whereas the bed at 25 feet seems to lense out and become a sandy clay. In the southwest, section D-C-B, it is difficult to determine whether these beds are continuous partly because of the lack of information. The trend is, however, toward

a coarsening of the total section to the southwest toward the Santa Cruz Mountains. Thus, if these beds are continuous to the southwest, they probably thicken and thus effectively merge. Toward the bay the section becomes predominantly more fine grained (clayey) with considerable thinning of coarser deposits.

Bay Mud

The previous unit is overlain by what is informally called the bay mud. The bay mud is a gray to dark gray (sometimes bluish-gray or black) silty clay which contains lenses and layers of sand, gravel, peat and shell fragments. The top few feet of the bay mud consist of a brownish-gray silty soil. The clay fraction varies from about 45 to 95% and is composed of micas, montmorillonitic material, some kaolinite and less than 10% each of quartz, feldspars and diatom and sponge fragments (Pestrong, 1972).

The bay mud is soft and plastic basically because it is a recent reposit. The base of the bay mud may become firmer due to the weight of overlying mud. The bay mud has a fairly high natural moisture content (moisture content as a percent of dry weight) ranging from 50 to 250% as opposed to 20 to 30% for the firm silty clay previously described*. The dry density of the bay mud varies from 50 to 80 lbs/ft³ as compared to higher values of 90 to 110 lbs/ft³ for the firm silty clay. Shear strengths also differ markedly between the bay mud and the firm silty clay

* All physical properties were obtained from engineering boring logs.

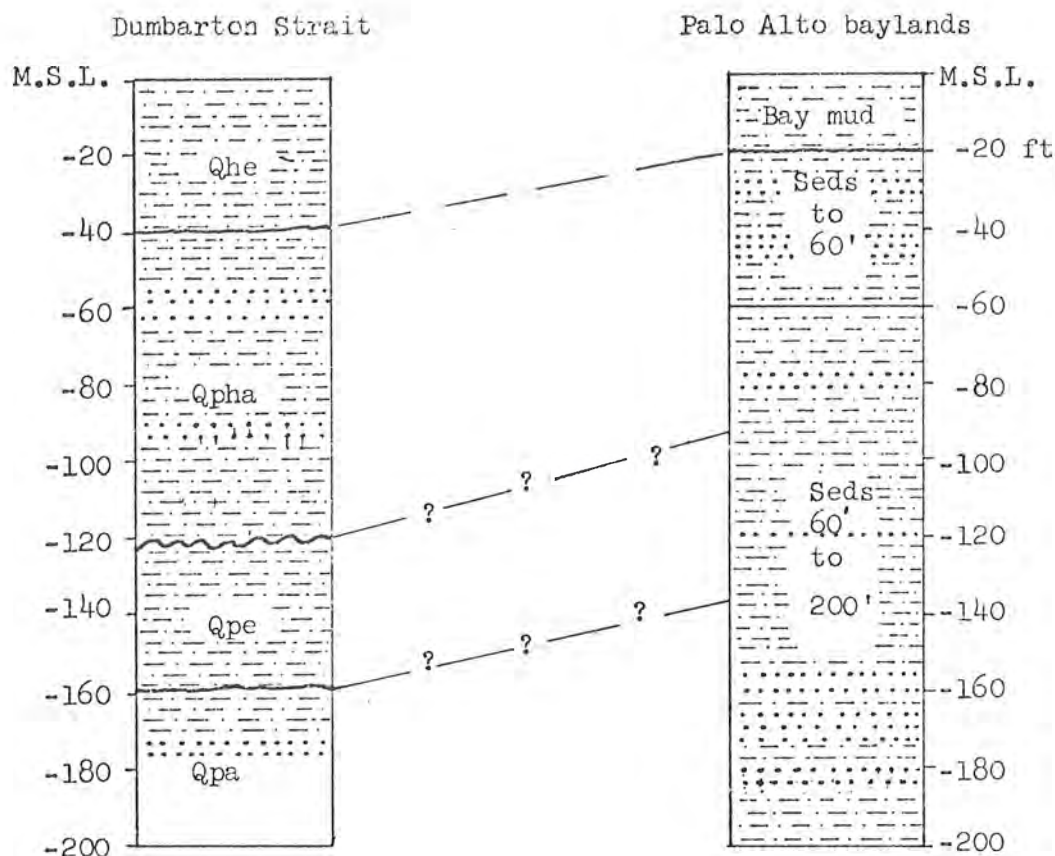
with the bay mud having values of 100 to 600 lbs/ft² and the firm silty clay 1000 to 2500 lbs/ft². The relatively high moisture content and low dry density and shear strength of the bay mud serve to distinguish it from the firm silty clay at lower depths.

The bay mud varies from 0 to 20 feet thick (see fig. 4) throughout the Palo Alto baylands and thins fairly consistently to the southwest. It appears to thin and thicken locally which is probably the result of deposition of the unit on an irregular alluvial surface.

Interpretation of the Sediments and Geologic History

Atwater, et al., (1976) have recently interpreted the environments of deposition of the sediments described above by looking in detail at preserved borings drilled along the site of the Dumbarton Bridge which is located about two miles northwest of the Palo Alto baylands. Based on many criteria, including texture, physical properties, and microscopic constituents, they developed a cross-section (across the Dumbarton Strait) which delineates the different environments.

Four of the units that Atwater, et al., delineated are shown generalized in figure 6. This section is from the west side of the Dumbarton Strait. The basal unit, Qpa, is described as undivided terrestrial and estuarine deposits of Pliocene(?) to late Pleistocene age. This unit is relatively thick and its uppermost section is shown in figure 6 from a depth of 180 to 160 feet. These deposits consist of alluvial clay, silt, sand and gravel. Overlying Qpa at an average thickness of 30 to 40 feet is Qpe which is mainly clay and silty clay interpreted to be estuarine in origin because it contains estuarine diatoms, bivalves and foraminifers. Qpe is believed to have formed during the high stand of the sea during the Sangamon interglacial age (about 75-



Clay, silty and sandy clay with some silt



Sand and gravel



Disconformity ($10^4 - 10^5$ years)



Conformable or slightly disconformable ($0 - 10^4$ years)

Qhe: Holocene estuarine deposits

Qpha: Late Pleistocene to Holocene alluvial deposits

Qpe: Late Pleistocene estuarine deposits

Qpa: Pliocene (?) to late Pleistocene terrestrial and estuarine deposits

Figure 6. Correlation of Dumbarton Strait and Palo Alto baylands stratigraphies. Both sections represent the geology at the edge of the present bay. Dumbarton Strait section was derived from Atwater, Hedel and Helley, 1976 (in technical review).

125,000 years ago). Unconformably overlying Qpe is alluvial clay, silt, sand and gravel of late Pleistocene to Holocene age (bracketed to be younger than 100,000 years and older than about 7,000) and is designated as Qpha. This material extends up to the base of the bay mud and was deposited during the Wisconsin glacial age. The last unit, Qhe, is referred to as the bay mud in this report and has a variable thickness of 0 to 60 feet in the Dumbarton Bridge area. Qhe is estuarine in origin, no older than 10,000 years (post Wisconsin) in the bay area and still being deposited today.

The inferred correlations between the sediments in the Dumbarton Strait and Palo Alto baylands areas are shown in figure 6. Note that the separation between alluvial and estuarine material is not based solely on differences in grain size. Alluvial sediments commonly contain large amounts of clay and are distinguished from estuarine deposits by a lack of estuarine organisms.

Briefly then the 200 feet of sediments below the Palo Alto Baylands have been deposited by alternating alluvial and estuarine environments in about the last 150,000 years. During the Sangamon the sea inundated the Palo Alto baylands area and deposited a fairly thick sequence of clays over a late Pleistocene alluvial surface. Sometime in the Wisconsin the sea retreated exposing the estuarine deposits which were partly eroded and covered with alluvial sediments. Near the end of this glacial period the sea once again covered the area and deposited the present bay mud. This inundation did not reach the Palo Alto baylands area until about 2000 to 3000 years ago (Atwater and Hedel, 1976). About 1000 years ago sediment accumulated to the surface of the slowly rising bay so that

tidal marsh deposits could start to form. In the last 1000 years the tidal marshes have grown upward and bayward to form the extensive natural marshes that existed in the 1800's (fig. 3).

SUBSURFACE WATER

The flow and occurrence of water in the sediments described in the last section is now discussed. Most of this information has been compiled from reports by the Santa Clara Valley Water District (SCVWD) and the California Department of Water Resources.

REGIONAL SETTING

The Palo Alto baylands is located in what is referred to as a pressure zone. That is, the aquifers are confined and under pressure. The source of freshwater recharge to these aquifers is from a forebay zone located a few miles southwest of the baylands. This zone trends in a northwest-southeast direction at the southeastern foot of the Santa Cruz Mountains. The forebay zone consists mainly of coarse alluvial sediments in which the water is unconfined. During rainy months water from San Francisquito Creek and Matedero, Barron and Adobe Creeks (drainage area of 27 mi²) recharges the unconfined aquifers of the forebay zone as it flows out of the Santa Cruz Mountains. Water from the unconfined aquifers flows into several confined aquifers in the northeast which are separated by thick sequences of clay aquicludes. Regionally, the water-bearing section becomes finer grained to the northeast toward the San Francisco Bay with a general thinning of the confined aquifers as clay aquicludes dominate the section.

GROUNDWATER

Deep Zone

As mentioned earlier, at a depth of approximately 150 to 200 feet the sediments are predominantly sand and gravel and average about 20 to 30 feet thick. These sediments transmit significant quantities of water and will be referred to as the deep aquifer. The deep aquifer is confined by a thick sequence of clay which extends up to an average depth of 60 feet. Pumping tests show that this aquifer is continuous to the north and east of the baylands area (California Department of Water Resources Bull., 1967). In the east, across the bay in what is called the Niles subarea, this aquifer is called the Centerville aquifer. To the west, in what is called the San Francisquito subarea, the deep aquifer is discontinuous as also shown by pumping tests. This discontinuity is used to delineate two different groundwater subareas, namely the San Francisquito and Niles subareas.

Recently, pumping tests were conducted within the Palo Alto baylands by Brown and Caldwell. Their tests by Embarcadero Road (see fig. 9 for test well location) indicate that the deep aquifer is fully confined and artesian with an average transmissivity of 6300 gpd/ft (gallons/day per ft²) and a storativity of 0.002 (Jenks and Adamson, 1974). From their calculations Jenks and Adamson have concluded that the aquifer is also anisotropic with transmissivities as high as 12,500 gpd/ft in one direction and as low as 3000 gpd/ft in another. The shallow zone aquifers (to be discussed presently) were monitored during the tests on the deep aquifer and showed no response to the pumping. Thus the deep aquifer appears hydraulically sealed from the shallow aquifers.

The piezometric surface is not well defined for the deep aquifer but has been measured in a recently installed well (which has a perforated interval of 191.1 to 196.5 feet deep), 6S/2W-5F3, to be 25 feet below mean sea level. The Santa Clara Valley Water District reports a range from 29 to 96 feet in 1972 in the general area. Local pumping in the baylands has lowered the piezometric surface and caused hydraulic gradients to wells and, at times of high pumpage, caused a general flow of water inland. Figure 7 shows the elevation of groundwater in 1973 in aquifers less than 200 feet deep (Jenks and Adamson, 1973). This level represents conditions immediately to the south and southwest of the Palo Alto baylands.

The clay deposits separating the shallow aquifers from the deep aquifer are fairly extensive to the east and are referred to as an aquiclude or aquitard depending on its ability to transmit water. Clay aquitards can hold large amounts of water and under a high vertical hydraulic gradient can transmit significant amounts of water if they cover a large area. Transmission of water vertically may also be produced by favorable connection of thin discontinuous sand lenses which provide "holes" through the aquiclude.

Shallow Zone

The shallow zone (extending to a depth of 60 feet) basically contains leaky confined aquifers interfingered with aquitards. The aquifers are relatively thin and consist of highly variable sand and gravel deposits. The total thickness of the shallow aquifers averages about 10 feet and is mainly limited to a zone of about 10 to 50 feet deep.

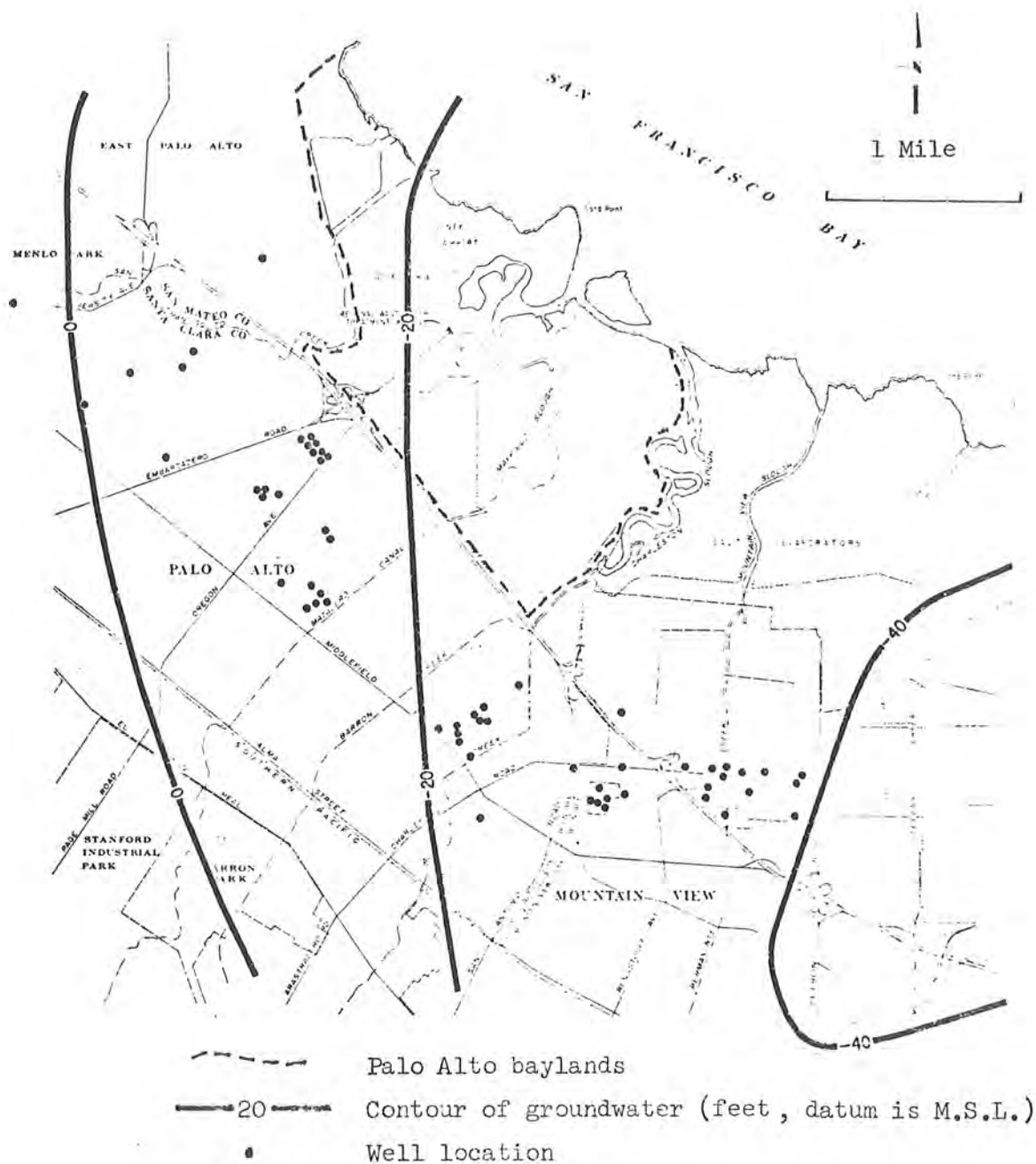


Figure 7. Approximate lines of equal elevation of groundwater in 1973. Includes aquifers of first 200 feet below area south and southwest of Palo Alto baylands. Source: Jenks and Adamson, 1973.

These aquifers thin out readily but most likely are interfingered because the zone appears hydraulically continuous throughout the area. The shallow aquifers continue in the east and are called the Newark aquifer in the Niles subarea.

Pumping tests by Embarcadero Road (by Brown and Caldwell) on two different aquifers at depths of 25 and 45 feet showed that the two aquifers were hydraulically connected. The tests showed that the 45 foot aquifer is leaky and gains water from the 25 foot aquifer above. Analysis of the pump test data indicated the aquifer at 45 feet has a calculated transmissivity of 8700 gpd/ft and a storativity of 0.000036. Calculations for the aquitard above it gave a vertical hydraulic conductivity of 0.032 gpd/ft and storativity of 0.001. A transmissivity of 3500 gpd/ft and storativity of 0.002 were determined for the aquifer at 25 feet. It must be kept in mind that these members represent a very localized situation in the Palo Alto baylands. For the method of analysis of the tests and the appropriate calculations see Jenks and Adamson (1974).

Wells tapping the shallow aquifers show water levels of just a few feet below the ground surface. The Santa Clara Valley Water District reports 1972 conditions ranging from 5 feet above to 5 feet below mean sea level. Several different heights have been measured from the shallow zone and indicate that the aquifers are locally discontinuous. The piezometric surface of this zone is essentially flat in the baylands area but when inland pumping is high a hydraulic gradient toward the inland is produced. The result is the intrusion of saline water from the south San Francisco bay area to inland aquifers.

Figure 8 shows the general occurrence and movement of ground water in the first 60 feet of deposits. The water occurs in several different modes because of the character of the deposits. Recharge occurs from unconfined aquifers in the west. The water table and surface water of the bay is generally higher than the piezometric surface of the shallow confined aquifers and thus there is a small vertical hydraulic gradient down into the confined aquifer through the near surface aquitard. Generally the aquitard will contain some amounts of sand and silt and exhibit some permeability. Finally, since the aquifer of the deep zone below has a piezometric head of 20 feet or more lower than the shallow zone aquifers, then water may percolate very slowly down through its confining aquitard. Figure 8 shows the conditions of high inland pumpage which causes groundwater to flow from northeast to southwest. The unconfined ground water within 10 feet of the surface will be discussed in the section on the near surface hydrogeology.

WATER QUALITY

Recently several of the wells in the Palo Alto baylands area have been sampled as part of a study of the salt water intrusion that is occurring in the aquifers of the shallow zone. In the summer of 1972 the Santa Clara Valley Water District sampled 16 wells in the area and the city of Palo Alto sampled ten. Also in 1974 water samples were taken from several monitoring wells during the pumping tests performed by Brown and Caldwell.

From this data Table 1 has been compiled and shows the chloride content of groundwater in different locations, at different depths and

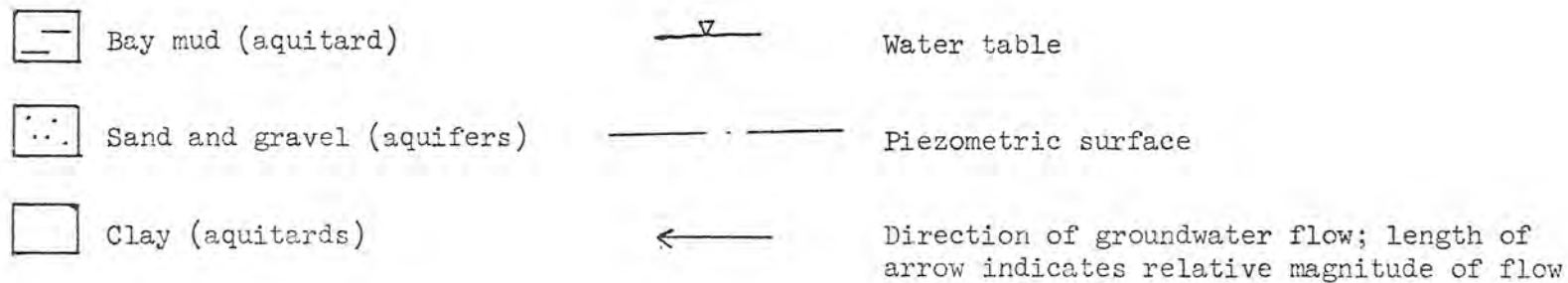
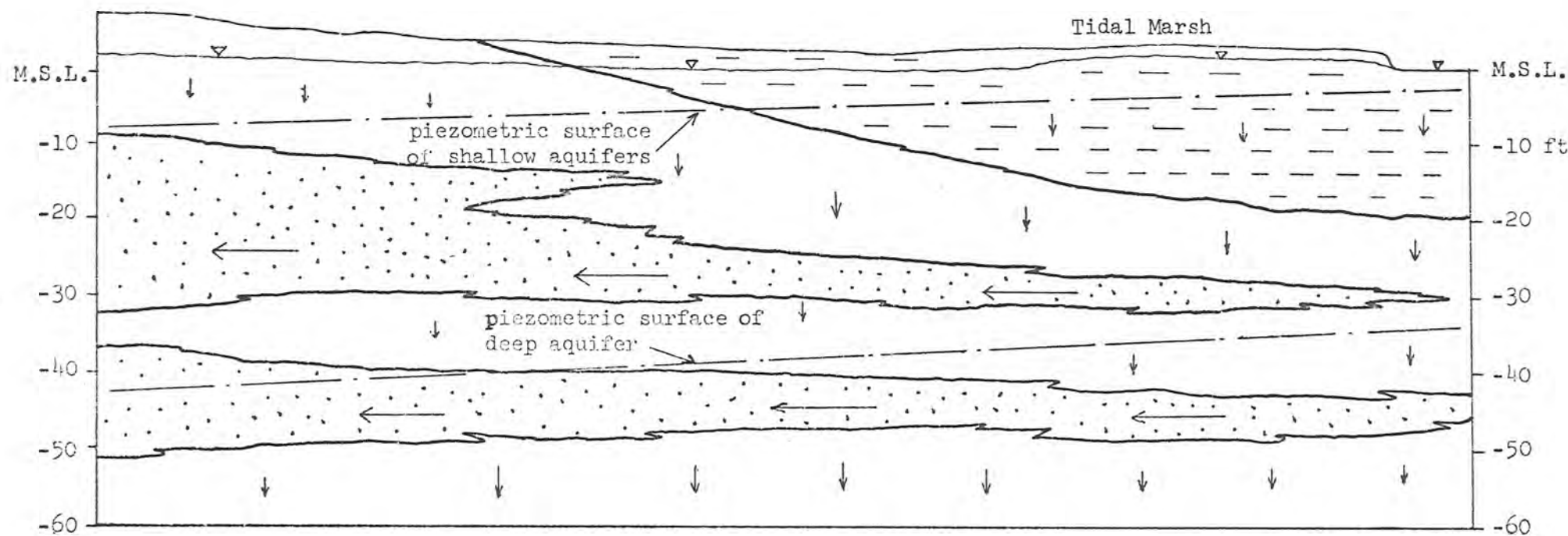


Figure 8. General occurrence and movement of groundwater in the Palo Alto baylands.

TABLE 1

CHLORIDES, pH AND TOTAL DISSOLVED SOLIDS OF VARIOUS
WATER SAMPLES TAKEN FROM WELLS IN THE PALO ALTO BAYLANDS AREA
(ADAPTED FROM JENKS AND ADAMSON, 1973 AND 1974)

<u>Date</u>	<u>Name or owner</u>	<u>Location</u>	<u>Perforated interval (depth in ft)</u>	<u>Chlorides (mg/l)</u>	<u>pH</u>	<u>Total dissolved solids (mg/l)</u>
10/10/74	Duck Pond	5S/2W-32C2	175-190	380	-	-
7-9/72	Calif. Dept. of Water Resources	5S/2W-34N1 5S/2W-34N2	77-82 177-184	14,000 186	7.7 8.65	28,610 546
7-9/72	Palo Alto Yacht Harbor	5S/2W-32F10	185-198	204	8.25	746
9/19/74	I/E Well (20 ft)	(see fig. 9)	20*	4,360	-	-
9/20/74	"	"	"	4,280	-	-
9/20/74	"	"	"	4,200	-	-
9/4/74	I/E Well (45 ft)	"	45*	3,510	-	-
9/4/74	"	"	"	3,390	-	-
9/3/74	"	"	"	3,190	-	-
8/29/74	I/E Well (180 ft)	"	180*	29	-	-
8/30/74	"	"	"	26	-	-
8/31/74	"	"	"	27	-	-
7-9/72	Tom's Well	6S/2W-5F1	21-31	6,500	12.15	12,180
"	"	6S/2W-5F2	40-50	10,300	9.20	17,440
"	"	6S/2W-5F3	190-200	170	8.25	560
10/10/74	"	6S/2W-5F1	21-31	15,000+	-	-
"	"	6S/2W-5F2	40-50	15,000+	-	-
"	"	6S/2W-5F3	190-200	30	-	-

TABLE 1 (CONT)

<u>Date</u>	<u>Name or owner</u>	<u>Location</u>	<u>Perferated interval (depth in ft)</u>	<u>Chlorides (mg/l)</u>	<u>pH</u>	<u>Total dissolved solids (mg/l)</u>
8/23/74	Chabot Terrace	6S/2W-6B10	shallow	210	-	-
8/23/74	St. Francis	6S/2W-C17	shallow	72	-	-
8/23/74	Amarillo	6S/2W-L10	shallow	70	-	-
8/23/74	Amarillo	6S/2W-L11	shallow	80	-	-
7-9/72	McGregor	6S/2W-8H1	284*	13	8.14	252
7-9/72	Trainer	6S/2W-8K1	60*	111	7.75	1,092
7-9/72	Samuma	6S/2W-8M	25-27 28-31 38-42	56	7.45	772
7-9/72	Reutter	6S/2W-6N10	26-28	125	7.38	982

* Perferated interval not specified. Approximate depth of interval given.

different times in the Palo Alto baylands (see fig. 9 for location of wells). For some water samples pH and total dissolved solids are indicated. The trends in Table 1 are readily apparent. The aquifer of the deep zone has relatively low chloride values of 186, 204 and 380 mg/l (milligrams/liter) near the edge of the bay while about a mile inland the aquifer has lower values of 13, 26, 27, 29, 30 and 170 mg/l. The aquifers of the shallow zone show a drastic change from the deep aquifer, with values higher than 15,000 mg/l in Tom's Well which is adjacent to a brackish slough in the Palo Alto Flood Control Basin one mile southwest of the bay. Inland, away from saline water, the chloride content in the shallow aquifers is lower but still high at 3000 to 4000 mg/l. Farther inland, west of U.S. Highway 101, the shallow zone shows normal chloride content ranging from 56 to 210 mg/l. Thus saline water intrusion in the shallow zone seems to be limited to about one and a half miles inland as of the date the samples were taken. These data and others on the shallow aquifers were used by the SCVWD to show the extent of the chloride concentration in 1930, 1939 to 1949, and 1972, as shown in figure 10.

The high chloride content in the shallow aquifers near the bay has long been known, but the process of chloride intrusion is not totally understood. Originally, before high pumpage of wells, the piezometric head of the aquifers was probably higher than the existing near surface water table and had a slight hydraulic gradient toward the bay. But since extensive pumping has occurred in inland areas the piezometric head has been lowered below the water table producing a downward vertical hydraulic gradient and, at times, a horizontal hydraulic gradient through the shallow aquifers away from the bay. Therefore today's conditions

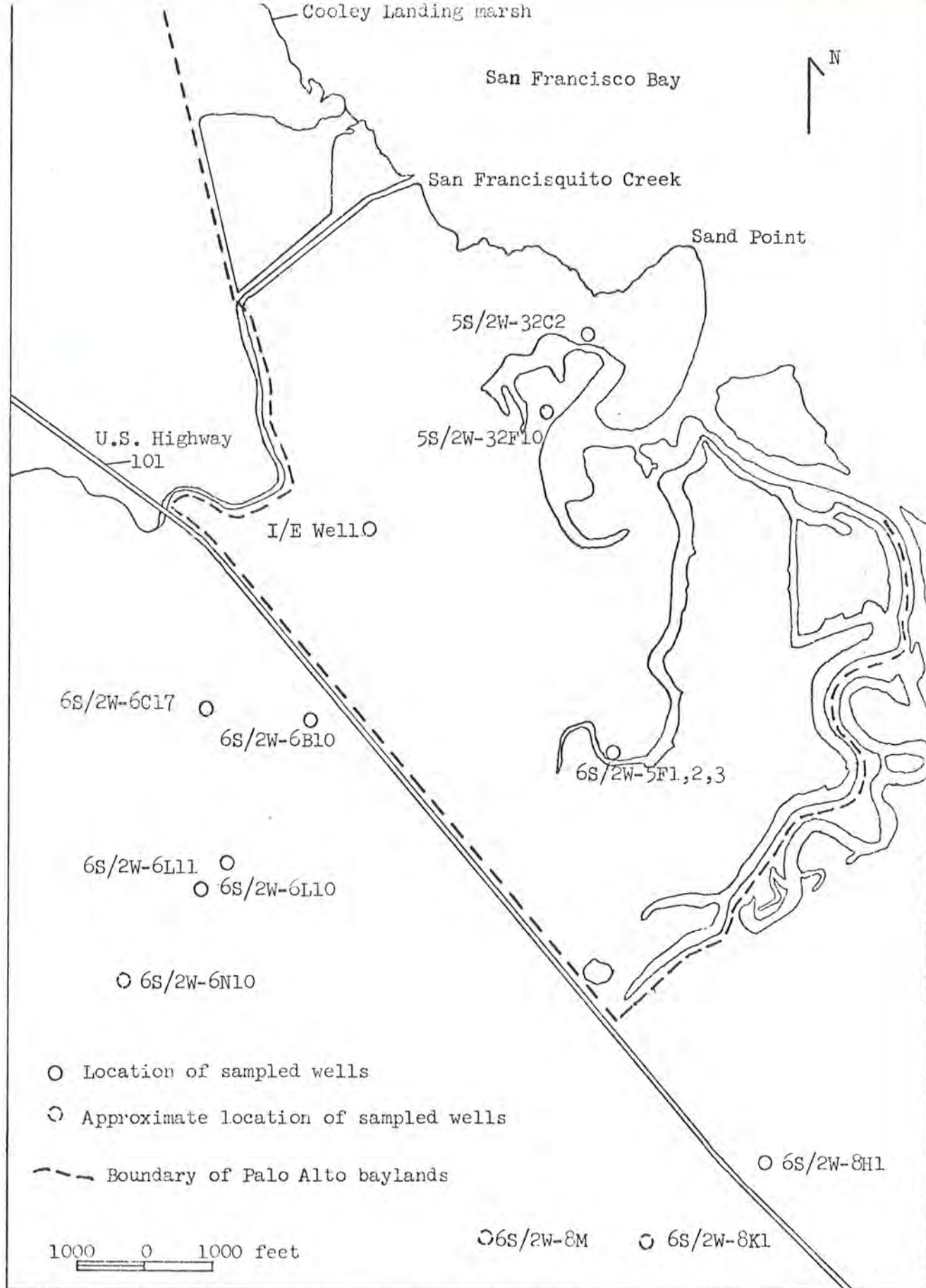
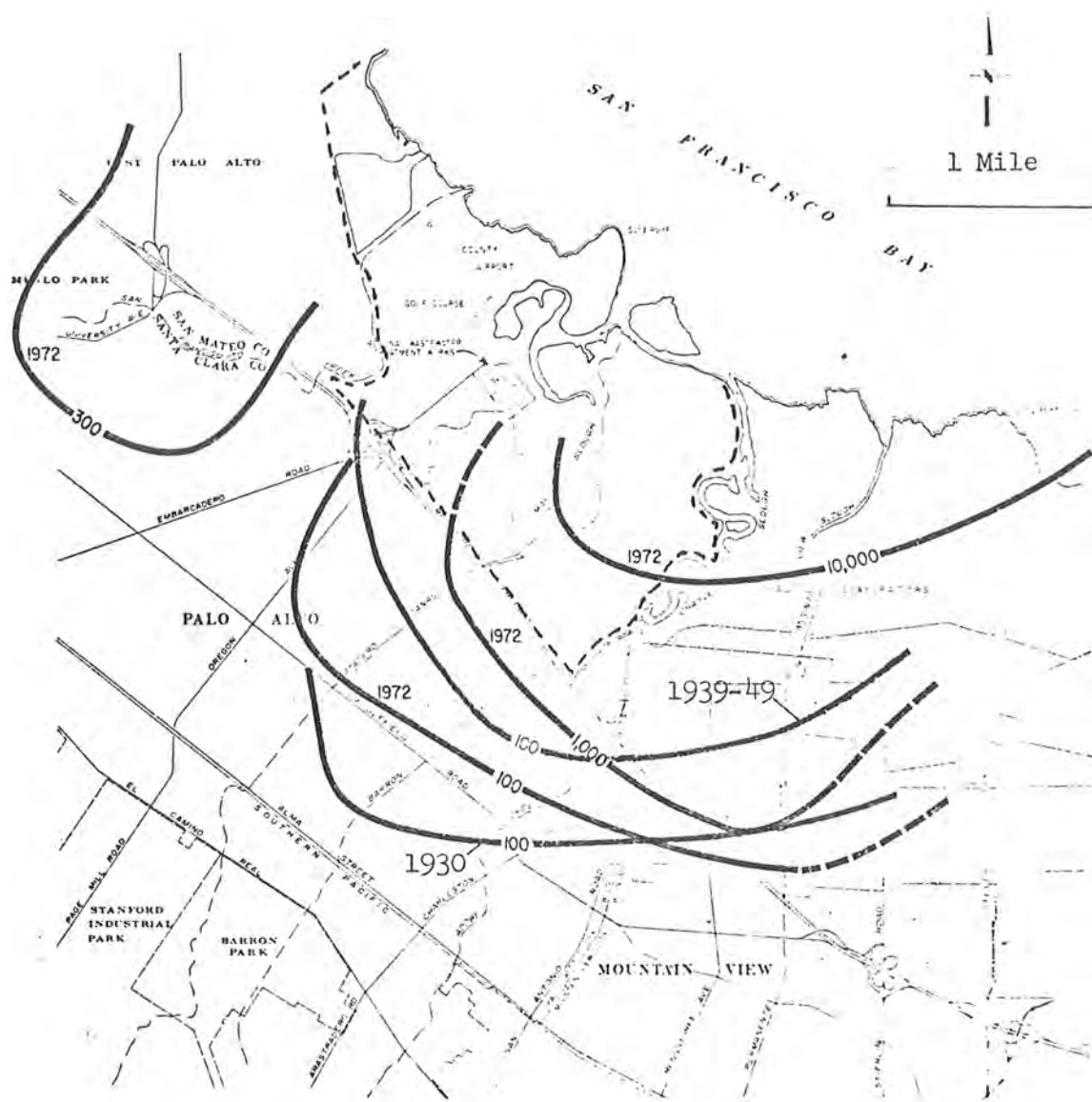


Figure 9. Location of wells sampled for chloride content. Wells 5S/2W-34N1 and 2 are located at the edge of the bay on the east side of area shown.



