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HYDRAULIC LABORATORY REPORT NO. 142

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PROGRESS REPORT ON MODEL STUDIES OF THE SACRAMENTO-SAN JOAQUIN DELTA CENTRAL VALLEY PROJECT, CALIFORNIA

By

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and
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- - -

Denver, Colorado
April 10, 1944

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SUBJECT: PROGRESS REPORT ON MODEL STUDIES
OF THE
SACRAMENTO-SAN JOAQUIN DELTA

CENTRAL VALLEY PROJECT, CALIFORNIA

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Denver, Colorado,
April 10, 1944

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

Branch of Design and Construction
Engineering and Geological Control
and Research Division
Denver, Colorado
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Laboratory Report No. 142
Hydraulic Laboratory
Compiled by: D. J. Hebert
F. C. Lowe
Reviewed by: J. E. Warnock

Subject: Progress report on model studies of the Sacramento-San Joaquin Delta, Central Valley, California.

1. Introduction. The Central Valley project is a vast undertaking to resolve the numerous interrelated water problems of this large valley. The two principal rivers of the valley are the Sacramento and the San Joaquin. One of the problems arises from the fact that while two-thirds of the water used in the valley is used in the San Joaquin portion, only one-third of the total annual river flow into the valley is contributed by the San Joaquin River. The problem is further complicated by the fact that flow of both rivers drops so low during the summer months of some years that ocean salinity is propagated upstream far enough to seriously affect the agricultural development of the Sacramento-San Joaquin Delta. One phase of the project deals with this double problem of water deficiency and distribution, and it is this phase which constitutes the subject of the model study being reported herewith.

By means of Shasta Dam on the Sacramento River, enough storage is provided to insure a minimum flow sufficient to provide for water use in the San Joaquin Valley, for use in the Delta area, and for keeping the salinity encroachment below a tolerable value in the Delta. To accomplish this threefold purpose some means must be provided for distributing this Sacramento River water. It is proposed to divert the required amount from the Sacramento River by a pumping plant and convey it across the Delta to another pumping plant, called Delta-Mendota, which will provide the first stage for its delivery to the upper San Joaquin Valley. During the transfer, some of the water will be diverted to supply the requirements of the Delta.

Two plans for transferring water across the Delta have been proposed. The first plan, the so-called Delta Cross Channel, involves the transfer of water across the Delta to Delta-Mendota pumping plant by a canal constructed solely for this purpose. At various points along the canal, turnouts would be provided to release water to the river channels for use in the Delta and for salinity control. The second plan, the so-called State Plan, proposes to convey water across the Delta by using present river channels with some enlargements by dredging. With no direct delivery to the Delta-Mendota pumping plant, the required flow (net) must be induced by the draft head of pumping.

By reason of certain contracts between some of the water users and the Bureau of Reclamation, the water pumped at Delta-Mendota must meet certain standards as to quality which are certain to be met by the Delta Cross Channel plan but at a greatly increased cost over that of the State Plan. In the State Plan, however, the transfer water is exposed to possible contamination by the waters of the Delta channels which would make it unsatisfactory under the terms of the contracts. Before this latter plan can be considered, it must be determined whether or not harmful mixing will occur. The hydraulic problem involved in any such determination represents a very complex example of unsteady flow, and, since theoretical solutions for even the simplest cases of this type are none too rigorous, it was decided that only by means of an hydraulic model could such a determination be made. More details of the background of the decision to build an hydraulic model are given in the two memoranda which are included in this report as appendix 1 and appendix 2.

2. Model scales. The geometric scales of the model were set at 1 to 4,800 horizontal and 1 to 100 vertical, as explained in the memorandum to Chief Engineer from J. E. Warnock, appendix 2. The horizontal scale was controlled principally by the limitations of available laboratory space, once the problem area had been determined. The problem area includes the entire tidal basin because the tidal variation at any station is influenced by reflections which are controlled by the conditions upstream. The limits were extended to Mossdale Bridge and Sacramento by distorting a few sections as shown in figure 1. The vertical scale was established by balancing the allowable distortion as indicated by precedent with limitations of laboratory equipment and instrumentation.

It has been firmly established by other experimenters that progressive wave travels with a velocity equal to $\sqrt{gd}$ where d = depth and g = gravity acceleration component. From this relationship the wave-velocity scale is determined as the square root of the depth ratio, since g can be assumed constant. Since the wave velocity is directly related to flow velocity in all known wave theories, it can be assumed that the same scale holds for all velocities. With the geometric and the velocity scales set, all other pertinent scales can be computed as shown by the following tabulation. All scales are expressed as the ratio of the prototype quantity to the corresponding model quantity.

Quantity	Designation	Scale Ratio
Length, horizontal	L_r	4,800
Length, vertical	D_r	100
Velocity	$V_r = (D_r)^{1/2}$	10
Time	$T_r = L_r (V_r)^{-1}$	480
Area, horizontal	$(L_r)^2$	2.304×10^7
Area, vertical	$D_r L_r$	4.8×10^5
Volume	$(L_r)^2 D_r$	2.304×10^9
Discharge	$(L_r)^2 D_r (T_r)^{-1}$	4.8×10^6
Hydraulic radius (r_r) not constant; varies with channel shape		
Roughness (based on Manning's formula)	$n_r = (r_r)^{2/3} (L_r)^{-1/2}$	
Reynolds' number	$R_r = V_r r_r (\nu)^{-1}$	

The last two scales were used only in a more or less qualitative way. From the roughness scale it is evident that the model must be rougher than the prototype or that the value of N in Manning's formula for open channels must be higher for the model than for the prototype. The Reynolds' number scale was used only to show that laminar or near laminar flow could be expected in the model. The time scale can be expressed in more convenient form as follows:

1 month	prototype	=	90 minutes model
1 day	"	=	3 minutes model
1 hour	"	=	$7\frac{1}{2}$ seconds model

3. Model construction. As a first step in building the model the entire area was circumscribed by a concrete wall 12 inches high and 4 inches thick. A wood strip and a steel angle were cast into the top of this wall. The steel angle provided a convenient level datum for any part of the model. Small brass pins were driven into the wood strips until the heads were flush to outline a coordinate system corresponding to a 4,000-foot interval in the prorotype. By stringing lines between the brass pins, any section of the model could be quickly aligned.

In the usual fixed-bed model the river channels are molded in concrete with templates, either inside or outside, for guides. The large distortion of the comparatively narrow prototype channels in the present case resulted in such narrow model channels that it was necessary to devise a new method of model construction. The method which proved to be

both fast and accurate consisted principally of casting the river channels by pouring concrete around cores which accurately represented the water mass of the channels as indicated by sounding maps. The various steps of the method are illustrated in figure 2. A piece of wallboard was cut to the plan of a particular section of river and the locations of the sounding sections were marked upon its under side in addition to a pair of intersecting coordinate lines. Inside templates of the river cross sections were cut from cardboard and fastened to the wallboard. The spaces between templates were filled with modeling clay shaped to the templates. After this core was stiffened by attaching it to a wooden frame, it was shellacked and suspended between two flexible vertical forms, leveled, aligned, and secured by weights to prevent movement during the pouring and setting of the concrete. As soon as the concrete in each section had hardened, the next section was set up and a new pour made against the preceding section to eliminate troublesome joints. The islands formed by these river channel castings were filled with pea gravel and topped with a thin coating of concrete to approximately +10.0 feet U. S. Geological Survey datum, making a continuous surface where it joined the sides of the river channel blocks.

4. Model apparatus. Because of the large time scale it was necessary to have some type of tide gage which would give a continuous indication of river stage rather than the usual type of point gage which must be set to the water surface before being read. At the same time, this gage must have sensitivity to 0.001 foot, which corresponds to 0.10 foot prototype. These requirements were met with inclined manometers having a slope of 1 to 10 and graduations on the sloping scale of 0.01 foot. Errors due to surface tension were held to a minimum by adding colored aerosol, a wetting agent which reduces the surface tension approximately 65 percent, to the manometer fluid. The coloring additive served to expedite observations. The gages were adjusted for zero and slope by means of level water surfaces in the model. Details of the gages showing the manner of connecting them into the model are shown in figure 3.

The water used in the Delta by crops, weeds, and water surfaces, and designated as consumptive use, was assumed to be concentrated first at nine points and later at fourteen points, and was assimilated by adjustable drains. The drains were of two types; either a 1/4-inch plastic tube grouted into the channel wall or a 1/4-inch plastic siphon as shown in figure 3. In both cases the discharge end was placed as low as possible to minimize the effect of variations in head due to tidal fluctuation, and a rubber hose clamp served for adjusting the discharge. The methods used to allocate the total consumptive use to the various drains will be discussed subsequently.

The river inflow controls were more elaborate and consisted of a small constant-head tank with a needle-valve control that had a very fine adjustment. The tank was supplied from the city water mains. Model discharges were so small, 1,000 second-feet prototype being only 5.92 cubic

centimeters per second, that they were measured volumetrically, using metric units because standard beakers calibrated in these units were available. The model tides were created by a plunger-type mechanism which duplicated a complete lunar cycle of tides rather than a mean tide. This type was selected because it had the small inertia required by the large time scale and the complexity of the tide. The month of August 1941 was selected as a representative lunar month because prototype records for this period were available and the season of 1941 represented a favorable salinity condition. The tide-generating machine was located in a basin at the downstream end of the model. The principal features of this machine, as shown in figure 4, are the tide-producing mechanism which consists of a plunger, a counterbalance, and operating piston, and the control mechanism which consists of a float, a cam, two pendulums, and a control valve. Tides were created by displacing water with the counterbalanced plunger whose size was determined from the tidal prism volumns given in Bulletin 27.* Since the buoyancy

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* Publication of the Division of Water Resources, State of California, "Variation and Control of Salinity in Sacramento-San Joaquin Delta and Upper San Francisco Bay - 1931."

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of the water caused the weight of the plunger to change as it submerged, the counterbalancing pulley was made cam-shaped so that the unbalanced force was never greater than 20 pounds.

The plunger was raised or lowered by a two-way piston attached to the frame forming the housing of the plunger. A compensating type of control was used, that is, a control which made the tide plunger move in such a manner that the water surface followed a given pattern, or cam. While the plunger movement must bear some relation to the tides, it need not be evaluated, since the plunger merely acts as a compensator to raise or lower the water surface in the plunger basin as required. The control float indicated the actual water surface at any time, while the control cam indicated the required water surface at any time. The movement of the float was magnified and set in a horizontal direction by a pulley-string mechanism. A point on the horizontal string was attached to the bottom of the counterbalanced float pendulum. Parallel with the float pendulum, the cam pendulum followed the movement of the cam. Attached to the cam pendulum was a delicate four-way control valve having a high-pressure inlet, a pressure line to each side of the plunger piston, and an exhaust. This valve was operated by the float pendulum. When the float pendulum was in line with the cam pendulum, the control valve was shut off, for the water surface was the same as that indicated by the tide cam. When the float pendulum was not in line with the cam pendulum, the control valve was opened, permitting water under pressure to flow into one side of the plunger piston and exhaust from the other side. The piston would then move the plunger up

or down until the correct water level was obtained and the valve was shut off automatically. Some of the difficulties encountered in the development of this machine will be discussed under the heading of tide verification studies.

In selecting a method for measuring model salinities, it was necessary to consider three different types of water; saline ocean water, acceptable water from the Sacramento River, and polluted water from the San Joaquin River. The difficulties involved in tracing and separating the three types become insurmountable with the usual methods of measuring concentrations by titration or electrolytic conductivity. The method finally adopted for measuring the salinity involves the use of the spectrophotometer. This instrument permits a fast and accurate determination of the component concentrations contained in a mixture of two solutions of different colors and, with lesser accuracy, of three solutions of different colors by direct instrument readings of the color density at different wave lengths. A more complete description of instrument, as well as the details of the color-salinity technique, will be found in appendix 3. From salinity studies in the prototype as reported in Bulletin 27, the variation of salinity in the various river sections was sufficiently small to justify the elimination of salt in the model, since the evidence is clear that no salt-water wedge exists. The effect of density on velocities was assumed to be negligible compared to the tidal action. Degree of salinity was represented by the concentration of a color which, from tests of stability, staining qualities, and ease of visual observation, was selected as Patent Blue, a biological stain. With the exception of one test to verify that the influence of density is negligible, it will be understood that in the following pages the concentration of Patent Blue in the model will be called salinity.

5. Tide verification studies. Before attempting to carry out the principal objective of the model study, which is to investigate various plans for transporting water across the Delta, it was first necessary to establish the validity of the model as a means of predicting the behavior of the prototype. To do this, a series of verification studies were made in which various features of the model were adjusted until known occurrences in the prototype could be duplicated in the model.

One of the largest factors controlling hydraulic conditions in the Delta is the flow created by the action of the tides. This tidal flow, which extends through the entire Delta, involves discharges many times larger than normal stream flows and is a large factor in the propagation of salinity. The first step in the verification studies was that of making the tidal flow of the model duplicate that of the prototype which is a matter of record. In general, this process consisted of forcing the correct tidal height variation at Antioch by means of the tide generator and adjusting the roughness of the model channels until variations at other selected points were also correct. It was accepted that

duplication of tide-gage variation established the correct tidal flows in the model, since a volumetric measurement of the model channels between elevations +3 and +5, prototype, indicated a discrepancy of less than 5 percent from those computed in Bulletin 27.

All the tidal-flow studies were made on the basis of the tide-gage records for the month of August, 1941. The gage record at Antioch was used to construct the tidal cam which is a part of the tide machine. The locations of the prototype tide gages which were duplicated in the model are listed below, and their locations are shown in figure 1.

Sacramento River	San Joaquin River	Mokelumne River
Three Mile Slough	Antioch	Georgiana Slough
Walnut Grove	Three Mile Slough	New Hope Bridge
Snodgrass Slough	Burns Cutoff	
Sacramento	Brandt's Bridge	
	Mossdale Bridge	
	Old River (Mansion House)	
	Middle River (Borden)	
	Grant Line Canal	

To conserve time, comparisons were made for three periods of three days each. The periods chosen, August 7 to 9 inclusive, August 16 to 18 inclusive, and August 25 to 27 inclusive, represent the different tides which occur during a lunar cycle. The prototype tide-gage records at each station for the test periods were reduced to a common datum, U. S. Geological Survey mean tide, corrected for cumulative time errors resulting from the driving clocks running too fast or too slow, and plotted to convenient scales on transparent paper. Reproductions of these plots were used for recording the readings of model tide gages to facilitate model-prototype comparisons. To obtain the model tidal variation, an observer read and recorded the reading on the prepared plots, at the signal of a bell which was controlled by the tide cam to ring at 7-1/2-second intervals, or 1 hour prototype. The speed of the tide cam thus controlled model time, and it was adjusted to make one revolution, representing 27 days 22 hours, in 83 minutes and 45 seconds, or a scale of 1 to 480. The adjustable feature of the tide cam was used later to study the effect of changing the time scale.

The first attempts to operate the model with the initial design of tide machine were disappointing. This first design utilized the jet and the receiver plate principle, with air as the motive power. Due to the compressibility of the air, the plunger would move in jerks which set up local waves that made the control float oscillate. This oscillation was transmitted through the valve to the plunger, which aggravated the original jerking, and the mechanism was soon vibrating out of control. The basic arrangement of the tide machine was changed to eliminate this auto-oscillation. The float was eliminated and the

plunger linked to the float pendulum so that the movement of the plunger was directly proportional to the movement of the cam follower. By using damping springs on the control valve, a fairly smooth plunger movement was obtained.

Observations of model tides, for the model as constructed, indicated that they were nearly in proper phase but far too great in amplitude, particularly at Sacramento where the range was even greater than that at Antioch (6 feet compared with 5 feet). The significance of this test was that the damping action of channel friction affects tidal amplitude far more than tidal phase.

While there appears to be no definite procedure for adjusting roughness in tidal models except by trial and error, some conception of the required amount of the type of roughness selected was obtained in the following manner. The reach of the Sacramento from Sacramento to Snodgrass Slough was selected for this purpose since it represented a single, reasonably uniform channel. The slope of the prototype hydraulic gradient for this reach was computed for several discharges by Manning's formula, using the value of N recommended for prototype channel conditions. Equivalent discharges were added to the model, with the stage controlled by an obstruction below Snodgrass Slough. The hydraulic slope was measured by reading the tide gages at each end of the reach. Artificial roughness in the form of zigzag strips of hardware wire cloth was added until the proper slope, as computed for the prototype, was obtained. While this test gives only an approximation of the amount of artificial roughness required for adjustment of the particular reach used, it served as a starting point for the trial-and-error process which followed. The approximate roughness for other reaches of the Sacramento River was obtained by varying the amount of screen in accordance with the distortion of hydraulic radius. From similitude relations, as shown previously, the roughness required to counter the distorted slope of the model depends upon the distortion of the hydraulic radius which is a function of channel shape. For the smaller channels, such as Georgiana Slough, the distortion is so large that no artificial roughness should be required.

Studies of the Sacramento River revealed several things which were useful in later tests. Roughness in the large channel downstream from Junction Point had such a slight effect that it could be neglected. This seems logical when the very low velocities in this reach of the prototype are considered. The river discharge had little effect on the tides in this reach or on the amplitude at Walnut Grove and Snodgrass Slough, but it did raise the mean tide at these latter stations. At Sacramento the river discharge decreased the amplitude of the tide and raised the mean height. Improvement in amplitude was accompanied by improvement in phase, although the latter was not very sensitive.

In the study of the San Joaquin system an attempt was made to install

roughness in a logical manner by computing the roughness scale of certain channels and using the experience gained in the Sacramento tests. The roughness patterns did not follow any apparent logical pattern, as was later discovered. The following general results were found:

(1) Three Mile Slough was fairly good in amplitude and phase.

(2) In some cases tides at Burns Cutoff were out of phase.

(3) The amplitude at Old and Middle Rivers was too low.

(4) Tides at Mossdale Bridge were fairly good.

The most serious defect was the low amplitude of tides at Old and Middle Rivers. Removing roughness from these rivers did not improve the amplitude. Obviously some other factor than roughness was prevailing in Old and Middle Rivers. It was suspected that the small islands in the middle of the rivers might be the cause. In building the model the general elevation of these islands was assumed to be 0.00, U.S.G.S., because the true elevation could not be ascertained from the available maps. Consequently they were flooded except for very low tides. If, actually, they were submerged in the model and not in the prototype, it would follow that the amplitude of tides would be low in the model because the tidal prism would be too large. Therefore these islands were built up with clay, and the amplitude of tides in Old and Middle Rivers was increased favorably.

Tides in the Mokelumne River were somewhat low in amplitude but were considered satisfactory since further refinements were anticipated in later verification studies after revision of the tide machine. During these tests the problem of maintaining the correct tide at Antioch became increasingly difficult because each adjustment changed the tidal prism and required an adjustment of the plunger movement. The tide-generating machinery was revised to eliminate this defect. The jet-receiver-plate type control valve was replaced by the four-way valve shown in figure 4, and water was substituted as the operating fluid. These changes smoothed out the action of the plunger to such an extent that it was possible to use the original scheme where the plunger acts to compensate any difference in water levels as indicated by the float and the cam. After several adjustments, a good tide at Antioch was obtained which was independent of changes in tidal prism. To demonstrate this independence a comparison was made with all roughness removed from the model (maximum tidal prism) and with the channels blocked above Antioch (minimum tidal prism). The tide at Antioch was identical for both conditions.

Further adjustment of model roughness was made by starting at Three Mile Slough and working upstream. Taking the Sacramento River first, the amplitude at Three Mile Slough was a little low and more so at Walnut Grove. A decrease in resistance below Walnut Grove increased the

amplitude but lowered the mean tide elevation. Conditions at Snodgrass Slough and Sacramento paralleled those at Walnut Grove. The amplitude at Three Mile Slough was raised by eliminating most of the roughness downstream. This improved conditions to a satisfactory degree at the three upstream stations, pending the final over-all adjustments.

In the San Joaquin system the tide was out of phase at Three Mile Slough and was corrected by removing some roughness downstream. The tide at Burns Cutoff was still out of phase by about one and one-half hours although the amplitude and the general characteristics were right. Conditions at Brandt's Bridge and Mossdale Bridge were fair in both phase and amplitude; in Old and Middle Rivers, good in phase but low in amplitude; and in the Mokelumne River, good in both phase and amplitude. These conditions were comparable to those in the Sacramento River and were likewise considered satisfactory pending the final adjustment. Before attempting the final over-all adjustment, the following miscellaneous tests were made:

(a) To verify that surface tension was a negligible factor, a wetting agent, Aerosol, was added to the model in sufficient quantity to reduce the surface tension approximately 65 percent. No appreciable change in tidal flow could be detected.

(b) Roughness placed in Grant Line Canal improved the tides at Old and Middle Rivers.

(c) The time scale of the tides was arbitrarily varied by changing the speed of the tide cam. For the first change, the time of one hour prototype was made equivalent to five seconds model or a time scale of 1 to 720. Since the depth scale was unchanged, this change of time scale is equivalent to distorting the length in the direction of making it too long and increasing the tidal volume. The effect of both changes was evident in the tide at Middle River. The tide was behind in phase by about one and one-half hours prototype, and the amplitude was decreased.

In the second change, one hour prototype was made equivalent to ten seconds or a time scale of 1 to 360. The effects of this change are the inverse of the first change; the length and the tidal volume are both decreased. The tide at Middle River was ahead in phase by about one and one-half hours, and the amplitude was increased. Channel friction was probably affected very little by this distortion of time scale; so any changes are attributable to the relative changes in length and tidal volume. It is clear from these two tests that the time scale as computed is very close to the best value.

The final adjustment of the model consisted in minor refinements at various spots in the model to improve tides at nearby stations. In

these final adjustments a natural balance of the tides in each system became apparent because whenever tides at one station were improved by some adjustment, the tides at nearby stations were also improved. A final verification test was made, reading all stations simultaneously, and the results are shown in figures 5 to 18. Few of the stations were in perfect agreement, but none of the tides was in error more than 0.20 foot prototype, which is only 0.002 foot model. Considering the intermingling channels, type of tides, and large model scale, it is believed that this is a good tidal verification test.