— 5 — Contour of chloride content (mg/l)

- - - - - Palo Alto baylands

Figure 10. Lines of equal chloride concentration in shallow aquifers less than 150 feet below the surface.
Source: Jenks and Adamson, 1973.

allow for the slow percolation of saline bay water through the near surface aquitard into the shallow aquifers. The saline water is then brought inland through the shallow aquifers under the horizontal hydraulic gradient.

There are a number of ways saline water contamination might occur in the shallow aquifers. If there exists a vertical hydraulic gradient from the bay to the aquifers below significant quantities of saline water can be transmitted downward even through material that is predominantly clay. For example, assuming a vertical permeability of 0.02 gpd/ft^2 under a unit hydraulic gradient of 1 ft/ft (Darcy velocity of one foot per year), close to 630 acre-ft of water may move across an aquitard covering one square mile (California Dept. of Water Resources Bull., 1973). The phenomenon of chemico-osmotic coupling could also help in contaminating the shallow aquifers. Where the aquifers contain fairly fresh water below a saline body of water a high salt concentration gradient is established which forces saline water down into the aquifers. Finally, exposure of the shallow aquifers directly to the bay water can occur either naturally in the bay channel or artificially by dredging and/or faulty wells.

NEAR SURFACE HYDROGEOLOGY

Of most concern in this study is the behavior of the near surface hydrogeology of the tidal marshes of the Palo Alto baylands. This section describes most of the field work done in this study and, to the knowledge of the writer, is the first such study in the tidal marshes of the San Francisco Bay area. This work is concerned both with the natural marsh areas and the modified area of the Palo Alto Flood Control Basin. In support of these studies two groups of piezometers were installed in the Cooley Landing marsh and the Palo Alto Flood Control Basin (fig. 2).

METHODS

A total of 39 shallow piezometers were installed during the field investigation. In the Palo Alto Flood Control Basin 27 piezometers were installed with the aid of a motorized auger (4" in diameter) run on tractor treads. In the Cooley Landing marsh 12 piezometers were installed by hand auger (3" in diameter). Plastic pipe of 1-1/2" inner diameter and 2" outer diameter was cut and perforated before installation into the augered holes. After insertion of the pipe, 1/2" river gravel was poured in the hole around the pipe at the interval desired. Bentonite mixed with water was used to seal the upper foot near the ground surface. The piezometers were capped by either a threaded cap or by pipe couplings closed at one end by a piece of plexiglas. Samples

of the materials from the various borings were placed in styrofoam cups, the cups marked and sealed with plastic caps.

Pumping tests and water quality sampling were performed with a hand worked plastic pump which has a hydraulic lift of fifteen feet (Plate 6). Volumes of water from the pumping tests were measured by use of a five gallon glass water bottle.

All water levels in the piezometers were measured with a steel tape marked in hundreths of a foot. A weight was suspended at the end of the tape, the taped chalked and then lowered into the piezometer for a water level measurement.

TIDAL MARSHLANDS

General Surface Conditions

Cooley Landing marsh, located in the northern extent of the Palo Alto baylands, was concentrated on in the study of the near surface hydrogeology of the tidal marshes. This marsh and others of the baylands are developed on bay mud which has been deposited in the last 2000 to 3000 years.

There are basically three physiographic features in the tidal marshlands: (1) the tidal marsh, (2) the tidal flat, and (3) the tidal channels. The tidal flat is devoid of vegetation and exists at an elevation between mean high and mean low tide (Plates 1 and 2). It is located bayward of the tidal marshes and slopes very gently toward the center of the bay. The tidal flat muds appear completely saturated at all times.



Plate 1. Sinuous marsh channel near the edge of Cooley Landing marsh (looking south). Spartina lines the channel banks. Water is approaching high tide.



Plate 2. Edge of Cooley Landing marsh (looking west). Spartina lines the edge and Geukensia (common mussel) is exposed on upper tidal flat.

The surface of the tidal marsh exists close to mean high tide and is almost perfectly flat throughout its extent (Plate 2). Locally there are subtle elevation differences on the order of 1/2 foot in the inter-distributary areas. The channels in the tidal marsh have developed from the bi-directional flow of the tides and are part of a complex drainage network (fig. 3). The channels are sinuous and in places are as high as fourth-order segments. The main channels are predominantly steep-banked and flat-bottomed and have an average depth of 3 to 5 feet and range from about 5 to 15 feet wide (Plate 1). Inland, the main channels become narrower and shallower until they phase out completely. The tributaries have similar geometries but are shallower and narrower. They normally join the main channel at a higher elevation than the bottom of the channel; that is, there usually exists a steep gradient near the entrance of the tributaries to the main channels.

Surface water. Tidal fluctuations dominate the character of these marshlands and are controlled by several factors as described by Pestrong (1965). The tides have two highs and two lows daily with the higher high tides followed successively by lower low water, low high water and high low water. Throughout this report mean sea level (M.S.L.), the average height of the surface of the sea for all stages of the tide, will be used as zero datum. At the Palo Alto Yacht Harbor, the various mean water heights have been calculated (Pestrong, 1965):

	<u>feet</u>
Highest tide (estimated)	+6.5
Mean higher high water	+3.9
Mean high water	+3.3
Mean sea level	0.0
Mean low water	-3.3
Mean lower water	-4.5
Lowest tide (estimated)	-7.0

High tides normally overtop the tidal marsh twice a day but during neap tides the fluctuations are reduced and for a period of three to five days twice a month neither high tide will flood the marsh.

The tidal marsh channels funnel the tidal waters in and out of the marsh during the flooding and ebbing of the tide. However, when the marsh is flooded water freely moves over the surface of the marsh. Figure 11 (Pestrong, 1965) shows the relationship of channel stage, discharge, velocity and suspended sediment in two locations of a channel located in the Dumbarton Bridge Point marsh. Peak discharges and velocities occur 1 to 1-1/2 hours before and after maximum stage. The highest velocities occur during ebb tide whereas the highest amount of suspended sediment occurs just at the beginning of flood tide.

Freshwater drainage into the Palo Alto marshes area occurs by San Francisquito Creek (fig. 2). This creek has extensive artificial levees on its banks where it enters the bay and does not flow directly into the tidal marshes.

Vegetation. The tidal marshland is dominated by *Spartinetum* (cord grass) and *Salicornietum* (pickleweed), the dominant plants of these being *Spartina leiantha* and *Salicornia ambigua*, respectively (Hinde, 1952). *Salicornia* dominates the tidal marsh at 3.9 feet about M.S.L. It can not tolerate as much sea water submergence as *Spartina* which is the dominate plant at elevations of .9 to 1.9 feet above M.S.L. *Spartina* has been observed in locations where submergence has occurred for 21 consecutive hours (Hinde, 1952). *Salicornia* and *Spartina* overlap in their vertical extent at heights of 1.9 to 3.9 feet above M.S.L. As a result of these

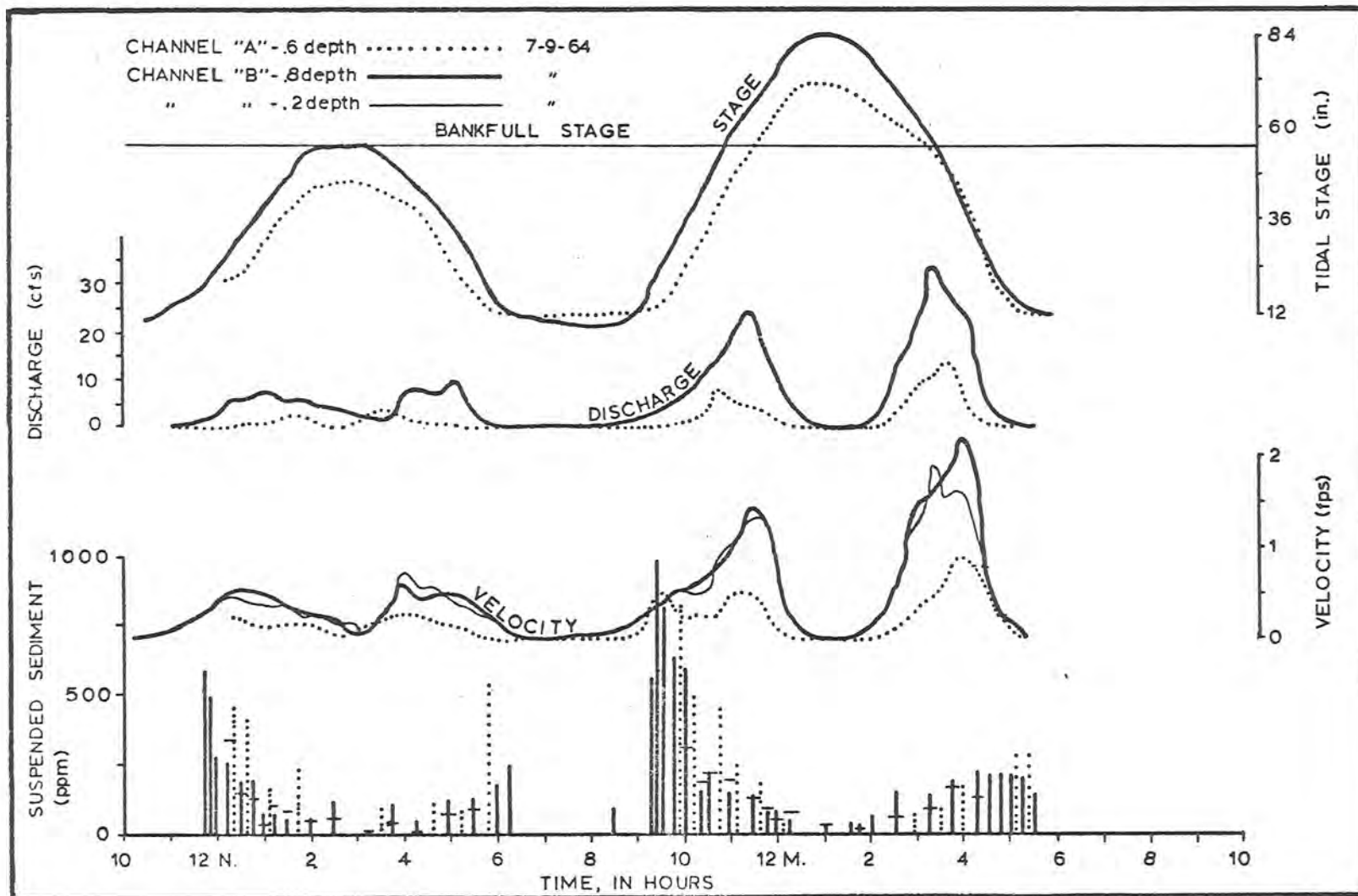


Figure 11. Tidal stage, velocity, discharge and suspended sediment content over one tidal cycle. Channel 'A' is upstream from channel 'B'. Source: Pestrong, 1965.

distributions, Salicornia dominates the marsh surface (Plates 1 and 2) and the channels (where marsh elevations are the highest) and often produces steep-sided channels because of its dense root structure. Commonly, Geukensia demissa (mussels) a mud boring clam, is found beneath these dense growths of Salicornia. Spartina on the other hand generally sits in loose silty muds and lines the channel sides and bottoms (Plate 1). Spartina also colonizes the upper tidal flat immediately adjacent to the edge of the tidal marsh (Plate 2).

Other plants in the tidal marsh include Distichlis spicata which is found between the vertical distributions of Spartina and Salicornia. Chaetomorpha, occurring in algal mats, is found on the bottoms of tidal channels and on the tidal flats.

Soils. The soils in the marshlands have been developed on the gray silty clay on the bay mud. On the surface the soil is gray but turns to a dark gray in the next few feet below the ground. It contains a dense root structure usually to a depth of three feet. Pestrong (1965) classified the soil as "organic clays and silts of medium to high plasticity displaying medium to high dry strength, none to very slow dilatency, and slight to medium toughness". Table 2 shows the average physical properties of soils from the Cooley Landing and PG&E marshes of the Palo Alto baylands as determined by Pestrong (1965). Note that the Salicornia soils have the least moisture and the highest dry density.

Cooley Landing Marsh Field Experiment

The water table in the tidal marshes is very close to the surface and in the area of study was found to be anywhere from a few inches to

TABLE 2

AVERAGE OF SOIL PHYSICAL PROPERTIES IN THE PALO ALTO BAYLANDS
(ADAPTED FROM PESTRONG, 1965)

<u>Location</u>	<u>Natural Moisture content (%)</u>	<u>Dry density (lbs/ft³)</u>	<u>Permeability (cm/sec)</u>	<u>Shear strength (lbs/ft²)</u>	<u>Organic content (%)</u>	<u>Median diameter (microns)</u>	<u>Percent clay</u>
PGE marsh							
Channel	125	38.3	.001	118	9.6	1.6	68
Tidal Flat	133	33.9	.0002	151	10.1	2.5	59
<u>Spartina</u> Marsh	149	36.4	.03	149	12.7	1.9	71
<u>Salicornia</u> Marsh	82	41.9	.04	345	18.1		
Cooley Landing marsh							
Channel	126	37.2	.0003	760	7.8	3.4	62
Tidal Flat	157	30.3	.0002	115	5.1	2.7	63
<u>Spartina</u> Marsh	145	36.7	.04	209	13.8	1.8	68

1-1/2 feet below the marsh surface. Constant inundations by high tides keeps the water table close to the surface. In order to determine the hydraulic characteristics of the marsh deposits shallow piezometers were installed in the Cooley Landing marsh next to one of the main channels (which is approximately 200 feet from the edge of the marsh). Of particular interest here is how the water table responds to the fluctuations of tides in and out of the tidal marsh channel. Of further interest is the permeability of the material and the depth of the permeable section.

Figure 12 shows the characteristics of the material found to a depth of ten feet in the area where the piezometers were installed. The material was highly variable with depth. The first foot consists of moist brown silty clay with many roots. To a depth of about 2-1/2 feet the soil becomes a darker bluish-gray color and still contains many roots. At about this depth water begins to accumulate in the hole. From 2-1/2 feet to 6 feet the silty clay is generally gray and roots are much less abundant with depth. At a depth of 6 feet there is an abrupt transition to muddy peaty material which is reddish-brown and appears unsaturated. At 7 feet there is another abrupt change to wet dark gray sandy clay which grades down into predominantly dark gray clayey sand and gravel. The sand and gravel continues to 10 feet below the surface at which point augering was discontinued. Most of the materials, especially the first 7 feet, had a strong sulfurous odor (probably due to H_2S gas).

Based on the character of these materials piezometers were initially installed next to and 30 feet from the tidal marsh channel. Three piezometers were put in at these locations each tapping different zones:

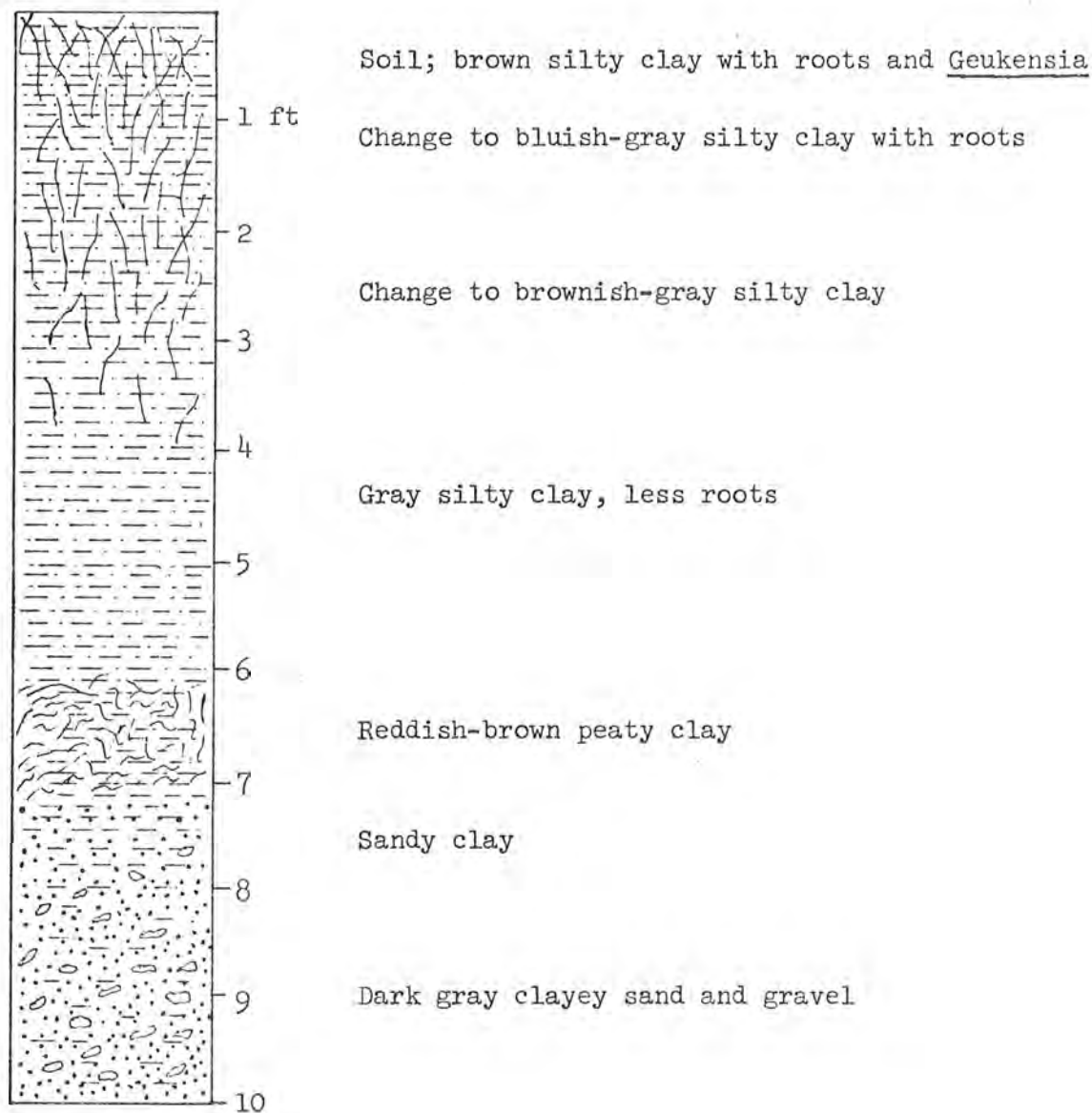


Figure 12. Character of the upper 10 feet of the Cooley Landing marsh deposits. Location of section is shown in figure 2.

(1) the soil and bay mud to a depth of 5 feet, indicated as C piezometers; (2) the sand and gravel at an interval of 7 to 10 feet, indicated as B piezometers; and (3) the whole section of soil, bay mud and sand and gravel indicated as A piezometers. Monitoring of these piezometers for one tidal cycle revealed fluctuations in the water levels of the A and B piezometers next to the channel. Based on this data a line of C piezometers tapping only the upper 5 feet was extended from the channel to a distance of 30 feet. A diagramatic cross-section of the total of 12 piezometers installed, with perforated intervals and lateral distances, is shown in figure 13. The piezometers are numbered from 1 to 8 from the channel. Plates 3 and 4 show the piezometer set-up during low tide and tidal flooding, respectively.

The channel at the piezometer set-up is about 4.4 feet deep and 8 feet wide at the top. It has a steep vertical bank on the south side where the piezometers are located. Plate 5 is a close up of the south side bank. From the marsh surface to a depth of about 3.5 feet the bank material contains mud with an abundance of roots and openings ranging from 1 to 5 millimeters in diameter. The origin of these holes is not known but could be due to Spartina stems (Pestrong, personal communication) or burying worms. The bank near the bottom of the channel appears very smooth and is devoid of roots or holes. The bank on the north side of the channel is not steep and is overgrown with Spartina. This bank has probably slumped into the channel and been smoothed by the tides. No porous structure is present on this bank.

The 12 piezometers were monitored continuously for a 45 hour period (May 4, 5, and 6) during neap tides when the marsh was not flooded.

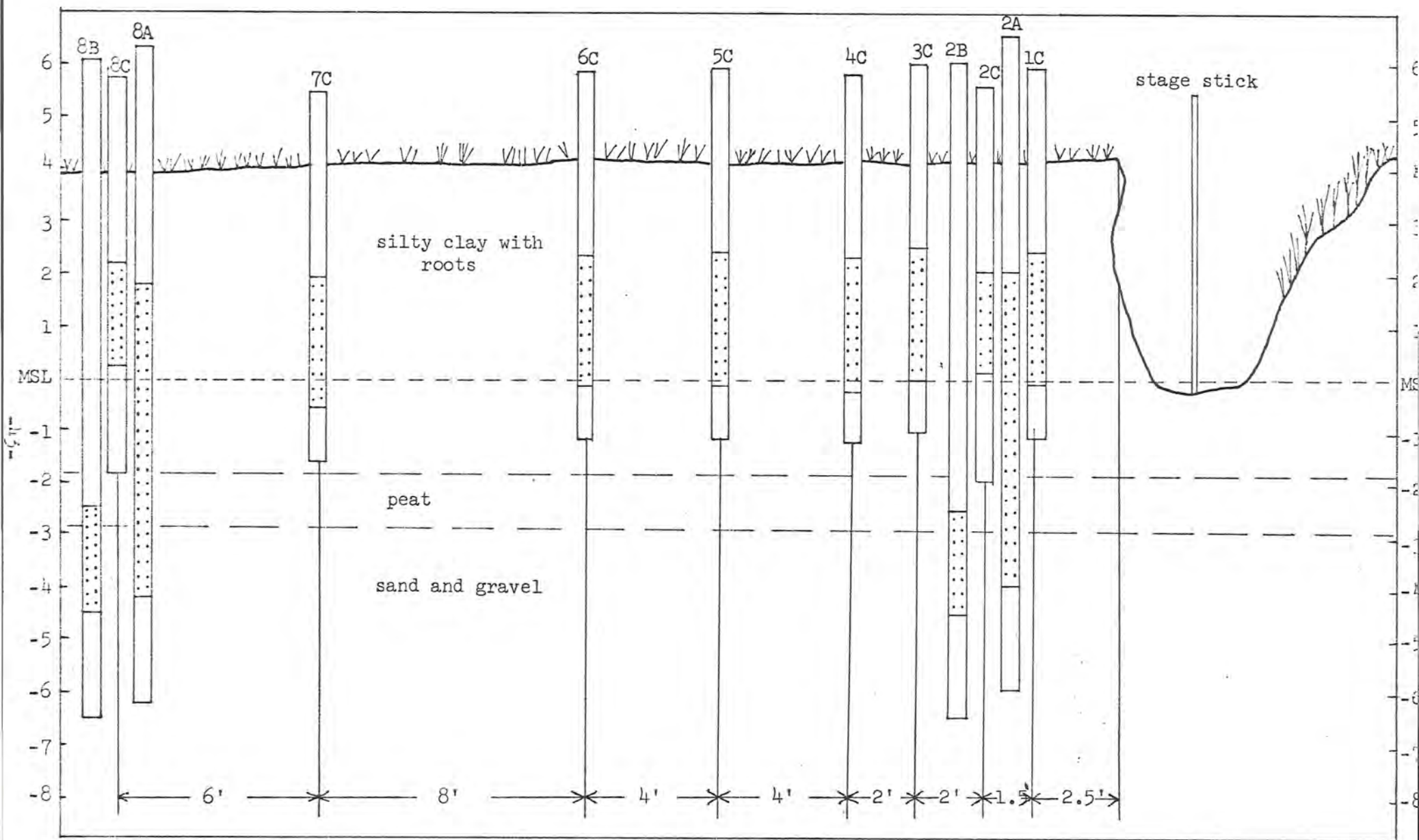


Figure 13. Diagrammatic cross-section of piezometers in Cooley Landing marsh. Spacing and perforated intervals are indicated. Piezometer groups 8A,B,C and 2A,B,C are each 30 and 4 feet from the channel, respectively. Vertical exaggeration is .625.



Plate 3. Piezometer set-up in Cooley Landing marsh (looking south). The row from the channel consists of the C piezometers.



Plate 4. Piezometer set-up during high channel stage.



Plate 5. North facing bank of the marsh channel near the piezometer set-up. Clay and root matrix contains holes of about 5 mm in diameter. Picture covers 4 feet.



Plate 6. Pumping of a piezometer in the Palo Alto Flood Control Basin. Five gallon bottle for measuring pumped volumes.

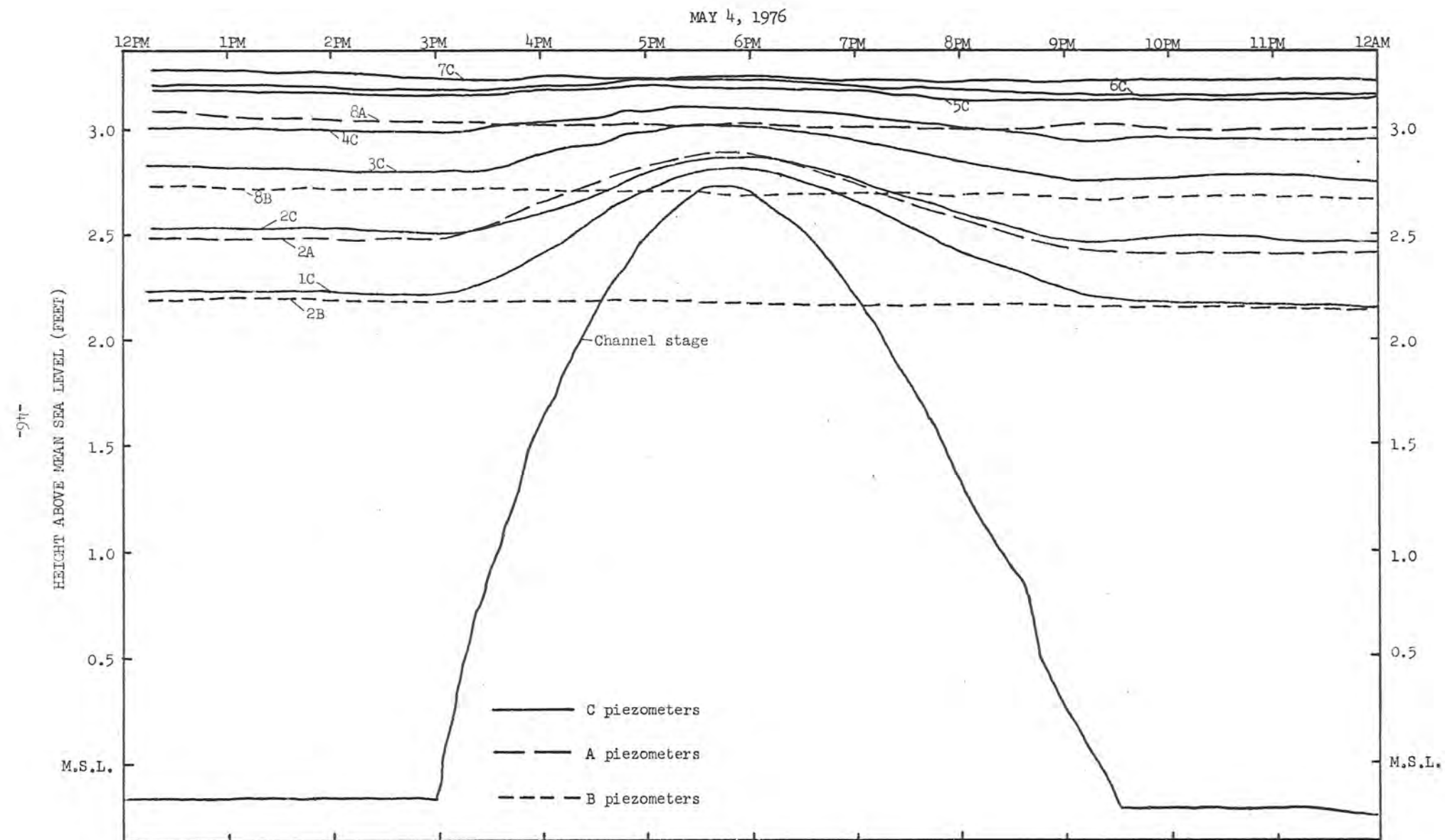


Figure 14. Plots of the water levels of the piezometers in Cooley Landing Marsh. Data was taken at 15 minute and 1 hour intervals during high and low channel stage, respectively. Piezometer 8C is very similar to piezometer 7C.

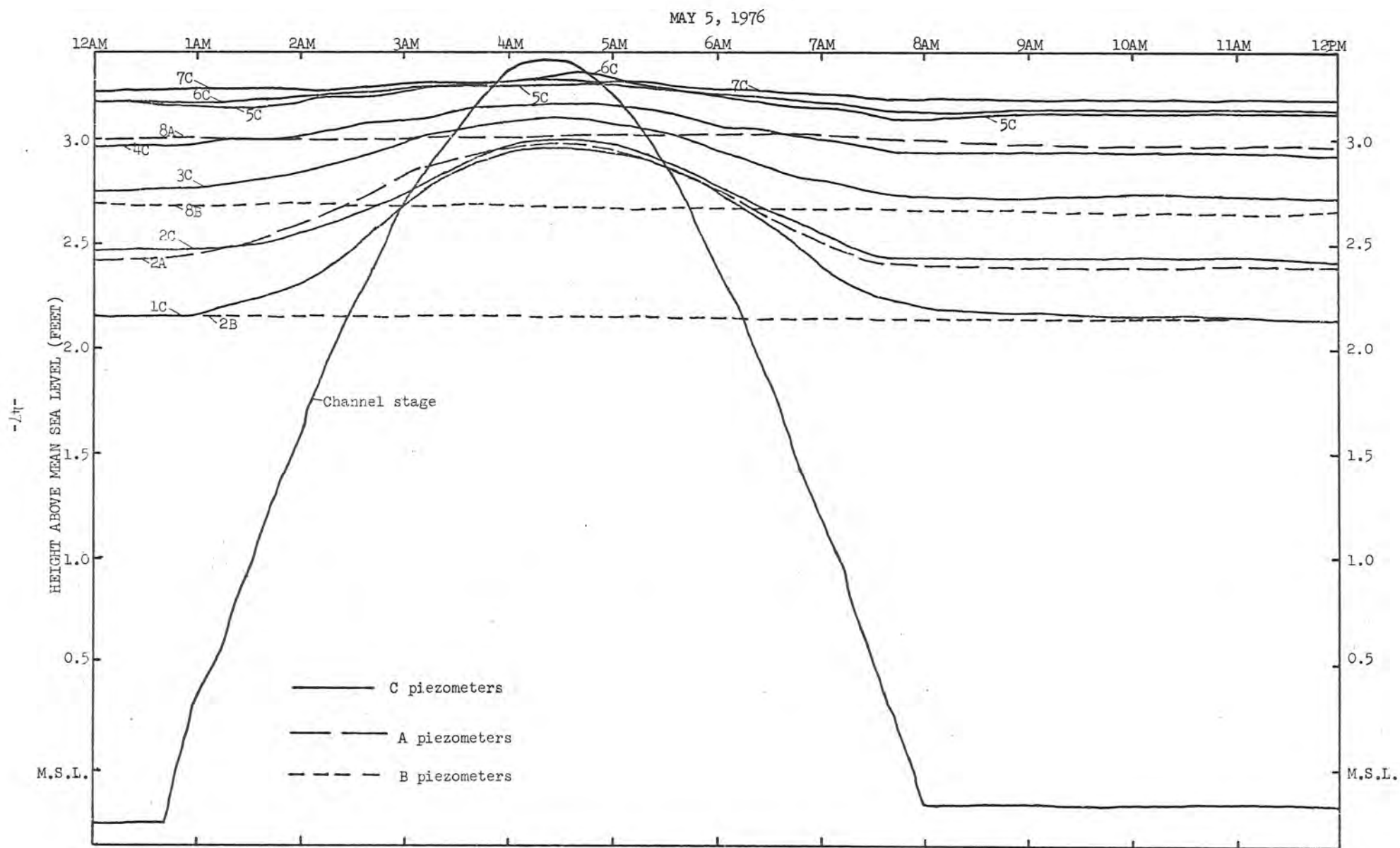


Figure 14 (cont)

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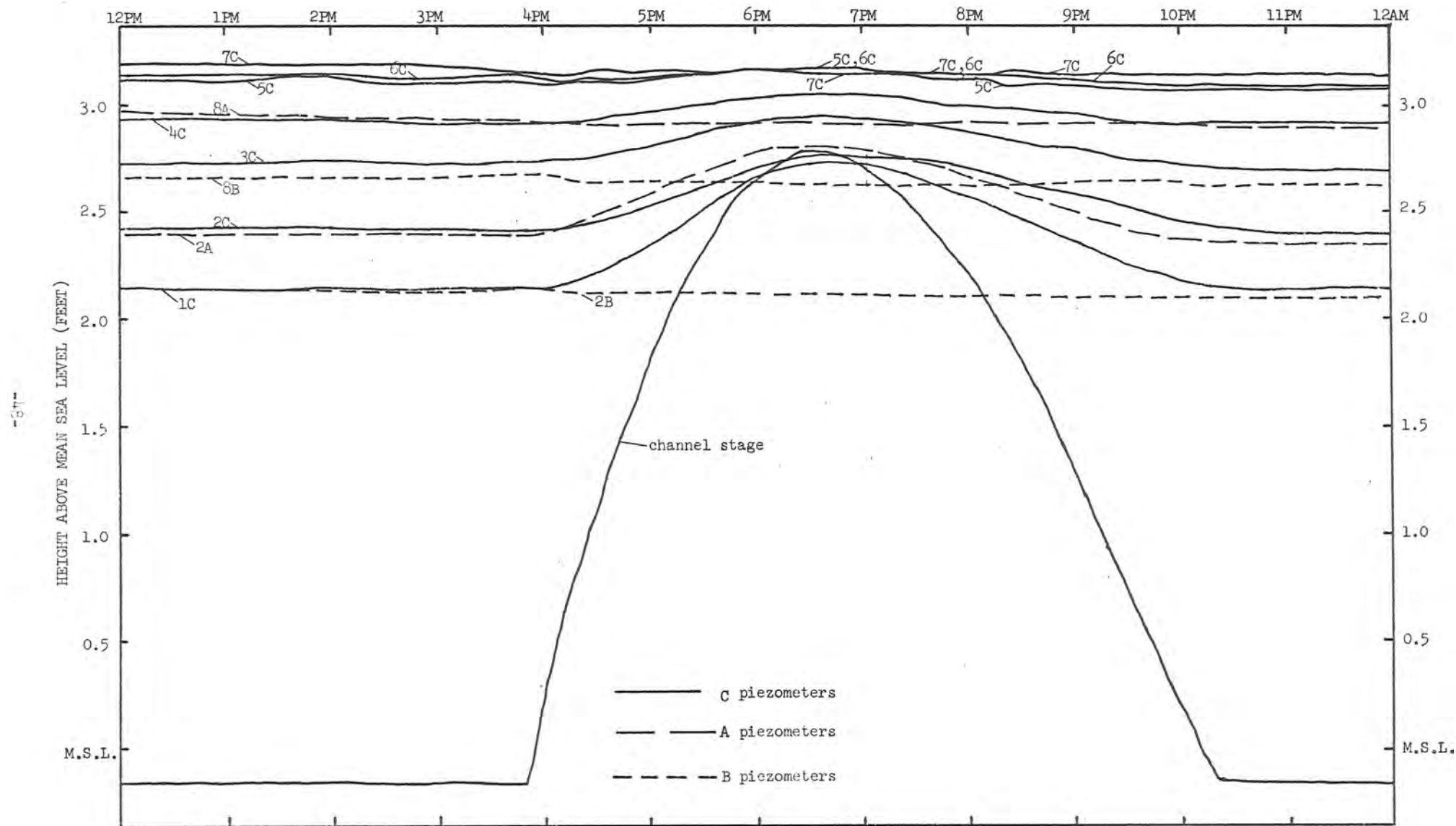


Figure 14 (cont)

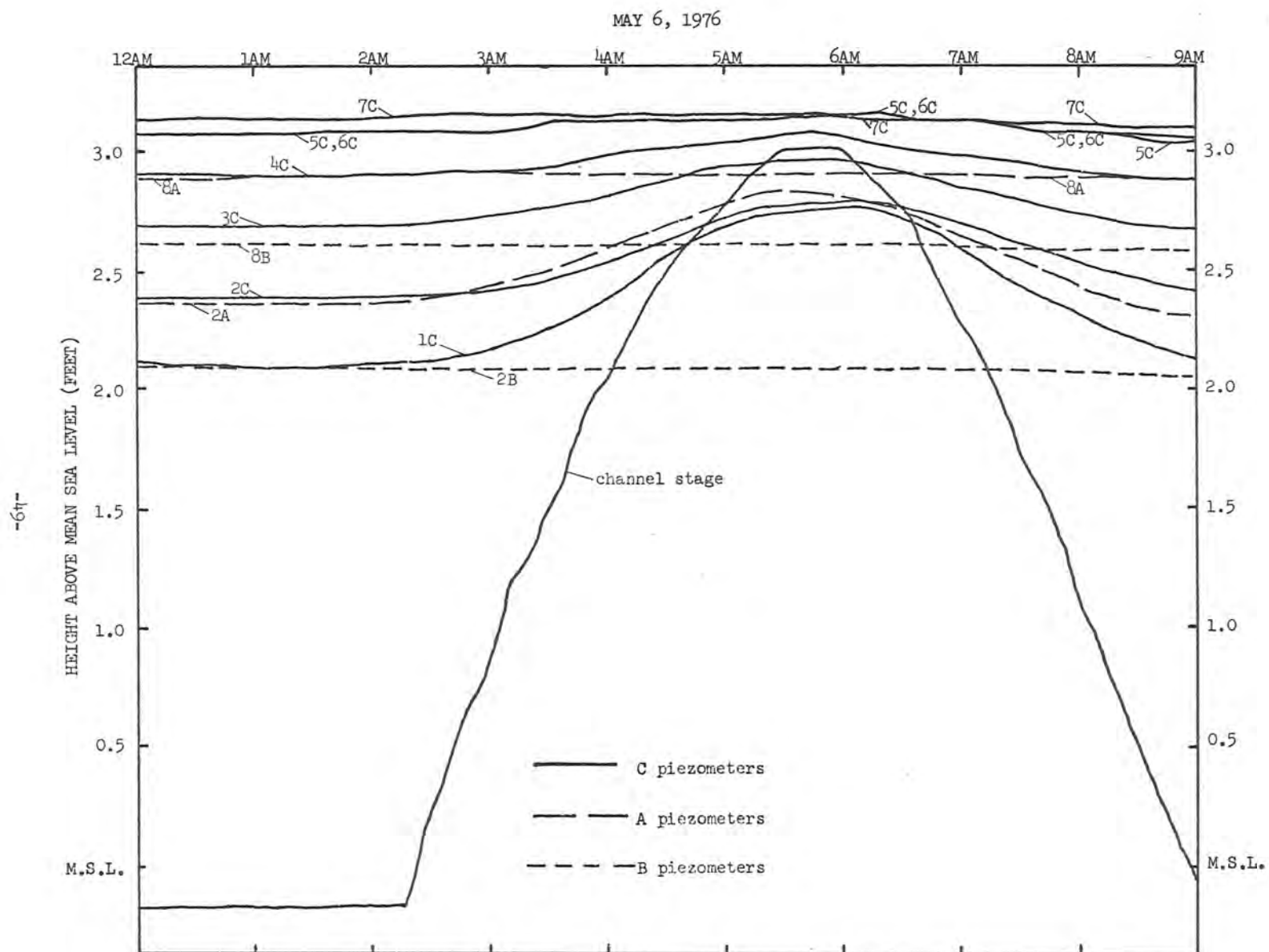


Figure 14 (cont)

Figure 14 shows the piezometer levels plotted for the entire period. The large fluctuating curve is the channel stage which was measured by a marked wooden stick placed in the middle of the channel. The four peak channel stages occurred at heights of 4.6, 5.2, 4.65 and 4.9 feet above M.S.L. Most of the piezometers responded to the tides with the magnitude of fluctuations depending on the height of the channel stage.

The water levels of the shallow piezometers (1C to 8C) start to rise when the channel stage rises and all peak at about the same time approximately 15 to 30 minutes after the channel stage reaches its maximum level. The magnitude of the water level fluctuations is greater near the channel and becomes progressively smaller away from the channel. Also note that the peaks occur at successively higher elevations away from the channel. During low channel stage, when the marsh is draining, the levels appear to stabilize. Finally, throughout the whole tidal cycle note that the water table constantly slopes toward the channel.

The levels of the A and B piezometers also yield some interesting results. The level of piezometer 2A (tapping the bay mud and sand and gravel) shows similar behavior to that of piezometers 2C but seems to peak about 5 to 20 minutes earlier. Piezometer 8A, 30 feet from the channel, showed a gradual decline in water level for the 45 hour period of monitoring. Its level averaged .25 feet below that of piezometer 8C. Piezometer 2B (tapping the sand and gravel), 4 feet from the channel, showed a water level an average of .3 feet below piezometer 2C during low tide and throughout the 45 hours showed no fluctuations, just a gradual decline in water level (a total of .14 feet). Piezometer 8B also showed a gradual lowering in water level. The behavior of the B piezometers, especially

near the channel, indicates that the gravel and sand is hydraulically sealed from the soil zone above. In addition, since the water level rises above the sand and gravel the zone must be confined. If confined, this sand and gravel aquifer does not exhibit any response to tidal loading.

Vertical movement of the ground surface and the piezometers with the tides was monitored. The piezometers were surveyed from a gravel road raised above the marsh located several hundred feet to the north of the piezometer set-up. Surveying of the piezometers and ground surface showed that neither moved at any time when they were monitored.

Development of a Water Table Model

The data described in the last section present a unique opportunity for the analysis of the behavior of the hydrogeologic system by use of a theoretical model. That is, the characteristics of the material of the tidal marsh such as the permeability and the coefficient of storage plus the thickness of the permeable layer can be explored by comparison of the field data to a theoretical model which is thought to accurately describe the hydrogeologic processes occurring in the field. Therefore, a theoretical model has been developed that attempts to simulate the channel-marsh hydrogeologic system.

The surface of the marsh can be described as an unconfined aquifer. That is, the material is assumed to have some permeability, and the surface of the groundwater is considered as a free surface (i.e., at atmospheric pressure). The marsh-channel system can then be represented by figure 15 as an aquifer recharging and discharging from and to the channel as the channel rises and falls with the tide. In the physical

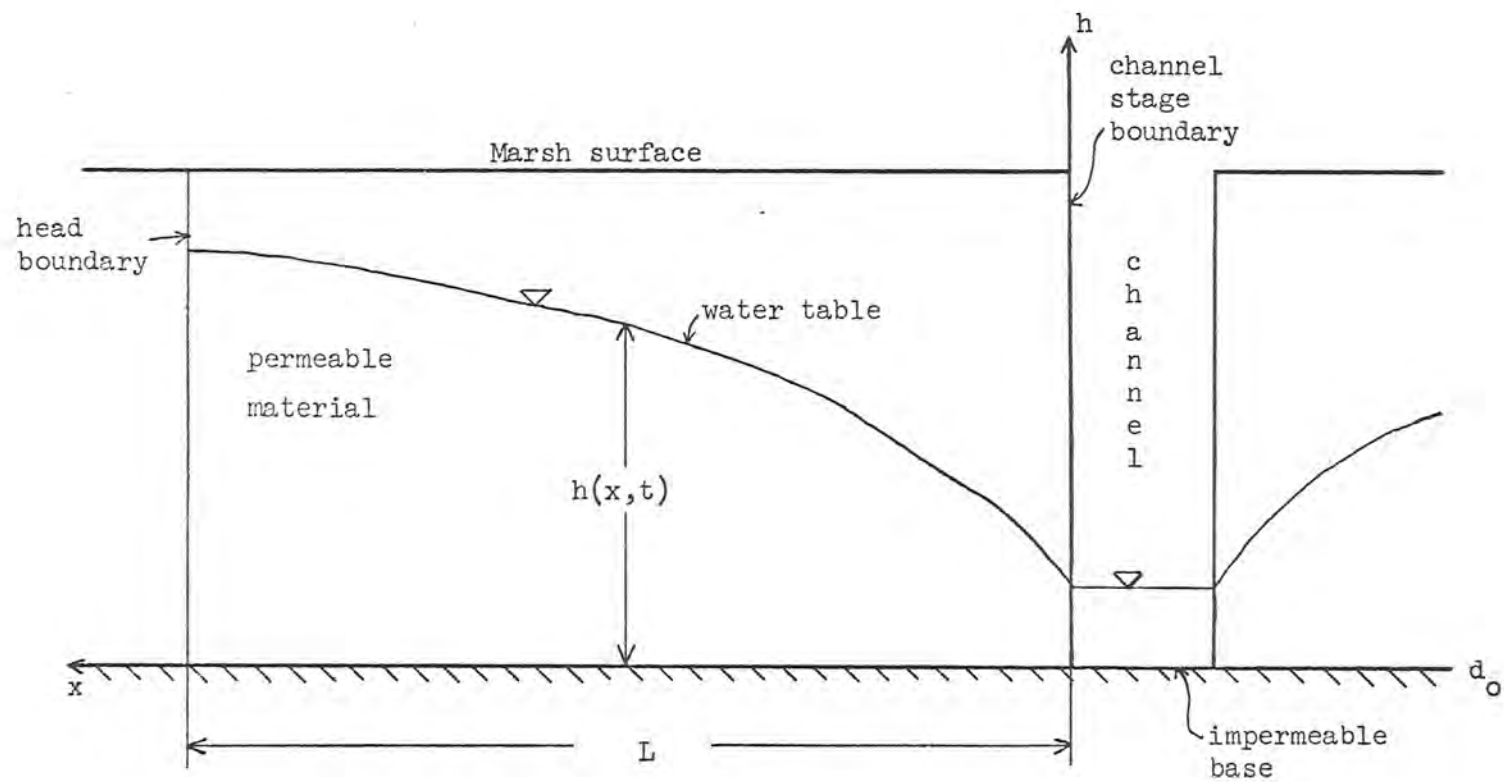


Figure 15. Diagram of water table model of channel-marsh hydrogeologic system.

model interchange of the aquifer with the unsaturated zone by infiltration and evapotranspiration is considered negligible. The base of the aquifer is considered to be an impermeable barrier established at a level designated as d_0 which is measured relative to M.S.L. Finally, the porous medium is assumed to be homogeneous and isotropic.

The governing equation for flow through this system is derived using the Dupuit-Forscheimer assumptions (Jacob, 1950). These state that in the porous medium (1) the flow is everywhere horizontal, (2) the velocity is uniform throughout the depth of flow and (3) the velocity at the free surface is proportional to the head gradient as expressed by

$$v = K \frac{\partial h}{\partial x} , \quad (1)$$

where

v = velocity in the horizontal direction;
 K = hydraulic conductivity;
 h = height of the water table above some datum;
 x = space coordinate.

The Dupuit-Forscheimer assumptions are acceptable for mild curvatures of the free surface. Using these assumptions the transient, one-dimensional flow law is expressed as

$$\frac{\partial^2 h^2}{\partial x^2} = \frac{2S}{K} \frac{\partial h}{\partial t} , \quad (2)$$

where

h = height of water table above the datum which is at the impermeable base (d_0);
 x = distance coordinate from the channel ($x = 0$) to head boundary ($x = L$);
 t = time;
 S = coefficient of storage;
 K = hydraulic conductivity or permeability.

In expanded form equation (2) is written as

$$2 \left[\left(\frac{\partial h}{\partial x} \right)^2 + 2h \frac{\partial^2 h}{\partial x^2} \right] = \frac{2S}{K} \frac{\partial h}{\partial t} .$$

Equation (2) is a quasi-linear parabolic partial differential equation. Its solution is a function expressed as $h = h(x, t)$ and cannot be obtained without specified auxiliary conditions. The boundary conditions of the channel-marsh system are the variable channel stage and the head* of one of the piezometers away from the channel (preferably at a distance from the channel where the head is near constant with time). The initial condition is simply the water table condition chosen at any specified time. These auxiliary conditions are defined mathematically as

$$\begin{aligned} h(x, 0) &= f(x) & 0 \leq x \leq L \\ h(0, t) &= h_0(t) & t > 0 \\ h(L, t) &= h_L(t) , \end{aligned} \quad (3)$$

where

$$\begin{aligned} f(x) &= \text{the initial condition function;} \\ h_0(t) &= \text{the channel stage boundary function at } x=0; \\ h_L(t) &= \text{the head boundary function at } x=L; \\ L &= \text{the distance from the channel edge to} \\ &\quad \text{the head boundary.} \end{aligned}$$

The model of the channel-marsh system is completely described by equation (2) and conditions (3).

For a better perspective of the solution of the channel-marsh model, equation (2) is nondimensionalized to the form

$$\frac{\partial^2 H}{\partial \xi^2} = \frac{1}{H} \frac{\partial H}{\partial \tau} - \frac{1}{H} \left(\frac{\partial H}{\partial \xi} \right)^2 \quad (4)$$

* head is equivalent to the height of the water table.

by substitution of the following equations:

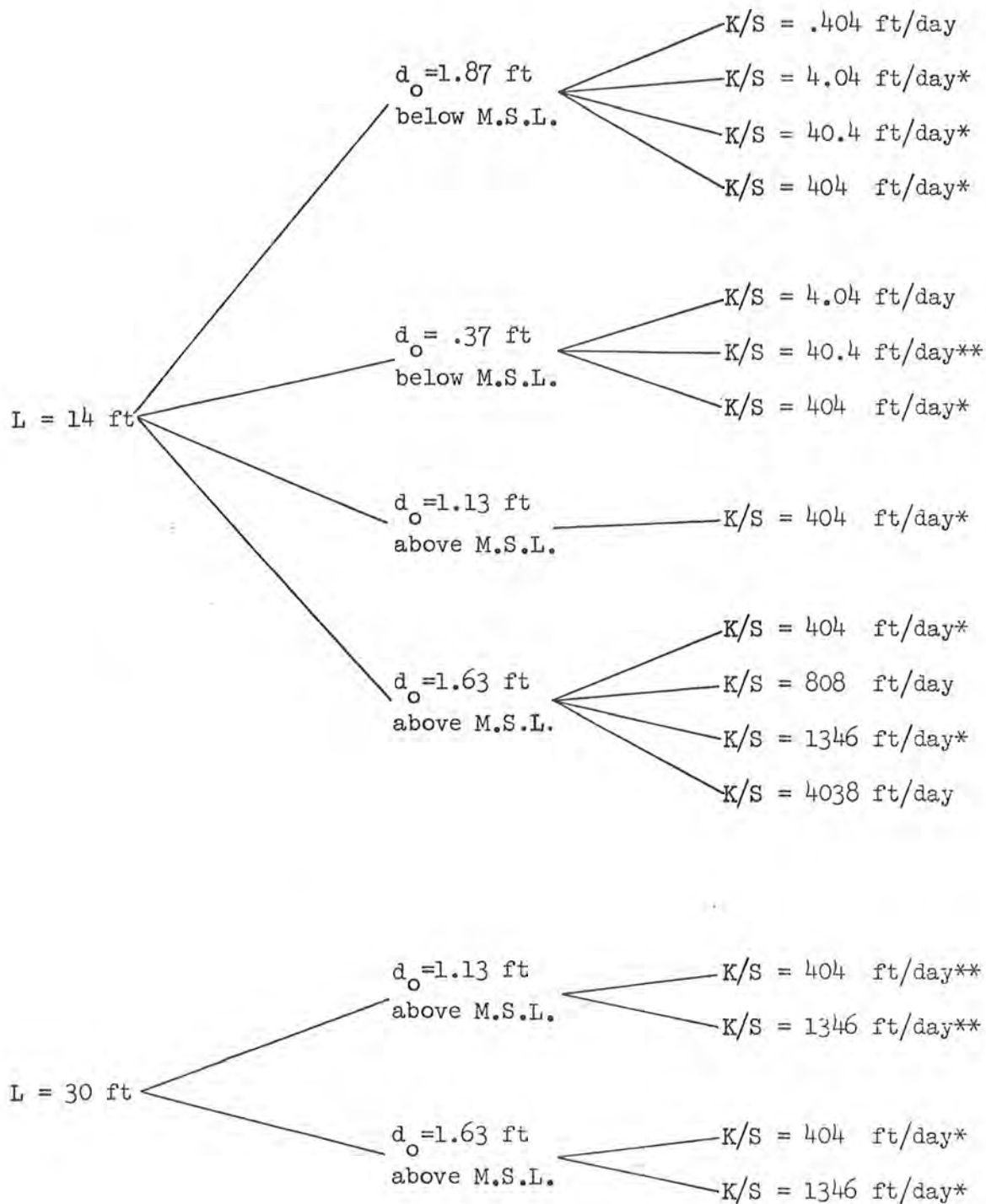
$$\begin{aligned}\xi &= \frac{x}{L} \\ \tau &= \frac{Kt}{SL} \\ H &= \frac{h}{L}.\end{aligned}\tag{5}$$

The symbols ξ , τ and H represent nondimensionalized distance, time and head, respectively. The auxiliary conditions are expressed as

$$\begin{aligned}H(\xi, 0) &= F(\xi) & 0 \leq \xi \leq 1 \\ H(0, \tau) &= H_0(\tau) & t > 0 \\ H(1, \tau) &= H_1(\tau).\end{aligned}\tag{6}$$

Here the range $0 \leq x \leq L$ is equivalent to $0 \leq \tau \leq 1$.

Equation (4) can be solved analytically using certain types of auxiliary conditions, but in this case the conditions are discrete. We must seek a numerical solution to the model. Douglas and Jones (1963) developed the predictor-corrector technique which numerically solves the partial differential equation of (4). The method divides the ξ and τ domains into $\Delta\xi$ and $\Delta\tau$ intervals with discrete points along each axis designated as ξ_i and τ_j , respectively, where $i = 1, 2, \dots, n$ and $j = 1, 2, \dots, m$. The values of nondimensionalized head at each point (ξ_i, τ_j) are then written as $H_{i,j}$; that is, $H(\xi_i, \tau_j) = H_{i,j}$. Equation (4) is now approximated by a set of finite-difference equations called the predictor and corrector each which advances the solution 1/2 time step. The predictor is written as



* Shown in text

** Shown in Appendix E

Figure 16. Different combinations of parameters L , d_o and K/S used in computer runs.

respectively, with the unknowns on the left side. The predictor solves for the $j + \frac{1}{2}$ time step and the corrector solves for the $j + 1$ time step. The value of the terms on the right side of equations (9) and (10) are known from the solutions of previous time steps and the auxiliary conditions of (6) which are now expressed as discrete functions:

$$\begin{aligned} H_{1,0} &= F(\xi_1) \\ H_{0,j} &= H_0(\tau_j) & i = 1, 2, \dots, n \\ H_{n+1,j} &= H_{n+1}(\tau_j). & j = 1, 2, \dots, m \end{aligned} \quad (11)$$

At each $\frac{1}{2}$ time step the predictor or corrector becomes a system of n linear equations which is tridiagonal. Thomas (1949) developed a method which easily solves this type of system of equations.

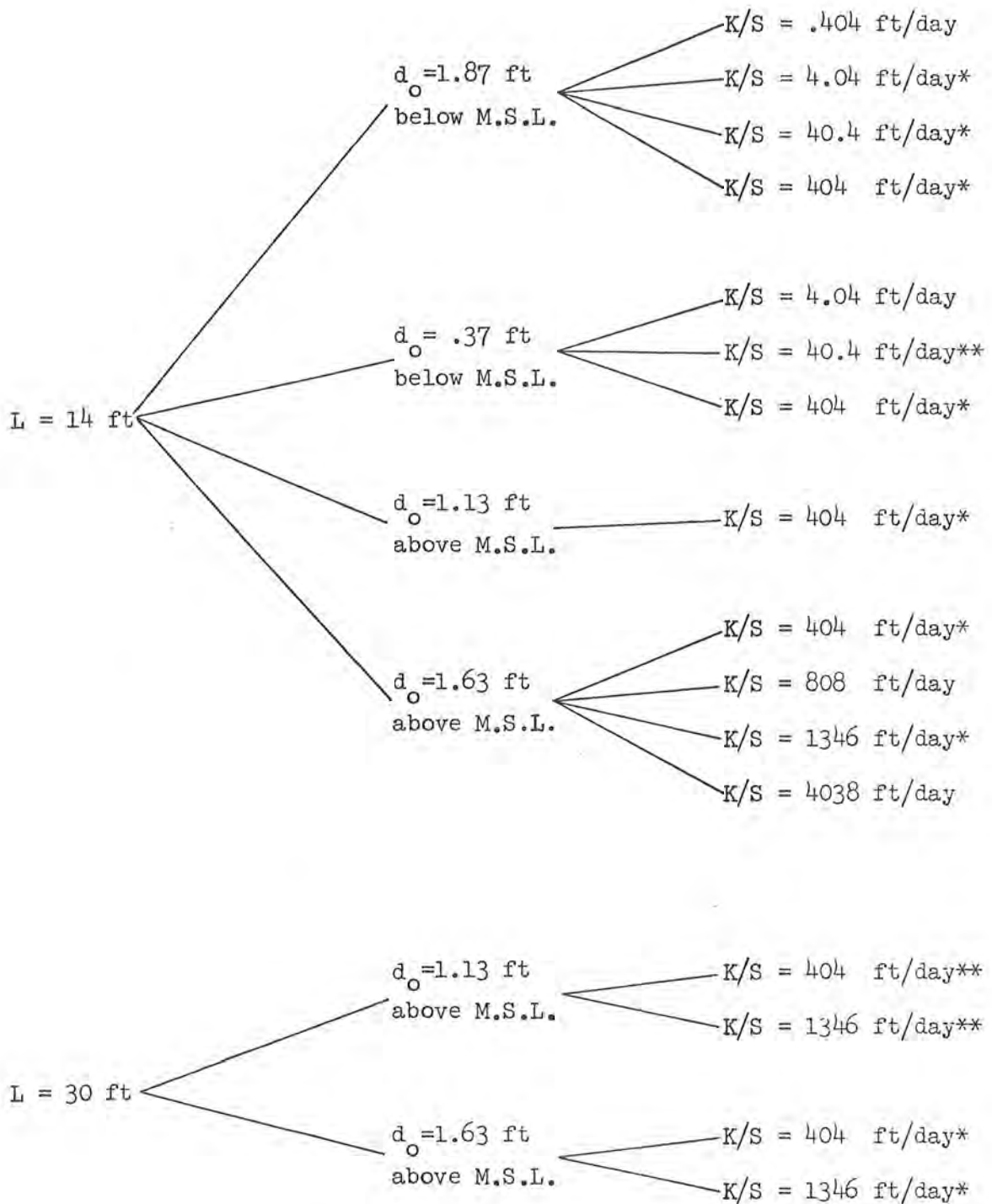
The accuracy of the finite-difference solution of equation (4) has been tested by Hornberger, et al., (1970) by comparing an exact analytical solution found by Boussinesq (1904) with the finite-difference solution of the same problem. The two solutions were found to be almost exactly the same. Therefore, for a reasonable use of $\Delta\xi$ and $\Delta\tau$ spacing the predictor-corrector is viewed as an accurate method for solving equation (4).

The channel-marsh model was developed into a computer program for use on Stanford University's IBM 360/168 digital computer. The program is listed in Appendix D along with sample input and output and a short user manual.

Simulation of the Channel-Marsh Hydrogeologic System

The water table model needs certain information in order to run and be compared to the field data. This information is (1) the initial and boundary conditions; (2) the hydrogeologic parameters of the porous material, K and S ; (3) the geometric parameters of the system L and d_o ; and (4) the dimensionalized distance and time intervals Δx and Δt . The initial and boundary conditions are obtained from the field data and once chosen are discretized according to a Δx and Δt spacing which is accurate enough to define the conditions. The length of the system, L , is automatically determined once the boundary conditions are set. The permeability (K), coefficient of storage (S) and impermeable base level (d_o) are, in this case, not known. Therefore these parameters were varied in an attempt to obtain a match with the field data. The technique of determining system parameters from the matching of a theoretical model with observed field data has been referred to as the inverse method. If a reasonable match is not obtained by varying the parameters then the assumptions used to derive the model's governing equation are not upheld in the field situation. In any event, a comparison of the model with the data field yields significant information concerning the behavior of the field situation.

Sixteen computer runs were made using different combinations of the parameters L and d_o and the ratio K/S as shown in figure 16. The effects of each were determined by varying each individually while holding all other conditions constant. Note that the permeability and storativity (K and S) are used as a ratio and thus a value of K can only be obtained by assuming a value of S .



* Shown in text

** Shown in Appendix E

Figure 16. Different combinations of parameters L , d_o and K/S used in computer runs.

The auxiliary conditions were taken from the field data chosen from the 15 hour period on May 5 starting at 12 AM and ending at 3 PM. These conditions were defined on a Δx and Δt spacing of one foot and 15 minutes (.0104 days), respectively.