Since blocking Three Mile Slough or Georgiana Slough did not affect tides either in the Sacramento or the San Joaquin Rivers, it became apparent that no index of flow through these sections could be obtained through tidal verification. Likewise, blocking Dutch Slough and False River did not affect tides at Old River. Therefore, while tidal verification tests give a reliable index of tidal flow in the model, in general the flow characteristics through these smaller sloughs and rivers are not necessarily correct.

6. Salinity verification studies. Another important feature of the Sacramento-San Joaquin Delta requiring verification is the intrusion of ocean salinity which has occurred in the past as the result of tidal action and stream flow. The control of this salinity has been the subject of investigations, many of which are reported in Bulletin 27.

Whereas the tidal-flow studies were known to be reasonably straightforward, as indicated by the results of a number of similar model experments, studies of salinity intrusion of the type experienced in the Sacramento-San Joaquin Delta have little precedent. Any theoretical basis for the similarity between model and prototype as regards the movement of salinity depends upon a knowledge of the mechanics of the phenomena. From the data reported in Bulletin 27, which show very definitely that the salinity is practically uniform across any section, it is clear that turbulence plays an important role. If this were not true, the salinity distribution would take the form of a salt-water wedge tapering upstream. The turbulence engendered by tidal flow was apparently sufficiently intense to overcome the tendency for the saline water to sink by reason of its greater specific weight. The type, scale, and intensity of the turbulence are factors which are generally accepted as being not susceptible of control in hydraulic models because of the conflicting restrictions imposed by the geometric scales and the physical properties of the model fluid. It was expected, therefore, that the model would not necessarily duplicate the prototype in this regard without adjusting empirically such quantities as discharge and time to offset the nonconformity of turbulence and its effects.

The salinity verification studies were of two distinct types, historical and equilibrium. In the historical tests the advance of salinity in the model was compared to that in the prototype for the same conditions

of stream flow, consumptive use, etc. In the equilibrium tests the river discharges were held constant over a period of time of sufficient length to allow the salinity conditions to reach equilibrium.

7. Preliminary historical tests - Season of 1931. The season of 1931 was selected for the first historical test because it represents an extreme condition, where the salinity reached Snodgrass Slough on the Sacramento River and Stockton and Grant Line Canal on the San Joaquin River, which permits a study of salinity movement in the entire Delta. The test consisted of duplicating the historical conditions as given in "Report of Sacramento-San Joaquin Water Supervision" for 1931 and observing the advance of salinity by analyzing the color of samples taken at various Delta stations.

The river discharges were obtained by scaling down the values listed in the 1931 report in accordance with the model discharge scale of 1 to 4.8×10^6. Due to the large time scale it was expedient to level the discharge over periods of ten days or more. The model discharges for each river are given in table 1.

Values of total consumptive use for the different months were taken from table 68, column 15, in the 1931 report. The values in this table are computed and not measured quantities. The Delta was classified according to crops of various types, bare lands, marsh lands, open water surfaces, etc., and, by applying unit rates for each class obtained by tank experiments, the total water use is obtained. In the model the total consumptive use was represented by nine drains. The discharge apportioned to each drain was assumed to be proportional to the ratio of the area represented by the drain to the total area. A list of the tracts represented by each drain is shown in table 2, and the model values of consumptive use are shown in table 3.

Net flow from the Delta, which may be either positive or negative, is the algebraic difference between the total inflow and the total consumptive use. Model values of this factor are shown in table 1. A drain in the plunger basin provided positive net flow, and a reservoir discharging into the basin provided negative net flow.

Since the model did not extend downstream to the point where constant salinity prevailed for the test period, which would be in the vicinity of Point Orient, it was necessary to force the salinity at Collinsville to follow the historical record. The prototype salinity measured at slack tide after high-high tide at Collinsville is plotted in figure 19. The erratic nature of the data is to a large degree caused by sampling after low-high tide instead of high-high tide, and no attempt was made to adjust for this feature. A mean curve was drawn through the points, as shown, and this curve was used to represent the variation of salinity at Collinsville for slack after high-high tide. For the model a color was selected to give the best accuracy over the

range of concentrations to be expected, with special emphasis on the lower concentrations. This color, or rather the concentration of Patent Blue which gave this color, was designated as 100 parts per 100,000 of chloride, and all other values were obtained by proportion. The actual technique by which a color reading on the spectrophotometer was converted to concentration is explained in appendix 3.

The advance of salinity was observed at 36 stations in the model, corresponding in all but three cases to prototype salinity observation stations. Samples were taken every 15 days, prototype (45 minutes model), during slack after high-high tide. The variation of model salinity with respect to time is compared with the prototype at representative stations in figures 19 to 30. For a more general over-all picture, a comparison between model and prototype was made by drawing lines of equal salinity on a plan of the Delta at the beginning of each month, see figures 31 to 35.

Since this test was duplicated later with more careful adjustment of the various factors, only a few general observations will be discussed. It has been pointed out previously that the propagation of salinity in the model was not expected to follow the prototype because the scale relationships involving turbulence could not be predetermined. Referring to figures 31 to 35, it is indicated that for two months, May and June, the model and the prototype compare fairly well. During this period the net flow was positive most of the time; so the advance of salinity represents an actual diffusion upstream in opposition to the stream flow. During the months of July and August, however, the model salinity moved too far in the San Joaquin portion and not far enough in the Sacramento portion. Since the net flow was negative in this period, there was an actual flow from the ocean into the Delta. Finally, the retreat of salinity which occurred in the prototype did not take place in the model. It would appear that the model diffusion rate was too high in the San Joaquin and the Lower Sacramento Rivers and too low in the Sacramento River above Junction Point. Before a decision could be reached on this point, there were several other factors to be considered.

(1) The model consumptive use was too high because no correction was made for curtailment of irrigation due to the salinity pollution.

(2) The consumptive-use drains were not located to the best advantage, and the method of allocating the total according to acreage did not give a true distribution.

3) The variation of salinity from high to low tide was much less than the prototype.

(4) A discharge of approximately 300 second-feet down the Mokelumne River in the period from July 26 to September 1 was inadvertently omitted in the model test.

(5) Rock Slough Dam was missing from the model, allowing a shorter route for the passage of salinity through Dutch Slough.

(6) The transfer flows through Three Mile and Georgiana Sloughs might be in error.

8. Season of 1941. An historical test of the 1941 season from July 1 to November 15 was made with the same procedure as that used in the preceding test. The schedule of discharges is shown in table 4. Values and distribution of consumptive use were the same as for the 1931 test. The controlled variation of salinity at Collinsville is shown in figure 36. Salinity measurements were limited to the lower end of the Delta below Rio Vista on the Sacramento River and below Central Landing and Holland pump on the San Joaquin River because the salinity did not advance beyond these points. Measurements at a few model stations are shown in figure 36.

Measurements of salinity in the prototype were discontinued, except for miscellaneous samples, on July 15; so no detailed comparison could be made. The value of the test lies in the fact that the prototype salinity at Antioch reached a maximum of approximately 100, which is the condition used for estimating control flows in Bulletin 27. It was indicated that the model salinity advanced too far on the San Joaquin River, especially at Rock Slough. The condition at Rock Slough is in large measure due to the absence in the model of Rock Slough Weir.

9. Revised historical tests. The preliminary historical tests indicated that several factors may be incorrectly represented in the model, and some of the possibilities have been listed. In order to resolve these possibilities and perhaps uncover additional ones, a conference was held in Denver, Colorado, from January 25 to February 2, 1944, attended by engineers Raymond Matthew and M. H. Blote from the office of the State Engineer of California, engineers O. G. Boden and I. G. Imrie from the Bureau's Delta Division, members of the laboratory staff and other Denver Office representatives. The discussions which took place during the conference brought about a better understanding by all parties concerned of the various problems connected with the Delta and the model study. Several changes were made in the model, some before and some during the conference.

(1) The variation of salinity during a tidal cycle was improved by relocating the tide machine as shown in figure 1.

(2) The dam across Rock Slough was installed in the model. Actually, Rock Slough Dam was not built until after 1931 but Sand Mound Slough Dam was in place at that time, and, since it has the same effect, it was assumed that Rock Slough Dam was in operation for the 1931 test.

(3) The model was corrected for the fact that the Stockton Ship Canal was only partially completed in 1931. The corrections were made by blocking the unfinished portions with clay which could be removed for tests of later years.

(4) The discharge down the Mokelumne River was included in the model schedule.

(5) Consumptive use in the Delta was revised. Under the direction of the state engineers who had gathered information relative to curtailment of irrigation in 1931, the actual amount of water available and distribution for consumptive use were revised. Instead of using a simple proportionality for distributing the total use, the 1931 crop survey was used.

The number of model drains was increased from 9 to 14. A list of the tracts represented by each drain is given in table 5. The locations of the new drains in the model are shown in figure 1. The consumptive use for each group of tracts was computed by applying the unit rates given in table 29 for different crops to the acreage of each crop within the group as listed in table 68 of the Water Supervisors' Report, 1931. Acreages of exterior water surface and aquatic growth for each group were estimated from maps, and the results are shown in table 5. This computation gave consumptive use for a year when there was no curtailment. To obtain the use with the curtailment of 1931, the unit rate was changed on the date of curtailment to the seepage rate for peat or sedimentary land, whichever applied. The modified use for the revised 1931 test is tabulated by totals for comparison with that of the first test in table 3.

1931 test.--The general procedure for the revised 1931 test was similar to the preliminary test except for the fact that salinity samples were taken at shorter intervals and a more careful control of the discharge was maintained. The results of this test are shown on the plots used for the preliminary tests, figures 19 to 30 and 31 to 35. The comparison between the two model tests indicates a definite improvement, but some discrepancies between model and prototype still exist. Until August 1 the two model tests are practically the same except for an improvement near Rock Slough which was no doubt caused by the weir in the second test. Up to this point the consumptive use was practically the same; so no change would be expected. Beginning in August the curtailment of irrigation began to manifest itself, and the use dropped from 237 to 169 cc per second in the model, as shown in table 1. The effects of curtailment are evident in the Old and the Middle Rivers sections, although even the revised model test showed too much salinity on this date. The same effects carry forward through September when the revised test showed a definite retreat which was missing in the first test.

The disparity between the Sacramento and the San Joaquin sections was not changed by the revisions. If it is assumed that any error in model diffusion is the same in both sections, this disparity must be due to some error in model discharge in the Sacramento River section. It is possible that the transfer flow through Georgiana Slough was too low in the model and that the flow of the Sacramento River below the junction was therefore too high and kept the salinity out. At the same time, the model transfer through Three Mile Slough might have been too high. This would decrease the flow downstream and permit the greater encroachment which did occur. These possibilities were studied further by equilibrium tests and will be discussed subsequently.

1941 test.--The second 1941 test was made with all the revisions discussed previously. The consumptive use, shown in table 4, was of course unmodified because there was no curtailment in 1941. The results shown in figure 36 are similar to those of the first test except for an improvement at Rock Slough.

10. The equilibrium tests. To follow a strict course, the model should have been verified by historical tests before any further studies were made. However, there was a lapse of time between the first and the second 1931 and 1941 historical tests, during which six equilibrium tests were run. Following the second 1931 and 1941 historical tests, four more equilibrium tests were run. The general procedure was to maintain a constant river discharge and a constant salinity in the plunger basin, while the salinity was allowed to advance upstream to equilibrium. In the prototype such a condition has never occurred because river flows do not remain constant. Nevertheless, when the Central Valley project is in operation, it is possible that the net flow from the Delta will remain at 3,300 second-feet for an entire season. According to the conclusions given in Bulletin 27 this discharge will be sufficient to hold the mean tidal cycle surface-zone salinity at Antioch to 100 parts per 100,000 and prevent the advance of salinity in the Delta beyond Emmaton and Jersey.

In the first equilibrium test, figure 37, the flow down the Sacramento River was 2,000 second-feet and the flow down the San Joaquin River 1,300 second-feet. No consumptive use was included. With the salinity in the plunger basin constant, the salinity advanced upstream and finally reached equilibrium in four and one-half hours (3 months prototype). Model salinities were expressed relative to the concentration at Antioch which was arbitrarily set at 100 at high tide. No attempt was made to obtain the mean salinity as tests indicated that the variation of salinity with tidal cycle was incorrect in the model. Relative to a salinity at Antioch of 100, the salinity was 60 at Emmaton, 50 at Jersey, and 10 at Webb Point. Although the salinity advanced too far into the Delta, the test was useful in that a cross-channel flow following the recommendation of the State Plan could be superimposed upon the control flow of 3,300 second-feet. The change of

salinity would then be indicative of the effectiveness of the State Plan. The revised flows were 7,900 second-feet down the Sacramento River with 5,900 second-feet diverted at Snodgrass Slough, no flow down the San Joaquin River, 4,600 second-feet from the Delta-Mendota intake, and 3,300 second-feet for salinity control. No consumptive use in the Delta was included. To put these flows in the model by actually diverting water would be difficult; so a discharge of 5,900 second-feet was put directly into Snodgrass Slough and only 2,000 second-feet in the Sacramento River by the method shown in figure 1. The results of this test indicated that if the salinity does advance properly in the model, the salinity at the Delta-Mendota pump will be 10 parts per 100,000, which would not meet requirements. As the salinity advanced too far in the model, a more reliable conclusion of this test is that the salinity at the Delta-Mendota pumps will be the same as the salinity in the San Joaquin River at the mouth of the Mokelumne River. The salinity at this point was not affected by transfer and Delta-Mendota pumping.

To finish the first equilibrium test, a quantity of fluorescein was put into Snodgrass Slough to permit observation of the flow of the diverted water. The principal direction of flow was observed to be down the north fork of the Mokelumne River, into the San Joaquin at the mouth of the Mokelumne, and thence up Old River to the pumping plant. Some color, however, was observed to go down the south fork of the Mokelumne and some up Middle River. Ocean salinity was picked up in the San Joaquin at the mouth of the Mokelumne, at the bifurcations of Old River and False River, Old River and Sand Mound Slough, and Old River and Rock Slough. (The dam at Rock Slough was not installed in this test.)

Equilibrium test 2 was essentially the same as test 1, with consumptive use added. The weir at Rock Slough was included for this test and all subsequent tests. The discharges were 3,400 second-feet down the Sacramento River and 3,900 second-feet down the San Joaquin River to provide 4,000 second-feet for consumptive use and 3,300 second-feet for salinity control. The equilibrium pattern shown in figure 38 was not greatly different from test 1, except that the dam at Rock Slough was effective in reducing salinity at Rock Slough.

After reaching equilibrium, the flows were changed to show the effect of transporting water across the Delta. The revised discharges were 12,500 second-feet down the Sacramento River, 9,200 second-feet diverted at Snodgrass Slough, 4,000 second-feet for consumptive use, 3,300 second-feet for control flow, 4,600 second-feet from the Delta-Mendota pumping plant, and no flow in the San Joaquin River. Again the pattern of the advance of salinity did not differ greatly from that of test 1, the salinity at the Delta-Mendota pumping plant being only slightly less than that in the San Joaquin at the mouth of the Mokelumne River, which was the same with or without diversion and pumping.

Equilibrium test 3 involved relocating the tide plunger basin. In preceding tests there was practically no change of salinity with respect to tidal cycle at Collinsville and Antioch, and a variation reasonably similar to the prototype was obtained only at stations upstream from Three Mile Slough on the Sacramento River and Jersey on the San Joaquin River. It follows that when the salinity is too high at Antioch and Collinsville for low tide, it will be too high at the upstream stations, since it is the same water moving back and forth. Such a condition would prevent correlation between the model and the prototype. The apparent cause for this lack of variation lay in the closeness of the tide plunger basin to the mouth of the Delta. The water at high tide at stations as far upstream as Mayberry and Curtis Landing would be drawn into the plunger basin and mixed with water of the high tides at Collinsville, and would be increased in salinity. While the desirable method for correcting this condition would be to extend the model to include Suisun Bay, such a revision was not considered practical because it would involve a major overhaul to the tide-generating machinery. Therefore, the tide plunger basin was relocated and separated from the mouth of the Delta by a narrow channel having sufficient length to prevent water in the model at high-high tide from reaching the tide plunger basin at low-low tide. Being narrow, the additional channel did not greatly increase the tidal prism volume. Tests were made to verify the tides, after which an equilibrium test was made, using the same discharges as in test 2 with no transfer. A definite improvement was observed in that the advance of salinity was not as great as formerly, see figure 39.

As this improvement was not sufficient to be completely satisfactory, it was suggested that the length of the approach channel separating the model and the plunger basin be increased. However, the salinity gradient, that is the change of salinity with respect to distance, was found to be greater in the approach channel than in the model channels, indicating that no great improvement could be obtained by increasing the length of the approach channel.

In the model the salinity at Collinsville at high tide was about three times as great as the salinity at low tide. This variation was considered sufficient to make a comparison of the mean tidal cycle salinity with the salinity at high-high tide. This comparison was necessary because the model equilibrium tests, based on 100 parts at Antioch, were compared with a prototype criterion based on a mean tidal cycle surface-zone salinity of 100 parts per 100,000 parts of chloride.

Equilibrium test 4 was a comparison of the readings at high-high tide and mean tide based on 100 parts at Antioch. The method of estimating the salinity at mean tide was to take the average of the readings at high-high tide and the following low-low tide. The salinities at mean tide based on 100 parts at Antioch did not differ greatly from the salinities at high-high tide also based on 100 parts at Antioch (figure 40).

In equilibrium test 5 the effect of changing the concentration of the base color was studied. In all preceding tests it had been assumed that the distribution of color when expressed relative to the color at Antioch was independent of the actual concentration. To verify this assumption, equilibrium tests were made with two different concentrations of Patent Blue. In one test the concentration was 0.1 percent of a given base solution and in the other it was 0.9 percent. A comparison of the results, as shown in figure 41, shows that the difference is small and probably not much more than the experimental accuracy for this type of measurement.

The reasons for not using salt in the model have already been fully discussed. To eliminate any uncertainty on this point, a test was made comparing colored fresh water and colored saline water. Although this test ran into unforeseen complications which resulted in incomplete data, sufficient observations were made to show that there was no appreciable change in salinity pattern with the addition of enough sodium chloride to give a density at Antioch of approximately 1.036 grams per cubic centimeter, which is equivalent to 180 parts per 100,000 of chloride. The test results are shown in figure 42. No indication of density flow was observed in the model except in the Sacramento River near Rio Vista where the salt concentration on the surface was 18 and at the bottom 37, based on 100 at Antioch. The nonexistence of a salt wedge in the model is additional evidence that none exists in the prototype where the density is no higher than in the model but the strength of turbulence opposing it much greater.

Following equilibrium test 6, a few more preliminary tests of the State Plan were made, primarily to study problems of technique and procedure for the final tests which will be made after completion of the salinity verification adjustments. In any test of the State Plan there are three distinctly different types of water and possibly a fourth which can become mixed before the Delta-Mendota pumping plant is reached. In the salinity verification studies, since the principal objective was to trace ocean salinity, one color was sufficient. To determine the quality of water delivered to Delta-Mendota under operation of the State Plan of diversion and delivery, it is necessary to trace ocean water, Sacramento River water, San Joaquin River water, and water stored in the channels of the Delta. This can be accomplished by using three different colors, with clear water representing the fourth or Delta water. The technique developed to handle the three colors is described in appendix 3. The quality and the quantity of water from each source must be known before the test results can be expressed in terms of total dissolved solids. The necessary data are available for all sources except the San Joaquin River with Friant Dam in operation. Studies to estimate the future quality and quantity of this source are now being made by the Branch of Project Planning. These tests were suspended during the conference from January 25 to February 2.

Equilibrium test 7 was a study of the effect of the flows through Three Mile and Georgiana Sloughs. It was pounted out during the conference that in apportioning the flows between the Sacramento and the San Joaquin Rivers allowance had not been made for the net flow through Three Mile Slough. Moreover, it was doubtful that the flows through the two sloughs were correct in the model. A test was made with 3,300 second-feet in the Sacramento River, transfers to the San Joaquin assumed as 1,300 second-feet through Georgiana Slough and 900 second-feet through Three Mile Slough, and no flow from the San Joaquin. These revised flows did not change the salinity pattern from that of previous tests so both Georgiana Slough and Three Mile Slough were blocked and the flows changed to 1,100 second-feet in the Sacramento River and 2,200 second-feet in the San Joaquin River. The effect of blocking the sloughs, as shown in figure 43, was to increase salinity in the Sacramento River above Three Mile Slough and to decrease it below Three Mile Slough. Salinity in the San Joaquin River was increased both above and below Three Mile Slough. The increase in salinity in the Sacramento above Three Mile Slough indicated that the flow in this section exceeded 1,100 second-feet before the sloughs were blocked, probably because the transfer through Georgiana Slough was smaller than assumed. The increase in salinity below Three Mile Slough indicated that the net flow in this section was less than 1,100 second-feet before blocking the sloughs, which means that the transfer of water through Three Mile Slough was greater than assumed. The increase in salinity in the San Joaquin River below Three Mile Slough substantiated the conclusion that the transfer through the slough was too high. The increase above Three Mile Slough is much more complex, for it is certain that in the test before blocking the sloughs the flow was less than 2,200 second-feet in this section. It is possible that the increase in salinity below Three Mile Slough was reflected upstream despite the greater flow. The action of Three Mile Slough in equalizing salinities between the two rivers was eliminated by blocking the slough, and this may have been a contributing factor.