Once all the information is specified it is substituted into the following equations derived from equations (5):

$$\begin{aligned}\Delta \xi &= \frac{\Delta x}{L} \\ \Delta \tau &= \frac{K}{S} \frac{\Delta t}{L} \\ H &= \frac{h}{L} .\end{aligned}\tag{11}$$

The nondimensionalized distance and time spacing, $\Delta \xi$ and $\Delta \tau$, and nondimensionalized auxiliary conditions, H , are then used in the finite-difference equations (9) and (10) to solve the problem step by step.

The first set of runs was made with the length of the profile (L) set at 14 feet and the base of the permeable section (d_0) set at 1.87 feet below M.S.L. This level is approximately the top of the peat layer and 2.4 feet below the bottom of the channel. Figure 17 shows the plot of the field data with time (solid lines) for the channel stage and piezometers 1C, 2C, 3C, and 4C (2.5, 4, 6 and 8 feet away from the channel respectively) compared with the theoretical piezometer levels (dashed lines). The K/S value for this run was set at 40.4 ft/day. The theoretical levels do not compare well with the field data in this case. The theoretical levels immediately drop off from the level of the initial conditions and then attain peaks 1/2 to 2 hours later than their respective field levels.

Also, the theoretical peaks are lower than the field peaks except for the peak of piezometer 1C. During low tide the theoretical levels approach a steady state much lower than the field levels. A plot of the water table profile with time for the theoretical and field situations (fig. 18) shows that the water table simply rises and falls with the channel stage. The theoretical water table falls at first but then rises above its initial level as the channel stage peaks. It then reaches a steady state profile much lower than the field profile during low channel stage.

An order of magnitude higher and lower K/S was then tried. A K/S of 404 ft/day (fig. 19) dropped the theoretical levels down lower than before ($K/S = 40.4$ ft/day) and brought the peaks closer together occurring 30 to 45 minutes after maximum channel stage is reached. The theoretical peaks are all higher than their corresponding field peaks. Steady state is reached soon after the channel stage is down at a level much lower than the field steady state. A K/S of 4.04 ft/day (fig. 20) shows virtually no response of the theoretical levels of piezometers 3C and 4C. The levels of piezometers 1C and 2C have very delayed responses with subdued peaks and show a gradual decline during low channel stage.

Raising and lowering the value of K/S shows the effect of increasing and decreasing permeabilities (assuming a specific value for S). An increase in K/S shows a faster response and brings the piezometer peaks higher and closer together and significantly drops the levels when the channel is near empty. A decrease in K/S reveals a slower response as is

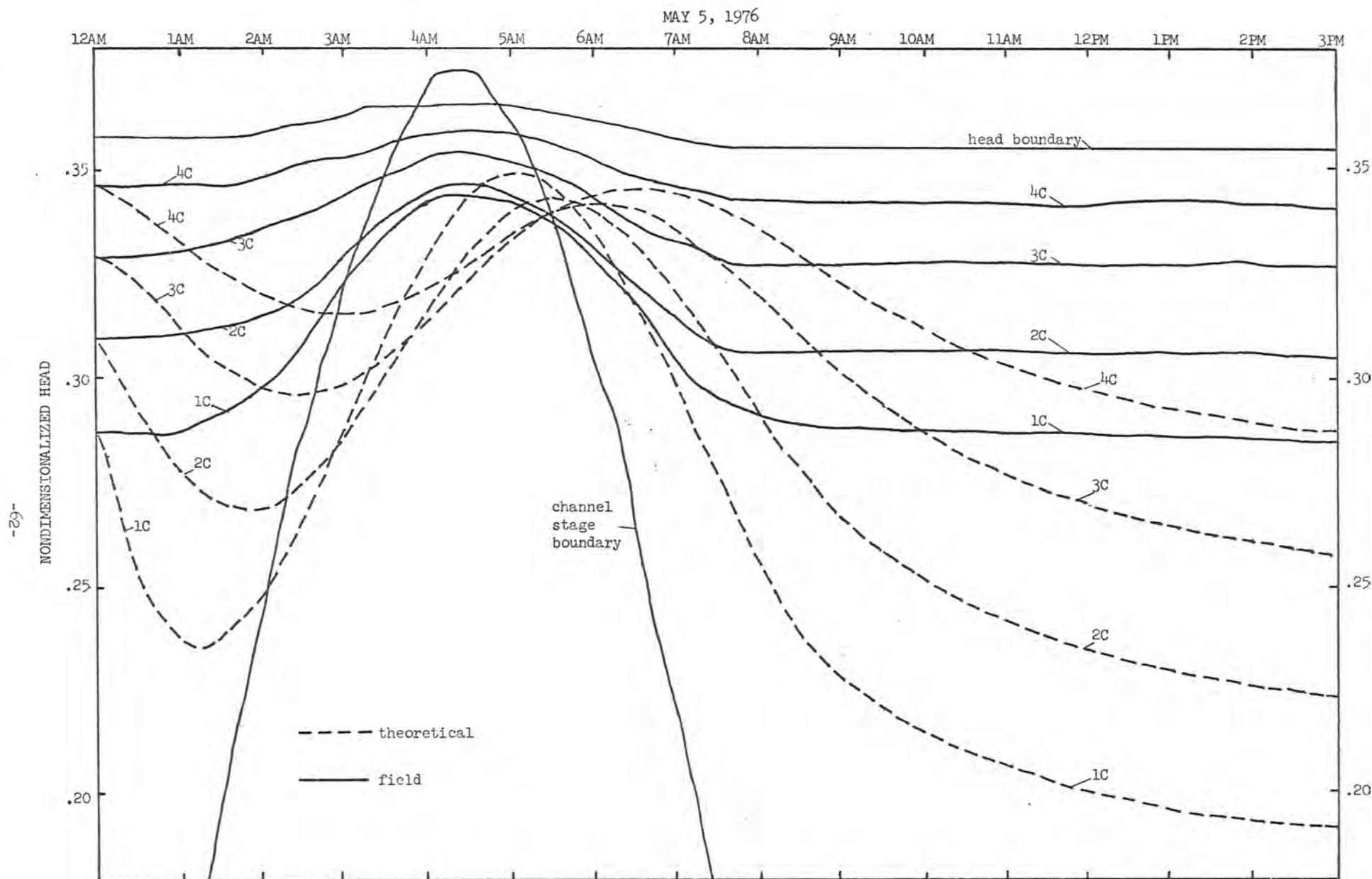


Figure 17. Comparison of field data with theoretical piezometer levels for $L=14$ feet, $d_o=1.87$ feet below M.S.L., and $K/S=40.4$ ft/day. Channel stage bottoms out at .1150.

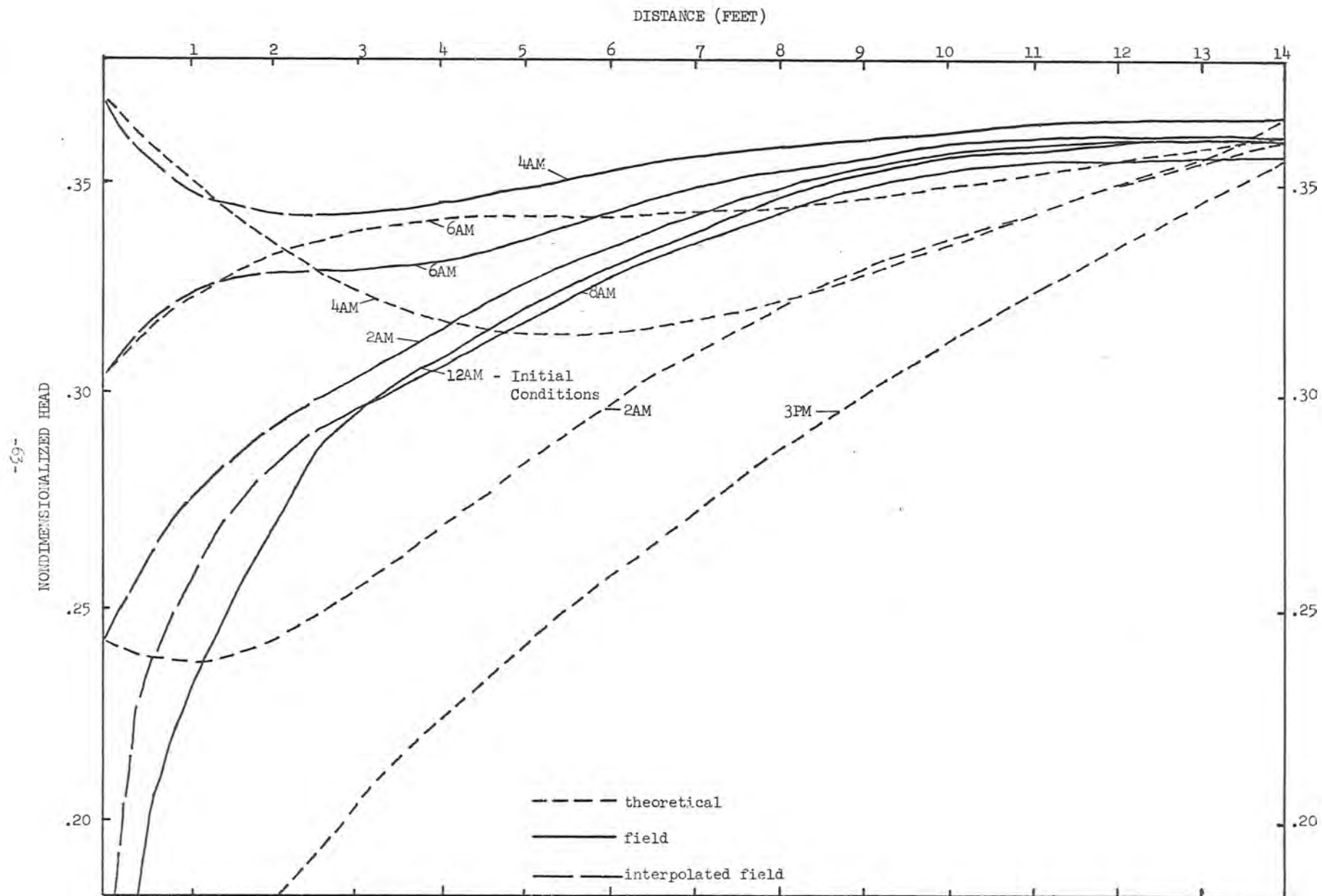


Figure 18. Comparison of field and theoretical water table profiles with time for $L=14$ feet, $d_0=1.87$ feet below M.S.L. and $K/S=10.4$ ft/day.

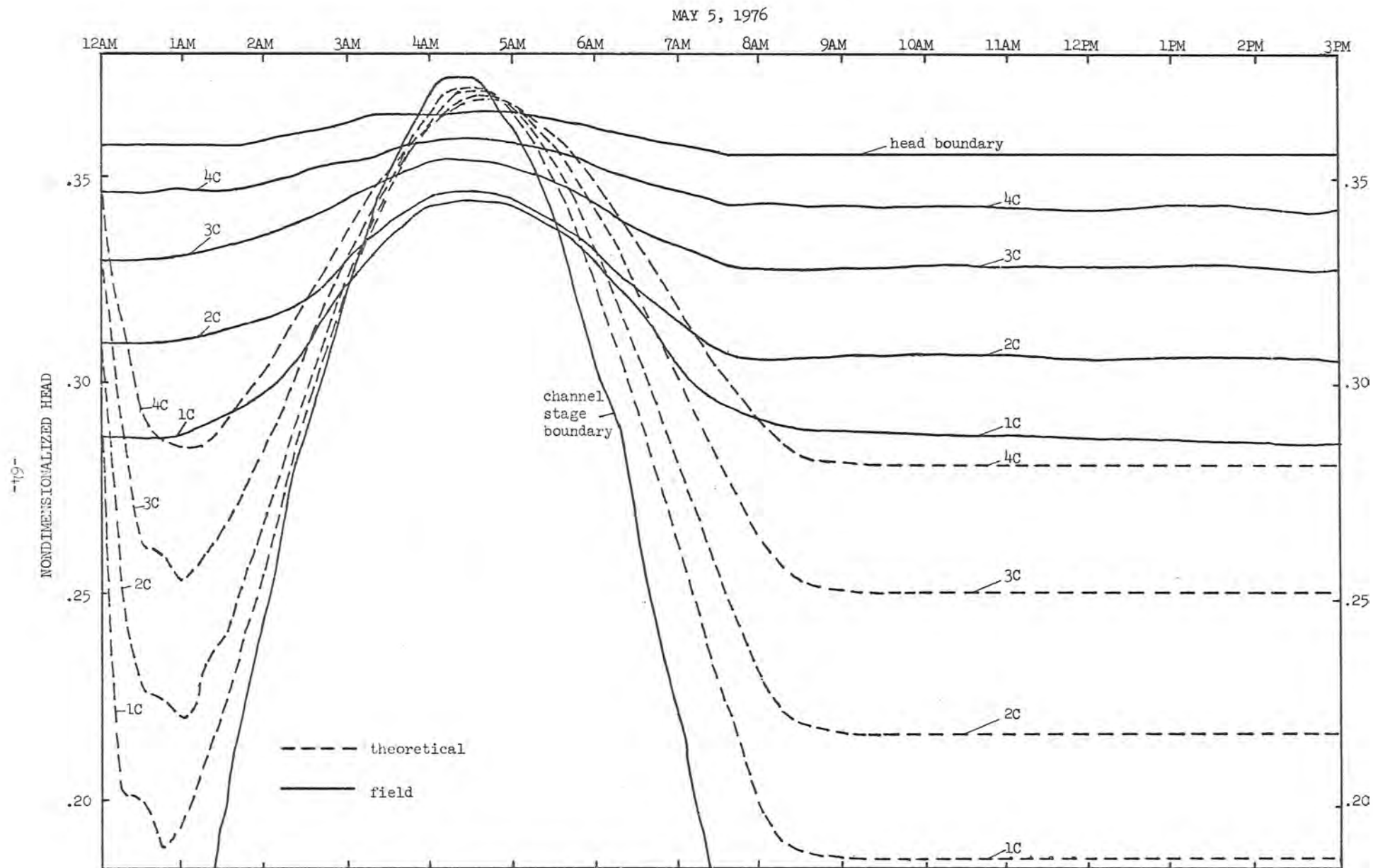


Figure 19. Comparison of field data with theoretical piezometer levels for $L=14$ feet, $d_0=1.87$ feet below M.S.L. and $K/S=404$ ft/day. At early times theoretical curves have slight numerical instabilities.

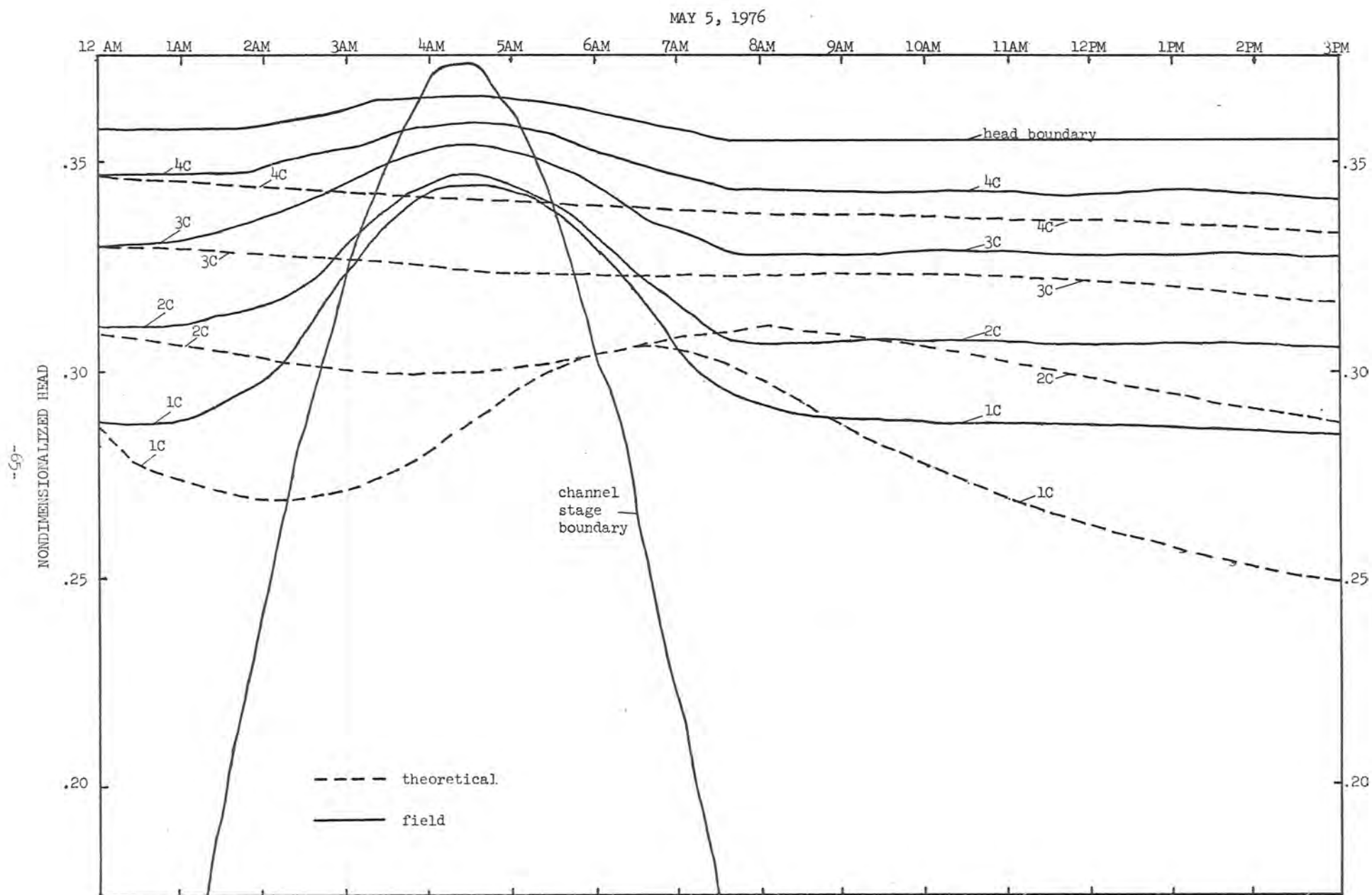


Figure 20. Comparison of field data with theoretical piezometer levels for $L=14$ feet, $d_0=1.87$ feet below M.S.L. and $K/S=4.04$ ft/day.

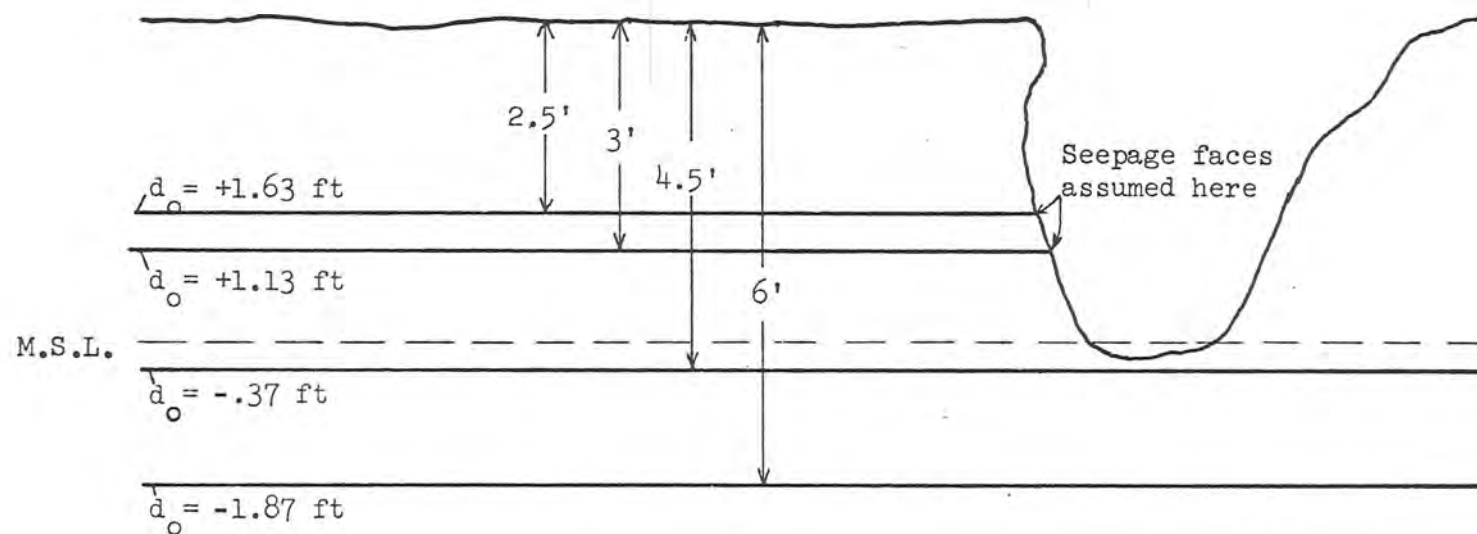


Figure 21. Different levels of d_o , the base of permeable section, used in computer simulations.

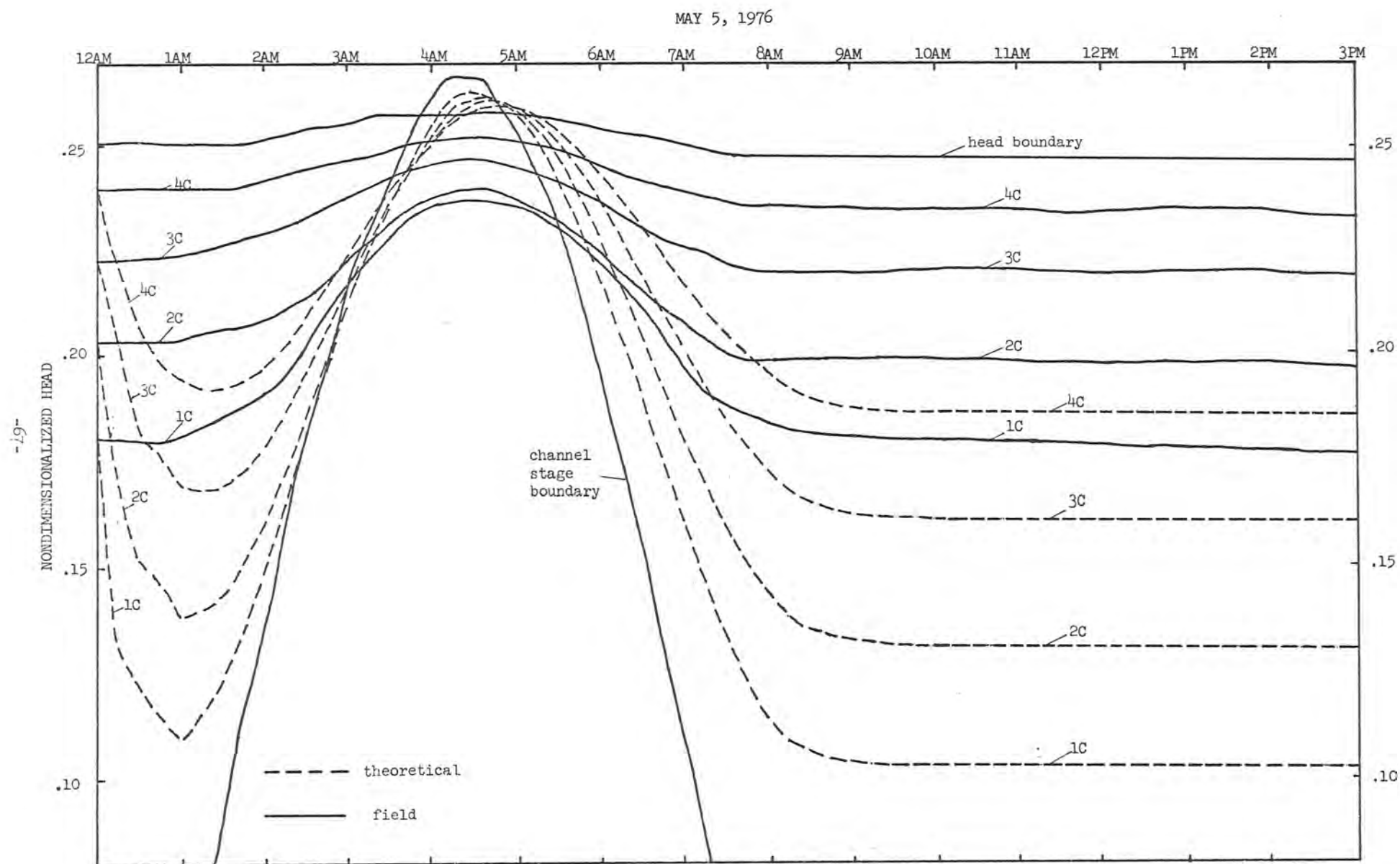


Figure 22. Comparison of field data with theoretical piezometer levels for $L=1\frac{1}{4}$ feet, $d_0 = .37$ feet below M.S.L. and $K/S=404$ ft/day. Channel stage bottoms out at .01.

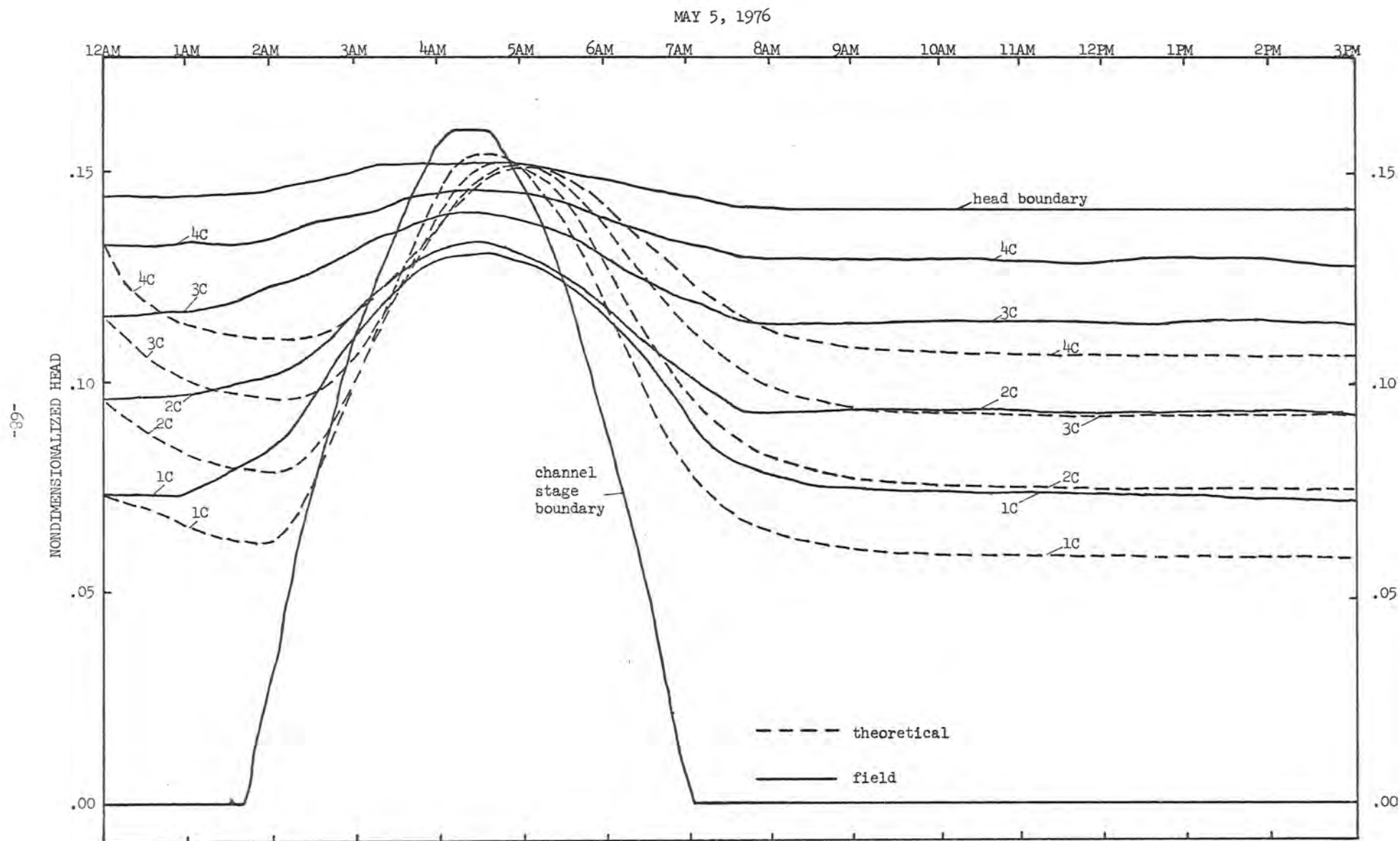


Figure 23. Comparison of field data with theoretical piezometer levels for $L=14$ feet, $d_0=1.13$ feet above M.S.L. and $K/S=404$ ft/day.

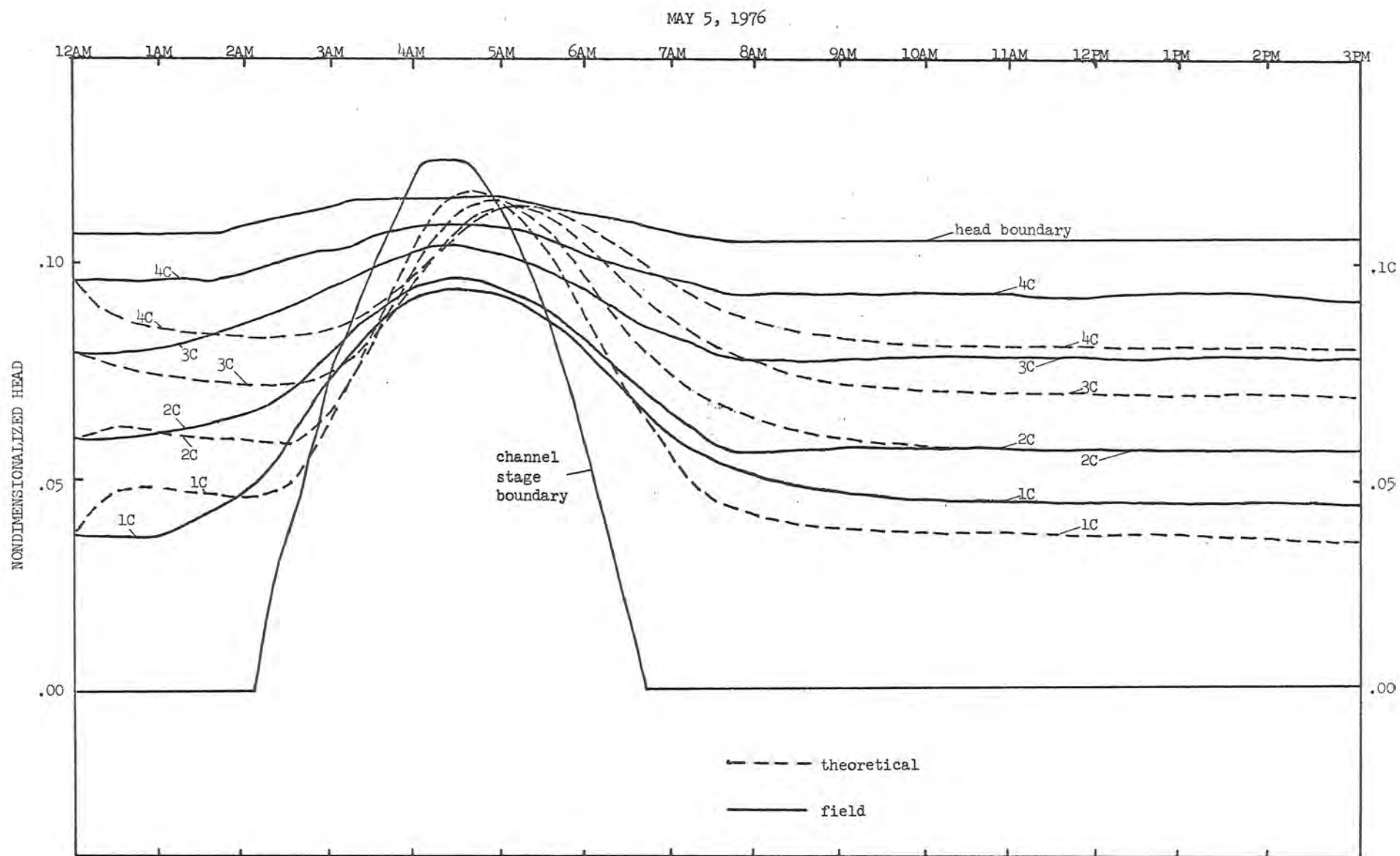


Figure 24. Comparison of field data with theoretical piezometer levels for $L=14$ feet, $d_0=1.63$ feet above M.S.L. and $K/S=404$ ft/day.

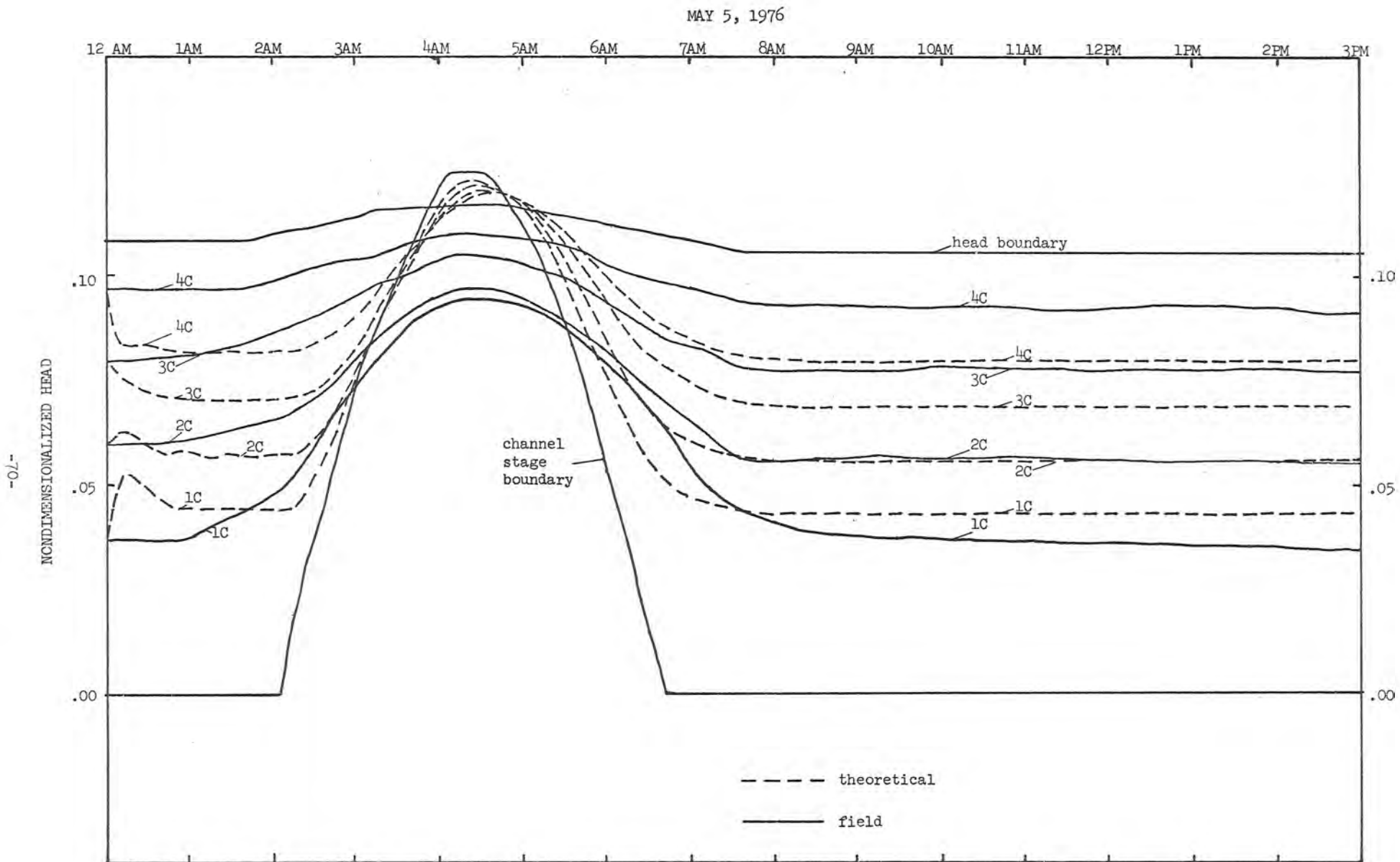


Figure 25. Comparison of field data with theoretical piezometer levels for $L=14$ feet, $d_o=1.63$ feet above M.S.L. and $K/S=1346$ ft/day. At early times theoretical curves have slight numerical instabilities.

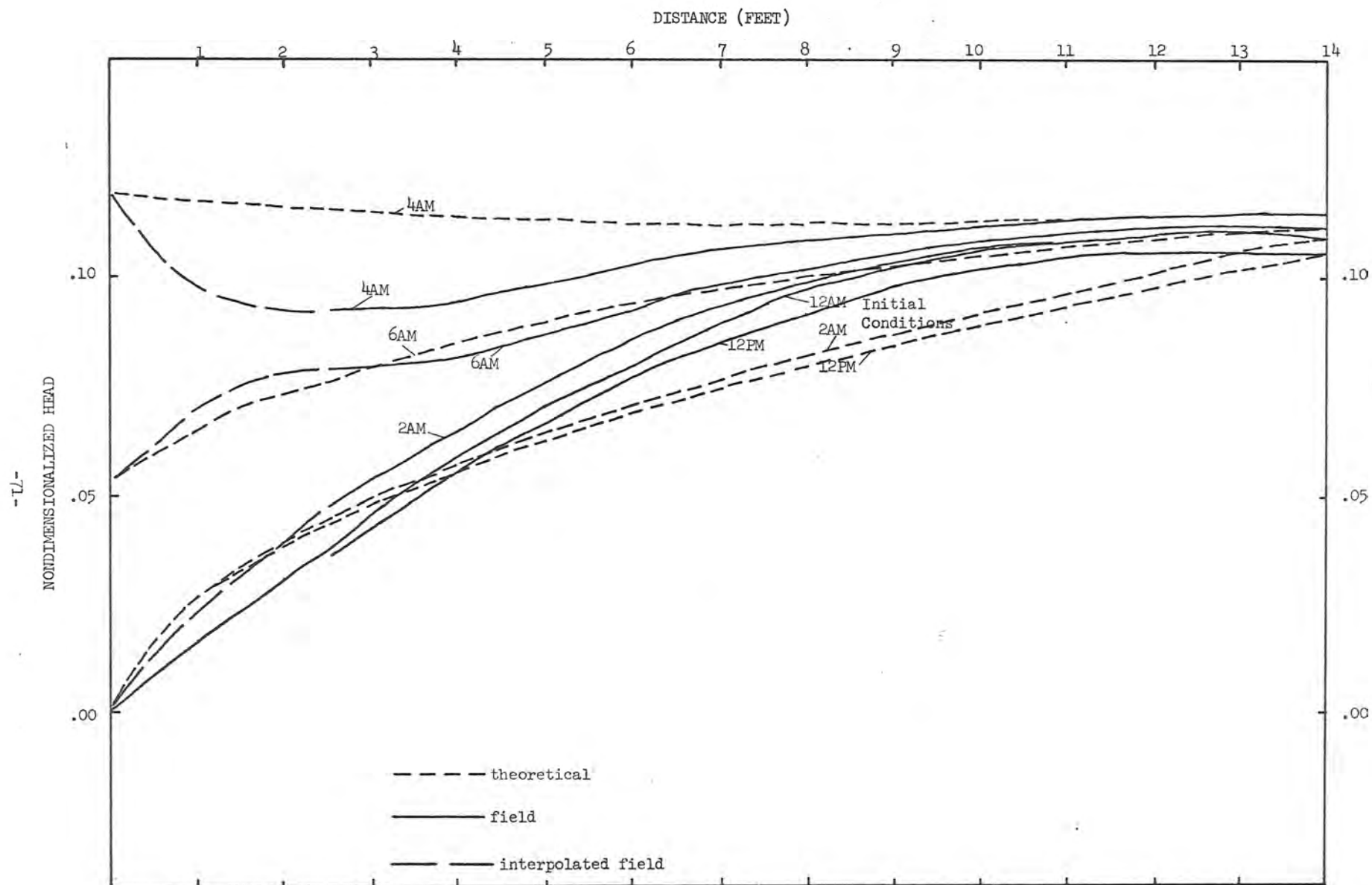


Figure 26. Comparison of field and theoretical water table profiles with time for $L=14$ feet, $d_o=1.63$ feet above M.S.L. and $K/S=1346$ ft/day.

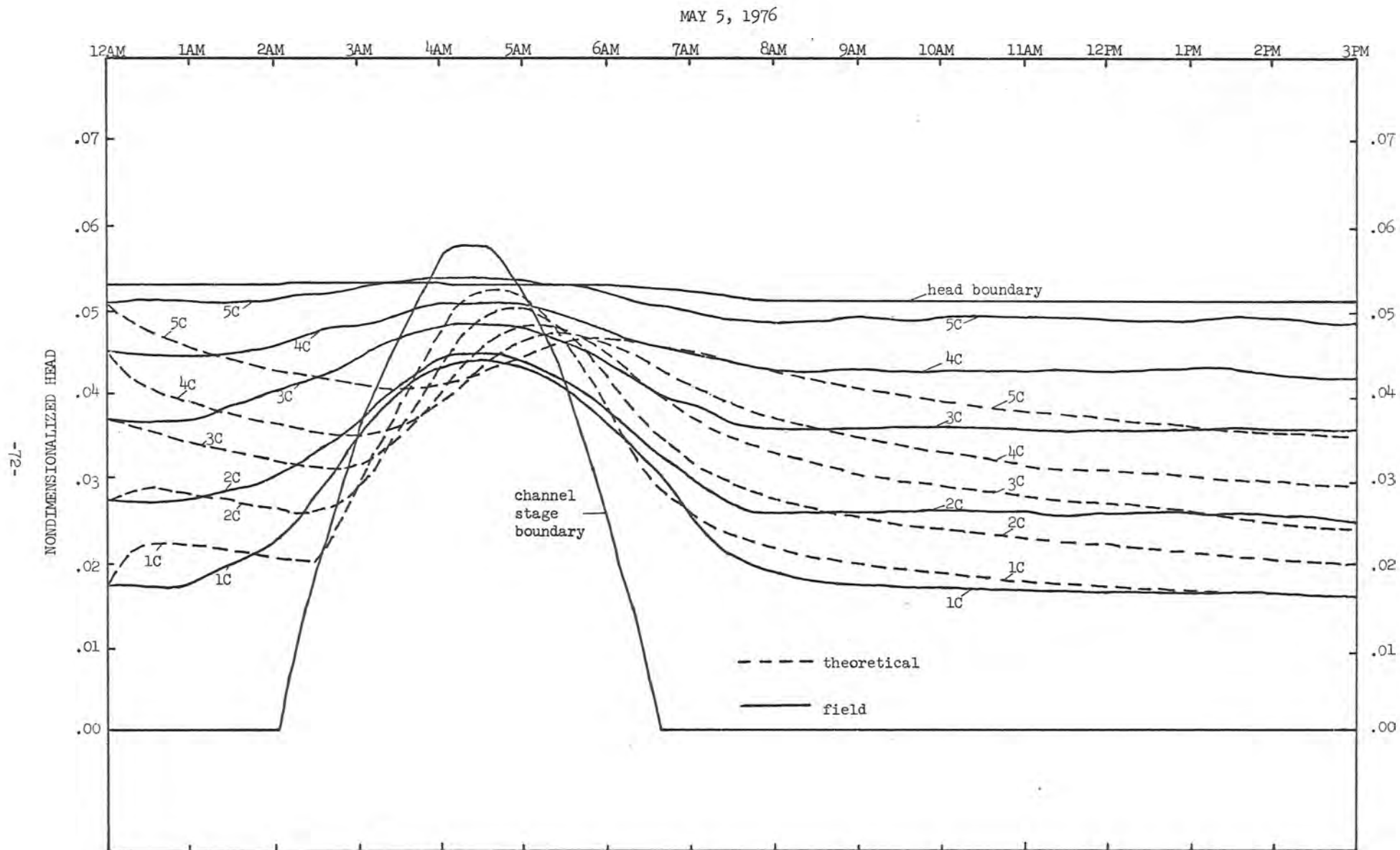


Figure 27. Comparison of field data with theoretical piezometer levels for $L=30$ feet, $d_0=1.63$ above M.S.L. and $K/S=404$ ft/day.

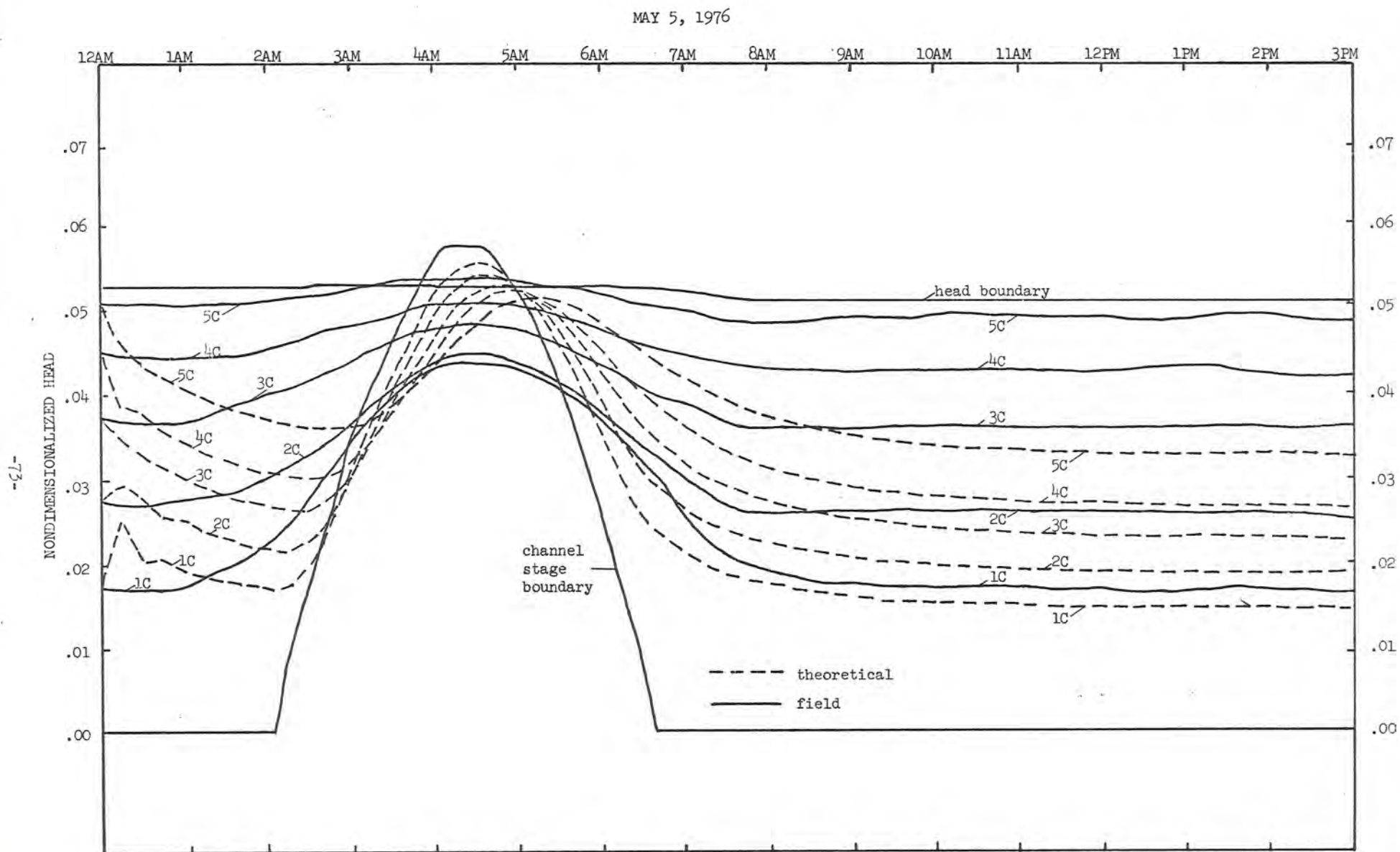


Figure 28. Comparison of field data with theoretical piezometer levels for $L=30$ feet, $d_o=1.63$ feet above M.S.L. and $K/S=1346$ ft/day. At early times theoretical curves have slight numerical instabilities.

shown by the lower and more delayed peaks. The very slow draining of the permeable section when the channel stage is low is also evidence of a slower response.

It appears that a high K/S is favorable because it places the theoretical peaks closer to the peak of the channel stage. This makes the theoretical levels closer to the field data. However, an increase in K/S also causes a significant drop in the theoretical levels when the channel stage is low. This effect can be reduced by raising the base of permeable section, d_o , up higher and thus effectively reducing the thickness of the permeable layer. Therefore, d_o was raised to three different levels: $-.37$, $+1.13$ and $+1.63$ feet referenced to M.S.L. (fig. 21). These levels are the same as 1.5, 3.0 and 3.5 feet above the peat layer, respectively. They also put the base of the section at .9 feet below the channel bottom, and .6 and 1.1 feet above the channel bottom, respectively. Thus, in the three cases the theoretical permeable layer is about 4.5, 3.0 and 2.5 feet thick (fig. 21).

Figure 22 compares the field data with the theoretical levels when the base of the permeable section is .37 feet below M.S.L. and K/S is 404 ft/day. The theoretical steady state is raised closer to the field data than for the case shown in fig. 10. The thickness of the permeable layer appears to control the vertical range of the theoretical levels.

In raising the base of the permeable section higher to .6 and 1.1 feet above the channel the computer model can not be run unless the channel stage is assumed to be located at the base of the permeable section whenever it falls below that level. (The channel stage is a necessary boundary condition and must be specified at all times in order to

solve the problem.) This assumption is unreasonable at best but can be interpreted as placing a seepage face at the base of the permeable section whenever the actual channel stage is below that level.

The comparison between the data and the theoretical piezometer levels for d_o of 1.13 feet above M.S.L. and K/S of 404 ft/day is shown in figure 23. A similar comparison is shown in figure 24 where d_o is 1.63 feet above M.S.L. and K/S is also 404 ft/day. Also, figure 25 shows the comparison for the same d_o but with a K/S of 1346 ft/day. These runs show better agreement with the field data. All show higher steady state levels. Figure 25 shows the theoretical piezometer levels peaking within 30 minutes of each other close to the same time as the field levels. The heights of the peaks do not match, but the steady state levels are nearly the same. The initial rise of the water levels can not be the same since the theoretical levels will not start to rise until the channel stage rises higher than 1.1 feet above the channel bottom.

Figure 26 shows how the water table profiles compare for the same conditions of figure 25. At 2 AM the theoretical profile has dropped below the initial level, whereas the field profile has started to rise. At peak channel stage (4 AM) the theoretical profile is almost level, whereas the field profile still slopes toward the channel. The profiles at 12 PM (low channel stage) are reasonably similar both sloping toward the channel.

Finally, comparisons were made with the length of the system (L) at 30 feet. The same levels of the base of the permeable section were tried at .6 and 1.1 feet above the channel bottom (d_o of 1.13 and 1.63 feet

above M.S.L.). For each of these a K/S of 404 ft/day and 1346 ft/day was used. Figures 27 and 28 show the comparison of the theoretical and field levels for a d_0 of 1.63 feet above M.S.L. and K/S values of 404 ft/day and 1346 ft/day. Figure 28 shows similar trends to that of figure 25 where L equals 14 feet. In the case of figure 28 the steady state of the theoretical curves reached too low a level. The theoretical peaks are delayed and become lower away from the channel whereas the field data show peaks occurring together with them higher away from the channel.

The best comparison was obtained from the theoretical conditions where L is 14 feet, d_0 is 1.1 feet above the channel bottom (1.63 ft above M.S.L.) and K/S is 1346 ft/day (fig. 25). If a coefficient of storage of .1 is assumed then the hydraulic conductivity, K, becomes 13,460 ft/day which is approximately 100,000 gallons per day per ft², a very high permeability which is equivalent to a clean gravel aquifer. This high permeability is expected since the field data show only a 15 to 30 minute delay between maximum channel stage and the peak of the piezometer levels next to the channel. The holes in the channel bank of a few millimeters in diameter also suggest a high permeability. In this system the flow must be through a secondary porous structure and not through a medium of grain to grain contacts. Other values of S and .2 and .01 yield a K of about 50,000 and 10⁶ gpd/ft² respectively. The conditions of fig. 25 also suggests a thickness of the permeable layer of 2.5 feet. Of course, raising d_0 above the channel bottom was unrealistic, but in the field the porous channel bank does extend close to 3.5 feet from the surface of the marsh. Thus d_0 gave a good indication of this aspect of

the system. These parameters obtained from the computer simulation are used as suggestions of the actual system's parameters and are not taken absolutely.

Since the water table model did not agree completely with the field data it is likely that some of the assumptions used in deriving the governing equation were not justified. For example, the permeable section is probably not of constant thickness with an impermeable base throughout the marsh. In all the computer runs water levels of piezometers away from the channel (like that of piezometer 4C) had fluctuations much greater in amplitude than their restrictive field curves. This suggests that the marsh is less permeable away from the channel and that the base of the permeable section may come closer to the marsh surface away from the channel.

Pumping Tests

Piezometers 2C, 4C, 5C, 8C and 8B were pumped individually for a few minutes. Figure 30 shows the recovery of the water levels of the piezometers after they had been pumped. Each of piezometers 8B and 8C had .5 gallons pumped from them and their water levels lowered 4.7 and 2.7 feet, respectively. Piezometers 5C and 2C (12 and 2.5 feet from the channel) had close to .25 gallons pumped from them and their levels were lowered 1.9 and 2.3 feet, respectively. All the piezometers were pumped during low tide so that the recoveries were not affected by fluctuations of the channel stage.

The recovery of the piezometer levels appears relatively slow. At first the recoveries are fairly rapid but level off in the next 10 to

40 minutes. In the tests, piezometers next to the pumped piezometers were unaffected except for piezometers next to 2C which showed draw-down of only a few hundredths of a foot. Paradoxically, these observations suggest that the marsh materials are much less permeable than indicated by the computer simulations. Material with a K of 100,000 gpd/ft² would certainly show a faster response to pumping.

One reconciliation of this discrepancy is that when the channel is at low stage it acts as a negative boundary and does not supply any water to the marsh. Thus piezometer level recovery could be very slow even though the material is very permeable.

On the other hand, if the negative channel boundary has little affect on the recoveries, then one must conclude that the material below the water table is relatively impermeable. This material probably has permeabilities of the order of .04 cm/sec (1 cm/sec = 2835 ft/day) as determined by Pestrong (see Table 2). The material above the water table at low tide (when the tests were performed) could still be very permeable. The upper part of the marsh is what the computer simulation suggests is permeable and thus this second hypothesis is not inconsistent.

Conclusions

Figure 29 is a diagrammatic cross-section of the inferred porous structure of the marsh deposits based on field observations and the results of the computer simulations and pumping tests. A highly permeable zone is shown adjacent to the channel to a depth of about 3.5 feet. The zone becomes shallower away from the channel and sits on top of a much less permeable zone.

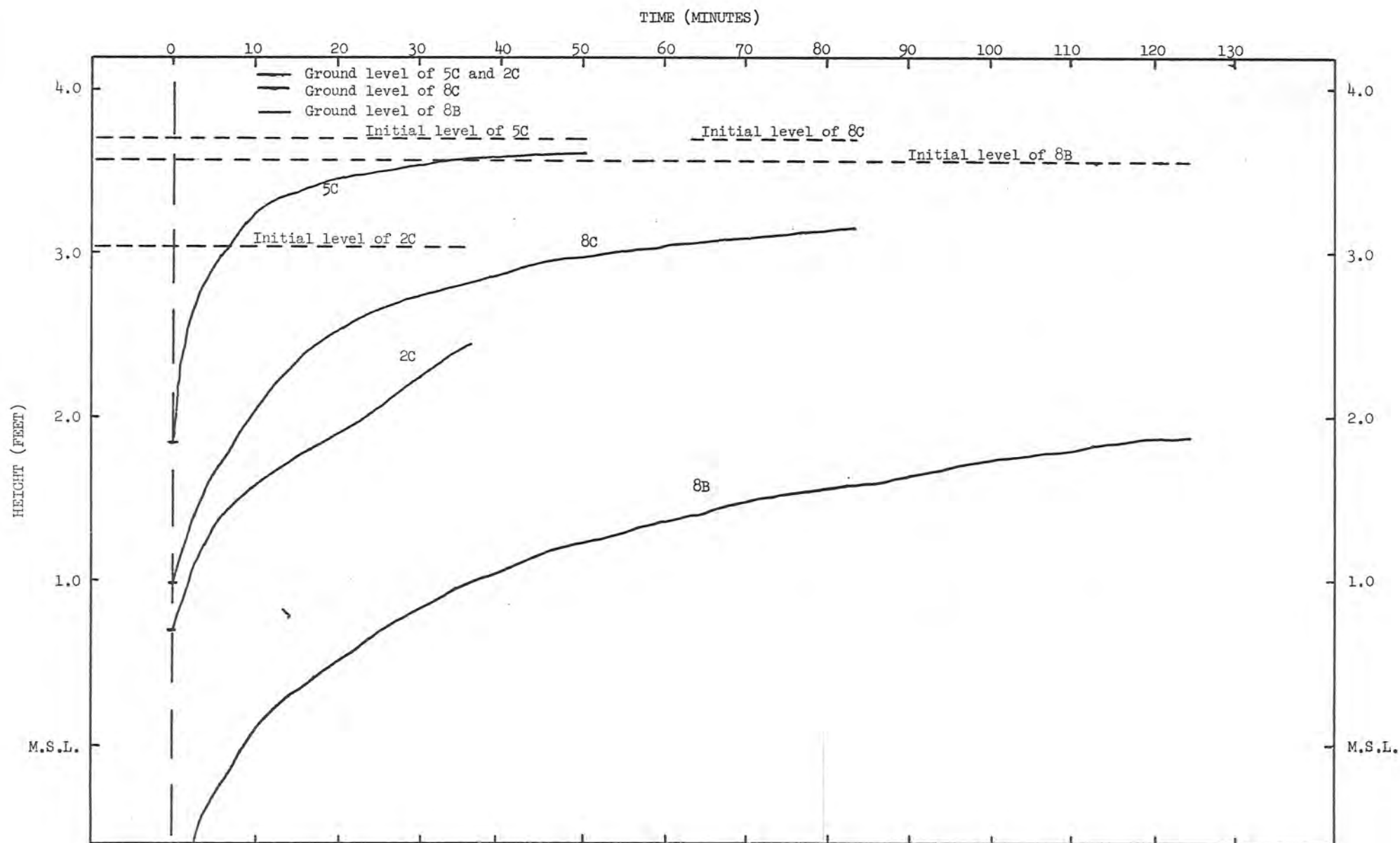


Figure 29. Water level recoveries of pumped piezometers in Cooley Landing marsh.

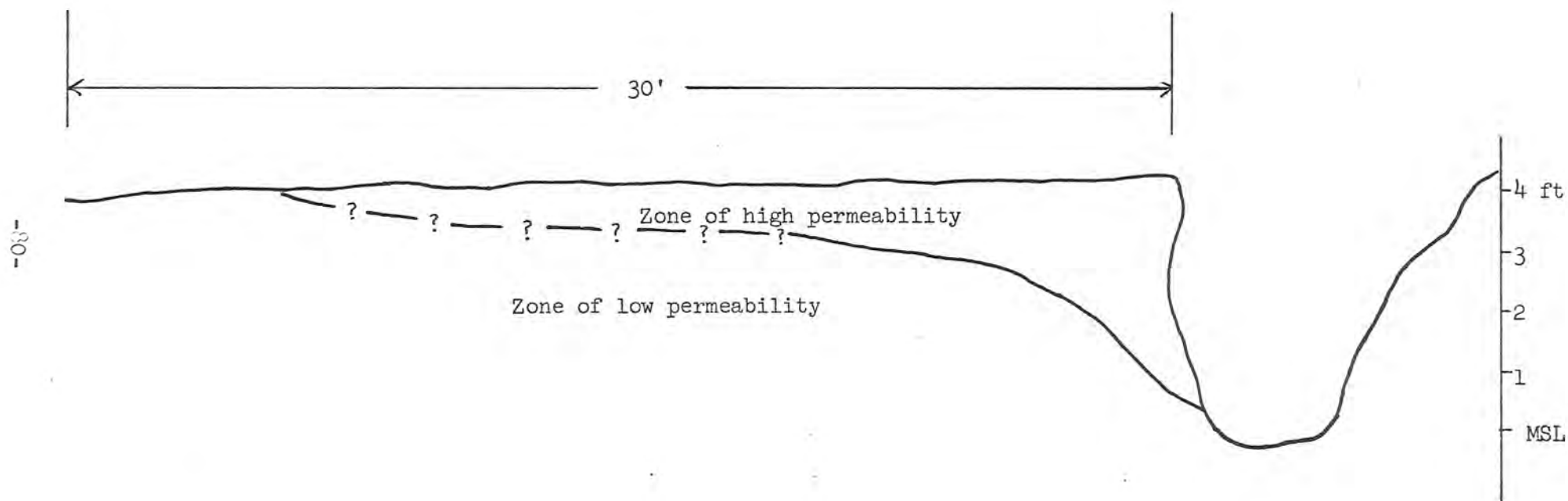


Figure 30. Diagrammatic cross-section of porous structure of marsh deposits near steep-banked tidal marsh channels.

This structure could produce successively smaller water table fluctuations away from the channel. If the upper zone is permeable enough, then the water table should respond almost instantly to the channel stage fluctuations. This is the case shown by the field data obtained. At low stage the water table will also assume a steady state much like the field data since the bottom of the permeable zone slants toward the channel.

PALO ALTO FLOOD CONTROL BASIN

Part of the Palo Alto baylands consists of areas that have been cut off from tidal fluctuations for some time. One such area is the Palo Alto Flood Control Basin (Plate 7) which consists of 618 acres and is located in the southern part of the baylands (fig. 2). In the 1950's this tract of land was dredged and leveed around its perimeter and used to control large floods during winter storms (Plate 9). Thus the area has gone through considerable change in the last 20 years since being removed from the influence of tidal fluctuations. A tidal gate (Plate 9) was installed at the bay edge of the flood basin which only allows water to flow out from the flood basin to the bay when the water level in the flood basin is higher than that of the bay.

Present Conditions

The flood basin is flat-lying like the rest of the baylands with elevations of about zero to 2 feet below M.S.L. The southwestern extent of the flood basin (near U.S. Highway 101) is at levels of 3 to 5 feet below M.S.L. The average elevation of the flood basin thus is several feet below that of the natural marshlands. The surface of the



Plate 7. Areal view of Palo Alto Flood Control Basin. White border is levee and dark border is dredged slough. Note remnant channels in interior of flood basin.



Plate 8. Remnant marsh channel in flood basin. Banks are about 3 feet high and lined with *Salicornia*. Bottom of channel is covered with salts.



Plate 9. Dredged slough with bordering levees (looking northwest). Note tidal gate in background. Salicornia dominates the foreground.



Plate 10. Remnant marsh channel filled with water. Note dry freshwater grasses which dominate the flood basin. Photo was taken in July.

Cooley Landing marsh is about 4 ft above M.S.L. and once was higher at about 6 feet. Withdrawal of groundwater at depth caused compaction of clay layers which resulted in subsidence of about 2 ft in this area (Poland, 1971). The flood basin area has subsided 3 ft since 1912 as measured at the Palo Alto Yacht Harbor. Thus the flood basin has lowered an additional 3 to 5 ft. This lowering is probably due to the compaction of the bay mud near the surface due to the loss of vibrant salt tolerant plants and some natural moisture content.