In none of the tests was the distribution predicted for the prototype with the recommended control flows even approximated. It was apparent then that some of the factors which contribute to salinity incursion will have to be adjusted before a verification can be achieved. One of the possible adjustments is a change in discharge scale. To evaluate the nature and the magnitude of such a change a test was made comparing salinity conditions for net flows of 3,300 and 6,600 second-feet, respectively. Since the test with 3,300 second-feet had been made with the transfer sloughs blocked, the same condition was held for the test with 6,600 second-feet. For both discharges the proportion was one-third in the Sacramento River and two-thirds in the San Joaquin River. The comparison shown as equilibrium test 8, figure 44, indicates that the salinities were reduced with the higher discharge, but not to values predicted for 3,300 second-feet in the prototype. As it seemed unlikely, in view of the agreement in the earlier portions of the 1931 tests, that an adjustment of 100 percent in the discharges would be required, an

attempt was made to evaluate the required adjustment from prototype data. The only period shown in available records during which the flow into the Delta remained constant was from September 20 to December 10, 1929. For this period the salinity dropped during October but remained more or less constant during November. Assuming that a state of equilibrium had been reached during November, the net flow for this period should be significant. The net flow for the period was about 6,100 second-feet, and it was estimated that the division was 2,270 down the Sacramento River and 3,830 down the San Joaquin River. The salinity gradient for this apparent equilibrium condition can be compared with that of the model for discharges of 2,200 and 4,400 second-feet in the Sacramento and the San Joaquin Rivers, respectively. When the salinities are expressed relative to that at Collinsville there is fairly close agreement, indicating a correction in discharge scale of only a few percent. These conflicting indications can be resolved only by more historical tests, which are planned.

11. Proposed testing program. Tests are planned in which various model quantities will be adjusted or modified in an effort to make the model duplicate an historical intrusion. The proposed adjustments are of two different types.

First, the mechanism by which salinity is diffused into the Delta will be altered with the same discharge and time scales. Tests are now being made along this line, and it has been shown that much improvement can be accomplished by this alteration. In these tests the tidal diffusion of the model was altered by changing the model channels below Jersey, particularly in the San Joaquin, from the rough, tortuous channels which duplicate the prototype to smooth, regular channels with easy curves. The effect of these changes was the elimination of many of the vortices which are too large in the model because of the distortion in scales. Most of the diffusion in the model probably is caused by these vortices, whereas in the prototype the action is more of an eddy diffusion. The term eddy is used here to designate that concept of modern turbulence theory which predicates the existence of periodic fluctuations, distributed in a random fashion throughout the fluid body, which affect an exchange of momentum, heat, salinity, or any other feature subject to transfer. In the case of momentum exchange, the net effect is one of shearing stresses and the mechanism is called eddy viscosity. For conservative concentrations such as heat and salinity, the net effect is a diffusion from higher to lower values and the action is called eddy diffusion. Eddy diffusion of the type described is no doubt a very small factor in the model because it follows from the Reynolds' number scale that the model turbulence is too small. The fact that the vortices in the model are too large does not in itself mean that the diffusion will be too high, because there must be some distortion to offset the lack of eddy diffusion.

Secondly, it is planned to accomplish some of the model adjustment of salinity incursion by altering the discharge and the time scales. Diffusion and stream flow are opposing factors, and the rate of advance of salinity can be controlled by changing either factor or a combination of both. Adjustments of the discharge or the time scales are alternate ways of accomplishing the same purpose. In the former case the scale will be changed so that a greater quantity of water will be discharged in a given period. In the latter case the same effect is achievod by allowing a given flow to operate for a shorter period of time. In either case the time scale of the tidal period, or, more simply, the speed of the tide cam, would be held constant. This is equivalent to thinking of the tidal fluctuation as merely a device to propagate salinity upstream. Any adjustment of tha model must be judged by comparing model and prototype on the basis of historical tests which are complicated and slow to make. It is to be expected, therefore, that it will take considerable time to complete adjustment of the model.

If it should become necessary to expedite the model tests so that a decision can be reached regarding the cross channel, the following procedure could be used: First, it would be assumed that the tide verification studies have established that in the main the distribution of flow among the various Delta channels is correct. Secondly, it would be accepted, from the recommendations of Bulletin 27, that with a salinity-control flow of 3,300 second feet no ocean salinity is encountered upstream from Jersey. Relative to this point it is pointed out that even though salinity intrusion upstream from Antioch is verified by historical tests, the value of salinity at Antioch must be accepted as 100 parts per 100,000 for 3,300 second-feet net flow. Equilibrium test 2 indicated that with water diverted and transferred according to the State Plan, the Delta-Mendota water contained only as much color as the water in the San Joaquin River at the mouth of the Mokelumne River. Therefore, if there is no ocean salinity above Jersey, there will be none in the Delta-Mendota water. On this premise tests can be made without waiting for salinity verification, considering only Sacramento and San Joaquin river flows and the water in the Delta channels at the start of diversion. Seasonal tests with various flows in the San Joaquin would indicate the changing proportions of water from the diverse sources, with time for each river flow. Tests made before and after altering the model to duplicate the proposed dredging would show its effect in reducing the percentage of San Joaquin river water. The percentage of San Joaquin water in the Delta-Mendota water can be measured, but the dissolved solids represented cannot be determined until the quality of this source is predicted.

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D. J. Hebert

F. C. Lowe

APPENDIX 1

COPY EWF

Denver, Colorado, January 16, 1943.

MEMORANDUM TO CHIEF ENGINEER
(H. R. McBirney)

Subject: Hydraulic model - Salinity control studies - Delta Division - Central Valley Project.

1. At a conference in your office January 11, 1943, on matters pertaining primarily to water supply and salinity control in the Delta region, the suggestion was made that a comprehensive study, utilizing a hydraulic model, be initiated, in an effort to determine which of the several construction plans now under investigation, for water distribution in that region, would produce the best results. The plans being investigated are in part as follows:

(a) The original State plan utilizing Snodgrass Slough and the Mokelumne River.

(b) A "Delta Cross Cut" route, utilizing river or presently constructed channels almost exclusively, in conjunction with the Delta-Mendota Canal.

(c) A "Delta Cross Cut" route entirely outside of existing channels and to the east, in conjunction with the Delta-Mendota Canal.

(d) Any combination of (b) and (c).

(e) American River storage and diversion plan.

(f) Possibly or ultimately the Salt Water Barrier.

2. The magnitude and complexity of this undertaking is such as to cause some misgivings as regards the beneficial or conclusive results that are probable. The prospects seem encouraging enough, however, to justify a thorough evaluation of the problem. Authorization for the following procedure is requested.

(a) With the data available in this office, give consideration to (1) scope of the undertaking, (2) procedures involved, (3) difficulties inherent, (4) location of model, (5) scale and area involved, (6) man-power required, (7) time required for completion, (8) estimate of cost, (9) assurance as to success of undertaking.

(b) The hydraulic laboratory section to head-up this study, assisted by the Hydrology-Investigation Section, the Canal Section, and any other group or individual involved.

3. The study should be followed promptly by a report to you, so that you will be in possession of the facts necessary for judging the merits of the undertaking and for issuing instructions as to further procedure.

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H. R. McBirney.

APPENDIX 2

JEW:EWF

Denver, Colorado, February 19, 1943.

MEMORANDUM TO CHIEF ENGINEER
(J. E. Warnock)

Subject: Hydraulic model - Salinity control studies - Delta Division - Central Valley Project.

1. In a memorandum on January 16, 1943, Mr. McBirney requested consideration of a hydraulic model of the Sacramento-San Joaquin Delta region to make a comprehensive study in an effort to determine which of the several construction plans now under investigation, for water distribution in the Delta region, would produce the best results.

2. In paragraph 2 of his memorandum, he requested that, based on data available in this office, consideration be given to

(1) Scope of the undertaking,
(2) Procedures involved,
(3) Difficulties inherent,
(4) Location of the model,
(5) Scale and area involved,
(6) Manpower required,
(7) Time required for completion,
(8) Estimate of cost,
(9) Assurance as to success of undertaking.

3. Based on a study of the introductory chapter of bulletin 27 (Department of Public Works, State of California) "Variation and Control of Salinity in Sacramento-San Joaquin Delta and Upper San Francisco Bay" 1931; a study of a topographic map of the Delta region assembled from 1:31,680 U.S.G.S. quadrangles; a review of literature on the subject of hydraulic models involving geometrical distortion and tidal phenomenon; and discussion of the problem with engineers in the Hydrology Investigation and Canal Sections, certain conclusions have been reached.

4. Scope of the undertaking. The problem in this case is the study of an estuary as distinguished from a river involving fluctuation of flow due to hydrological conditions and from harbors or bays in which tidal action is the predominating factor. The movement of flow through the Sacramento-San Joaquin Delta is influenced by the hydrology of the contributing rivers and by the oceanography of Suisun Bay directly and the Pacific Ocean indirectly. To make a study of the flow conditions of the Delta all of those factors must be present in the model, which means

that there is no approach to the solution through use of a model of a portion of the region. It appears therefore that a model must include all of the Sacramento River below Hood (figure 1), one of the proposed points of diversion; all of the San Joaquin River below Mossdale Bridge, the site of the pumping intake for the Delta-Mendota Canal; and sufficient length of Suisun Bay in which to install equipment for developing the tidal cycle. A line across Suisun Bay $4\frac{1}{2}$ miles below Pittsburg has been selected as the downstream end of the model. In elevation, the 5-foot contour was followed roughly in establishing the necessary limits of the model.

The great expanse of the region makes a reasonable geometrically undistorted scale economically and technically infeasible so no consideration has been given to such approach. The model must be distorted by using different horizontal and vertical scales.

5. Procedures involved. In the use of a distorted model it is necessary to look upon it as a mechanical means of solving the equations of fluid motion for conditions which are too complex for mathematical representation rather than a pictorial or topographic representation. Any hydraulic system which can be used to predict the behavior of a prototype should be classed as a model whether or not there is any similarity of outline. Then a method must be discovered for transferring the data from the model to the prototype. It is apparent that a distorted model is dissimilar to the prototype in several important aspects which modify the model's conformance to the theoretical laws of similitude. The trustworthiness and usefulness of the model are based not on theoretical consideration, but on a practical operation known as model verification. The principle underlying the process of model verification is simply that if a model can reproduce accurately events which are known to have occurred, it can be depended upon to predict accurately events which will occur as the result of certain given operations. The soundness of this principle rests on inductive reasoning rather than a mathematical proof. There are necessary qualifications to this principle, the most important being (1) the past event must not be radically different from the future event - a distorted model constructed to study a low-water condition cannot be used for a flood condition, (2) the event must be definite and must have occurred over an appreciable period of time, and (3) the event must not be a freak, for if the model is adjusted to reproduce a freakish occurrence, it will not reproduce normal events. In the case of a model of the Delta region, it would be constructed based on topographic surveys available or obtainable; the model would be operated and adjusted until it would duplicate a past condition such as the salinity encroachment of 1924 or 1931. Then, with the model adjusted or verified for a past event, the water from the Sacramento River would be diverted through the proposed channel via Snodgrass Slough, and the effects of retardation of salinity encroachment from Suisun Bay, and consumption of water by pumping at the Delta-Mendota Canal and Contra Costa Canal intakes would be observed.

6. Difficulties inherent. There are a number of difficulties to be overcome, the outstanding one being the element of time allowable for the study. It is difficult to judge the time needed, as we have little or no precedent except our experience in 1939-40 with the model of the Little Dalles on the Columbia River. Another difficulty is space in which to build the model. The water supply is not as simple as in previous studies in that three types of water must be introduced into the model - saline water through Suisun Bay, water of acceptable quality through the Sacramento River, and polluted water through the San Joaquin River. Once these are mixed in the model they will have to be dumped into the sewer, as it will not be possible to recirculate as had been the practice in other studies. Laboratory equipment will have to be developed capable of measuring the extremely small discharges in the model.

7. Location of the model. Consideration has been given to installing the model either in the hydraulic laboratory or in a garage type building near the Customhouse. Since garage space does not appear to be available within a reasonable distance of the Customhouse, a model with a horizontal scale of 1:4800 has been adopted. That scale is the largest workable scale which will fit into the hydraulic laboratory. The model to that scale is shown in place on figure 2.

8. Scale and area involved. The area of prototype involved has been discussed under (4), and the area involved in the model insofar as laboratory floor space is concerned is shown on figure 2. The scale of 1:4800 for the horizontal dimensions at first thought appears outlandishly small, particularly after years of thinking in terms of undistorted models in which, because of hydraulic factors, a scale of less than 1:100 was seldom considered. For the present, the vertical scale is left unestablished, as it must be based on hydraulic considerations which may not be determined until the model is under construction or even in operation. In any case those factors are capable of manipulation within the limits of our laboratory facilities. There is precedent for these conclusions as follows:

Prototype	Seine France	Rangoon Burma	Severn England	Columbia U.S.A.	Mississippi U.S.A.
Experimenter	Vernon-Harcourt	Gibbs	Gibson	O'Brien	Waterways Exp. Station
Purpose	Channel Improvement	Channel through outer bar	Effect of dam on silting and currents	Estuary and bar-channels	Flood control
Horizontal scale	40,000	8,068 7,050	8,500	3,600	2,000
Vertical scale	400	192	200	128	100
Depth distortion	1:100	1:42	1:42.5	1:28	1:20

In his paper in Trans. A.S.C.E., Vol. 104, 1939, "Geometric Distortion in Hydraulic Models," Kenneth D. Nichols says "... In the foregoing models, the range in depth scales was only 1:50 to 1:200, compared to a range in length scales of 1:50 to 1:2000. (He was discussing a group of models with horizontal scales of 1:2000 or less and did not include any of the above except the Mississippi River model). The range in depth distortion was from 1 to 20, and the range in slope distortion was from 1 to 26. Models of the larger prototypes were built with the greater degree of geometric distortion." O'Brien, in his study of the Columbia estuary, used a horizontal scale of 1:3600 with a vertical scale of 1:64 in his early experiments. He found this distortion too great and changed to 1:128 for the vertical scale in later experiments. Assuming a depth distortion of 1:48 for the present, a vertical scale of 1:100 appears reasonable for a model of the Delta region. Even though the model were built to a vertical scale of 1:100 and subsequent operation showed the desirability of another vertical scale, it would be a simple matter to convert, since it would entail only a change of the templets. The horizontal control would remain fixed.

9. Manpower required. To determine only the merits of the State's plan to divert Sacramento water through Snodgrass Slough down to the Mokelumne River, it is estimated that the following time will be required:

Design of model (incl. acquisition of necessary information from outside sources)	2 months
Construction of model	3 months
Verification of model	3 months
Testing effectiveness of diversion scheme	2 months
Total	10 months

That time may be reduced since part of the construction can be completed while the design and acquisition of data is in progress. On the basis of 10 months for the original tests, it is estimated that the following manpower will be required:

1 engineer	5	man-months	at $402.36	$ 2,011.80
1 associate engineer	10	" "	" 319.02	3,190.20
1 assistant "	10	" "	" 233.19	2,331.90
2 carpenters	2	" "	" 206.83	413.66
1 tinner	1	" "	" 206.83	206.83
2 plumbers	1	" "	" 206.83	206.83
1 model-maker	8	" "	" 212.91	1,703.28
2 mechanics	10	" "	" 206.83	2,068.30
				$12,132.80*

*Includes present overtime salary.

By completion of work in progress the engineering personnel can be made available within two weeks and the laboratory personnel is now available.

10. Time required for completion. This item has been estimated under (9).

11. Estimate of cost.

Engineering (from item 9)	$ 7,500.00
Laboratory and shop personnel (from item 9)	4,500.00
Travel	300.00
Materials, equipment, etc. (not estimated in detail)	1,000.00
	$13,300.00
Contingencies, 10%	1,330.00
	$14,630.00 or
	$15,000.00

12. Assurance as to success of undertaking. In the opinion of the personnel of the hydraulic laboratory, the use of a distorted model to study the feasibility of the State Plan for diversion of Sacramento River water into the San Joaquin River is entirely practical. Assuming sufficient topographic and hydrographic data available on which to construct a model and adjust or verify it to some past event such as the salinity encroachment of 1924 or 1931, there is little reason to doubt but that the feasibility of the State Plan can be determined. It must be remembered, however, that the success of the undertaking will be qualitative rather than quantitative. It would be unreasonable to expect to determine quantities with anything but average success because of the very minuteness of the quantities involved in the model.

The assurance as to the success of this proposed model can best be measured by the success of other experimenters in the same type of undertaking. Several models of rivers, estuaries, and harbors have been successful in the solution of problems involving silt transportation and deposition which is considered to be one of the most difficult to solve with models. In a study of the Delta region by model, the silt is not considered as a factor which is a factor of simplification.

13. If the decision is made to proceed with this model study on the basis herein outlined, it is considered advisable for Associate Engineer D. J. Hebert to be sent to the U. S. Waterways Experiment Station, Vicksburg, Mississippi, for a week or ten days to become thoroughly familiar with the technique of distorted and tidal models and the instrumentation of sach. It is also considered advisable for the writer to be sent to Sacramento to obtain first-hand information as to field data and to discuss the problem with field men who are thoroughly acquainted with the region.

- - -

J. E. Warnock

APPENDIX 3

Use of Spectrophotometer in Model Studies of Sacramento-San Joaquin Delta

All determinations of concentration in the model testing were made with a spectrophotometer. The theory and the application of this instrument are fully discussed in many textbooks on chemical analysis, and it will suffice here to describe the instrument only very briefly.

The spectrophotometer is a combination of a photometer - an instrument for measuring light intensities, and a monochromator - a device for isolating light of any desired wave length. For a given wave length the light absorbed by a medium, such as a colored solution, decreases in intensity in accordance with an exponential function known as the Beer-Lambert Law which is

$$\mathrm{Log}_{10} \left(\frac{I_o}{I}\right) = K C L$$

where K is a constant for any wave length, C is the concentration, L is the thickness of the absorbing medium, and I_o and I refer to the original and the transmitted intensities, respectively. By reason of the variation in light transmission with wave length, it is possible to determine the concentration of two or more solutions of different colors when mixed. To date most of the tests have involved only one color, Patent Blue, which was used to represent ocean salinity, as explained in the text. In the following data it will be understood that all concentrations are expressed in terms of milliliters of the base solution per 100 milliliters of water. The base solution was 0.5 grams of Patent Blue per liter of water.

Preliminary tests of Patent Blue solutions indicated small deviations from the Beer-Lambert Law; so it was necessary to calibrate transmission against concentration at the selected wave length. The optimum wave length at which absorption is a maximum was determined as 630 millimicrons. When the tests required heavier concentrations, a wave length of 530 millimicrons was used and another calibration of transmission against concentration was made. The two calibrations were prepared as tables.

With these calibration tables available, a typical determination would proceed as follows: A sample of colored water from the model was transferred to a rectangular glass cuvette, 40 millimeters in depth, which was placed in a holder containing another cuvette filled with clear water from the model. The holder was inserted in the spectrophotometer with the clear sample in front of the light beam, and the galvanometer scale was adjusted to a reading of 100. The holder

then was slid inward until the colored sample was in front of the light beam. The reading on the galvanometer is the percentage transmission which is used with the calibration tables to find concentration.

Three-color tests. In later tests on the Delta model it will be necessary to determine the component parts of a mixture of waters from as many as four sources. Water from three sources will be colored solutions of a given concentration of red, yellow, and blue, while the fourth source will be clear water. In the mixture, each color will be diluted by the presence of water from the other sources. The resultant concentration of each color, expressed in percent of the concentration at its source, will represent the percentage of water from that source. It follows that the percentage of clear water from the fourth source will be 100 minus the total from the other three sources.

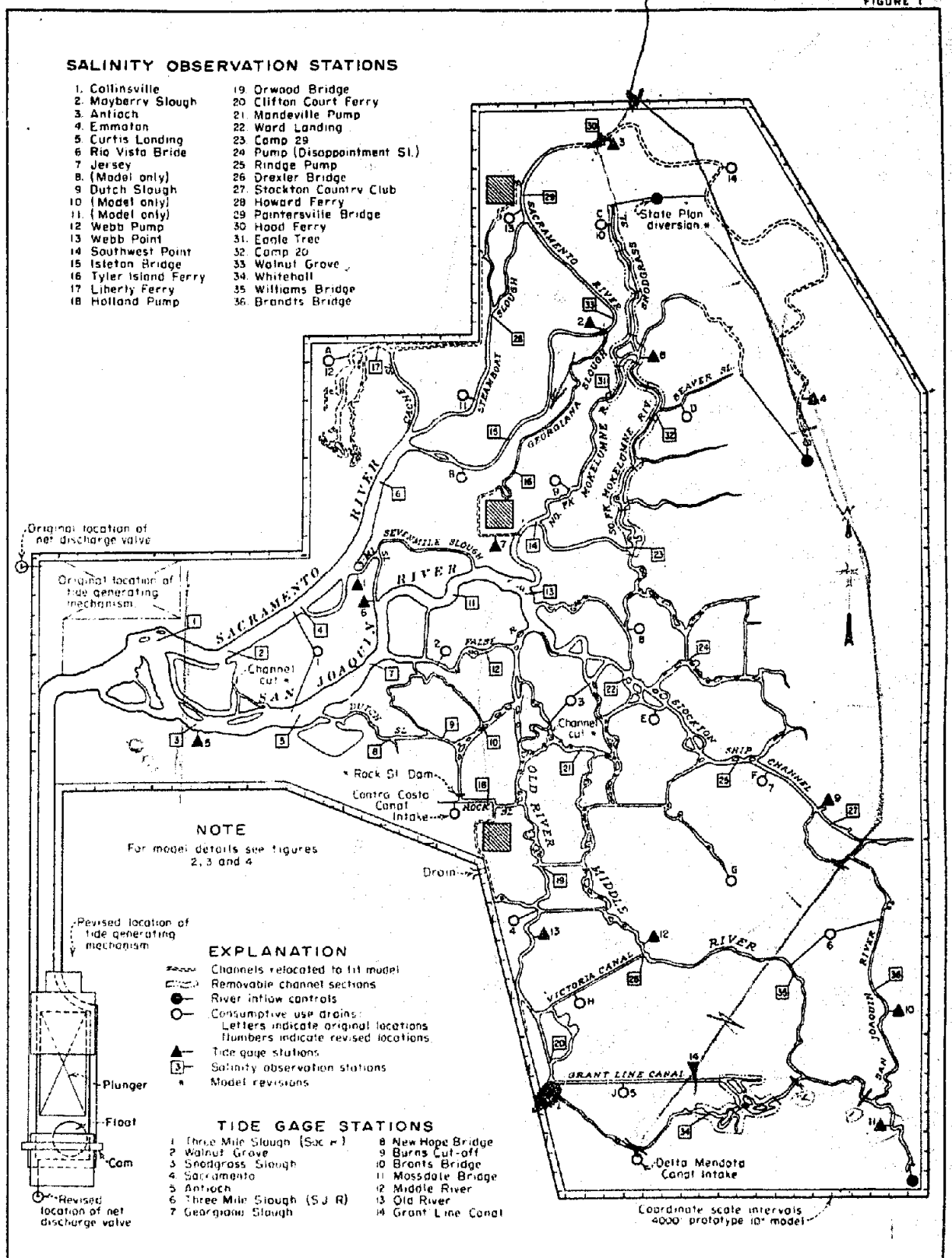
In developing the technique for this procedure, the major difficulty has been in the selection of suitable chemicals for coloring the water. The criteria for their selection were (1) that the spectral-transmission curves must be simple with single absorption bands so located that the absorption of two colors would be a minimum when the absorption of the third was a maximum; (2) that the chemicals must be stable in tap water containing Ca^{++} ions and CO_3^{--} ions, that is, they must be stable in themselves and not fade or coagulate when exposed to light or time; (3) that they must not stain concrete or paint; and (4) that they must be available. Patent Blue, a biological stain, was used in the salinity measurements and was selected as the blue. Picric acid was selected as the yellow. No red could be found which would not fade, coagulate in tap water, or stain badly. Certified D. & C. Red No. 8 (Fast Red), a cosmetic dye, was selected when it was shown that the addition of Calgon would prevent it from coagulating in tap water.

The spectral-transmittance curves for these colors indicated that suitable wave lengths would be 400 millimicrons (mμ) for the yellow, 500 for the red, and 630 for the blue. Actually, the best wave length for the yellow was 350 millimicrons, but this involved changing filters on the instrument. Each color was calibrated at the selected wave lengths and transmittance-concentration curves were drawn. The yellow color was ideal, having an intense absorption at 400 millimicrons and practically none at 500 and 630 millimicrons. The fast red had a high absorption at 500 millimicrons, slight absorption at 630, and an absorption at 400 of about one-third that at 500. The Patent Blue had a high absorption at 630 millimicrons and low absorption at 400 and 500. The relatively high absorption of fast red at 400 millimicrons was undesirable, but was not considered especially significant because correction factors would be applied to each reading.

To find the concentration of yellow, red, and blue in a given sample of the mixture, the first step is to measure the percentage transmission at wave lengths of 400, 500, and 630 millimicrons, respectively. An approximate concentration for each color at its special

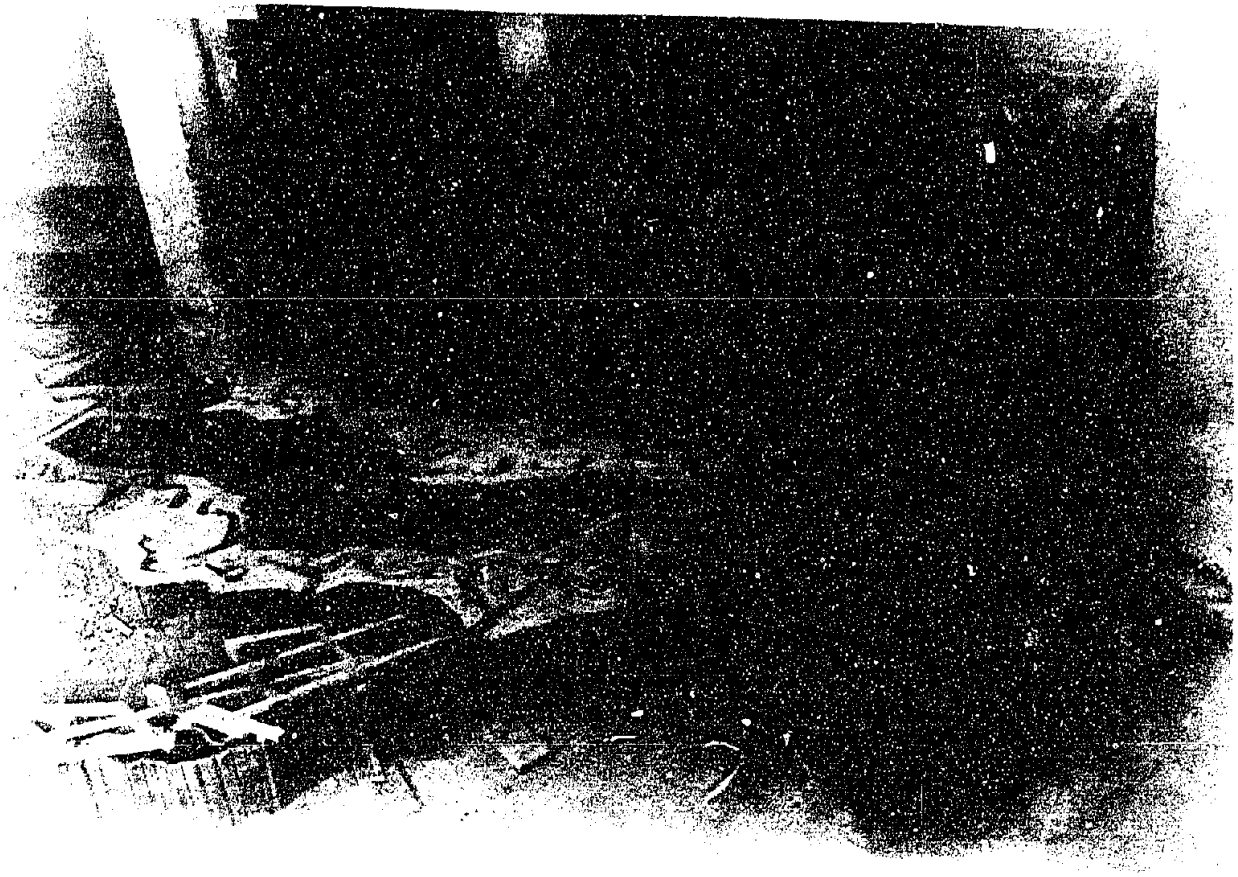
wave length is obtained by assuming that there is no interference from the other two colors. Using these approximate values to make corrections for interference, a more accurate determination can be made. Repetition of the process will give concentrations to any desired accuracy. The interference curves are not shown because they are incomplete.

FIGURE 1

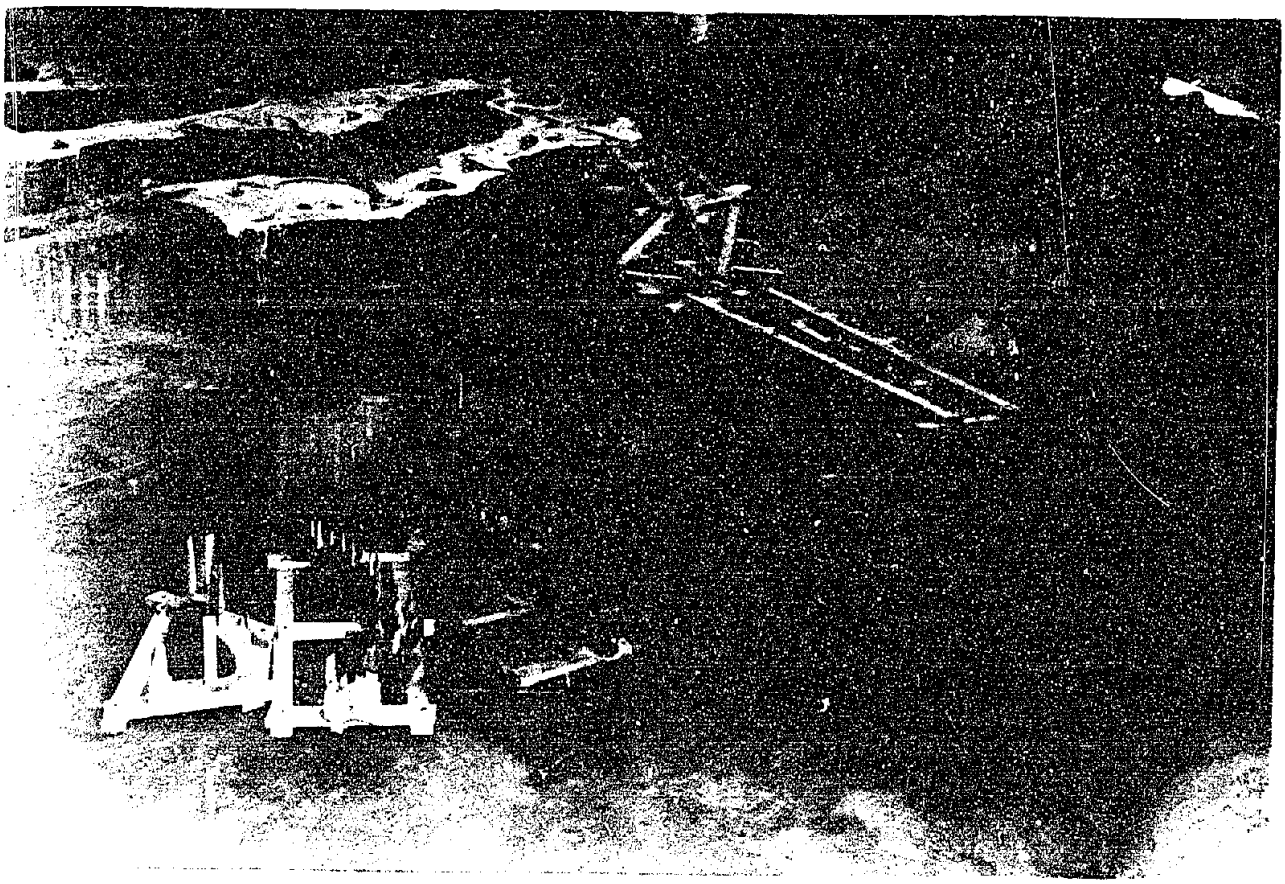


HYDRAULIC MODEL OF SACRAMENTO - SAN JOAQUIN DELTA

MODEL SCALES 1:4800 Horizontal
1:100 Vertical



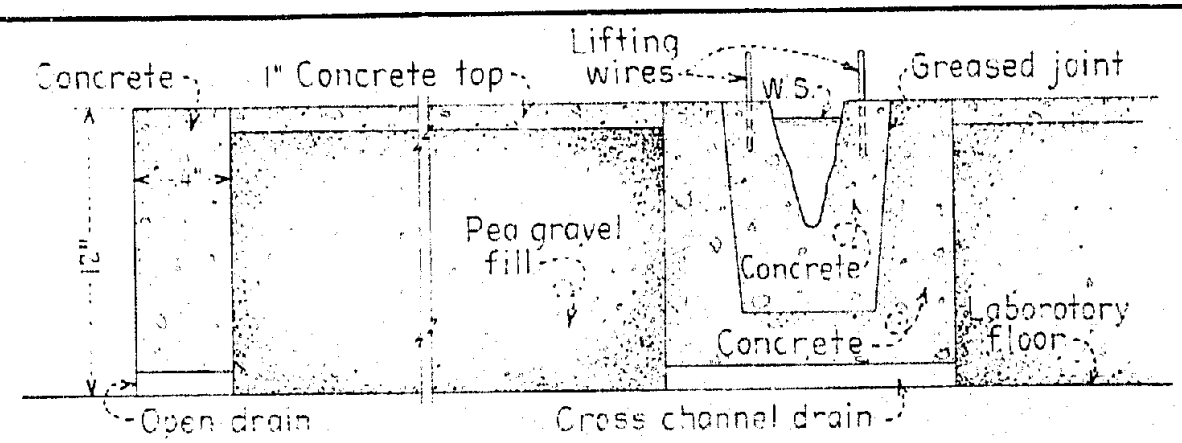
MODEL DURING CONSTRUCTION



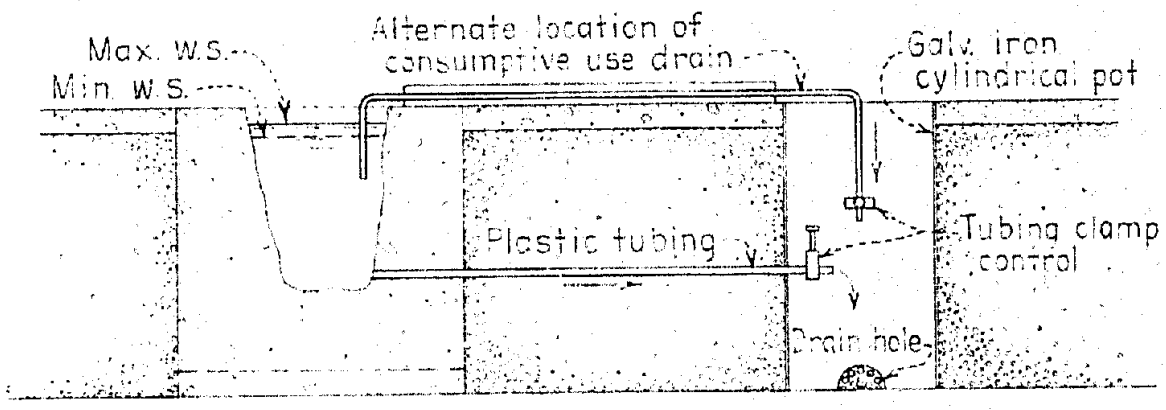
DETAILS OF MODEL CONSTRUCTION

HYDRAULIC MODEL-SACRAMENTO-SAN JOAQUIN DELTA

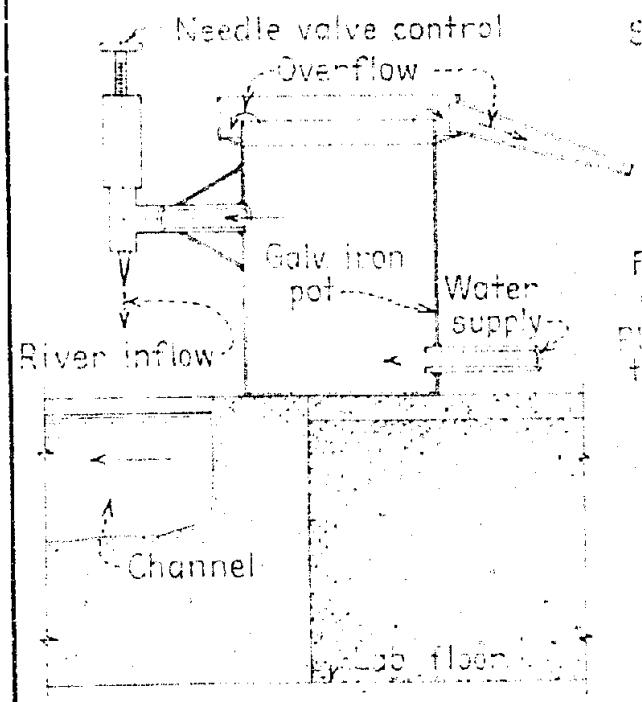
FIGURE 3

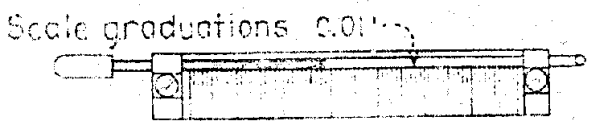


BOUNDARY WALL REMOVABLE CHANNEL

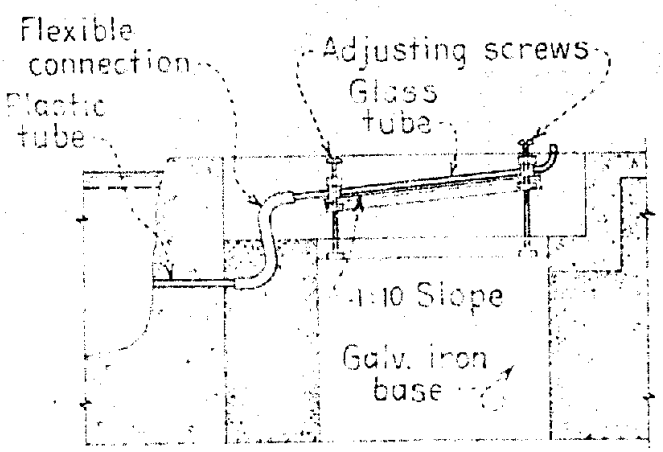


TYPICAL CHANNEL CONSUMPTIVE USE DRAIN





PLAN OF MANOMETER



RIVER INFLOW CONTROL TIDE GAGE - MANOMETER

MODEL OF SACRAMENTO - SAN JOAQUIN DELTA

TYPICAL DETAILS

FIGURE 4

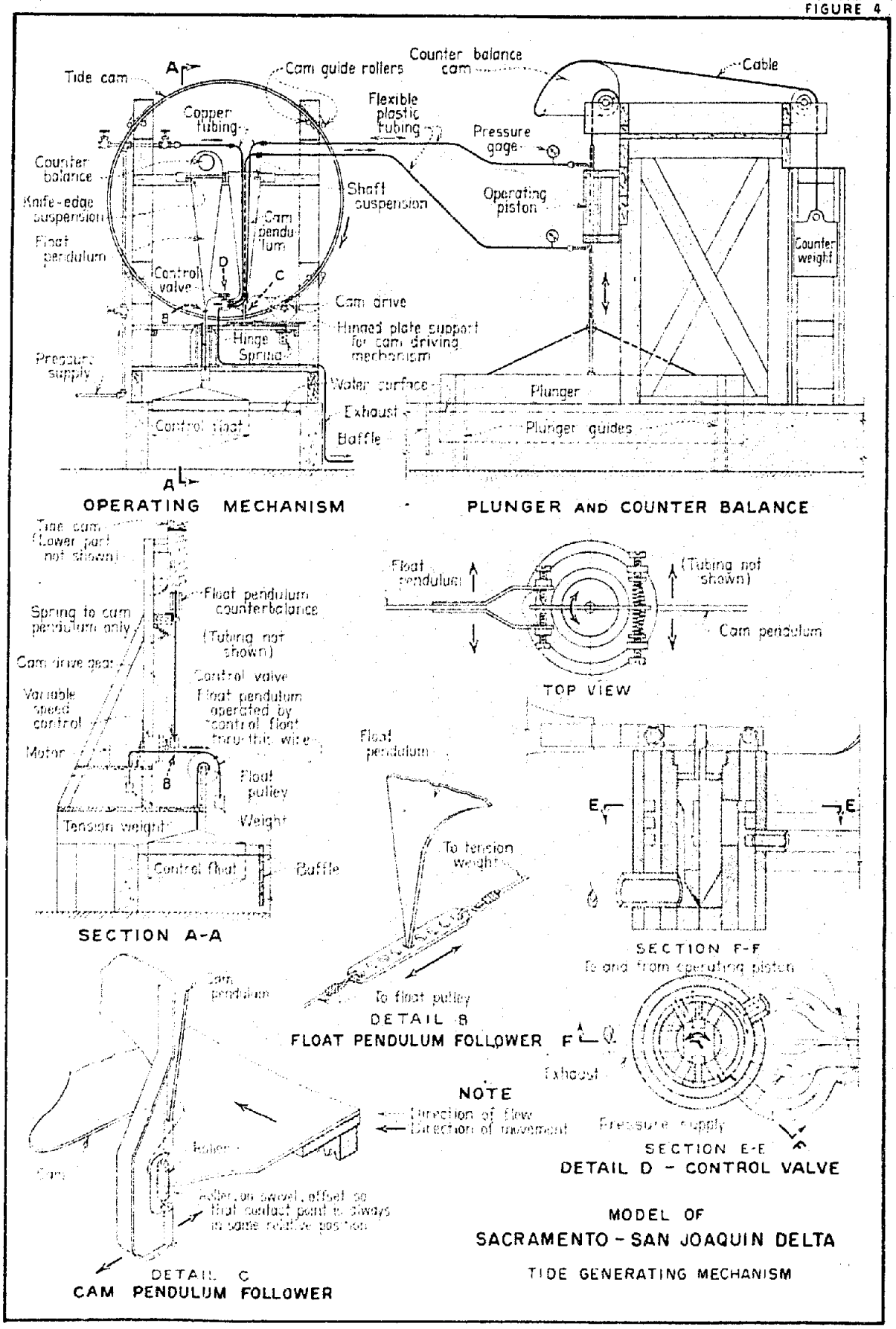
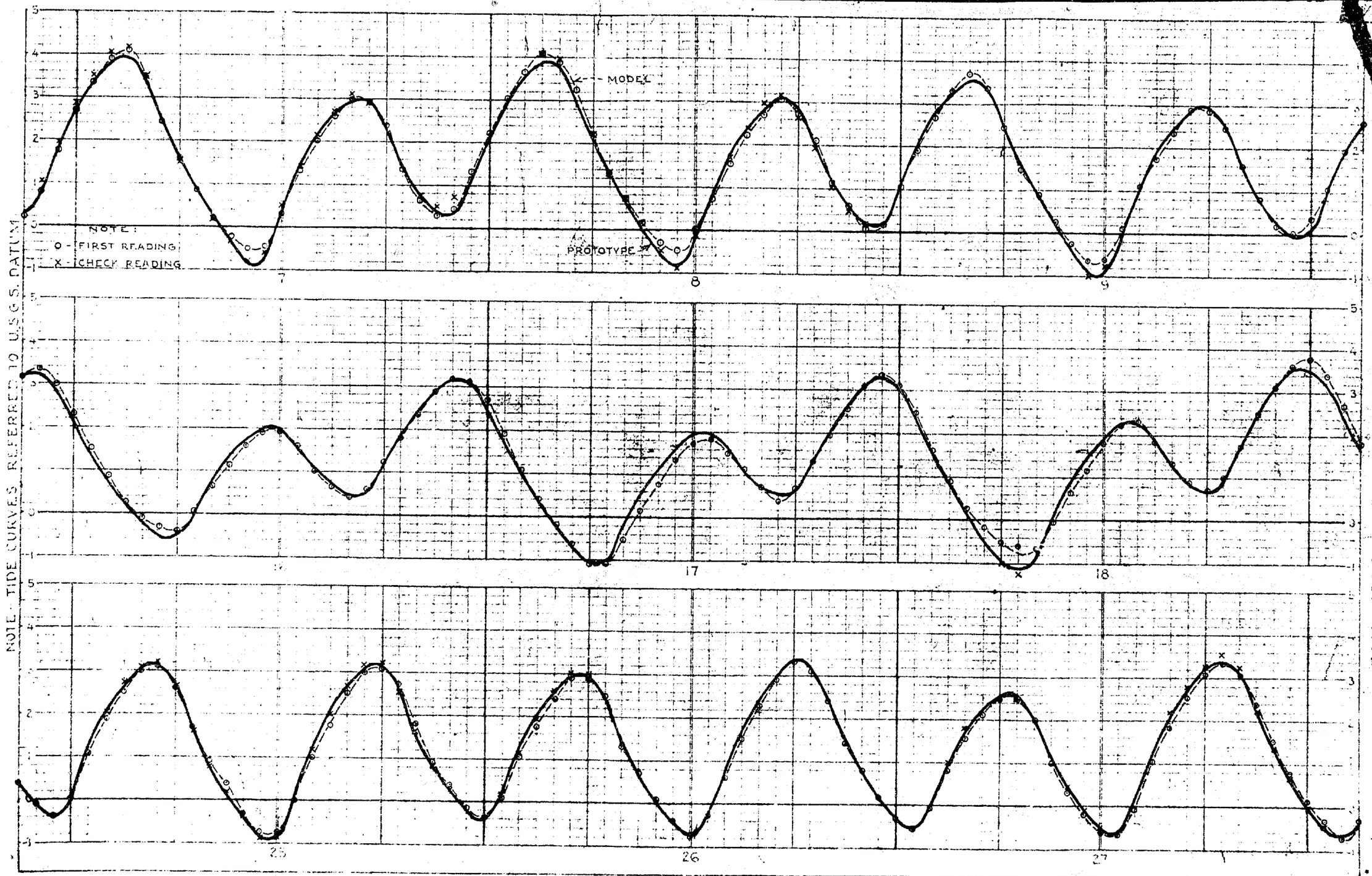