The flood basin has many sinuous channels of different size which have maintained some of their form since the area was closed off. These channels appear on Plate 7 as black to gray lines in the interior of the flood basin. The larger channels are an average of 3 feet deep and range from 20 to 30 feet wide (Plates 8 and 10). The smaller channels on the average are 2 feet deep and 10 feet wide. Most of the old natural channels are not filled with water since the elevation of the standing water in the dredged slough is commonly below the level of the channel bottoms. The bottoms of the large natural channels are flat (Plate 8) and often contain precipitates produced from the evaporation of standing water.

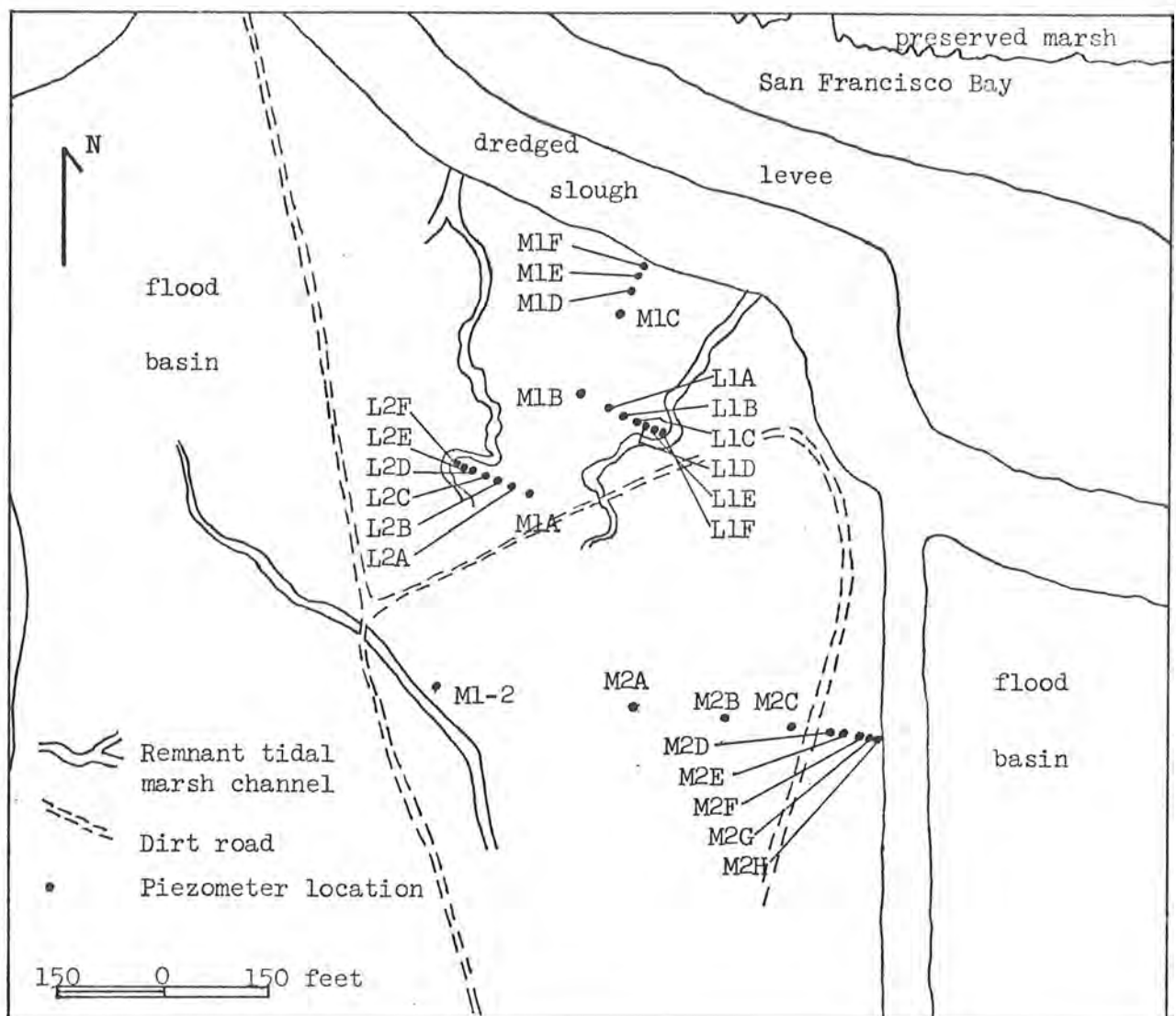
Since the closing off of the flood basin freshwater grasses have established themselves in the highest elevations in the flood basin. This grass dies off in the summer and appears as a very light tone on Plate 7. In Plate 7 the dark areas bordering the flood basin is standing water in the dredged slough, while the dark in the interior areas is produced by Salicornia which lines old natural channels and covers areas of lower elevation.

Matedero and Adobe and Barron Creeks drain into the flood basin on its north and south side, respectively. Combined they have a drainage area of close to 27 square miles. There are no recorded flows on these creeks near the flood basin but during heavy storms the creeks discharge large volumes of fresh water into the flood basin. The water then drains out to the bay when the level in the bay is lower than that in the flood basin. During the summer the basin is basically dry. Water in the dredged slough slowly evaporates throughout the summer.

The groundwater in the northern part of the flood basin was studied by installing twenty-seven piezometers in various lines (fig. 31). The piezometers were perforated from 5 to 6 feet below the ground and gravel packed from 1 to 6 feet. There are two main lines (M1 and M2) each at right angles to the dredged slough plus two lateral lines (L1 and L2) to small dry remnant channels. These piezometers were installed mainly to monitor tidal fluctuations in the flood basin when part of the tidal cycle will be allowed to flow in and out of the area.

The material found in installing the piezometers was dark gray silty clay (bay mud) capped by 1 to 2 feet of brown soil. The root zones of the freshwater grasses and Salicornia are restricted to about the first foot. Figure 4 shows the depth of the bay mud in the flood basin on Section A - B.

In the area of the piezometers the bay mud is about 20 feet thick. Firm to stiff silty clays are commonly found below the bay mud. Thus downward vertical percolation is probably severely restricted due to the predominance of clayey sediments near the surface.



SPACING AND ELEVATION OF PIEZOMETERS

M1-2	-0.75	M1-2		M1A		M1B	
300'		216'		78'		96'	
M1A	-0.95	M2A	-0.72	L2A	-0.71	L1A	-0.80
256'		256'		32'		64'	
M1B	-0.93	M2B	-0.48	L2B	-0.94	L1B	-0.41
128'		128'		16'		32'	
M1C	-0.39	M2C	+0.15	L2C	-1.02	L1C	+0.13
96'		64'		8'		16'	
M1D	-0.22	M2D	-0.20	L2D	-0.82	L1D	-0.79
24'		32'		4.2'		5.5'	
M1E	-0.98	M2E	-0.43	L2E	-0.83	L1E	-0.93
4'		16'		1.7'		2.5'	
M1F	-1.65	M2F	-0.50	L2F	-0.91	L1F	-1.21
		8'					
		M2G	+0.09				
		2.4'					
		M2H	-0.22				

Figure 31. Location of piezometers in the Palo Alto Flood Control Basin. See figure 2 for location of area.

The occurrence of groundwater in the flood basin was studied in June and July. At this time of year the water in the dredged slough is relatively low at about 3.5 feet below M.S.L. The groundwater in the area ranges from 2 to 3 ft below the ground surface or about 3.5 to 4.5 ft. below M.S.L. (Ground elevation is approximately .5 to 1.5 ft below M.S.L.) The water table near the dredged slough is controlled basically by the height of the water in the slough. The water table next to the slough varied from about 4.1 to 3.4 feet below M.S.L. during this period. The height of the water in the dredged slough varies by a small amount due to leakage of the tidal gate.

The water table slopes inland at gradients from .4 to 1 ft per 700 ft depending on the water level of the slough. The inland areas seem unaffected by the levels of the dredged slough but did change. In a four week period piezometers L2A through L2F showed a drop in the water table of .1 ft per week. For example, piezometer L2C had water levels of -4.40, -4.53, -4.59 and -4.72 ft on 6/15, 6/23, 6/29 and 7/7, respectively (see Appendix C for water level data). The gradual drop in the water table during this time of year is probably caused by evapotranspiration. Since the freshwater grasses are dead at this time of year and Salicornia is relatively shallow rooted, the dominant effect is probably evaporation

Pumping Tests

In order to develop some idea of the permeability of the flood basin pumping tests were performed similar to those in the Cooley Landing marsh. Nine of the piezometers in the flood basin were pumped. Table 3 shows the amount each piezometer was pumped and how they recovered.

TABLE 3

DATA FROM PUMPING TESTS PERFORMED ON PIEZOMETERS IN THE
PALO ALTO FLOOD CONTROL BASIN

Piezometer pumped	Initial water level (ft)*	Approx. level pumped to (ft)*	Approx. Volume pumped (gal)	<u>Details of Recovery of Pumped Piezometer</u>				<u>Effects on other piezometers</u>
				<u>Period of time measured (min:sec)</u>	<u>Level recovered to (ft)*</u>	<u>Amount recovered (ft)</u>	<u>Recovery (%)</u>	
M2H	-3.85	-5.27	not measured	12:25	-4.04	1.23	86	M2G lowered .56 ft M2F lowered .05 ft
M2C	-3.97	-6	.2	no significant recovery in 5 minutes				
M1-2	-4.14	-4.16	not measured	almost instantaneous recovery				
L2F	-4.41	-4.90	not measured	2:00	-4.71	.19	26	L2E lowered .03 ft
M1F	-3.98	-7.70	not measured	15:10	-5.45	1.47	40	M1E lowered .08 ft
M1A	-3.73	-7.80	2	38:30	-4.11	3.79	93	
L1F	-4.29	-5.46	2.5	9:00	-4.29	1.17	100	
L1B	-4.29	-4.97	2.5	5:55	-4.32	.65	96	
M2B	-4.14	-4.91	1	7:25	-4.15	.76	99	

*levels referenced to M.S.L.

It is difficult to make comparisons from one piezometer to another since it was difficult to pump the level down the same amount in each piezometer.

The piezometers show a wide range of response. For example, Piezometer M1-2 was pumped continuously for about 5 minutes and its water level went down only .02 ft. On the other hand, piezometer M2C was pumped dry and showed no significant recovery in the next 5 minutes. These results indicate that the bay mud is not as hydraulically consistent as it appears from boring to boring. In some places the ground may have dessicated to a relatively deep level and thus store significant amounts of water in cracks. Piezometers M2H and M1F near the dredged slough can be continuously pumped and have fairly rapid recovery because of the positive boundary produced by the dredged slough.

Piezometers L1F, L1B and M2B showed fairly rapid recovery. They could not be pumped down to very low levels apparently because water was flowing rapidly back into the piezometers. They were pumped down 1, 17, .68, .77ft, respectively, and all totally recovered within 10 minutes.

Piezometers a few feet from the pumped piezometers were measured to see if they were affected by the pumping. Most showed drawdown of only a few hundredths of a foot. Piezometer M2G was lowered .56 ft when piezometer M2H was pumped for several minutes.

It is difficult to compare these results with those of the Cooley Landing marsh since the same pumping conditions were difficult to obtain. Piezometers 2C, 8C, and 5C were pumped down 2.34, 1.73, and 1.85 ft respectively and in 30 minutes had recovered 1.55 (66%), .77 (45%), and 1.68 ft (91%). On the other hand, in the flood basin, piezometers like

M1A, L1F, L1B, M2B and M1-2 (none near a positive boundary) showed faster response with most recovering the first few minutes after pumping ended. The difference in response between the two areas could be that the flood basin is somewhat more permeable at depths below the water table than the Cooley Landing marsh. On the other hand, the presence of a negative boundary in the Cooley Landing marsh could also account for the difference. Qualitatively, though, the piezometers in both areas seem to respond in the same order of magnitude.

WATER QUALITY

Water samples were taken from the Cooley Landing marsh and the Palo Alto Flood Control Basin in order to obtain a general idea of the quantity of basic constituents in the water. Surface water and water from various piezometers in Cooley Landing marsh and flood basin were analyzed for chloride, total dissolved solids and salinity (Table 4). All piezometers sampled were pumped before samples were taken.

In the flood basin the dredged slough (Plate 9) showed chloride, total dissolved solids and salinity content lower than the average of the piezometers sampled in the flood basin. The piezometer samples had average values of 15,920, 30,538 and 26,244 mg/l, respectively for chloride, TDS and salinity, whereas the surface water had 13,050, 25,080 and 21,510 respectively. If the surface water sample is representative, then the ground water is more concentrated with chloride and other salts. A sample from an evaporating pond in the flood basin near the U.S. Highway 101 shows the highest chloride content of 21,000 mg/l. This content is evidently produced by evaporation of the pond during the summer.

TABLE 4

CHLORIDES, TOTAL DISSOLVED SOLIDS AND SALINITY OF WATER SAMPLES TAKEN
FROM COOLEY LANDING MARSH AND PALO ALTO FLOOD CONTROL BASIN

<u>Date</u>	<u>Location</u>	<u>Chloride (mg/l)</u>	<u>TDS (mg/l)</u>	<u>Salinity (mg/l)</u>
7/11/76	<u>Cooley Landing marsh</u>			
	Tidal channel	18,400	24,900	30,330
	Piezometer 2C	17,500	38,330	28,850
	Piezometer 8C	18,500	35,150	30,500
	Piezometer 8B	19,300	36,420	31,810
	Average of piezometers	18,433	36,633	30,387
6/29/76	<u>Palo Alto Flood Control Basin</u>			
	Pond near U.S. Highway 101	21,030	39,960	34,670
	Dredged slough	13,030	25,080	21,510
	Piezometer M2H	11,000	21,420	18,130
	Piezometer L1F	19,500	37,000*	32,150
	Piezometer M1A	16,900	31,370	27,860
	Piezometer M2B	14,300	28,900	23,570
	Piezometer M1-2	17,900	34,000*	29,510
	Average of piezometers	15,920	30,538	26,244

* estimated

Water from the Cooley Landing marsh indicates higher contents of these constituents. The piezometers sampled have an average chloride content of 18,433 mg/l. A similar chloride content was found in the channel near the piezometers during high tide.

ENVIRONMENTAL RESTORATION OF THE PALO ALTO FLOOD CONTROL BASIN

The city of Palo Alto presently plans to allow natural tidal fluctuations into the Palo Alto Flood Control Basin initially up to an elevation of 2 feet below M.S.L. and later to 1.7 feet below M.S.L. This project is part of an effort to bring back tidal marshes in the Palo Alto baylands. The gate now present will be modified to be automatically controlled to allow water in the flood basin when the water level is below the -2 foot level. The automatic gate will not allow water into the basin when the bay is higher than -2 feet. Figure 32 shows the areal extent of surface water in the flood basin when the water is at this -2 foot level.

The maximum water level allowed in the flood basin will be -1.7 ft. This level was set so that the freshwater grasses in the basin, which exist at higher elevations, will not be damaged by the saline bay water. Water Resources Engineers (1975) developed a surface water model of the flood basin and determined that tidal fluctuations up to the -1.7 ft level will not effect the flood control capacity of the basin during major winter storms.

Since the lower part of the tidal cycle will be allowed into the flood basin, water will stand in the channels for longer periods of time than in the natural tidal marshes. On some days, when low tides are not extreme, the channels will not be drained. Although the flood basin materials have low permeabilities, the presence of water in the remnant

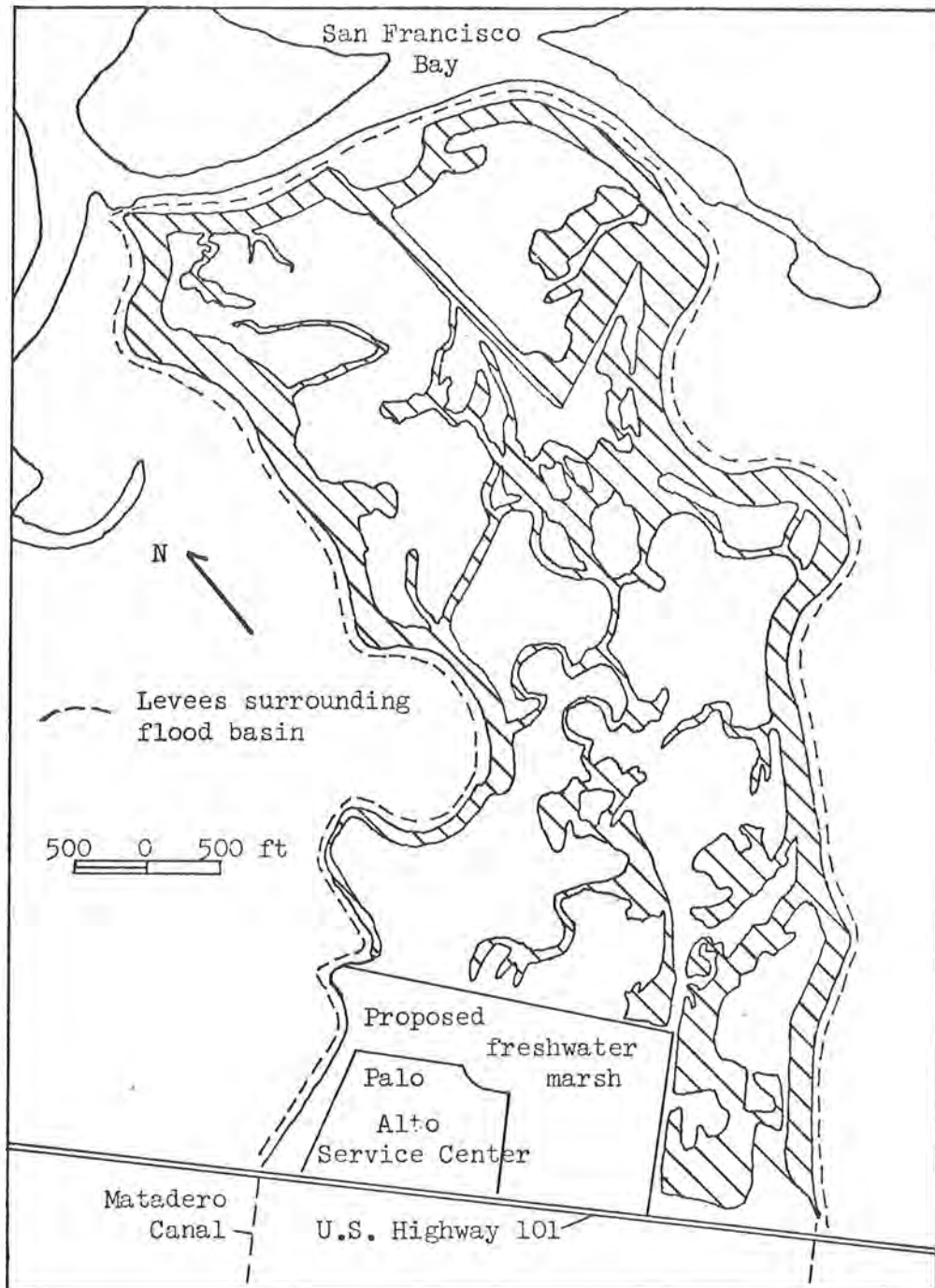


Figure 32. Areal extent of surface water in Palo Alto Flood Control Basin when water level is 2 feet below mean sea level. Source: Water Resources Engineers (1975).

channels for a large part of the day will eventually raise the water table level up near the -1.7 ft level. This means that the present water table will rise an average of 2 to 3 feet. The new water table level will be close to the surface and will not affect the freshwater grasses if the level stays more than 1/2 foot below the ground surface.

The hydraulic conditions in the channels of the flood basin will be different than those in the natural marshes. If hydraulic conditions are an important factor in developing the porous bank structure in the Cooley Landing marsh, then, at this time, it is difficult to determine whether the same structure will develop in the flood basin.

The reintroduction of tidal fluctuations will make the brackish water in the flood basin more saline. If there is significant percolation down into the shallow aquifers, then these aquifers will possibly become more contaminated than they are now. Figure 4, though, shows the flood basin being underlain by clays for several feet. Therefore, the contamination of the shallow aquifers from the flood basin will probably be insignificant. In any event, the County of Santa Clara is installing injection and extraction wells along the bay side of U.S. Highway 101 in order to halt salt water intrusion occurring in the shallow aquifers.

Studies of the flood basin will continue when the tide gates are modified. The 27 piezometers installed will help monitor the behavior of the water table when the tides are re-established.

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

The sediments 200 feet below the Palo Alto baylands were produced by alternating alluvial and estuarine environments in the last 150,000 years. The Pacific Ocean twice inundated the San Francisco Bay area during the Sangamon and post Wisconsin interglacial ages and deposited thick sequences of fine-grained estuarine deposits. During glacial periods, alluvial clay, sand and gravel was deposited.

Aquifers occur in two separate zones in the Palo Alto baylands area. A deep aquifer exists at depths of 150 to 200 feet and is separated from shallow confined aquifers by a relatively thick sequence of clay deposits. The shallow aquifers are highly variable in thickness but are probably interfingered and thus hydraulically continuous. Domestic pumping in inland areas has produced sea water intrusion in the shallow aquifers. Saline bay water probably percolates slowly down through the sediments into the shallow aquifers.

It appears that there is a permeable zone next to steep-banked tidal marsh channels as indicated in figure 29. This zone is limited to the first 10 to 20 feet from the channel and sits on fairly impermeable material. Work should be continued on this part of the tidal marshes of the Palo Alto baylands to verify the depth and extent of this zone. Infiltration tests made at different levels in the near surface of the deposits should determine the true geometry of the permeable zone. In addition, different computer models could be developed in order to obtain a better match with the field data and determine the characteristics of the deposits more exactly.

The interaction of soil moisture and the water table in the tidal marshes proves to be a very interesting area of study. Models of soil moisture-water table systems have been developed by Pikul (1974) and Neuman (1972) and might be appropriately applied to the tidal marshes.

The Palo Alto Flood Control Basin contains many remnant channels and appears to have low permeabilities similar to those of the natural tidal marshes. If the specific characteristics of these materials, like permeability and storativity, can be obtained from several locations in the flood basin it is possible to construct a model that would approximate the behavior of the water table when tidal fluctuations are re-introduced. This water table could be a two-dimensional version of the one used in this study. In addition, construction of a regional model of the flood basin could help in establishing how the flood basin interacts in the total hydrogeologic system of the alluvial fans extending to the bay from the Santa Cruz Mountains. This type of model would require knowledge of the geometry and characteristics of the aquifers (described in this study), recharge from the Santa Cruz Mountains and domestic pumping rates.

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APPENDIX A

SOURCE OF WELL AND ENGINEERING BORING LOGS

SOURCE OF LOGS LOCATED IN FIGURE 4

USGS = United States Geological Survey

SCVWD = Santa Clara Valley Water District

<u>Number</u>	<u>Source</u>	<u>Source number</u>	<u>Number</u>	<u>Source</u>	<u>Source number</u>
1	USGS	5S/2W-30C1	46	SCVWD	33NB1
2	USGS	5S/2W-30C2	47	"	32RB1
3	USGS	5S/2W-30F1	48	App. B	W2
4	USGS	5S/2W-30F2	49	City of Palo Alto	G7
5	USGS	5S/2W-30G1	50	SCVWD	5DB1
6	USGS	5S/2W-30G2	51	"	6S/2W-5D1
7	USGS	5S/2W-30G3	52	"	5CB1
8	USGS	5S/2W-30G4	53	City of Palo Alto	G4
9	USGS	5S/2W-30H1	54	"	G5
10	SCVWD	5S/2W-30N80	55	SCVWD	6S/2W-6C17
11	"	5S/2W-31D80	56	"	6S/2W-6D2
12	"	32DB2	57	"	6AB1
13	"	32DB1	58	City of Palo Alto	G6
14	"	32EB1	59	SCVWD	5AB1
15	"	32EB2	60	"	4DB1
16	"	31HB1	61	"	5HB1
17	"	32EB3	62	App. B	W3
18	"	32BB2	63	SCVWD	5HB2
19	"	32BB1	64	"	5GB1
20	"	32BB3	65	"	5FB2
21	"	32BB4	66	"	5EB2
22	"	32FB1	67	"	5EB1
23	"	32GB1	68	"	5FB1
24	App. B	W1	69	"	5LB3
25	SCVWD	32HB1	70	"	5LB1
26	City of Palo Alto	G2	71	"	5LB2
27	SCVWD	32FB2	72	"	5JB1
28	SCVWD	32MB2	73	"	5RB2
29	"	5S/2W-31J80	74	"	4NB1
30	"	5S/2W-32M1	75	"	5PB1
31	City of Palo Alto	G1	76	"	5QB1
32	SCVWD	TH/OW-3	77	App. B	W4
33	"	I/E Well	78	SCVWD	5RB3
34	"	31KB1	79	"	4NB2
35	"	TH/OW-1	80	"	6S/2W-5Q80
36	"	31QB2	81	"	5RB1
37	Ca. Trans. Dept.	-	82	"	6S/2W-8B80
38	SCVWD	31LB1	83	"	6S/2W-8A80
39	"	31LB2	84	"	6RB1
40	"	31PB1	85	"	6RB2
41	"	31PB3	86	"	7AB1
42	"	31PB2	87	"	7AB2
43	"	31QB1	88	"	6S/2W-7A1
44	"	32JB1	89	"	8DB1
45	City of Palo Alto	G3	90	"	8BB1

<u>Number</u>	<u>Source</u>	<u>Source number</u>
91	SCVWD	8BB2
92	"	8GB6
93	"	8GB1
94	"	8GB2
95	"	8GB3
96	"	8GB5
97	"	8GB4
98	"	6S/2W-8A81
99	"	6S/2W-8H1
100	"	6S/2W-7F1
101	"	8EB1
102	"	8EB2
103	"	6S/2W-8M1
104	"	6S/2W-7J80
105	"	6S/2W-8L80
106	"	6S/2W-8J1
107	"	6S/2W-8Q80
108	"	6S/2W-8R1

APPENDIX B

LOGS OF BORINGS IN PALO ALTO FLOOD CONTROL BASIN

BORING W1

<u>Depth below surface (ft)</u>	<u>Description</u>
0-3	Top soil; brown to dark brown
3-15	Moist gray to dark gray clay
15-20	Moist gray to dark gray clay with shells
20-25	Brownish-red stiff clay
25-32	Gradation to dark gray clay

BORING W2

0-2	Brown top soil
2-11	Moist dark gray clay
11-16	Dry, firm bluish-green clay
16-20	Dry, firm dark bluish-green silty clay
20-23	Moist brown sandy clay
23-30	Saturated brown clayey sand with some gravel
30-32	Dark brown clayey sand and gravel

BORING W3

0-2	Brown top soil
2-5	Dark gray clay
5-9	Very dark gray firm clay
9-12	Greenish-blue firm sandy clay
12-32	Brownish-green firm clay with some sand

BORING W4

0-5	Gray top soil
5-10	Brownish-green clay
10-13	Wet brownish-green clay
13-32	Sandy gravel; gravel is well rounded

APPENDIX C
WATER LEVEL DATA

WATER LEVELS OF PIEZOMETERS IN COOLEY LANDING MARSH

45 HOUR MONITORING

(MAY 4, 5 and 6, 1976)

The column labelled "piezometer level" corresponds to the following piezometers:

Piezometer
level

2A
2B
1C
2C
3C
4C
5C
6C
7C
8C
8A
8B

The elevations of the lips of the piezometers above mean sea level are:

<u>Piezometer</u>	<u>Elevation</u>
2A	6.57
2B	6.05
1C	5.92
2C	5.60
3C	6.00
4C	5.87
5C	5.93
6C	5.83
7C	5.46
8C	5.75
8A	6.31
8B	6.10

Note: Mean sea level is base datum for all water level measurements.

The following data are read by following the Time column. The set of columns labelled Time, Piez. level and Channel stage are read across and down the pages.