Tide cam
Cam guide rollers
Counter balance cam
Cable
Copper tubing
Flexible plastic tubing
Pressure gage
Counter balance
Knife-edge suspension
Shaft suspension
Operating piston
Float pendulum
Cam pendulum
Control valve
Counter weight
Cam drive
Hinged plate support for cam driving mechanism
Hinge
Spring
Pressure supply
Water surface
Plunger
Exhaust
Control float
Baffle
Plunger guides
OPERATING MECHANISM
PLUNGER AND COUNTER BALANCE
Tide cam (Lower part not shown)
Float pendulum counterbalance
Spring to cam pendulum only
(Tubing not shown)
Cam drive gear
Control valve
Variable speed control
Float pendulum operated by control float thru thin wire
Motor
Float pulley
Weight
Tension weight
Control float
Baffle
SECTION A-A
Float pendulum
(Tubing not shown)
Cam pendulum
TOP VIEW
Float pendulum
To tension weight
To float pulley
DETAIL B
FLOAT PENDULUM FOLLOWER
SECTION F-F
To and from operating piston
Exhaust
Pressure supply
SECTION E-E
DETAIL D - CONTROL VALVE
Cam pendulum
NOTE
Direction of flow
Direction of movement
Roller
Cam
Roller on swivel, offset so that contact point is always in same relative position
DETAIL C
CAM PENDULUM FOLLOWER
MODEL OF
SACRAMENTO - SAN JOAQUIN DELTA
TIDE GENERATING MECHANISM

FIGURE 5



SAN JOAQUIN - SACRAMENTO DELTA
SALINITY CONTROL STUDIES
1:500 MODEL

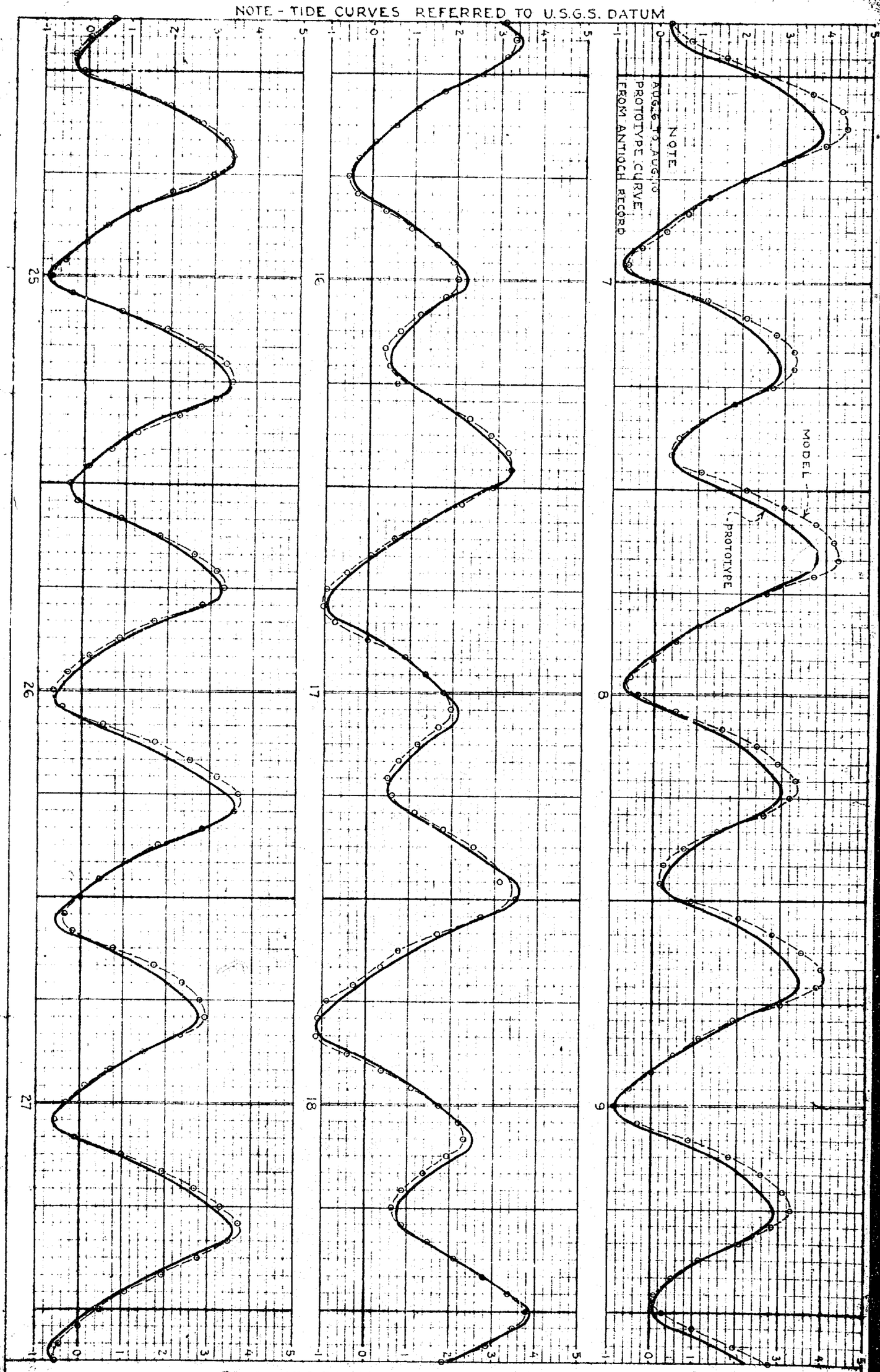
TIDE CURVES AT ANTIOCH

FOR AUG. 1951

TEST RECORDER

DATE

NOTE - TIDE CURVES REFERRED TO U.S.G.S. DATUM



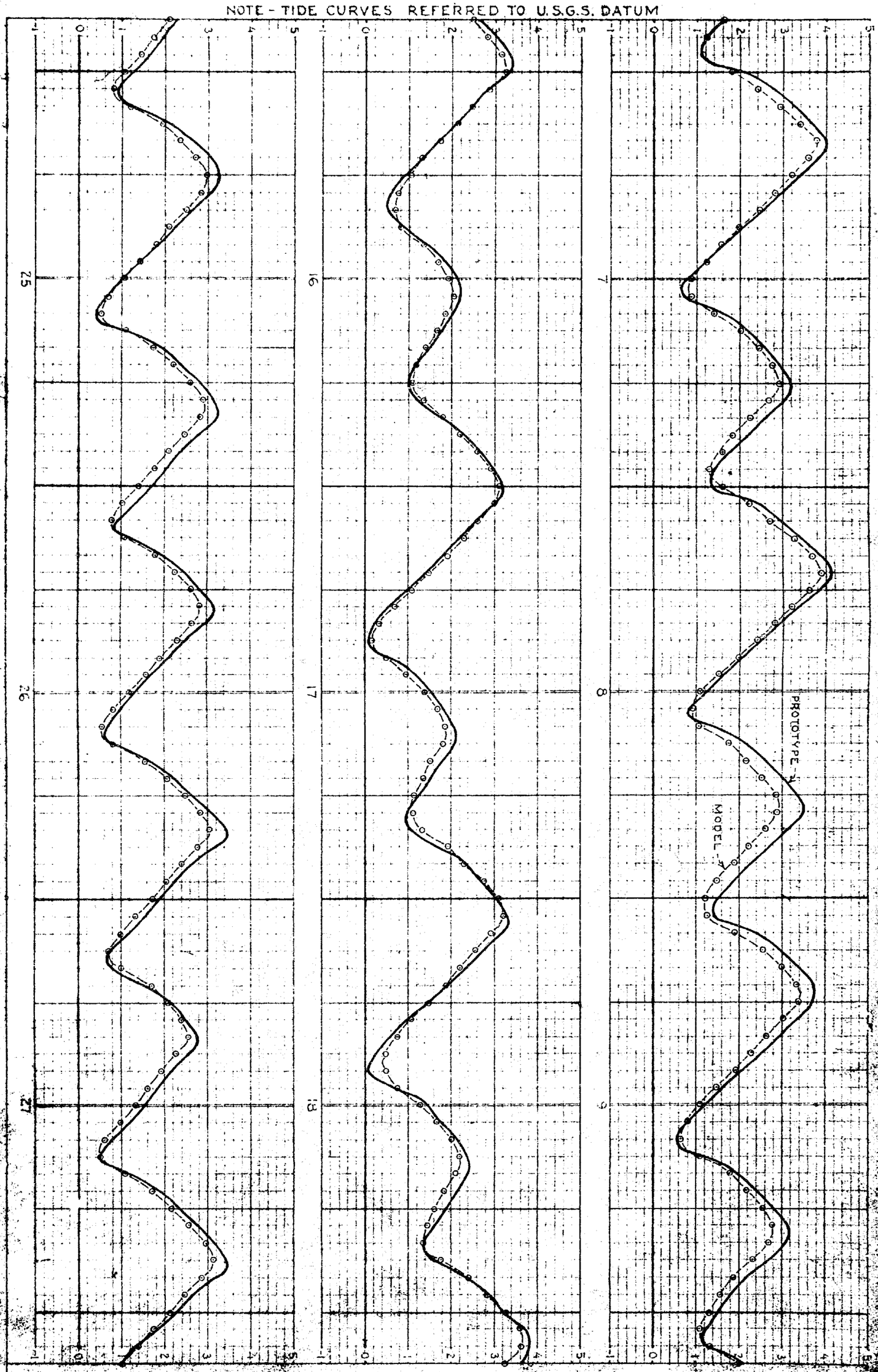
SAN JOAQUIN - SACRAMENTO DELTA

SALINITY CONTROL STUDIES - 1:4800 MODEL

TIDE CURVES AT THREE MI. SLOUGH (SACRAMENTO) FOR AUG. 1941

TEST..... RECORDER..... DATE.....

NOTE - TIDE CURVES REFERRED TO U.S.G.S. DATUM



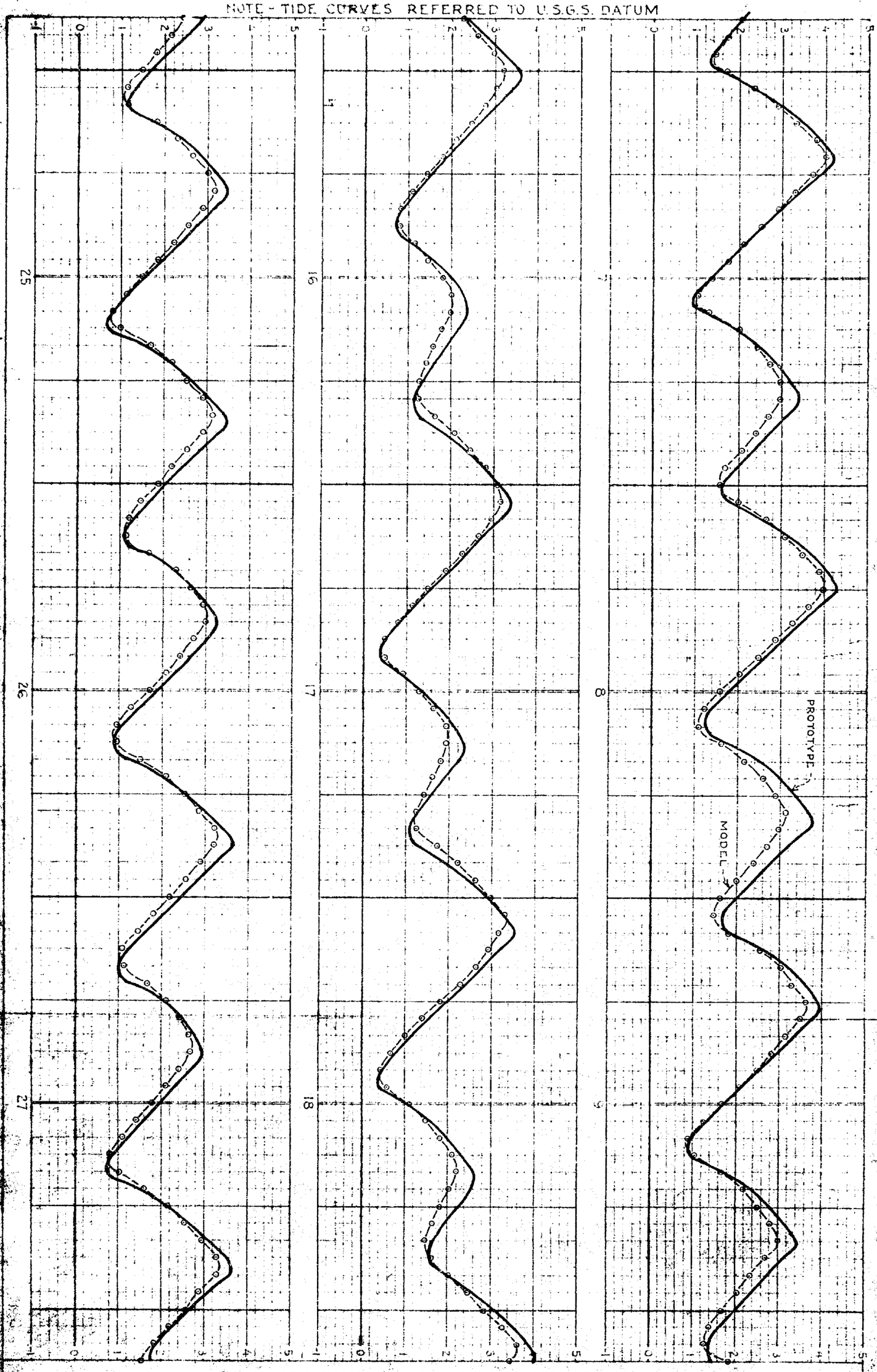
SAN JOAQUIN - SACRAMENTO DELTA

SALINITY CONTROL STUDIES - 1:4800 MODEL

TIDE CURVES AT WALNUT GROVE **FOR AUG. 1961**

TEST ..... RECORDER ..... DATE .....

NOTE - TIDE CURVES REFERRED TO U.S.G.S. DATUM



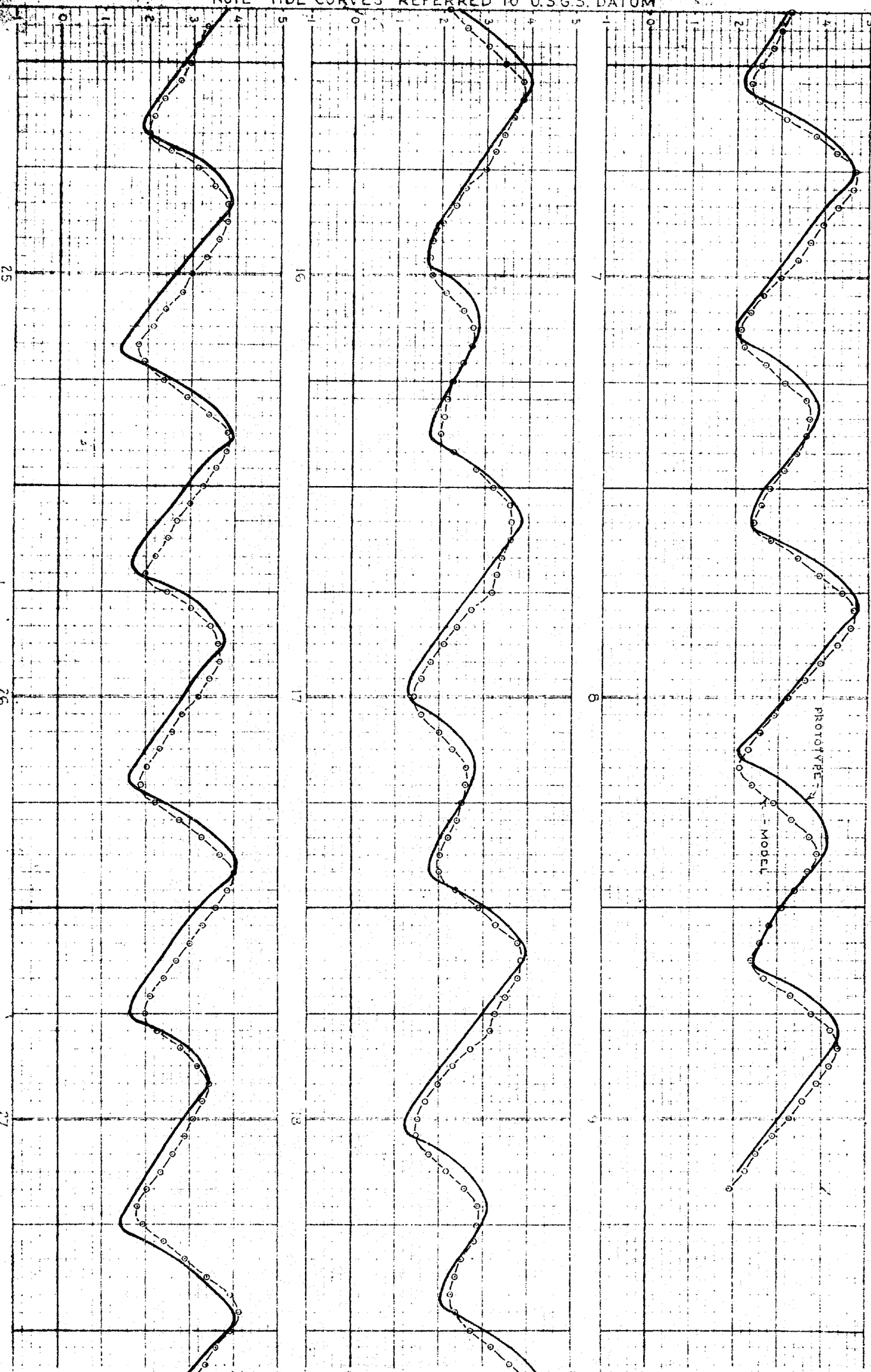
SAN JOAQUIN - SACRAMENTO DELTA
SALINITY CONTROL STUDIES - 1:4800 MODEL

TIDE CURVES AT SNODGRASS SLOUGH FOR AUG. 1941

TEST ..... RECORDER ..... DATE .....

FIGURE 8

NOTE - TIDE CURVES REFERRED TO U.S.G.S. DATUM



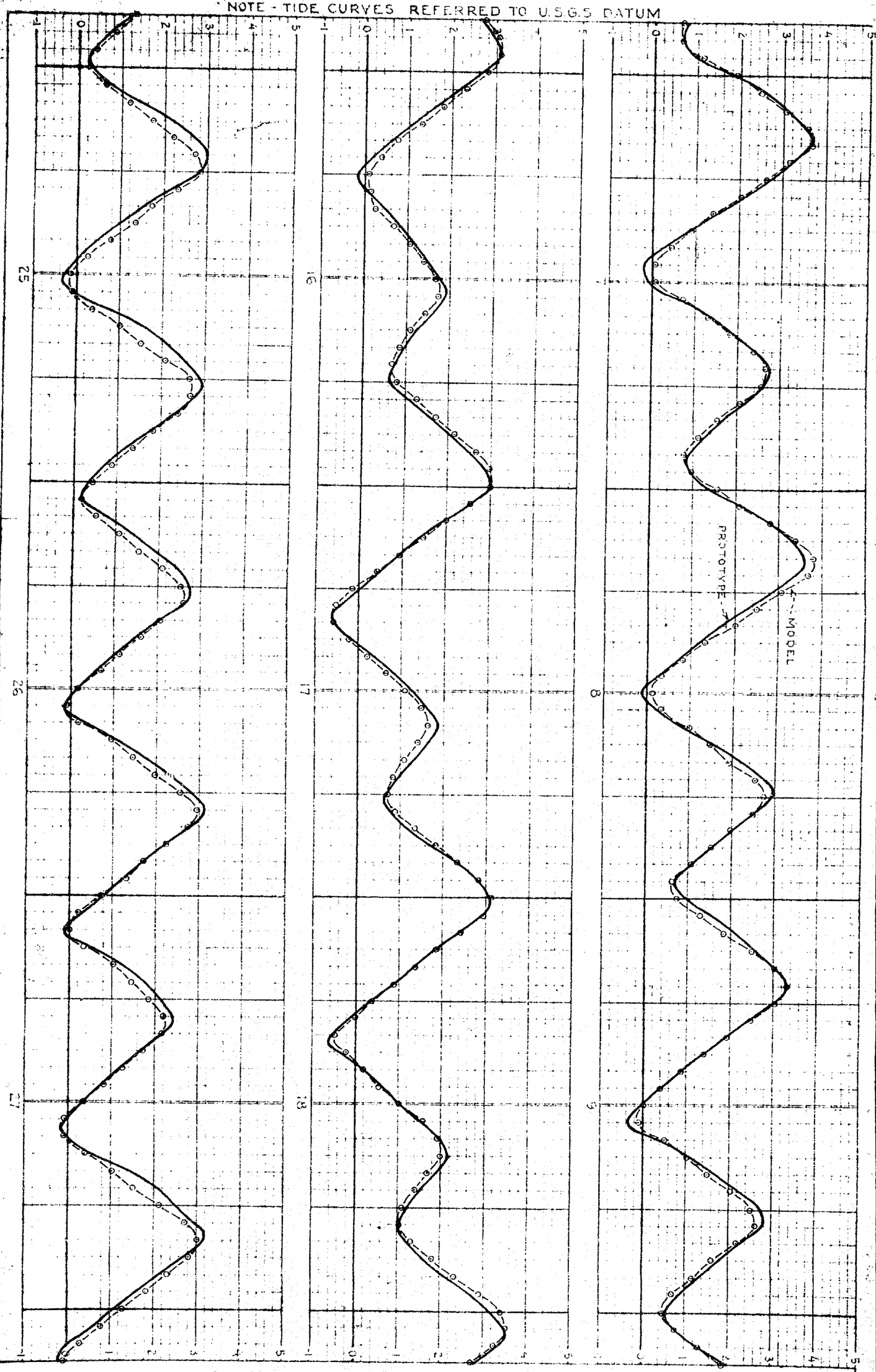
SAN JOAQUIN - SACRAMENTO DELTA
SALINITY CONTROL STUDIES - 1:1500 MODEL

TIDE CURVES AT SACRAMENTO **FOR AUG. 1941**

TEST RECORDER DATE

FIGURE 9

NOTE - TIDE CURVES REFERRED TO U.S.G.S. DATUM



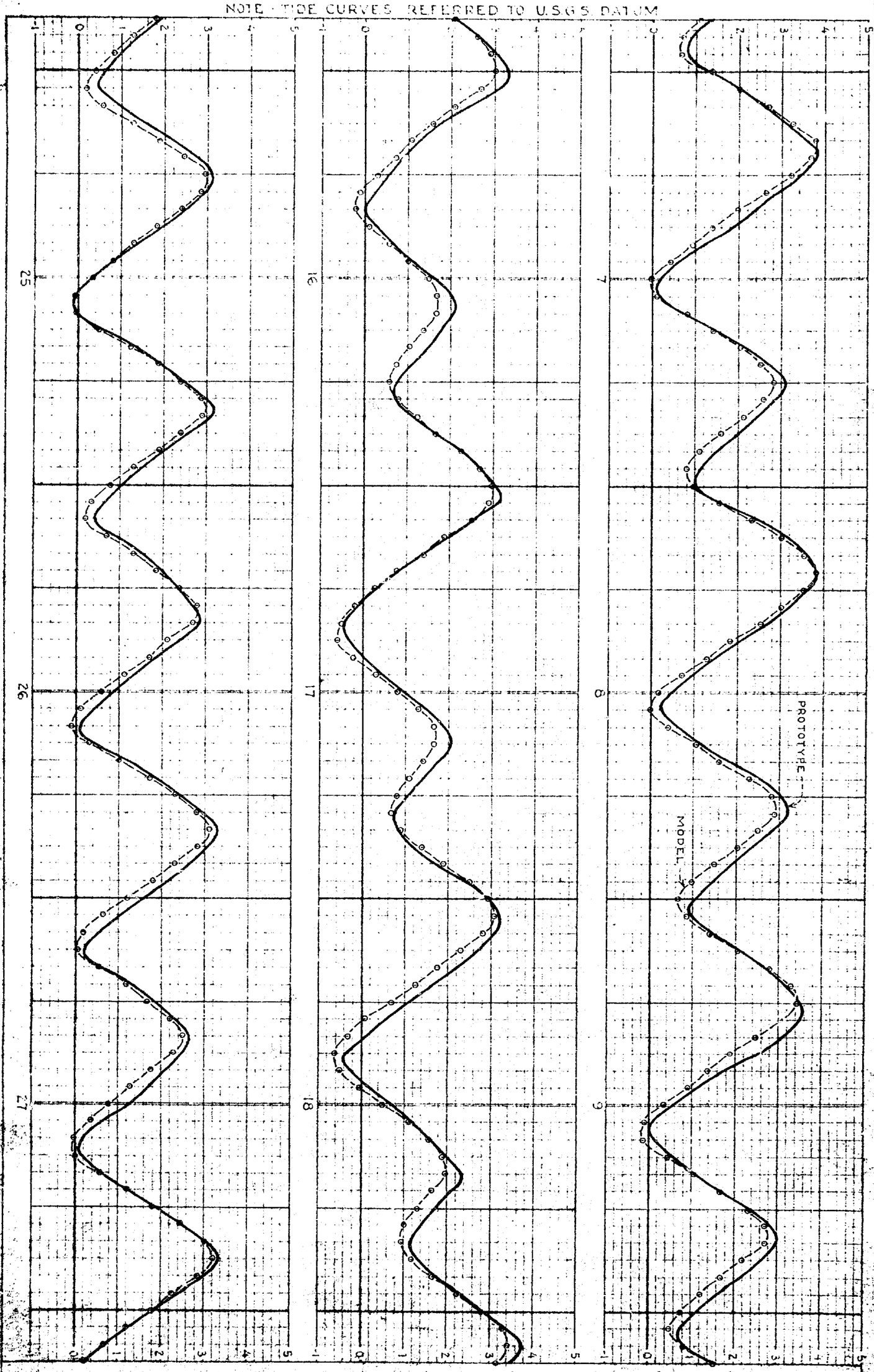
SAN JOAQUIN - SACRAMENTO DELTA
SALINITY CONTROL STUDIES - 1:4200 MODEL

TIDE CURVES AT THREE MILE SLOUGH (S.J.) FOR AUG. 1941

TEST ..... RECORDER ..... DATE .....

FIGURE 10

NOTE - TIDE CURVES REFERRED TO U.S.G.S. DATUM



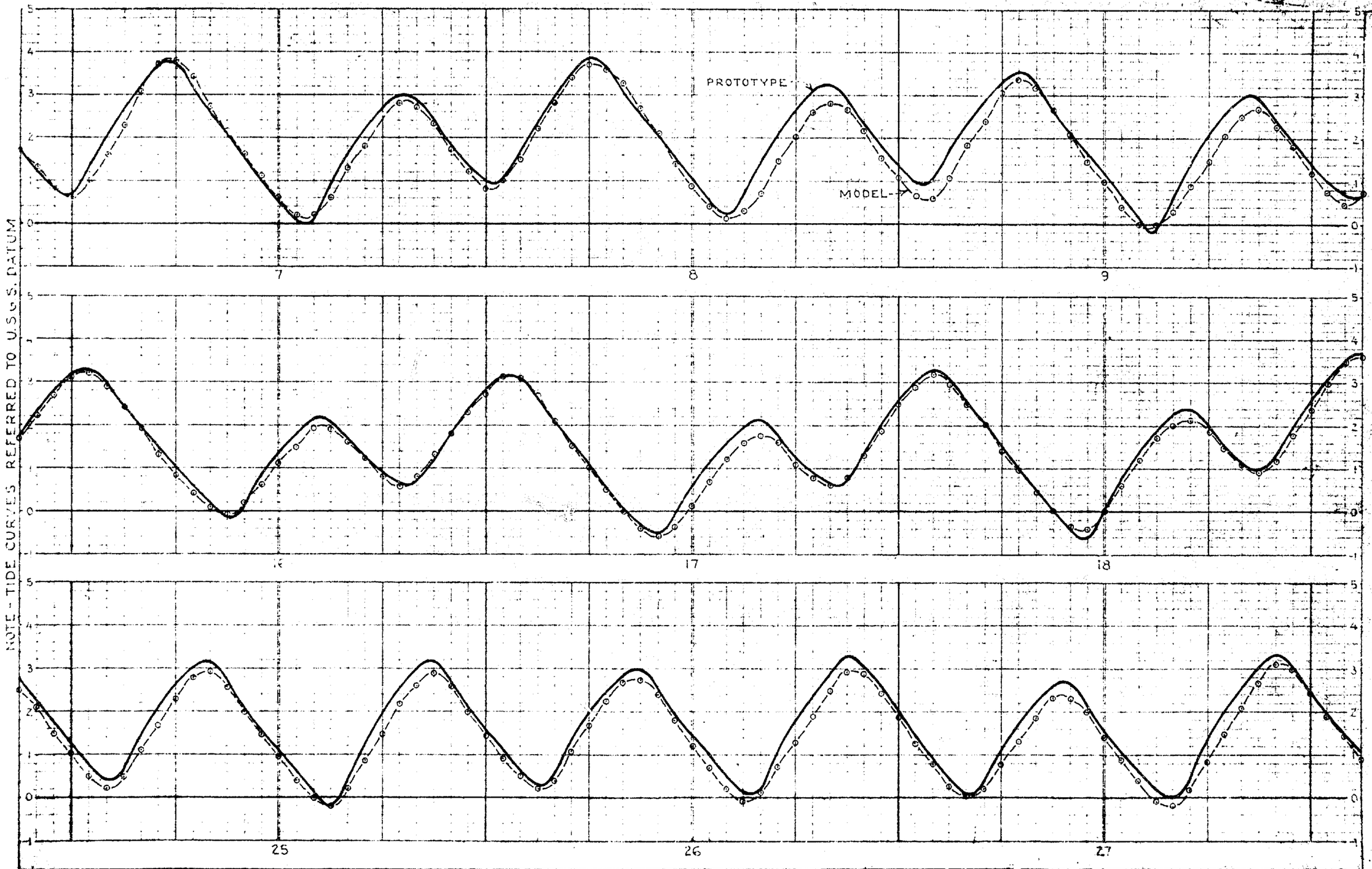
SAN JOAQUIN - SACRAMENTO DELTA
SALINITY CONTROL STUDIES - 1:4800 MODEL

TIDE CURVES AT GEORGIANA SLOUGH FOR AUG. 1941

TEST RECORDER DATE

FIGURE

FIGURE 12

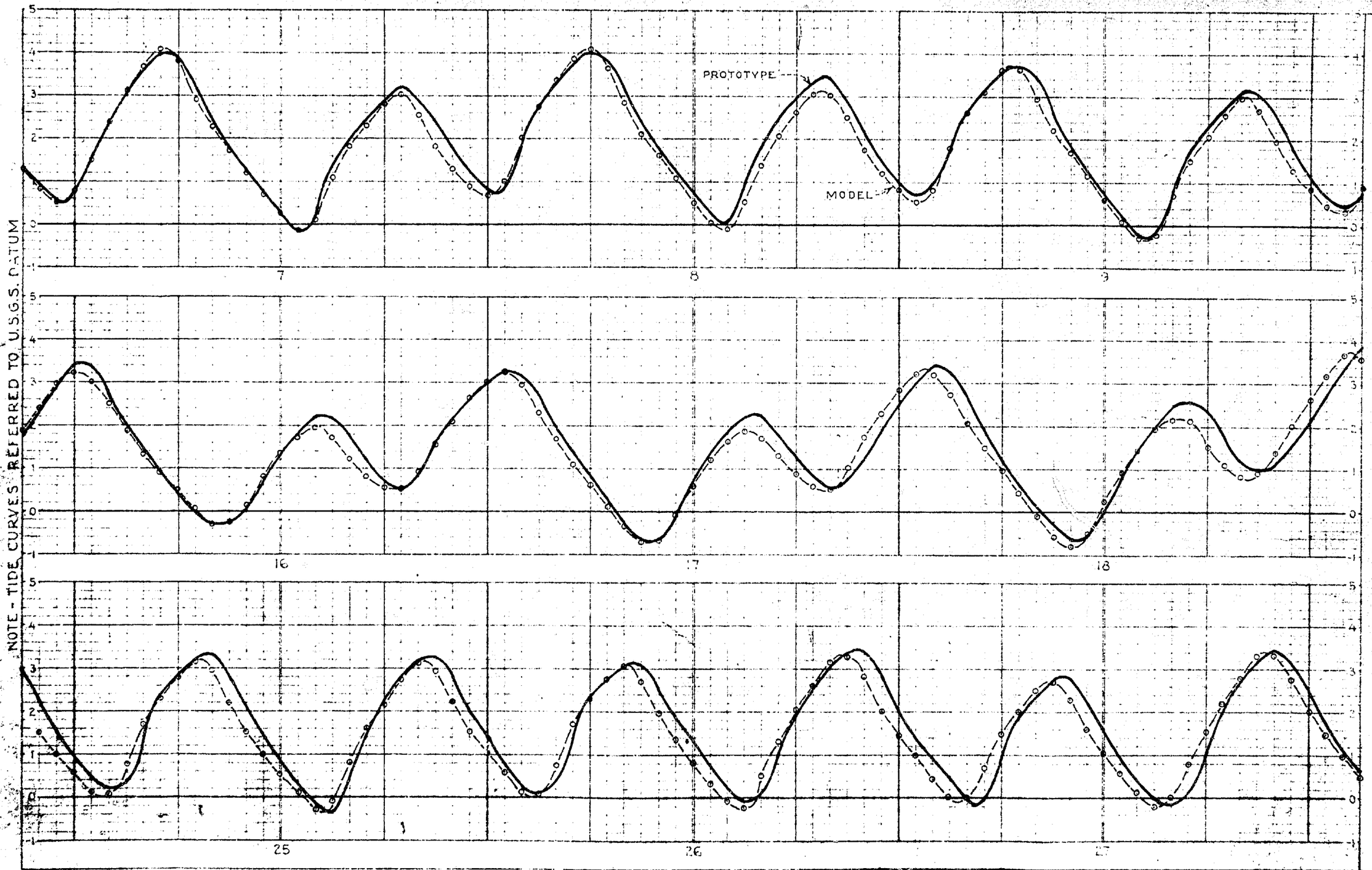


SAN JOAQUIN - SACRAMENTO DELTA
SALINITY CONTROL STUDIES - 1:4800 MODEL

TIDE CURVES AT NEW HOPE BRIDGE FOR AUG. 1941

TEST _____ RECORDED _____ DATE _____

FIGURE 13

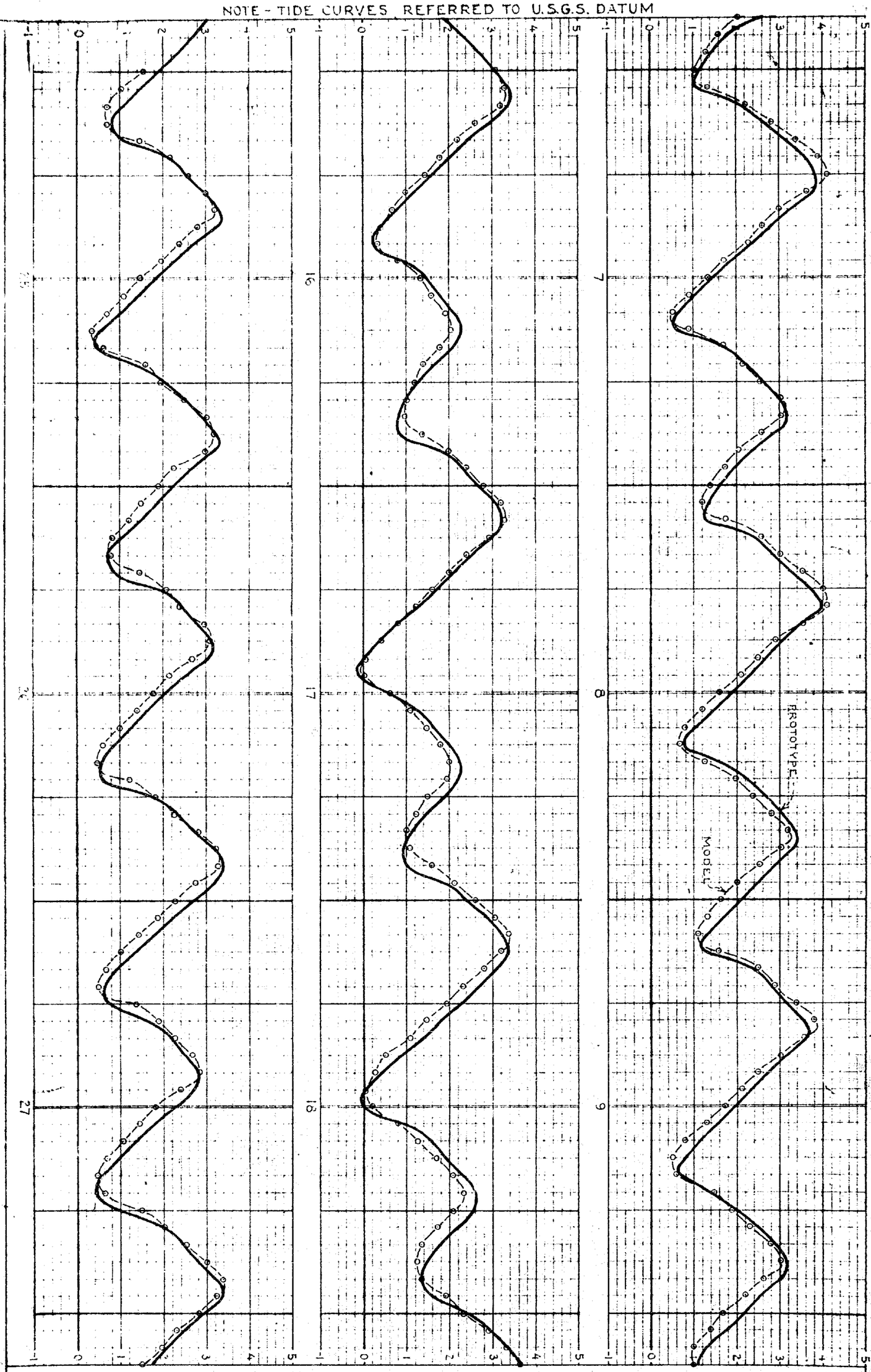


SAN JOAQUIN - SACRAMENTO DELTA
SALINITY CONTROL STUDIES 1:1 MODEL

TIDE CURVES AT BURNS CUTOFF FOR AUG. 1941

TEST RECORDER DATE

NOTE - TIDE CURVES REFERRED TO U.S.G.S. DATUM



SAN JOAQUIN - SACRAMENTO DELTA

SALINITY CONTROL STUDIES - 1:4800 MODEL

TIDE CURVES AT BRANDTS BRIDGE FOR AUG. 1941

TEST..... RECORDER..... DATE.....