May 4, 1976

<u>Time</u>	<u>Piez. level</u>	<u>Channel stage</u>	<u>Time</u>	<u>Piez. level</u>	<u>Channel stage</u>	<u>Time</u>	<u>Piez. level</u>	<u>Channel stage</u>
11:15AM	2.49	-.16	12:12PM	2.49	-.16	1:00	2.47	-.16
	2.19	'	12:13	2.19	'	1:01	2.20	'
	2.22	'	12:14	2.23	'	1:02	2.23	'
11:18	2.50	'	12:15	2.52	'	1:03	2.52	'
	2.81	'		2.82	'		2.81	'
11:20	3.00	'	12:16	3.00	'		3.00	'
11:24	3.19	'	12:17	3.17	'	1:05	3.17	'
	3.22	'	12:18	3.20	'	1:06	3.20	'
11:28	3.28	'		3.27	'		3.27	'
	3.29	'	12:20	3.28	'	1:07	3.29	'
11:30	3.07	'		3.05	'		3.03	'
	2.72	'	12:21	2.71	'	1:09	2.71	'
2:01	2.47	-.16	3:00	2.47	-.13	3:30	2.54	.91
	2.18	'	3:01	2.18	-.09	3:31	2.18	.92
2:03	2.22	'	3:01	2.21	-.06	3:32	2.29	.94
2:04	2.52	'	3:02	2.50	.00	3:34	2.54	.96
2:05	2.80	'	3:03	2.80	.03		2.84	.97
	2.99	'	3:04	2.98	.04		3.01	.97
2:06	3.16	'	3:05	3.15	.09	3:35	3.16	1.00
	3.19	'		3.18	.11		3.19	1.00
2:07	3.26	'	3:06	3.24	.12	3:36	3.23	1.02
2:08	3.27	'	3:07	3.26	.16	3:37	3.27	1.05
	3.02	'	3:08	3.01	.20	3:38	3.01	1.07
2:10	2.71	'		2.71	.22		2.70	1.09
			3:20		.64	3:45		1.24
			3:25		.75	3:50		1.40
						3:55		1.51
4:05	2.69	1.67	4:30	2.73	2.11	4:45	2.78	2.30
4:06	2.18	1.69		2.18	2.12	4:46	2.18	2.32
4:07	2.44	1.71	4:32	2.59	2.12	4:47	2.65	2.33
4:08	2.61	1.72	4:33	2.68	2.12	4:48	2.75	2.34
	2.90	1.72	4:34	2.93	2.12		2.97	
4:09	3.03	1.74		3.05	2.13		3.08	2.35
4:10	3.18	1.77	4:35	3.19	2.15	4:49	3.20	2.35
	3.20	1.78	4:36	3.21	2.16		3.22	2.35
4:11	3.25	1.79		3.24		4:50	3.24	2.36
4:12	3.25	1.82	4:37	3.25	2.20	4:51	3.26	2.38
4:13	3.01	1.83	4:38	3.02	2.24		3.01	
4:14	2.70	1.84	4:39	2.70	2.25	4:52	2.70	2.39
4:22		1.97						

May 4, 1976 (cont)

<u>Time</u>	<u>Piez. level</u>	<u>Channel stage</u>	<u>Time</u>	<u>Piez. level</u>	<u>Channel stage</u>	<u>Time</u>	<u>Piez. level</u>	<u>Channel stage</u>
5:00PM	2.81	2.48	5:15	2.84	2.59	5:30	2.87	2.70
	2.18	2.50		2.17	2.60		2.17	
5:01	2.70	2.50	5:17	2.76	2.62	5:31	2.79	2.71
	2.79	2.50		2.82	2.63	5:32	2.85	2.71
5:02	2.97	2.50	5:18	3.01	2.64		3.01	2.71
5:03	3.08	2.50	5:19	3.10	2.64	5:33	3.10	'
5:04	3.20	2.51		3.20	'	5:34	3.19	'
	3.22	'	5:20	3.23	'	5:35	3.23	'
5:05	3.24	'		3.24	'		3.24	'
5:06	3.25	2.52	5:21	3.25	2.65	5:36	3.24	'
	3.01	2.53		3.01	'		3.00	'
5:07	2.70	2.54	5:22	2.69	'	5:37	2.69	'
6:00	2.87	2.70	6:29	2.81	2.52	6:45	2.78	2.37
	2.16	2.69		2.16	'		2.16	'
6:01	2.81	'		2.74	2.51	6:47	2.70	2.36
6:02	2.86	2.68	6:31	2.82	2.49		2.79	'
	3.02	'		2.97	'	6:48	2.96	2.35
6:03	3.09	'	6:33	3.07	'		3.07	2.34
6:04	3.19	'		3.18	2.48	6:50	3.17	2.33
6:05	3.23	2.67	6:34	3.21	'		3.22	2.32
	3.24	2.66		3.23	'	6:51	3.22	2.31
6:06	3.25		6:35	3.24	'	6:52	3.24	2.30
	3.00			3.00	'		3.00	'
6:07	2.69	2.65	6:36	2.69	'	6:53	2.69	2.29
7:02	2.72	2.19	7:15	2.69	2.00	7:30	2.65	1.79
	2.17	'		2.16	1.99	7:31	2.16	1.77
7:03	2.63	2.18		2.59	1.98		2.52	1.75
	2.74	2.17	7:17	2.71	'		2.68	1.74
7:05	2.93	2.16		2.91	1.97	7:33	2.89	'
	3.05	2.15	7:19	3.04	1.95		3.03	'
7:06	3.17	2.14		3.15	'		3.16	'
	3.19	2.12		3.19	1.94	7:35	3.20	'
	3.22	'		3.22	'		3.22	1.73
	3.24	'	7:22	3.24	1.92		3.23	1.71
7:08	3.00	2.11		2.99	1.91		3.00	1.70
7:09	2.69	2.10	7:23	2.69	1.89	7:38	2.67	'

May 4, 1976 (cont)

7:45PM	2.60	1.59	8:01	2.56	1.30	8:37	2.48	.83
	2.16	1.57		2.16	1.28		2.16	
7:48	2.46	1.54		2.40	'		2.30	
	2.63	1.51	8:04	2.59	1.27		2.51	
	2.86	1.49		2.84	'		2.79	
7:49	3.01	'		2.99	1.26		2.97	
	3.13	1.48		3.13	1.25		3.12	
7:51	3.19	1.47	8:06	3.17	1.24		3.16	
	3.21	1.46		3.22	1.23		3.21	
7:52	3.23	1.45		3.23	1.22		3.23	
	2.99	1.44		2.99	1.21		3.01	
7:53	2.69	'	8:08	2.67	1.19	8:45	2.66	.50
			8:15		1.10			
			8:22		1.01			
			8:30		.92			
9:01	2.43	.24	10:00	2.40	-.21	11:00	2.40	-.21
	2.15			2.15	'		2.15	'
	2.23			2.17	'		2.16	'
	2.46			2.49	'		2.46	'
	2.75			2.76	'		2.77	'
	2.94			2.95	'		2.94	'
	3.12			3.13	'		3.14	'
	3.15			3.15	'		3.16	'
	3.22			3.22	'		3.22	'
	3.22			3.22	'		3.21	'
	2.99			2.99	'		2.98	'
9:14	2.67	.06	10:15	2.67	'	11:17	2.67	'

May 5, 1976

12:00AM	2.41	-.26	1:00	2.44	.31	1:30	2.49	.89
	2.15		1:07	2.15	.41	1:32	2.14	.96
	2.15		1:10	2.17	.44	1:35	2.23	
	2.45		1:12	2.47	.47	1:37	2.49	
	2.74		1:14	2.76	.51		2.80	1.05
	2.98		1:15	2.97	.54	1:38	2.98	
	3.16		1:16	3.14	.58	1:39	3.14	1.10
	3.16			3.16	.59		3.18	
	3.21		1:17	3.22		1:40	3.23	
	3.22		1:19	3.22			3.21	
	2.99		1:21	2.98			2.98	
	2.66		1:22	2.67	.72	1:44	2.67	1.24

May 5, 1976 (cont)

2:00AM	2.58	1.52	2:30	2.69	2.16	3:00	2.82	2.68
2:01	2.14	1.57	2:33	2.14	2.21		2.14	
	2.31			2.49		3:04	2.69	2.72
2:04	2.55		2:35	2.63	2.24		2.75	
2:06	2.84	1.64	2:36	2.90		3:08	2.98	2.74
	3.01			3.06			3.08	
2:07	3.18			3.19	2.31		3.25	
	3.19	1.74	2:40	3.21			3.23	
	3.21		2:42	3.24			3.24	
2:11	3.22		2:44	3.24			3.22	
	2.98	1.80		2.99	2.40		2.99	
2:14	2.66		2:46	2.66		3:14	2.67	2.83

3:30	2.89	3.02	4:00	2.96	3.31	4:30	2.97	3.39
	2.15		4:01	2.13	3.32	4:31	2.14	
	2.83	3.05	4:04	2.93			2.94	3.36
	2.86		4:06	2.96	3.33	4:35	2.98	3.35
3:35	3.03	3.07		3.08			3.08	
	3.13		4:09	3.15	3.34	4:36	3.16	
3:38	3.24			3.24	3.35	4:38	3.25	
3:39	3.24			3.27			3.29	
	3.25	3.15		3.26		4:40	3.26	
	3.23		4:11	3.22			3.23	
	2.99			3.01			3.01	
3:44	2.66	3.16	4:13	2.66	3.35	4:44	2.65	3.30

5:02	2.92	3.19	5:30	2.85	2.88	6:00	2.74	2.36
	2.14			2.14			2.14	
5:03	2.92	3.16		2.84			2.72	
	2.93			2.86			2.75	2.33
	3.05	3.14		3.00			2.92	
	3.14			3.10			3.04	
	3.23			3.22			3.18	
5:10	3.24	3.13	5:40	3.22		6:10	3.20	2.28
	3.26			3.24			3.22	
	3.22			3.22			3.20	
	3.01			3.01			3.01	
5:15	2.66	3.06	5:45	2.66	2.65	6:14	2.65	2.20

May 5, 1976 (cont)

6:31AM	2.60	1.81	7:00	2.49	1.21	7:30	2.41	.51
	2.14			2.15			2.14	
6:33	2.57	1.75	7:04	2.36	1.14	7:34	2.25	.43
	2.63		7:05	2.52	1.11	7:38	2.42	.36
	2.83	1.72	7:06	2.79			2.72	
	3.03		7:07	2.97	1.08	7:41	2.93	.29
	3.15		7:08	3.14			3.09	
	3.18			3.16			3.12	
	3.21			3.20		7:45	3.18	.19
	3.21		7:10	3.19	1.01		3.17	
	3.00			2.98			2.96	
6:45	2.66	1.49	7:12	2.65	.92	7:52	2.65	.09

8:30	2.37	-.17	9:30	2.38	-.18	10:30	2.40	-.18
	2.14	'		2.14	'		2.14	'
	2.17	'		2.15	'		2.15	'
8:35	2.42	'		2.42	'		2.42	'
	2.71	'		2.72	'		2.72	'
	2.92	'	9:40	2.92	'		2.92	'
	3.10	'	9:45	3.11	'		3.12	'
	3.12	'		3.12	'		3.12	'
	3.18	'		3.18	'		3.17	'
	3.17	'		3.17	'		3.18	'
	2.96	'		2.95	'		2.65	'
8:46	2.64	'	9:55	2.64	'	10:40	2.65	'

11:33	2.39	-.18	12:30PM	2.38	-.18	1:30	2.39	-.18
	2.13	'		2.13	'		2.12	'
	2.14	'		2.13	'		2.14	'
	2.41	'	12:35	2.41	'		2.41	'
	2.71	'		2.71	'		2.72	'
	2.91	'		2.92	'		2.92	'
	3.11	'	12:39	3.10	'		3.12	'
	3.12	'		3.13	'		3.14	'
	3.17	'		3.18	'		3.17	'
	3.17	'		3.17	'		3.18	'
	2.94	'		2.93	'		2.92	'
	2.65	'	12:43	2.65	'		2.64	'

May 5, 1976 (cont)

2:30PM	2.37	-.18	3:30	2.37	-.18	3:58	2.39	.19
	2.11	'		2.13	'		2.12	
	2.12	'		2.16	'	3:59	2.13	.24
	2.40	'		2.35	'	4:00	2.40	.29
	2.71	'		2.73	'		2.71	
	2.90	'		2.90	'	4:01	2.90	.33
	3.09	'		3.15	'	4:02	3.10	.36
	3.11	'		3.10	'		3.09	
	3.18	'		3.14	'	4:04	3.13	.41
	3.16	'		3.15	'		3.16	
	2.91	'		2.90	'	4:05	2.90	.45
	2.66	'		2.65	'		2.63	
			3:55		.02	4:10		.63
4:15	2.42	.74	4:30	2.48	1.14	4:45	2.53	1.49
	2.11			2.11			2.11	
	2.17		4:32	2.22	1.19		2.28	
	2.42			2.45		4:48	2.49	1.56
	2.73		4:33	2.76	1.24		2.78	
4:18	2.91	.84		2.94			2.95	
	3.09			3.10			3.10	
	3.11		4:35	3.11	1.28		3.11	
	3.14			3.15			3.14	
	3.16			3.16		4:50	3.14	1.61
4:22	2.89	.94	4:37	2.90	1.34		2.90	
	2.62			2.63		4:52	3.62	1.66
4:25		1.01	4:40		1.39	4:55		1.72
5:00	2.58	1.82	5:15	2.64	2.11	5:30	2.69	2.34
	2.11			2.11			2.11	
5:02	2.35	1.85		2.42	2.14		2.53	
	2.52		5:17	2.58			2.61	
	2.81			2.84			2.87	
5:04	2.96	1.89	5:19	2.99	2.17	5:33	3.00	2.36
	3.11			3.13			3.13	
	3.13			3.13			3.14	
	3.15			3.14		5:35	3.14	2.39
	3.15		5:22	3.15	2.21		3.15	
5:07	2.90	1.96		2.90			2.90	
	2.62			2.62		5:36	2.62	
5:10		2.02	5:25		2.25			

May 5, 1976 (cont)

5:45PM	2.73		6:00PM	2.67	2.64	6:15	2.79	2.74
	2.11			2.10			2.10	
5:46	2.59	2.53		2.66			2.69	
	2.66		6:02	2.70			2.73	
	2.89			2.92	2.67		2.92	
5:48	3.02	2.56		3.03			3.04	
	3.14			3.15			3.16	
	3.14			3.15			3.16	
	3.15		6:04	3.15	2.68		3.14	
5:50	3.15	2.57		3.15		6:20	3.15	2.74
	2.91			2.91			2.90	
	2.62		6:06	2.61	2.69		2.61	
5:55		2.60	6:10		2.72	6:35		2.77

6:45	2.78	2.76	7:15	2.75		7:30	2.72	2.47
	2.10			2.10	2.60		2.09	
	2.71			2.68			2.63	
	2.75			2.75			2.73	
6:48	2.93	2.74		2.91		7:33	2.89	2.45
	3.04		7:18	3.02	2.58		3.00	
6:50	3.15		7:19	3.13			3.11	
	3.16			3.14			3.14	
6:51	3.14	2.73	7:20	3.14	2.57	7:35	3.14	2.43
	3.15			3.15			3.14	
	2.90			2.90			2.91	
6:52	2.61		7:21	2.62	2.56	7:37	2.61	2.39
6:55		2.72	7:25		2.52	7:40		2.39
7:00		2.68						
7:07		2.64						

7:45	2.68	2.34	8:00	2.65	2.19	8:15	2.62	2.08
	2.10			2.09			2.10	
7:47	2.59			2.55			2.49	
	2.71			2.68			2.65	
	2.87		8:02	2.85		8:18	2.83	1.93
7:49	2.99	2.30	8:03	2.98	2.14		2.97	
	3.11		8:04	3.11			3.08	
	3.14			3.13		8:20	3.12	1.89
7:51	3.13	2.28		3.13			3.15	
	-		8:05	3.14	2.12		-	
	-			2.90			-	
	-			2.61			-	
			8:10		2.10	8:24		1.86

May 5, 1976 (cont)

8:30PM	2.55	1.79	8:45	2.52		9:15	2.42	.99
	-			-			-	
	2.43		8:47	2.39	1.46		2.27	
8:34	2.61			2.58		9:20	2.52	.88
	2.80		8:50	2.80	1.33		2.73	
	2.95			2.95			2.90	
8:37	3.09	1.66		3.08			3.06	
	3.11		8:53	3.11		9:25	3.09	
	3.13			3.12			3.13	
8:39	-	1.62	8:54	3.15	1.29	9:27	-	.74
	-			2.90			-	
	-			2.62			-	
			8:57		1.28			

9:30	2.40	.67	9:48	2.36	.35	10:15	2.34	-.10
	2.09			-			2.09	
	2.23			2.18			2.14	
9:34	2.49	.61	9:52	2.45			2.42	
	2.72			2.71	.29		2.69	
	2.90			2.91			2.88	
9:37	3.06	.57		3.05			3.06	
	3.08		9:55	3.03			3.08	
	3.12			2.99			3.12	
	3.13			-			-	
	2.90			-			-	
9:42	2.61	.46		-			-	
			9:58		.19	10:23		-.16
			10:03		.14			

May 6, 1976

11:00	2.34	-.18	12:10AM	2.35	-.18	1:30	2.35	-.18
	-	'		2.09	'		2.08	
11:02	2.12	'		2.10	'		2.09	
	2.38	'		2.38	'		2.37	
	2.67	'		2.69	'		2.68	
	2.89	'		2.89	'		2.89	
	3.05	'	12:20	3.07	'		3.07	
11:10	3.07	'		3.07	'	1:40	3.08	
	-	'		3.13	'		3.12	
	-	'		3.12	'		3.14	
	-	'		2.89	'	1:45	2.91	
	-	'	12:26	2.60	'		2.60	

May 6, 1976 (cont)

2:30AM	2.38	.24	3:00	2.43	.86	3:30	2.50	1.44
	2.08		3:02	2.08		3:31	2.08	
	2.12		3:04	2.17	.94		2.25	
	2.39	.30	3:05	2.42		3:32	2.46	1.52
	2.70		3:06	2.72			2.76	
	2.91			2.91	1.03	3:33	2.93	
2:38	3.10	.41		3.09			3.13	
	3.10		3:09	3.09			3.13	
	3.15		3:10	3.15	1.16	3:36	3.14	
	3.12			-			3.12	
	2.90			-			2.89	
2:42	2.60	.51		-		3:39	2.60	1.67
2:45		.58	3:12		1.16			
2:50		.67	3:15		1.21			
2:55		.72	3:20		1.29			
			3:25		1.41			
3:45	2.54	1.90	4:00	2.60	2.02	4:15	2.64	2.29
	2.07			2.08	2.07		2.08	
	2.32			2.38			2.47	2.33
	2.50			2.53			2.57	
	2.79			2.82			2.85	
3:50	2.96			3.05		4:20	3.00	
	3.12			3.13		4:22	3.14	
	3.11			3.13			3.13	
	3.14	1.92	4:10	3.15	2.19	4:23	3.08	2.40
	-			3.13			-	
	-			2.90			-	
	-			2.60			-	
4:30	2.69	2.50	4:45	2.73	2.63	5:00	2.78	2.81
	2.08			-		5:01	2.08	2.85
	2.56			2.62		5:03	2.69	
	2.62			2.67		5:08	2.72	
	2.88			2.91		5:09	2.92	2.85
	3.01			2.98			3.04	
	3.15		4:50	3.15			3.15	
	3.13			3.15			3.14	
4:40	3.14	2.58		3.15		5:14	3.15	2.90
	-			3.14		5:20	-	2.95
	-			2.90		5:25	-	2.98
	-		4:55	2.60	2.74		-	

May 6, 1976 (cont)

5:30AM	2.82	2.99	6:00	2.81	3.01	6:33	2.73	2.73
	2.08			2.07	2.96	6:34	2.06	
5:33	2.76	3.01	6:06	2.77			2.70	
	2.73			2.79			2.75	
	2.96			2.94			2.90	
	3.07		6:09	3.04	2.94		3.00	
	3.15			3.16			3.13	
	3.14			3.15			3.14	
	3.16			3.13		6:39	3.13	2.63
5:40	3.13	3.01		3.13			-	
	-			2.92			-	
5:50	-		6:13	2.60	2.90		-	
						6:41		2.58
6:45	2.69	2.54	7:00	2.66	2.30	7:15	2.60	2.05
	2.07			2.07		7:16	2.07	2.04
6:48	2.64	2.49	7:02	2.57	2.28	7:17	2.49	2.03
	2.72			2.69			2.64	
	2.88			2.84		7:19	2.82	1.96
	2.99		7:03	2.98	2.26		2.96	
	3.13			3.12		7:20	3.09	1.95
	3.14			3.13			3.09	
	3.12		7:04	3.13	2.25	7:21	3.11	1.93
	3.12		7:06	-	2.23		3.13	
	2.90			-		7:22	2.89	
6:50	2.59	2.41		-			2.59	1.91
6:55		2.36	7:10		2.16	7:25		1.87
7:30	2.53	1.74	7:45	2.47	1.48	8:00	2.41	1.14
	2.06			2.06			2.06	
7:32	2.41	1.72		2.36			2.30	
7:34	2.60	1.70	7:47	2.56	1.43		2.52	
	2.79			2.75	1.40	8:03	2.73	1.07
7:35	2.94	1.67	7:50	2.92	1.38	8:04	2.90	1.06
	3.08	1.64		3.08		8:05	3.07	1.05
	3.09			3.08		8:06	3.08	
7:36	3.12	1.63		3.11			3.11	1.03
	-			3.11		8:07	-	1.02
	-			2.89			-	
	-		7:53	2.59	1.31		-	
7:40		1.60	7:55		1.24	8:10		.94
7:43		1.54						

May 6, 1976 (cont)

8:15AM	2.38	.79	8:30	2.34	.50	8:45	2.32	.18
8:17	2.07	.75		2.05			2.05	
	2.24			2.20			2.15	
8:20	2.48	.69		2.46		8:49	2.43	.12
	2.70			2.69			2.67	
8:21	2.89	.67		2.88		8:51	2.88	.08
	3.06		8:35	3.04	.38		3.05	
	3.07			3.06			3.16	
	3.10			3.11		8:53	3.10	.04
	3.12			-		8:54	3.10	.02
	2.88			-			2.87	
8:25	2.58	.60	8:40	-	.28		2.59	

9:15	2.29	-.18	9:40	2.50	-.18
	2.06	'		-	'
	2.11	'		2.09	'
	2.40	'		2.37	'
	2.67	'		2.64	'
	2.86	'		2.86	'
	3.04	'		3.03	'
	3.04	'		-	'
	3.10	'		-	'
	3.11	'		-	'
	2.87	'		-	'
	2.58	'		-	'

WATER LEVELS IN PALO ALTO FLOOD CONTROL BASIN

June 15, 1976

<u>Piezometer</u>	<u>Water level (ft below M.S.L.)</u>	<u>Piezometer</u>	<u>Water level (ft below M.S.L.)</u>
M1F	-3.98	L2A	-4.39
M1E	-4.09	L2B	-4.40
M1D	-4.16	L2C	-4.40
M1C	-4.24	L2D	-4.42
M1B	-4.30	L2E	-4.41
M1A	-3.69	L2F	-4.41
L1A	-4.23	M1-2	-4.34
L1B	-4.23	M2A	-4.27
L1C	-4.24	M2B	-4.07
L1D	-4.23	M2C	-3.97
L1E	-4.26	M2D	-3.98
L1F	-4.26	M2E	-3.95
		M2F	-3.92
		M2G	-3.91
		M2H	-3.85

June 23, 1976

M1F	-3.40	L2A	-4.52
M1E	-3.53	L2B	-4.52
M1D	-3.63	L2C	-4.53
M1C	-3.84	L2D	-4.54
M1B	-4.29	L2E	-4.55
M1A	-3.68	L2F	-4.53
L1A	-4.12	M1-2	-4.37
L1B	-4.05	M2A	-3.86
L1C	-4.06	M2B	-3.99
L1D	-4.06	M2C	-3.81
L1E	-4.10	M2D	-3.74
L1F	-4.09	M2E	-3.66
		M2F	-3.58
		M2G	-3.46
		M2H	-3.40

WATER LEVELS IN PALO ALTO FLOOD CONTROL BASIN (cont)

June 29, 1976

MLF	-4.10	L2A	-4.60
MLE	-4.13	L2B	-4.59
MLD	-4.15	L2C	-4.59
MLC	-4.22	L2D	-4.60
MLB	-4.40	L2E	-4.60
M1A	-3.73	L2F	-4.59
L1A	-4.28	M1-2	-4.49
L1B	-3.76	M2A	-4.45
L1C	-4.28	M2B	-4.14
L1D	-4.28	M2C	-4.07
L1E	-4.31	M2D	-4.02
L1F	-4.29	M2E	-4.00
		M2F	-3.97
		M2G	-3.91
		M2H	-3.89

July 7, 1976

MLF	-4.07	L2A	-4.71
MLE	-4.17	L2B	-4.71
MLD	-4.20	L2C	-4.72
MLC	-4.29	L2D	-4.73
MLB	-4.54	L2E	-4.73
M1A		L2F	-4.73
L1A	-4.39	M1-2	-4.61
L1B	-4.37	M2A	-4.56
L1C	-4.39	M2B	-4.18
L1D	-4.38	M2C	-4.03
L1E	-4.41	M2D	-3.98
L1F	-4.40	M2E	-3.95
		M2F	-4.04
		M2G	-3.81
		M2H	-3.77

Note: The stage of the dredged slough can be taken as the level of piezometer MLF.

APPENDIX D

COMPUTER PROGRAM OF THE WATER TABLE MODEL

MANUAL OF COMPUTER PROGRAM

The predictor-corrector finite-difference equations, eqs. (9) and (10), were developed into a computer program by Eduardo Aguado of the Geology Department of Stanford University. The writer subsequently modified the program to account for the variable boundary conditions (6). The program solves a set of n linear equations at each $1/2$ time step by using the Thomas algorithm (Thomas, 1949). The program is well documented and will not be described in detail here.

The input needed to run the program is listed below along with the equivalent symbol used in the text, an explanation of the input and the FORTRAN format for the input. The parameters are listed in the sequence they should appear in the data deck.

<u>Input parameters</u>	<u>Symbols in text</u>	<u>Explanation</u>	<u>Format for input</u>
NN	n	Number of points in ξ -direction used in finite-difference formulation	I4
DELX	$\Delta\xi$	Spacing of points along ξ -direction calculated from $\Delta\xi = \frac{\Delta x}{L}$	F9.5
DELT	$\Delta\tau$	Spacing of points along τ -direction calculated from $\Delta\tau = \frac{K}{S} \frac{\Delta t}{L}$	F9.5 (on DELX card)
TEND		The length of nondimensionalized time that program is to be run	F10.4
PL	L	Length of the water table profile (distance between the two boundary conditions)	F10.4
D	$-d_o$	Adjustment to level of base of permeable section (datum for water levels)	F10.4

NSM		Number of channel stage and head boundary measurements: Equal to $2 \frac{TEND}{DELTA} + 1$	I4
SS(I)	$H_o(\tau_j)$	Channel stage boundary condition (defined every 1/2 time step)	16F5.2 on each card
H(I)	$H_{n+1}(\tau_j)$	Head boundary condition (defined every 1/2 time step)	16F5.2 on each card
KPRNT		How often results will be printed (KPRNT=1 means every full time step)	I4
X(I)	$F(\xi_i)$	Initial condition	F10.4 (one on each card)

The program, with sample input and output, is listed in the following pages. For the particular run shown the values of L, K/S, Δx and Δt were 14 feet, 404 ft/day, 1 foot and 15 minutes (.0104 days), respectively. Thus $\Delta \xi$ and $\Delta \tau$ are calculated to be 0.0714 and 0.30, respectively. Since Δx is 1 ft and L is 14 ft, the number of points in the ξ -direction (excluding the two boundary conditions), NN, is 13.

All head values (height of the water table) input into the program are measured from M.S.L. Any adjustments to the level of the impermeable base (which is datum) are made through the parameter D (opposite sign of d_o). In this case D is +0.13 feet. The number of channel stage and head boundary measurements is 123. The auxiliary conditions are described in the text. KPRNT is set equal to 1 which means the results of every time step will be printed.

Listed on the first page of the output are some of the parameters

read into the program. The next pages show the calculated nondimensionalized head values as a function of space and time. The initial condition (nondimensionalized) is shown in the first row. The boundary conditions (nondimensionalized) are columns as shown in the output.

C

C

C X IS THE ARRAY OF NON-DIMENSIONED HEADS SPACED IN THE
C DIRECTION FROM THE STREAM TO THE CONSTANT HEAD BOUNDARY.

C IN THE PARTICULAR CASE HERE THE COEFFICIENTS OF THE TWO
C CCOEINGALS ARE ALL EQUAL TO 1 AND THEREFORE THERE IS NO
C NEED TO PASS ARRAYS A AND C TO THE SUBROUTINE.

C RHS2 IS THE ARRAY FOR THE RIGHT-HAND-SIDE VECTOR OF
C THE CORRECTOR SYSTEM. THE PREDICTOR SOLUTION (STORED
C IN RHS1) IS USED TO CALCULATE RHS2.

DIMENSION A(30,30), B(30), RHS1(30), RHS2(30), B(30), V(30), SS(200), IH(200)

Y AND ALPHA MUST BE OF DIMENSION NN AND BETA OF
DIMENSION NN-1.

-124-

```

C
C
C      NN IS THE NUMBER OF INTERNAL NODES IN THE PROFILE.
C      IT IS THEN ALSO THE NUMBER OF UNKNOWN IN THE PREDICTOR
C      AND CORRECTOR SYSTEMS.
3      READ (5,100) NN
4      WRITE (6,101) NN
C
5      ANN = NN * NN
6      N = NN - 1
C
C      DELX IS THE SPACING ALONG THE UNDIMENSIONALIZED
C      HORIZONTAL DIRECTION.
C
C      DELT IS THE SPACING IN THE UNDIMENSIONALIZED TIME
C      DIRECTION.
7      READ (5,102) DELX, DELT
8      WRITE (6,103) DELX
9      WRITE (6,104) DELT
C
C      TEND IS THE TIME LIMIT.
10     READ (5,105) TEND
11     WRITE (6,106) TEND
C
C      THE VARIABLE TIME IS INCREASED BY DELT AFTER EACH
C      ITERATION. WHEN TIME BECOMES EQUAL TO TEND WE HAVE
C      REACHED THE END OF THE COMPUTATION.
12     TIME = 0.0
C
C      READ IN PROFILE LENGTH, PL
13     READ (5,112) PL
14     WRITE (6,107) PL
C
C      READ IN ADJUSTMENT TO DATUM OF HEAD VALUES, D
C*
15     READ (5,112) D
16     WRITE (6,108) D
C
C      READ IN THE VARIABLE CHANNEL STAGE BOUNDARY, SS(I)
C      NSM IS EQUAL TO THE NUMBER OF STREAM STAGE MEASUREMENTS. IT IS TWO
C      TIMES THE NUMBER OF ITERATIONS
C      (TEND/DELT = NUMBER OF ITERATIONS)
17     READ (5,100) NSM
18     READ (5,113) (SS(I), I=1,NSM)
19     READ (5,113) (H(I), I=1,NSM)
C
C      CALCULATE UNDIMENSIONALIZED HEAD VALUES
20
21     DO 3 I=1,NSM
22       SS(I) = (SS(I) + D )/PL
23       H(I) = (H(I) + D )/PL
23       3 IF (SS(I) .LT. 0) SS(I) = 0.0
C
C      M KEEPS TRACK OF SS(I) VALUES. SET M = 1.
C

```

```

24      P=1
C
C      THE VARIABLE KOUNT AND KPRNT CONTROL HOW OFTEN
C      INTERMEDIATE RESULTS WILL BE PRINTED. AT EACH ITERATION
C      KOUNT IS INCREASED BY 1. WHEN KOUNT REACHES THE VALUE
C      KPRNT INTERMEDIATE RESULTS ARE PRINTED AND KOUNT BROUGHT
C      BACK TO ZERO.
C
25      KOUNT = 0
26      READ (5,100) KPRNT
27      WRITE (6,110) KPRNT
C
C      READ IN THE INITIAL HEADS AND CALCULATE NONDIMENSIONALIZED VALUES.
C
28      DO 10 I = 1, NN
29      READ (5,112) X(I)
30      X(I) = (X(I) + DJ)/PL
C
C      PRINT OUT HEADINGS AND INITIAL VALUES
C
31      WRITE (6,200)
32      200 FORMAT (1H1,10X,'NDIMENSIONALIZED HEAD VALUES AS A FUNCTION ',
33      1 'OF SPACE AND TIME')
34      WRITE (6,201)
35      201 FORMAT (////,50X,' X-DIRECTION')
36      WRITE (6,202)
37      202 FORMAT (1H0,3X,' TIME')
38      WRITE (6,210)
39      210 FORMAT (1H ,14X,'CHANNEL',103X,'HEAD')
40      WRITE (6,211)
41      211 FORMAT (1H ,15X,'STAGE',104X,'BOUNDARY')
42      WRITE (6,203) TIME,SS(N),(X(I),I=1,NN),H(M)
43      203 FORMAT (1H0,F8.5,4X,15F8.4)
C
C*****
C
C      BEGIN MAIN DO LOOP
C
C      MATRIX A IS TRI-DIAGONAL. THE COEFFICIENTS OF THE
C      CDDIAGONALS ARE ALL 1. THE COEFFICIENTS OF THE MAIN
C      DIAGONAL ARE FUNCTION OF THE PREVIOUS SOLUTION, DELX,
C      AND DELT.
C
43      20 DO 30 I = 1, NN
44      DO 30 J = 1, NN
45      IF (I.EQ. J) GO TO 23
46      JP = J + 1
47      JM = J - 1
48      IF ((I.EQ. JP).OR. (I.EQ. JM)) GO TO 21
49      A(I,J) = 0.0
50      GO TO 30
51      21 A(I,J) = 1.0
52      GO TO 30
53      23 A(I,J) = -(2.0*(DELX**2/(X(I)*DELT)))
54      30 CONTINUE
C
C
C      FILL IN ARRAY B FOR USE BY SUBROUTINE TRIDIA.
C
55      DO 35 I = 1, NN

```

```

56      35      B(I) = A(I,I)
C
C      THE RIGHT HAND SIDES OF THE EQUATIONS ARE NOW COMPUTED.
C      FOR THE FIRST AND LAST EQUATIONS THE RIGHT HAND SIDES
C      ARE FUNCTION OF THE BCLNARY CCNDITIONS SS(I) AND F(I),
C      RESPECTIVELY.
C
57      RHS1(I) = ((X(2) - SS(M))/(2.0 * DELX))**2
58      RHS1(I) = ((1.0/X(I))*RHS1(I))
59      RHS1(I) = - 2.0/DELT - RHS1(I)
60      RHS1(I) = DELX**2 * RHS1(I) - SS(M+1)
C
C      N IS EQUAL TO NN-1.
C
61      RHS1(NN) = ((H(M) - X(N))/(2.0 * DELX))**2
62      RHS1(NN) = ((1.0/X(NN))*RHS1(NN))
63      RHS1(NN) = - 2.0/DELT - RHS1(NN)
64      RHS1(NN) = DELX**2 * RHS1(NN) - F(M+1)
C
65      DO 40 I = 2, N
66      RHS1(I) = ((X(I+1) - X(I-1))/(2.0*DELX)) **2
67      RHS1(I) = ((1.0/X(I))*RHS1(I))
68      RHS1(I) = - 2.0/DELT - RHS1(I)
69      40      RHS1(I) = DELX**2 * RHS1(I)
C
C      WE NOW CALL SUBROUTINE TRIDIA TO SOLVE THE PREDICTOR
C      LINEAR SYSTEM OF EQUATIONS.
C
70      CALL TRIDIA (B, V, RHS1, N, NN, Y, ALPHA, BETA)
C .....
C .....
C      ON RETURN FROM TRIDIA WE TRANSFER THE SOLUTION VECTOR V
C      TO THE ARRAY RHS1.
C
71      DO 36 I = 1, NN
72      36      RHS1(I) = V(I)
C
C      WITH THE PREDICTOR SOLUTION WE RECOMPUTE THE
C      COEFFICIENTS OF MATRIX A FOR THE CORRECTOR. WE COMPUTE
C      ALSO A RIGHT-HAND-SIDE RHS2.
C
73      DO 50 I = 1, NN
74      DO 50 J = 1, NN
75      IF (I .EQ. J) GO TO 43
76      JP = J + 1
77      JM = J - 1
78      IF ((I .EQ. JP) .OR. (I .EQ. JM)) GO TO 41
79      A(I,J) = C.0
80      GO TO 50
81      41      A(I,J) = 1.0
82      GO TO 50
83      43      A(I,J) = -(2.0+(2.0*(DELX**2/(RHS1(I)*DELT))))
84      50      CONTINUE
C
C      FILL IN ARRAY B FOR USE BY SUBROUTINE TRIDIA.
C
85      DO 55 I = 1, NN
86      55      B(I) = A(I,I)