FIGURE 14

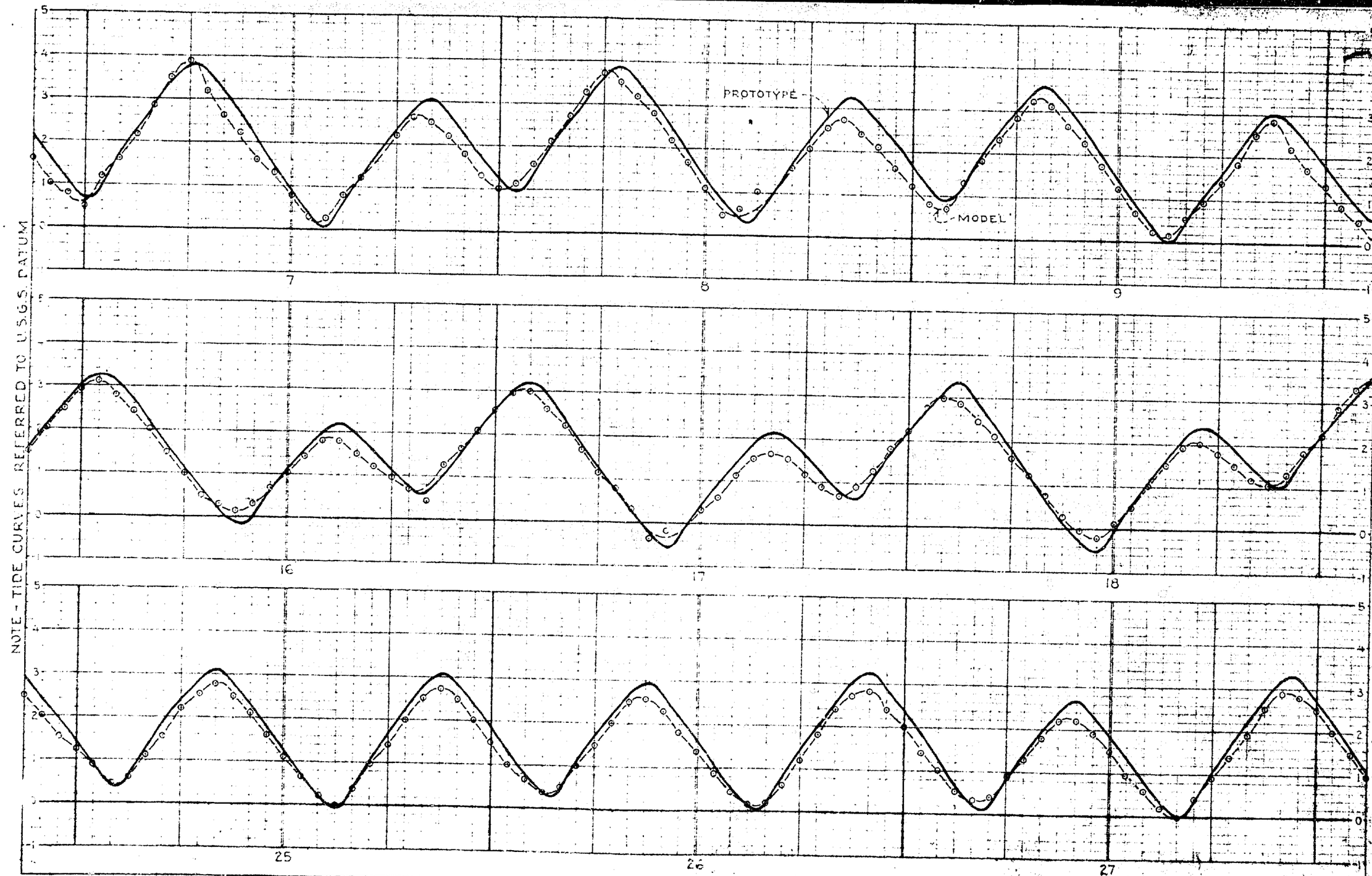
FIGURE 15

NOTE - TIDE CURVES REFERRED TO U.S.G.S. DATUM

SAN JOAQUIN - SACRAMENTO DELTA
SALINITY CONTROL STUDIES - 1:4800 MODEL

TIDE CURVES AT MOSSDALE BRIDGE FOR AUG. 1941

TEST _____ RECORDER _____ DATE _____



FIGURE

TIDE CURVES AT MIDDLE RIVER

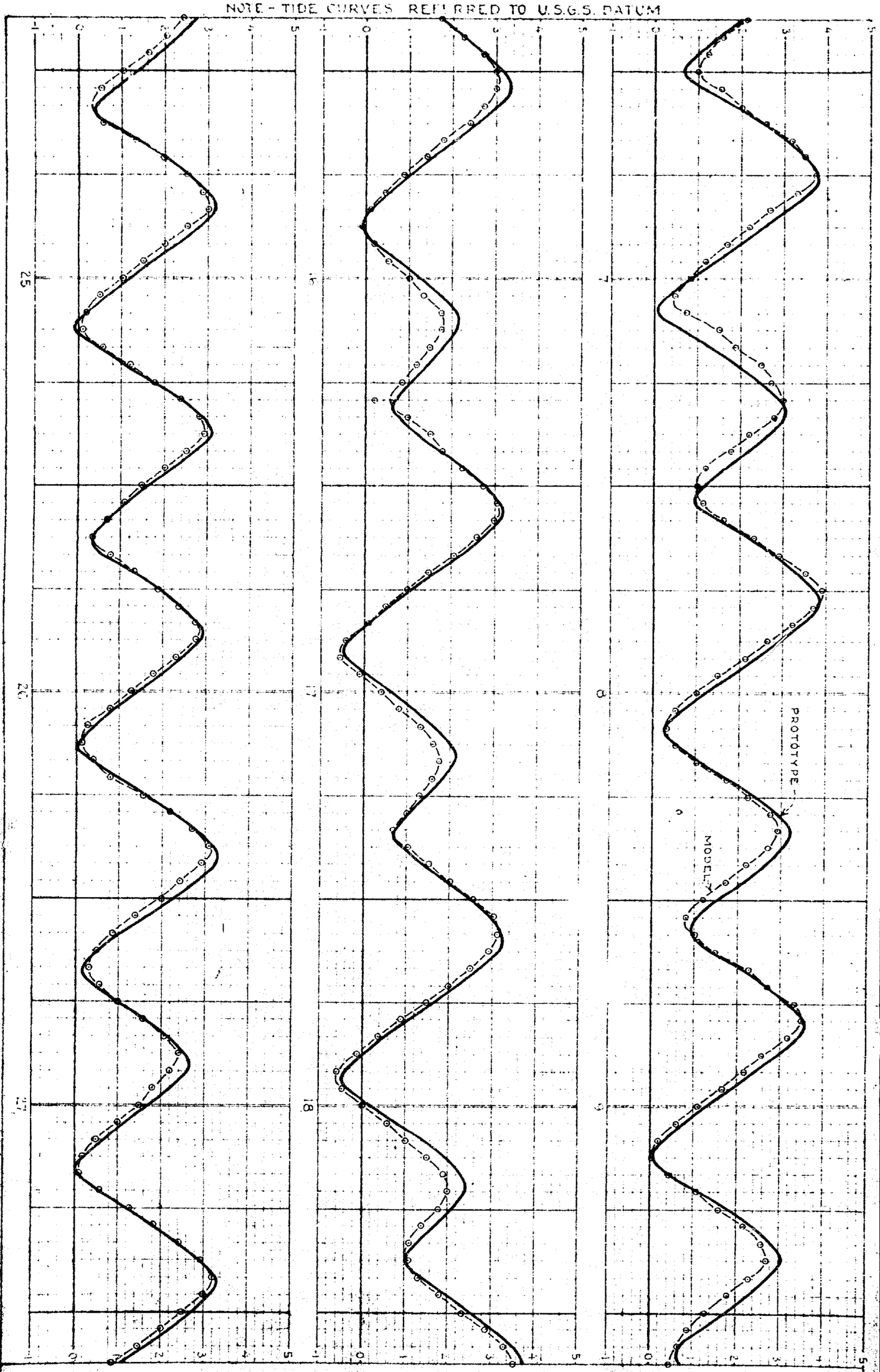
TEST 1 RECORDER

SAN JOAQUIN - SACRAMENTO DELTA
SALINITY CONTROL STUDIES 1:4800 MODEL

FOR AUG 19

DATE

NOTE - TIDE CURVES REFERRED TO U.S.G.S. DATUM



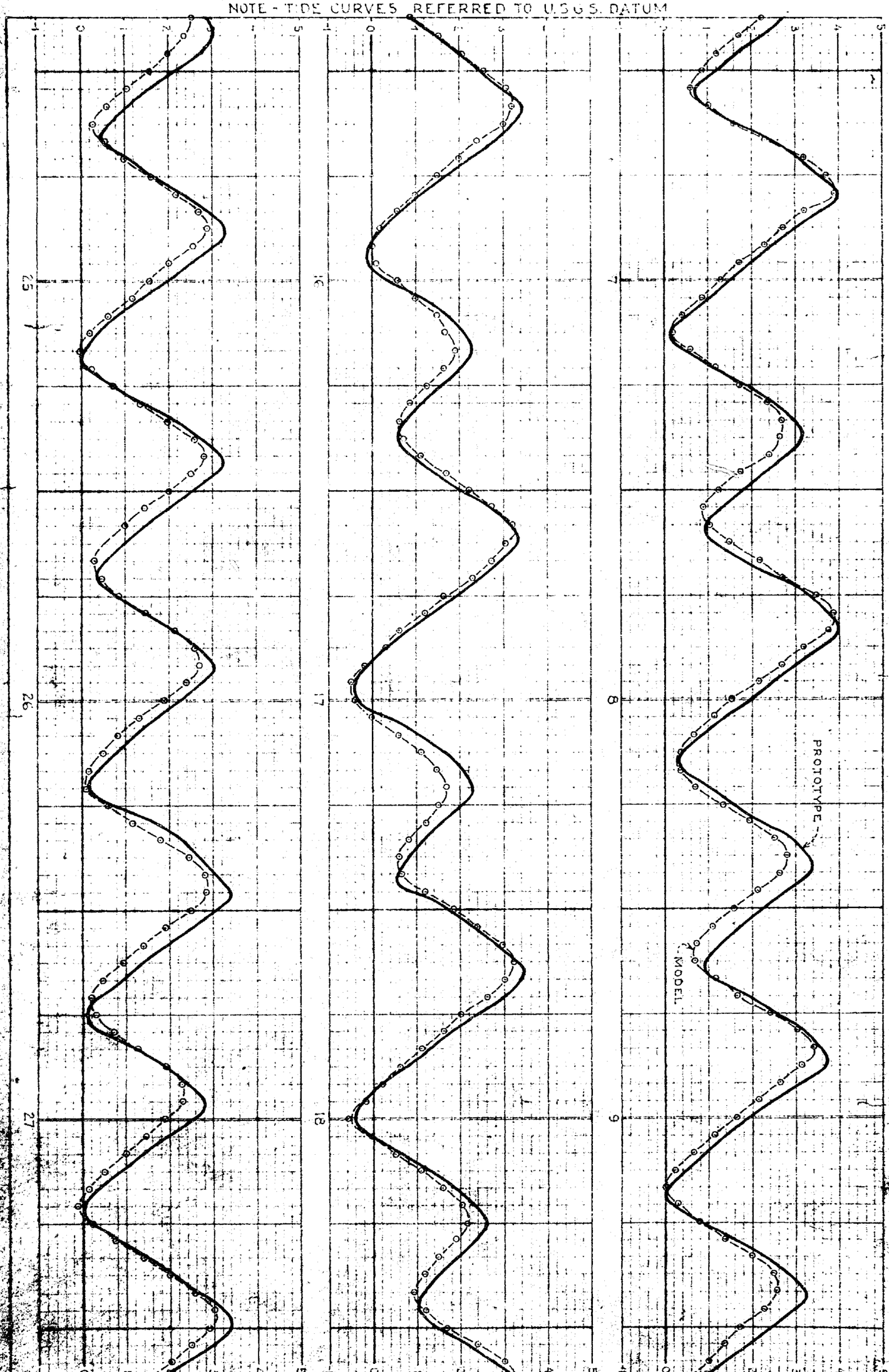
SAN JOAQUIN - SACRAMENTO DELTA
SALINITY CONTROL STUDIES - 1:4800 MODEL

TIDE CURVES AT OLD RIVER (MANSION HOUSE) FOR AUG. 1941

TEST ..... RECORDER ..... DATE .....

FIGURE 17

NOTE - TIDE CURVES REFERRED TO U.S.G.S. DATUM



SAN JOAQUIN - SACRAMENTO DELTA

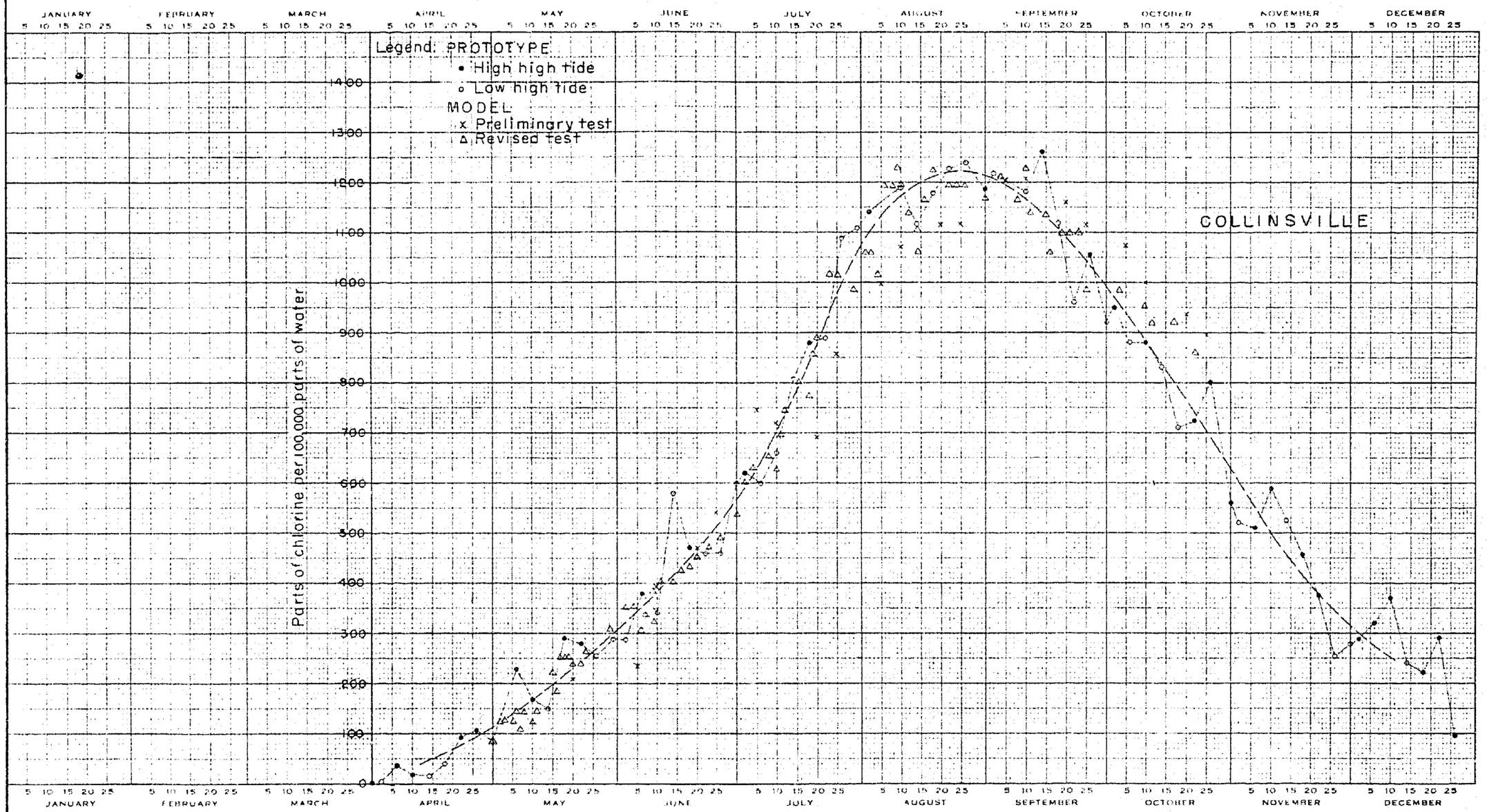
SALINITY CONTROL STUDIES - 1:4800 MODEL

TIDE CURVES AT GRANT LINE CANAL FOR AUG. 1941

TEST _____ RECORDER _____ DATE _____

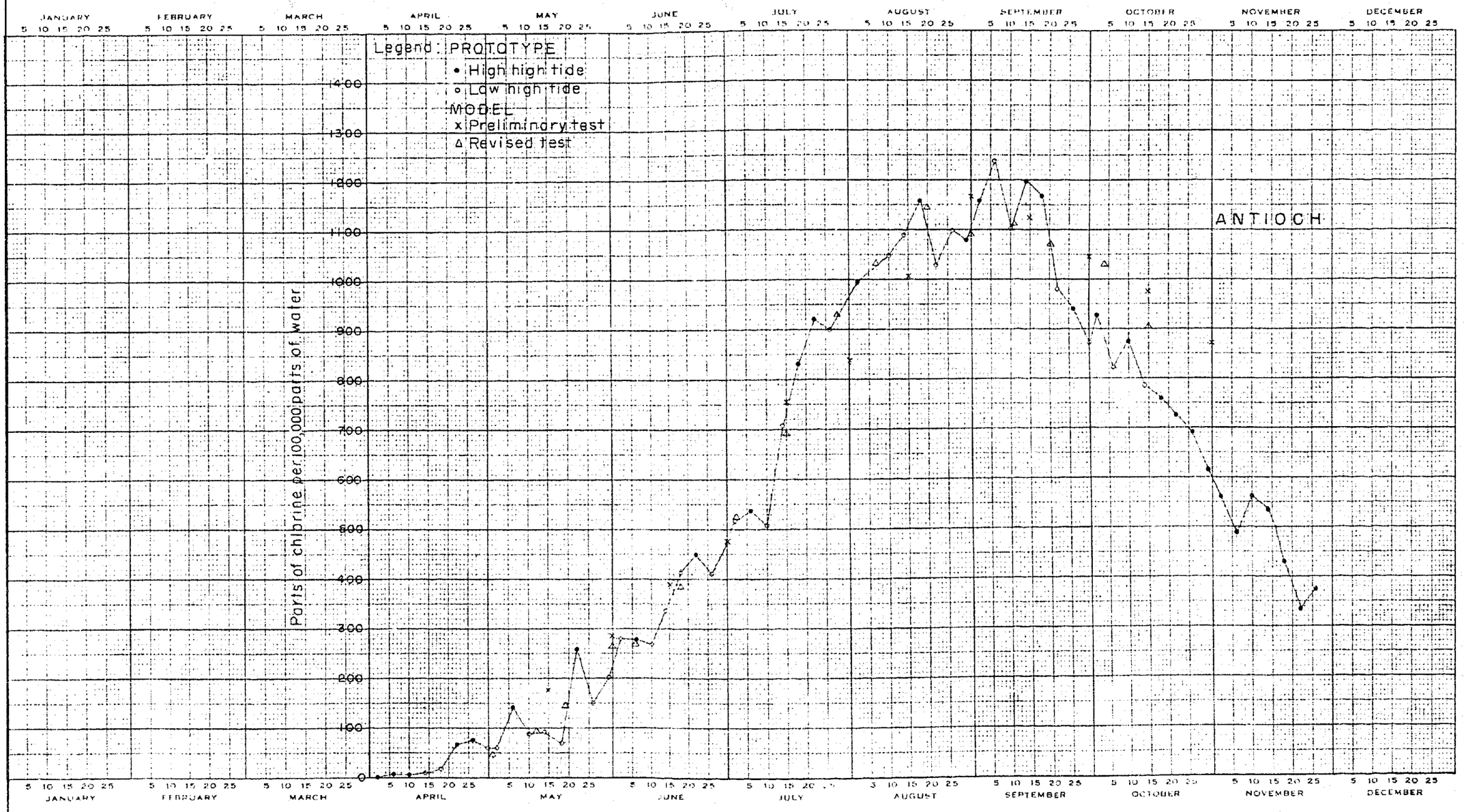
FIGURE

FIGURE 19



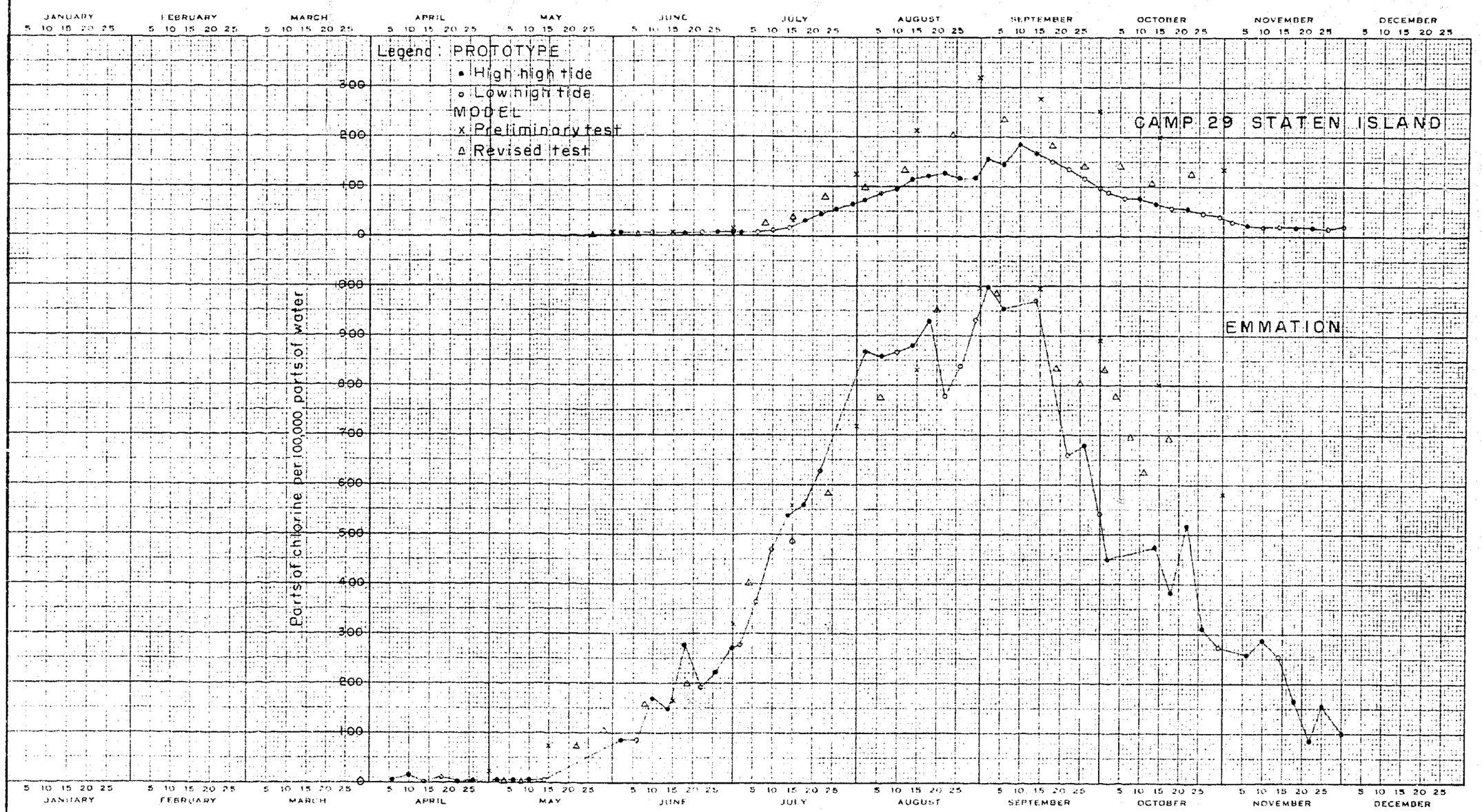
SACRAMENTO - SAN JOAQUIN DELTA
SALINITY CONTROL STUDIES 1:4800 MODEL
SEASON OF 1931