```

```

C
C
87      Z1 = X(2) - 2.0*X(1) + SS(M)
88      Z2 = ((2.0*DELX**2)*X(1)) / (DELT * RHS1(1))
89      Z3 = ((RHS1(2) - SS(M+1))*2) / (2.0 * RHS1(1))
90      RHS2(1) = - Z1 - Z2 - Z3 - SS(M+2)

C
C
91      Z1 = H(M) - 2.0*X(NN) + X(N)
92      Z2 = ((2.0*DELX**2)*X(NN)) / (DELT * RHS1(NN))
93      Z3 = ((H(M+1) - RHS1(N))*2) / (2.0 * RHS1(NN))
94      RHS2(NN) = - Z1 - Z2 - Z3 - H(M+2)
95      M = M + 2

C
96      DO 60 I = 2, N
97      Z1 = X(I+1) - 2.0*X(I) + X(I-1)
98      Z2 = ((2.0*DELX**2)*X(I)) / (DELT * RHS1(I))
99      Z3 = ((RHS1(I+1) - RHS1(I-1))*2) / (2.0 * RHS1(I))
100     60      RHS2(I) = - Z1 - Z2 - Z3

C
C      WE NOW CALL SUBROUTINE TRIDIA TO SOLVE THE CORRECTOR
C      LINEAR SYSTEM OF EQUATIONS.
C
101     CALL TRIDIA (B, V, RHS2, N, NN, Y, ALPHA, BETA)
C .....
C .....
C      ON RETURN FROM TRIDIA WE TRANSFER THE SOLUTION VECTOR V
C      TO THE ARRAY RHS2.
C
102     DO 65 I = 1, NN
103     65      RHS2(I) = V(I)

C
C      THE CORRECTOR SOLUTION IS NOW IN ARRAY RHS2. WE TRANSFER
C      IT TO ARRAY X TO BE READY FOR A NEW ITERATION OF THE
C      PRECICTOR.
C
104     DO 70 I = 1, NN
105     70      X(I) = RHS2(I)

C
C      KOUNT AND TIME ARE INCREASED.
C
106     KOUNT = KOUNT + 1
107     TIME = TIME + DELT

C
C      IF KOUNT IS EQUAL TO KPRNT WE PRINT INTERMEDIATE
C      RESULTS, IF NOT WE GO BACK FOR A NEW ITERATION.
C
108     IF (KOUNT .NE. KPRNT) GO TO 20

C
109     WRITE (6,203) TIME, SS(M), (X(I), I=1, NN), H(M)

C
C      KOUNT IS BROUGHT BACK TO ZERO.
C
110     KOUNT = 0
C
C

```

```

C   WHEN TIME LIMIT TEND IS REACHED WE STOP, OTHERWISE WE ITERATE AGAIN.
C
111      IF (TIME .LT. TEND) GO TO 20
C
112      STOP
C
C .....
C   FORMAT STATEMENTS.
C .....
C
113      100 FORMAT (I4)
114      101 FORMAT (I4,10X,'THE NUMBER OF ACDES PER HORIZON IS : ',I4)
115      102 FORMAT (2F9.5)
116      103 FORMAT (I40,10X,'THE X SPACING IS : ',F9.5)
117      104 FORMAT (I40,10X,'THE T SPACING IS : ',F9.5)
118      105 FORMAT (F9.5)
119      106 FORMAT (I40,10X,'THE TIME LIMIT IS: ',F9.5)
120      107 FORMAT (I40,10X,'THE LENGTH OF PROFILE IS ',F5.1,' FEET')
121      108 FORMAT (I40,10X,'ADJUSTMENT TO DATUM OF HEAD VALUES IS',F5.2,
122          1' FEET')
122      110 FORMAT (I40,10X,'INTERMEDIATE RESULTS WILL BE PRINTED ',
123          1' EVERY ', I2, ' ITERATIONS')
123      112 FORMAT (F10.4)
124      113 FORMAT (16F5.2)
C
C .....
C .....
125      END

```

```

126      SUBROUTINE TRIDIA (B, X, F, N, NN, Y, ALPHA, BETA)
C
C   THIS IS THOMAS' ALGORITHM FOR TRIDIAGONAL SYSTEMS.
C
C   BECAUSE IN THIS PARTICULAR CASE THE COEFFICIENTS OF THE
C   TWO CODIAGONALS ARE ALL EQUAL TO 1 WE DO NOT NEED TO EXPRESS
C   THE CODIAGONALS AS ARRAYS.
C
C   B IS THE ARRAY OF COEFFICIENTS OF THE MAIN DIAGONAL.
C
C   X IS THE ARRAY FOR STORING THE SOLUTION VECTOR.
C
C   F IS THE ARRAY OF RIGHT-HAND-SIDES.
C
C   NN IS THE NUMBER OF EQUATIONS IN THE SYSTEM.
C
C   N IS EQUAL TO NN - 1.
C
C   Y, ALPHA AND BETA ARE TEMPORARY ARRAYS USED IN THE
C   COMPUTATION.
C
C   THE NOTATION IS THAT FOUND IN THE DESCRIPTION OF THE
C   ALGORITHM GIVEN BY REASON I., FORNERGER G.M. AND
C   MCLZ F.J. IN THEIR BOOK 'NUMERICAL METHODS IN SUBSURFACE
C   HYDROLOGY' (NEW YORK 1971) EXCEPT THAT HERE ALL A(I)'S
C   AND C(I)'S ARE EQUAL TO 1 AND ARRAYS A AND C NEED NOT
C   BE USED.
C
127      DIMENSION B(NN), X(NN), F(NN),
128          Y(NN), ALPHA(NN), BETA(N)

```

```

C
C
128      ALPHA(1) = B(1)
129      BETA(1) = 1.0 / ALPHA(1)
C
130      CO 10 I = 2, N
131      ALPHA(I) = E(I) - EETA(I-1)
132      BETA(I) = 1.0 / ALPHA(I)
C
133      ALPHA(NN) = B(NN) - BETA(N)
C
134      Y(1) = F(1) / ALPHA(1)
C
135      DO 20 I = 2, NN
136      Y(I) = (F(I) - Y(I-1)) / ALPHA(I)
C
137      X(NN) = Y(NN)
C
138      DO 30 I = 1, N
139      J = NN - I
140      X(J) = Y(J) - BETA(J) * X(J+1)
C
141      RETURN
142      END

```

SDATA

THE NUMBER OF NODES PER HORIZCN IS : 13

THE X SPACING IS : 0.07140

THE T SPACING IS : 0.30000

THE TIME LIMIT IS: 18.00000

THE LENGTH OF PROFILE IS 14.0 FEET

ADJUSTMENT TO DATUM OF HEAD VALUES IS 0.37 FEET

INTERMEDIATE RESULTS WILL BE PRINTED EVERY 1 ITERATIONS

UNDIMENSIONALIZED HEAD VALUES AS A FUNCTION OF SPACE AND TIME

TIME	X-DIRECTION														HEAD BOUNDARY
	CHANNEL STAGE														
0.00000	0.0079	0.1214	0.1566	0.1886	0.2014	0.2129	0.2221	0.2314	0.2393	0.2443	0.2486	0.2507	0.2521	0.2529	0.2507
0.30000	0.0079	0.0748	0.1179	0.1430	0.1693	0.1875	0.2024	0.2125	0.2203	0.2276	0.2330	0.2382	0.2422	0.2456	0.2507
0.60000	0.0079	0.0816	0.1089	0.1357	0.1519	0.1680	0.1819	0.1951	0.2066	0.2156	0.2243	0.2315	0.2386	0.2457	0.2507
0.90000	0.0107	0.0697	0.1051	0.1254	0.1465	0.1623	0.1763	0.1880	0.1986	0.2092	0.2184	0.2274	0.2353	0.2424	0.2507
1.20000	0.0450	0.0765	0.0975	0.1216	0.1383	0.1549	0.1693	0.1828	0.1949	0.2053	0.2156	0.2247	0.2339	0.2431	0.2507
1.50000	0.0643	0.0864	0.1084	0.1230	0.1402	0.1544	0.1681	0.1804	0.1920	0.2035	0.2137	0.2235	0.2332	0.2415	0.2507
1.80000	0.0900	0.1023	0.1140	0.1306	0.1432	0.1567	0.1691	0.1812	0.1927	0.2030	0.2135	0.2231	0.2327	0.2424	0.2507
2.10000	0.1150	0.1210	0.1312	0.1391	0.1510	0.1617	0.1729	0.1836	0.1940	0.2046	0.2143	0.2241	0.2332	0.2417	0.2507
2.40000	0.1350	0.1395	0.1440	0.1530	0.1603	0.1695	0.1786	0.1882	0.1979	0.2070	0.2165	0.2255	0.2345	0.2438	0.2521
2.70000	0.1621	0.1605	0.1635	0.1660	0.1726	0.1790	0.1867	0.1946	0.2027	0.2114	0.2197	0.2284	0.2367	0.2446	0.2529
3.00000	0.1807	0.1808	0.1803	0.1836	0.1861	0.1905	0.1963	0.2027	0.2096	0.2166	0.2242	0.2315	0.2391	0.2470	0.2543
3.25559	0.1979	0.1955	0.1964	0.1965	0.1995	0.2026	0.2068	0.2116	0.2169	0.2230	0.2290	0.2356	0.2421	0.2483	0.2550
3.55559	0.2179	0.2149	0.2118	0.2122	0.2121	0.2142	0.2168	0.2204	0.2246	0.2291	0.2342	0.2393	0.2446	0.2504	0.2557
3.85559	0.2293	0.2268	0.2263	0.2245	0.2251	0.2256	0.2272	0.2294	0.2322	0.2358	0.2395	0.2439	0.2484	0.2529	0.2579
4.15559	0.2421	0.2392	0.2362	0.2355	0.2348	0.2353	0.2361	0.2376	0.2397	0.2420	0.2449	0.2479	0.2511	0.2547	0.2579
4.45559	0.2529	0.2497	0.2461	0.2454	0.2448	0.2440	0.2441	0.2447	0.2457	0.2473	0.2489	0.2510	0.2532	0.2553	0.2579
4.75559	0.2629	0.2597	0.2562	0.2545	0.2528	0.2515	0.2512	0.2510	0.2513	0.2517	0.2527	0.2537	0.2550	0.2566	0.2579
5.05559	0.2664	0.2643	0.2630	0.2604	0.2593	0.2578	0.2569	0.2562	0.2558	0.2558	0.2558	0.2562	0.2567	0.2571	0.2579
5.35559	0.2664	0.2654	0.2637	0.2634	0.2619	0.2612	0.2603	0.2596	0.2591	0.2586	0.2584	0.2582	0.2582	0.2585	0.2586
5.65559	0.2621	0.2624	0.2630	0.2622	0.2623	0.2617	0.2613	0.2605	0.2604	0.2601	0.2597	0.2594	0.2592	0.2588	0.2586
5.95559	0.2550	0.2568	0.2577	0.2592	0.2595	0.2600	0.2601	0.2601	0.2600	0.2597	0.2596	0.2592	0.2588	0.2584	0.2579
6.25559	0.2450	0.2483	0.2514	0.2529	0.2548	0.2555	0.2569	0.2575	0.2578	0.2581	0.2580	0.2580	0.2578	0.2574	0.2571
6.55559	0.2321	0.2375	0.2414	0.2454	0.2478	0.2502	0.2519	0.2533	0.2544	0.2551	0.2557	0.2561	0.2562	0.2565	0.2564
6.85559	0.2157	0.2233	0.2299	0.2346	0.2392	0.2426	0.2455	0.2475	0.2497	0.2514	0.2525	0.2536	0.2545	0.2551	0.2557

7.15998	0.1964	0.2070	0.2153	0.2228	0.2284	0.2335	0.2376	0.2411	0.2441	0.2465	0.2487	0.2504	0.2518	0.2532	0.2543
7.49998	0.1786	0.1906	0.2012	0.2096	0.2173	0.2235	0.2290	0.2336	0.2376	0.2411	0.2441	0.2468	0.2492	0.2514	0.2536
7.79998	0.1579	0.1736	0.1861	0.1970	0.2057	0.2135	0.2201	0.2259	0.2310	0.2354	0.2395	0.2431	0.2463	0.2494	0.2521
8.09998	0.1329	0.1533	0.1698	0.1826	0.1938	0.2030	0.2111	0.2181	0.2243	0.2298	0.2348	0.2393	0.2436	0.2475	0.2514
8.39998	0.1129	0.1362	0.1543	0.1695	0.1819	0.1928	0.2021	0.2103	0.2177	0.2242	0.2302	0.2357	0.2408	0.2456	0.2500
8.69998	0.0886	0.1179	0.1397	0.1567	0.1711	0.1831	0.1937	0.2020	0.2113	0.2189	0.2257	0.2322	0.2381	0.2437	0.2493
8.99998	0.0629	0.1002	0.1254	0.1451	0.1608	0.1743	0.1860	0.1963	0.2056	0.2139	0.2217	0.2289	0.2356	0.2420	0.2479
9.29998	0.0400	0.0863	0.1145	0.1352	0.1524	0.1667	0.1793	0.1905	0.2005	0.2097	0.2182	0.2261	0.2337	0.2408	0.2479
9.59998	0.0136	0.0726	0.1039	0.1268	0.1449	0.1603	0.1737	0.1856	0.1964	0.2063	0.2156	0.2242	0.2325	0.2404	0.2479
9.89998	0.0136	0.0699	0.0986	0.1205	0.1391	0.1549	0.1689	0.1815	0.1930	0.2036	0.2134	0.2226	0.2314	0.2397	0.2479
10.19998	0.0136	0.0674	0.0965	0.1184	0.1363	0.1520	0.1661	0.1788	0.1906	0.2015	0.2117	0.2214	0.2306	0.2395	0.2479
10.49998	0.0136	0.0671	0.0949	0.1164	0.1346	0.1503	0.1644	0.1773	0.1892	0.2003	0.2108	0.2207	0.2301	0.2391	0.2479
10.79998	0.0136	0.0660	0.0943	0.1157	0.1335	0.1493	0.1634	0.1764	0.1884	0.1996	0.2102	0.2202	0.2298	0.2391	0.2479
11.09997	0.0136	0.0660	0.0936	0.1145	0.1329	0.1486	0.1628	0.1758	0.1879	0.1992	0.2098	0.2200	0.2297	0.2389	0.2479
11.39997	0.0136	0.0655	0.0934	0.1147	0.1325	0.1483	0.1625	0.1755	0.1876	0.1989	0.2097	0.2198	0.2296	0.2389	0.2479
11.69997	0.0136	0.0656	0.0932	0.1144	0.1323	0.1480	0.1623	0.1753	0.1874	0.1988	0.2095	0.2198	0.2295	0.2388	0.2479
11.99997	0.0136	0.0653	0.0931	0.1144	0.1322	0.1479	0.1621	0.1752	0.1873	0.1987	0.2095	0.2197	0.2295	0.2389	0.2479
12.29997	0.0136	0.0654	0.0930	0.1142	0.1321	0.1478	0.1620	0.1751	0.1872	0.1986	0.2094	0.2197	0.2295	0.2388	0.2479
12.59997	0.0136	0.0653	0.0930	0.1142	0.1320	0.1478	0.1620	0.1751	0.1872	0.1986	0.2094	0.2196	0.2294	0.2388	0.2479
12.89997	0.0136	0.0654	0.0929	0.1141	0.1321	0.1478	0.1620	0.1750	0.1872	0.1986	0.2094	0.2196	0.2294	0.2388	0.2479
13.19997	0.0136	0.0653	0.0930	0.1142	0.1320	0.1478	0.1620	0.1750	0.1872	0.1986	0.2094	0.2196	0.2294	0.2388	0.2479
13.49997	0.0136	0.0653	0.0929	0.1141	0.1320	0.1477	0.1619	0.1750	0.1872	0.1986	0.2093	0.2196	0.2294	0.2388	0.2479
13.79997	0.0136	0.0653	0.0929	0.1142	0.1320	0.1477	0.1619	0.1750	0.1872	0.1986	0.2094	0.2196	0.2294	0.2388	0.2479
14.09997	0.0136	0.0653	0.0929	0.1141	0.1320	0.1477	0.1619	0.1750	0.1871	0.1986	0.2093	0.2196	0.2294	0.2388	0.2479
14.39997	0.0136	0.0653	0.0929	0.1141	0.1320	0.1477	0.1619	0.1750	0.1872	0.1986	0.2094	0.2196	0.2294	0.2388	0.2479
14.69997	0.0136	0.0653	0.0929	0.1141	0.1320	0.1477	0.1619	0.1750	0.1871	0.1986	0.2093	0.2196	0.2294	0.2388	0.2479
14.99996	0.0136	0.0653	0.0929	0.1141	0.1320	0.1477	0.1619	0.1750	0.1871	0.1986	0.2093	0.2196	0.2294	0.2388	0.2479
15.29996	0.0136	0.0653	0.0929	0.1141	0.1320	0.1477	0.1619	0.1750	0.1871	0.1986	0.2094	0.2196	0.2294	0.2388	0.2479
15.59996	0.0136	0.0653	0.0929	0.1141	0.1320	0.1477	0.1619	0.1750	0.1871	0.1986	0.2093	0.2196	0.2294	0.2388	0.2479

16.15595	0.0136	0.0653	0.0929	0.1141	0.1320	0.1477	0.1619	0.1750	0.1871	0.1986	0.2093	0.2196	0.2294	0.2388	0.2479
16.45994	0.0136	0.0653	0.0929	0.1141	0.1320	0.1477	0.1619	0.1750	0.1871	0.1986	0.2093	0.2196	0.2294	0.2388	0.2479
16.75993	0.0136	0.0653	0.0929	0.1141	0.1320	0.1477	0.1619	0.1750	0.1871	0.1986	0.2093	0.2196	0.2294	0.2388	0.2479
17.05991	0.0136	0.0653	0.0929	0.1141	0.1320	0.1477	0.1619	0.1750	0.1871	0.1986	0.2093	0.2196	0.2294	0.2388	0.2479
17.35990	0.0136	0.0653	0.0929	0.1141	0.1320	0.1477	0.1619	0.1750	0.1871	0.1986	0.2093	0.2196	0.2294	0.2388	0.2479
17.65989	0.0136	0.0653	0.0929	0.1141	0.1320	0.1477	0.1619	0.1750	0.1871	0.1986	0.2093	0.2196	0.2294	0.2388	0.2479
17.95988	0.0136	0.0653	0.0929	0.1141	0.1320	0.1477	0.1619	0.1750	0.1871	0.1986	0.2093	0.2196	0.2294	0.2388	0.2479
18.25987	0.0136	0.0653	0.0929	0.1141	0.1320	0.1477	0.1619	0.1750	0.1871	0.1986	0.2093	0.2196	0.2294	0.2388	0.2479

CODE USAGE OBJECT CODE= 7560 BYTES, ARRAY AREA= 6156 BYTES, TOTAL AREA AVAILABLE= 151552 BYTES

DIAGNOSTICS NUMBER OF ERRORS= 0, NUMBER OF WARNINGS= 0, NUMBER OF EXTENSIONS= 0

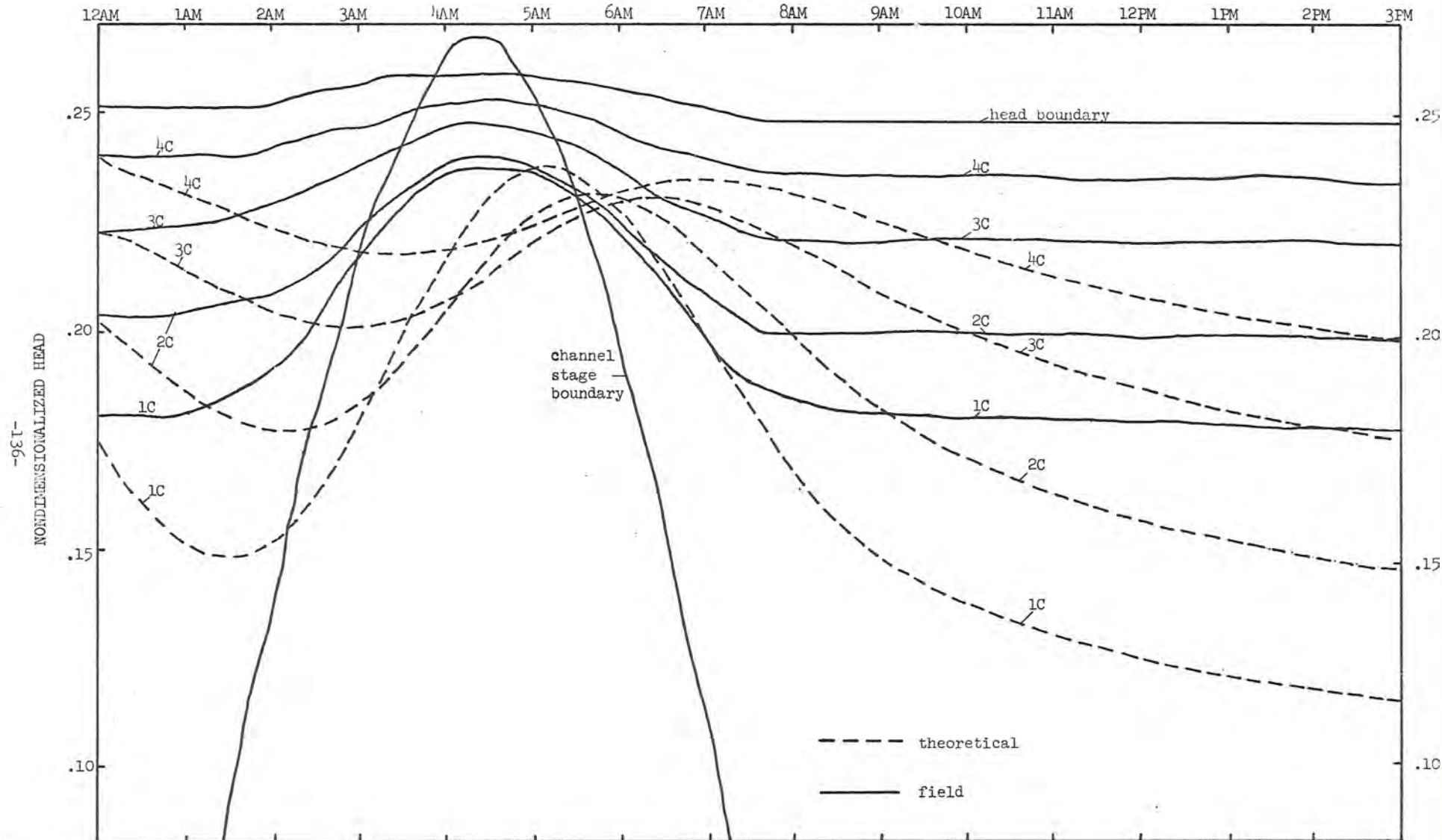
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\$STOP

APPENDIX E

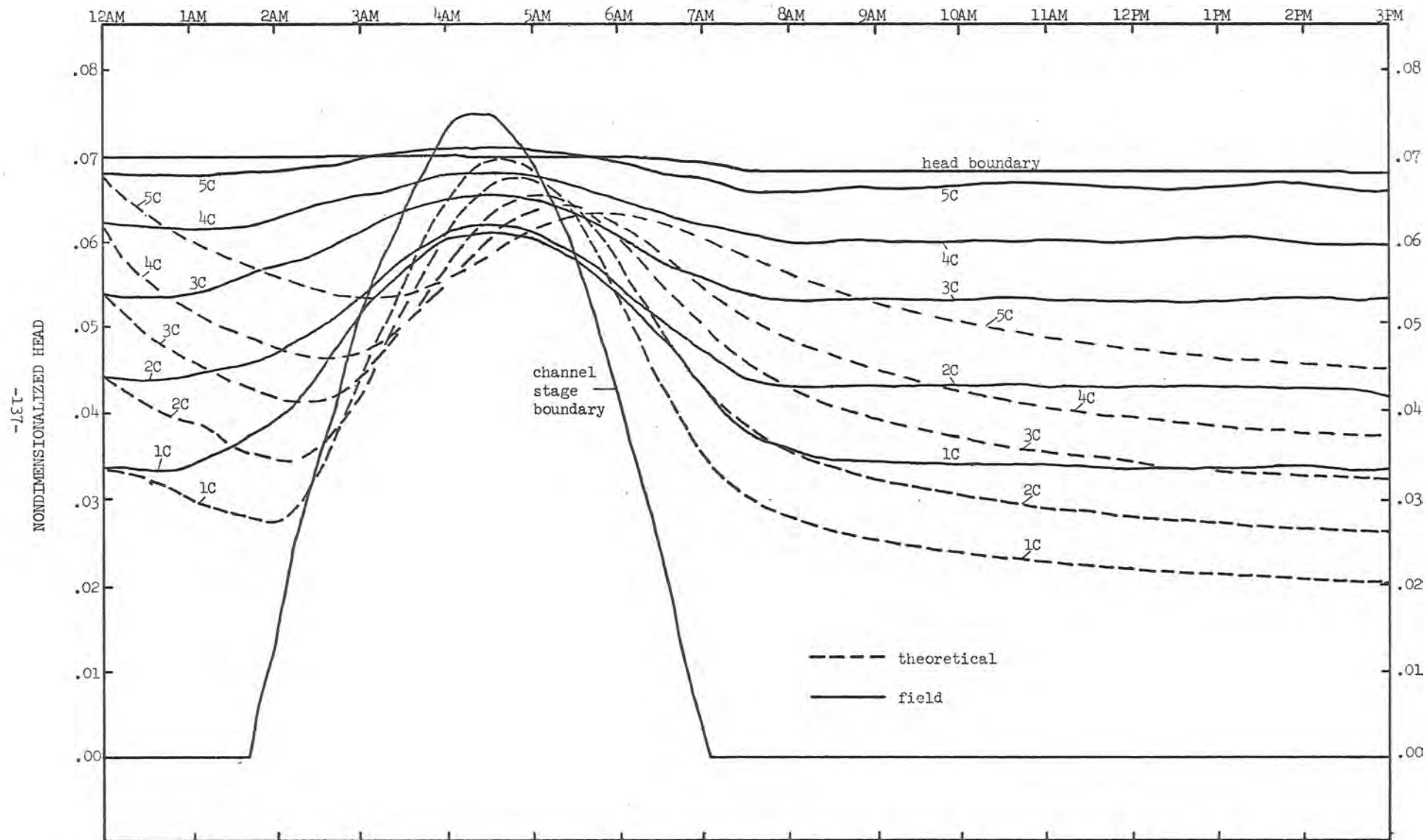
FIELD AND THEORY COMPARISONS

MAY 5, 1976



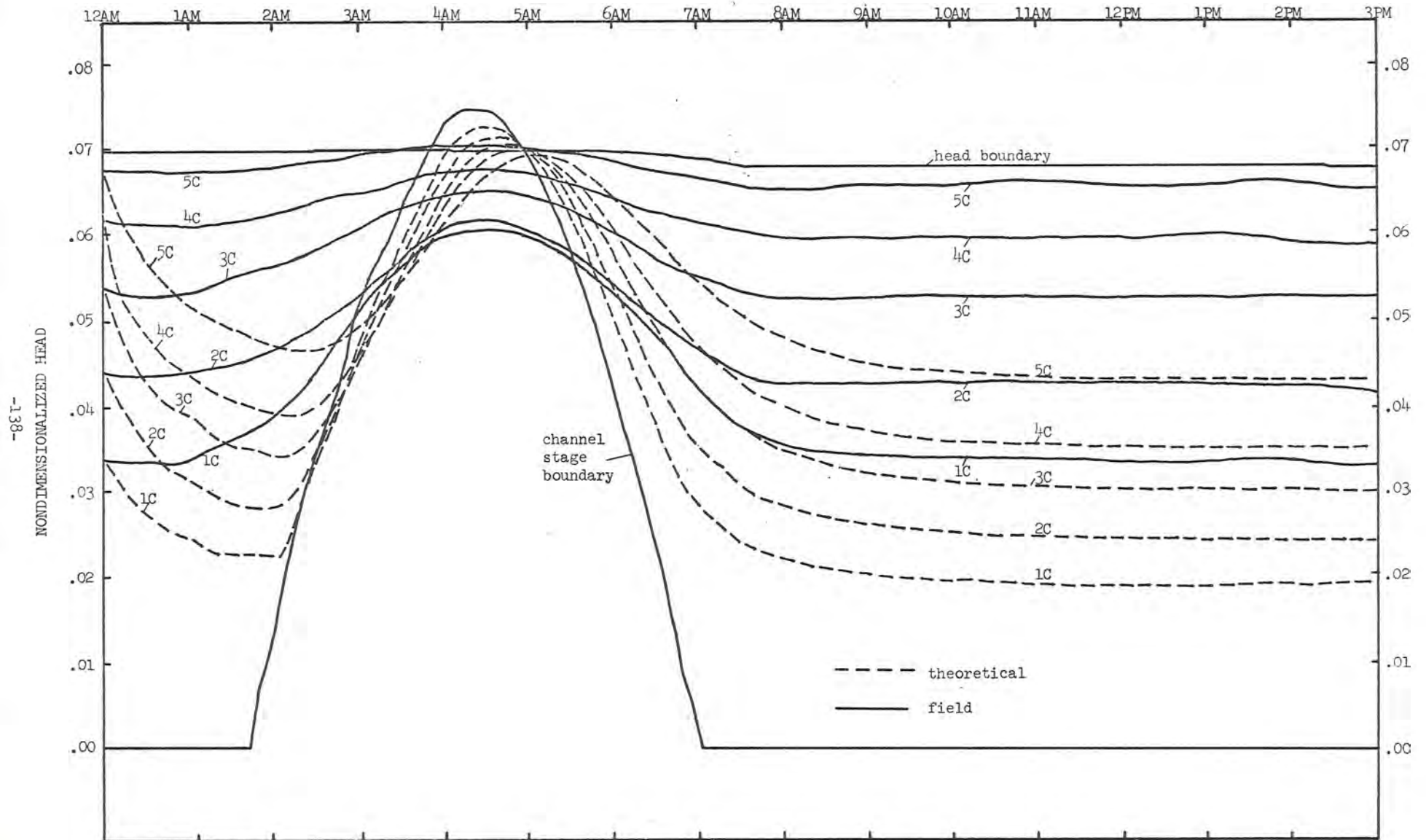
Comparison of field data with theoretical piezometer levels for $L=14$ feet, $d_0=.37$ feet below M.S.L. and $K/S=40.4$ ft/day. Channel stage bottoms out at .01.

MAY 5, 1976



Comparison of field data with theoretical piezometer levels for $L=30$ feet, $d_o=1.13$ feet above M.S.L. and $K/S=404$ ft/day.

MAY 5, 1976



Comparison of field data with theoretical piezometer levels for $L=30$ feet, $d_o=1.13$ feet above M.S.L. and $K/S=1346$ ft/day.