FIGURE 20



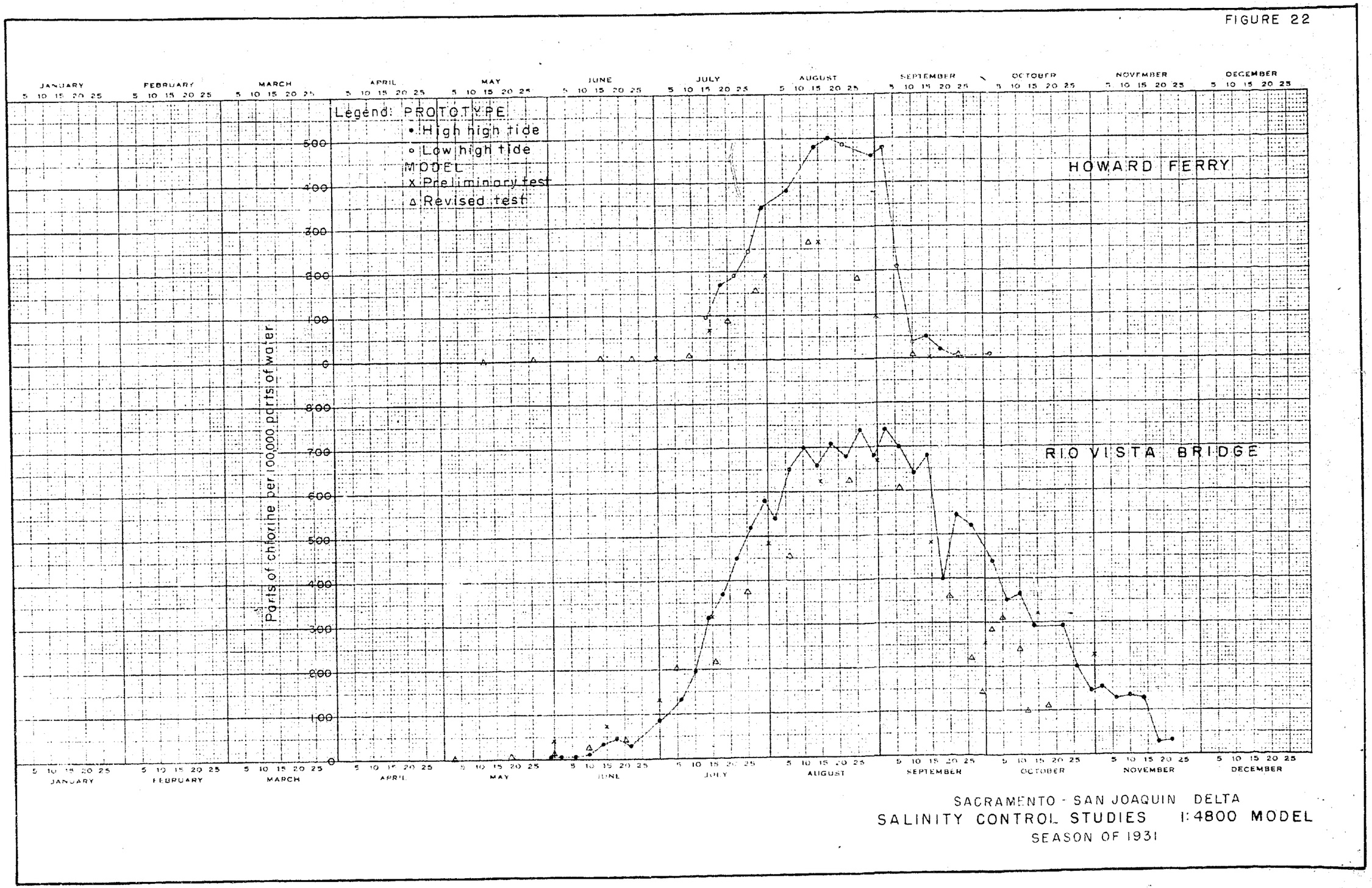
SACRAMENTO - SAN JOAQUIN DELTA
SALINITY CONTROL STUDIES 1:4800 MODEL
SEASON OF 1931

FIGURE 21



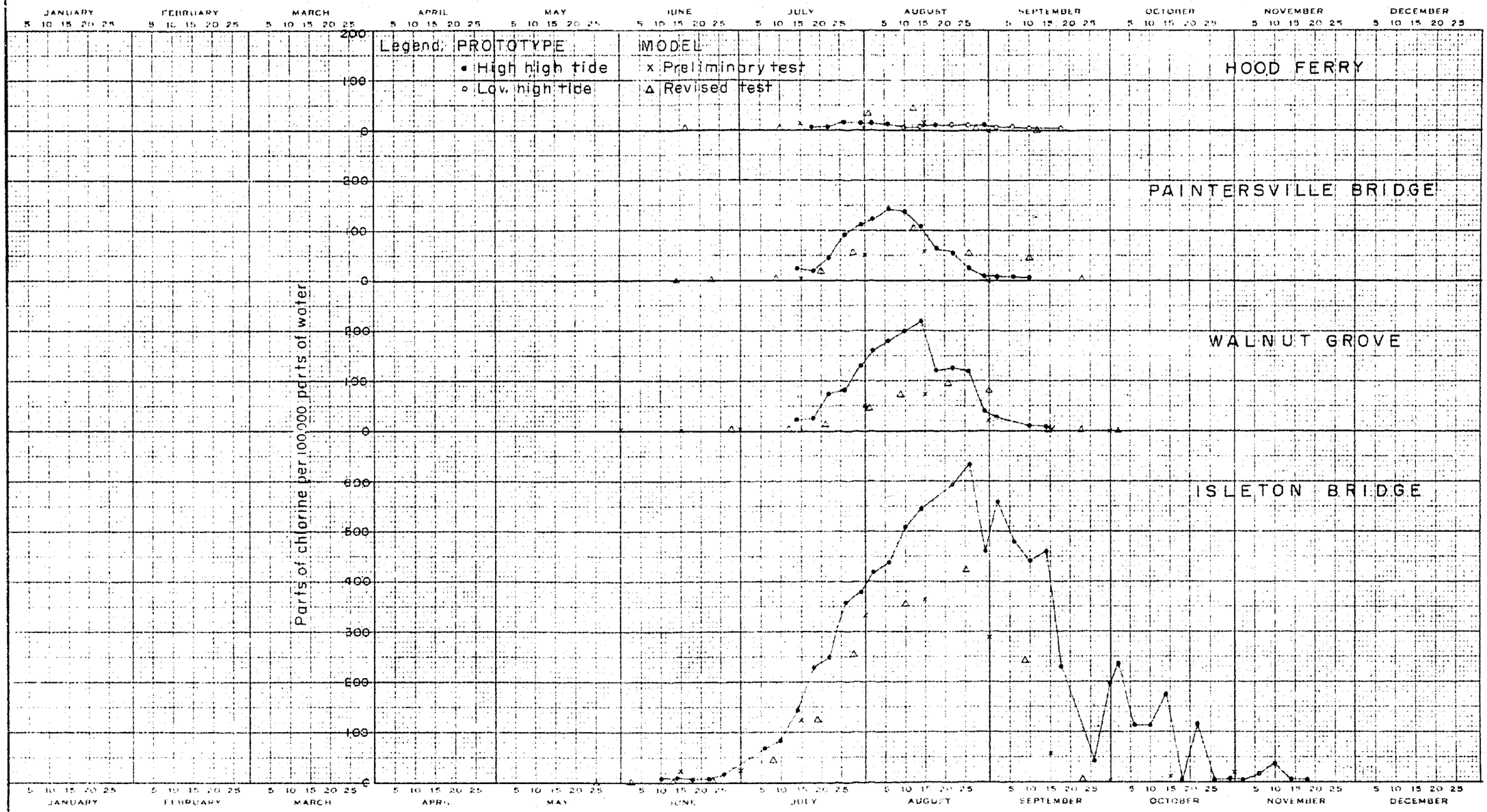
SACRAMENTO - SAN JOAQUIN DELTA
SALINITY CONTROL STUDIES 1:4800 MODEL
SEASON OF 1931

FIGURE 22



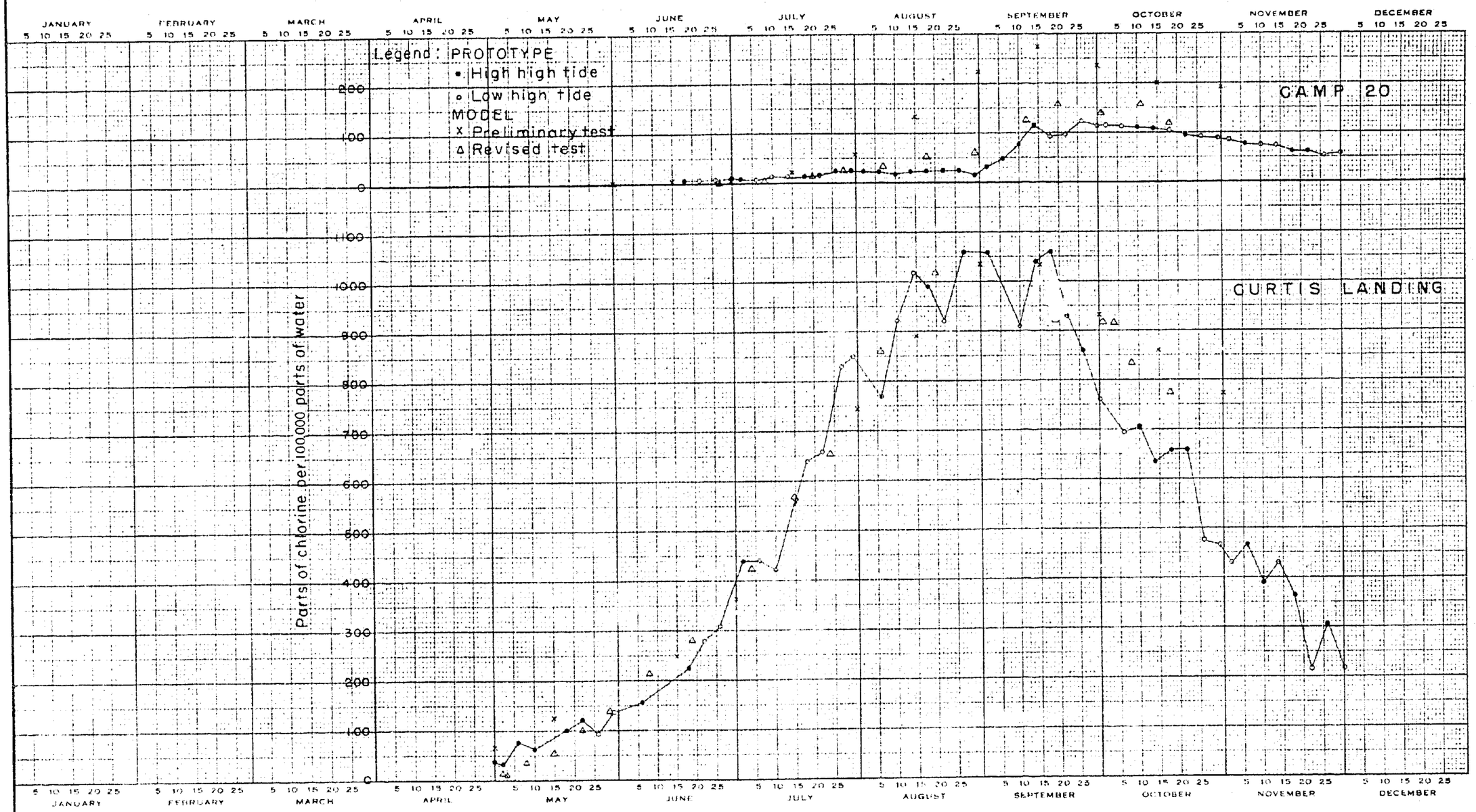
SACRAMENTO - SAN JOAQUIN DELTA
SALINITY CONTROL STUDIES 1:4800 MODEL
SEASON OF 1931

FIGURE 23



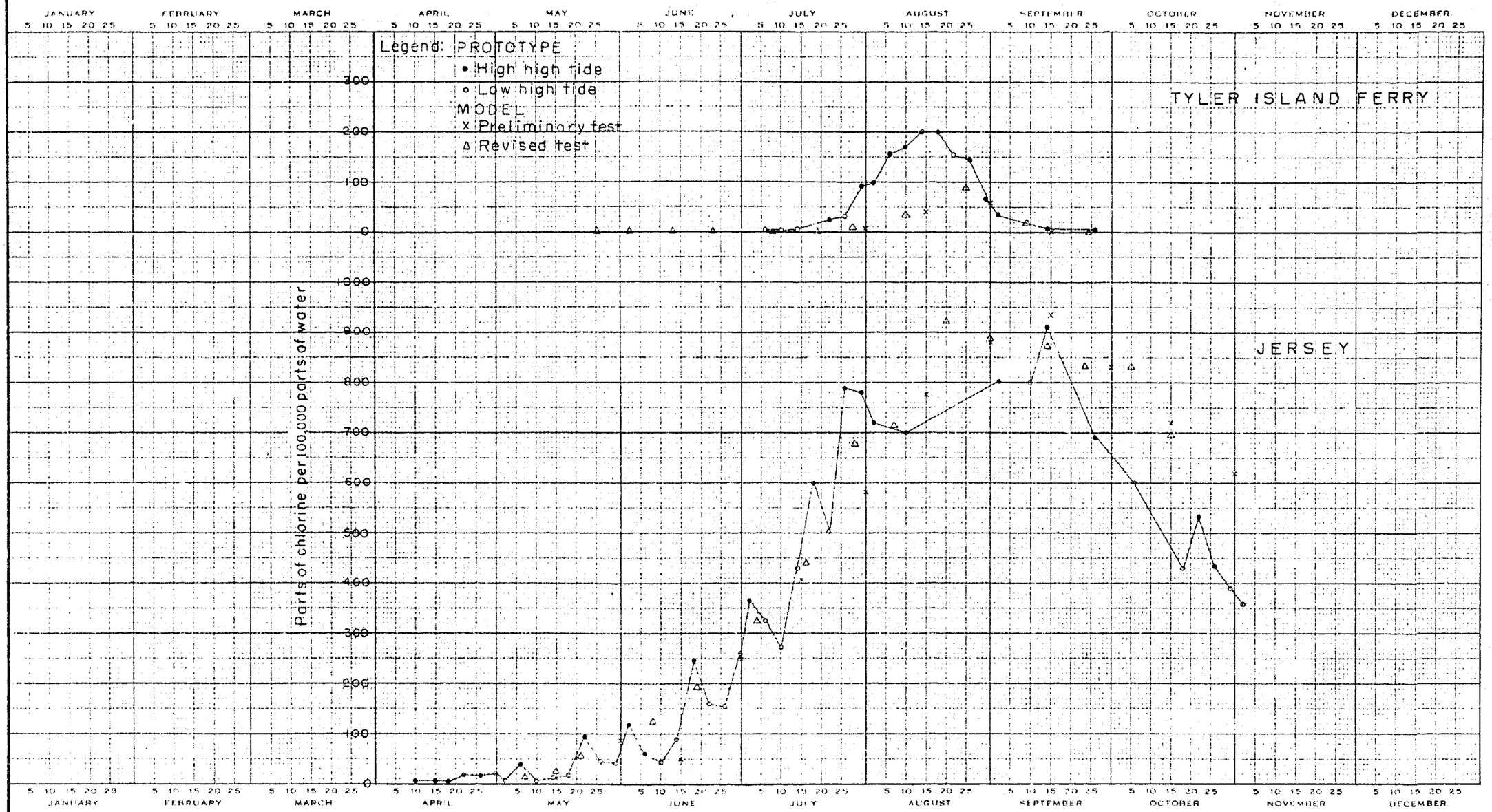
SACRAMENTO - SAN JOAQUIN DELTA
SALINITY CONTROL STUDIES 1:4800 MODEL
SEASON OF 1931

FIGURE 24



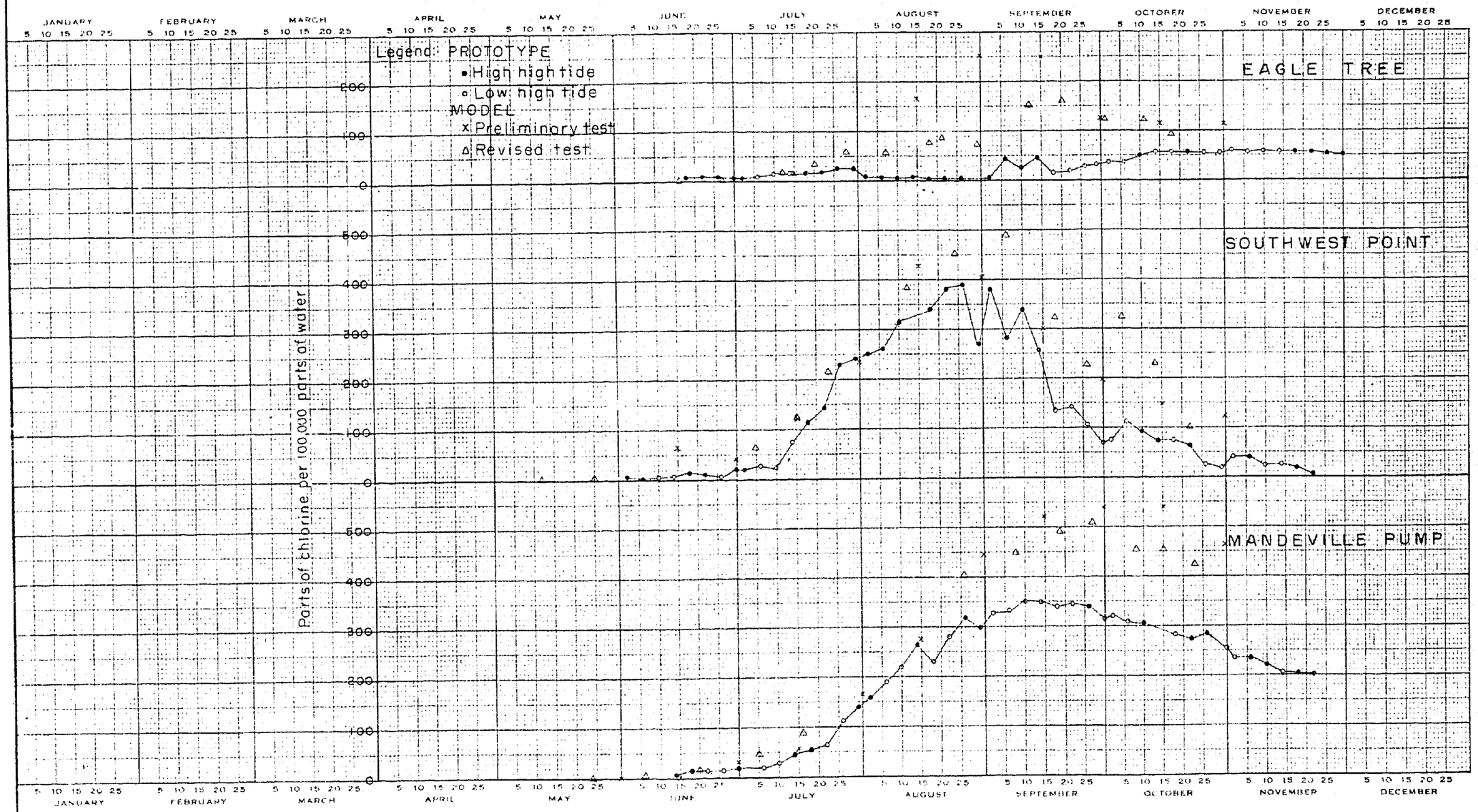
SACRAMENTO - SAN JOAQUIN DELTA
SALINITY CONTROL STUDIES 1:4800 MODEL
SEASON OF 1931

FIGURE 25



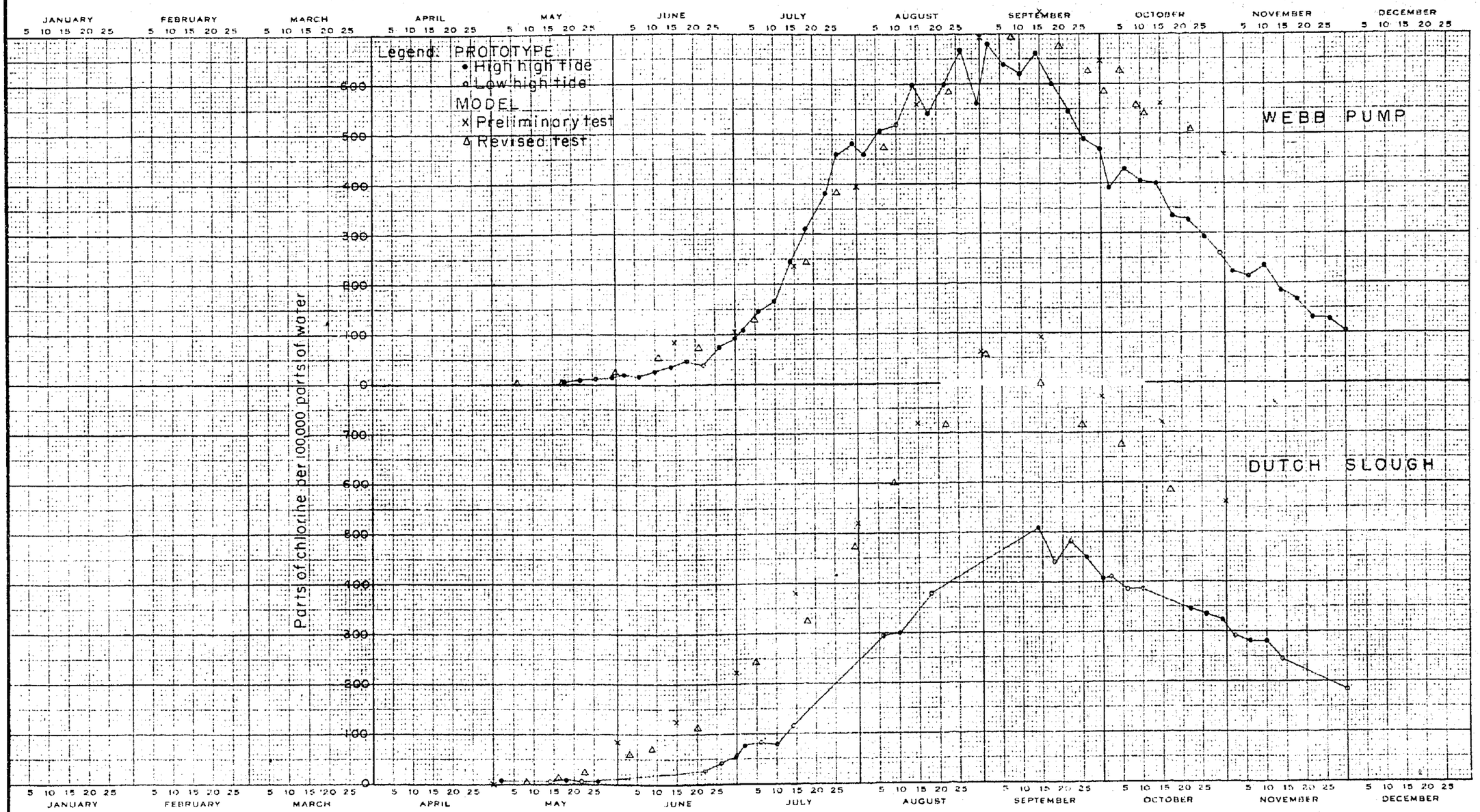
SACRAMENTO - SAN JOAQUIN DELTA
SALINITY CONTROL STUDIES 1:4800 MODEL
SEASON OF 1931

FIGURE 26



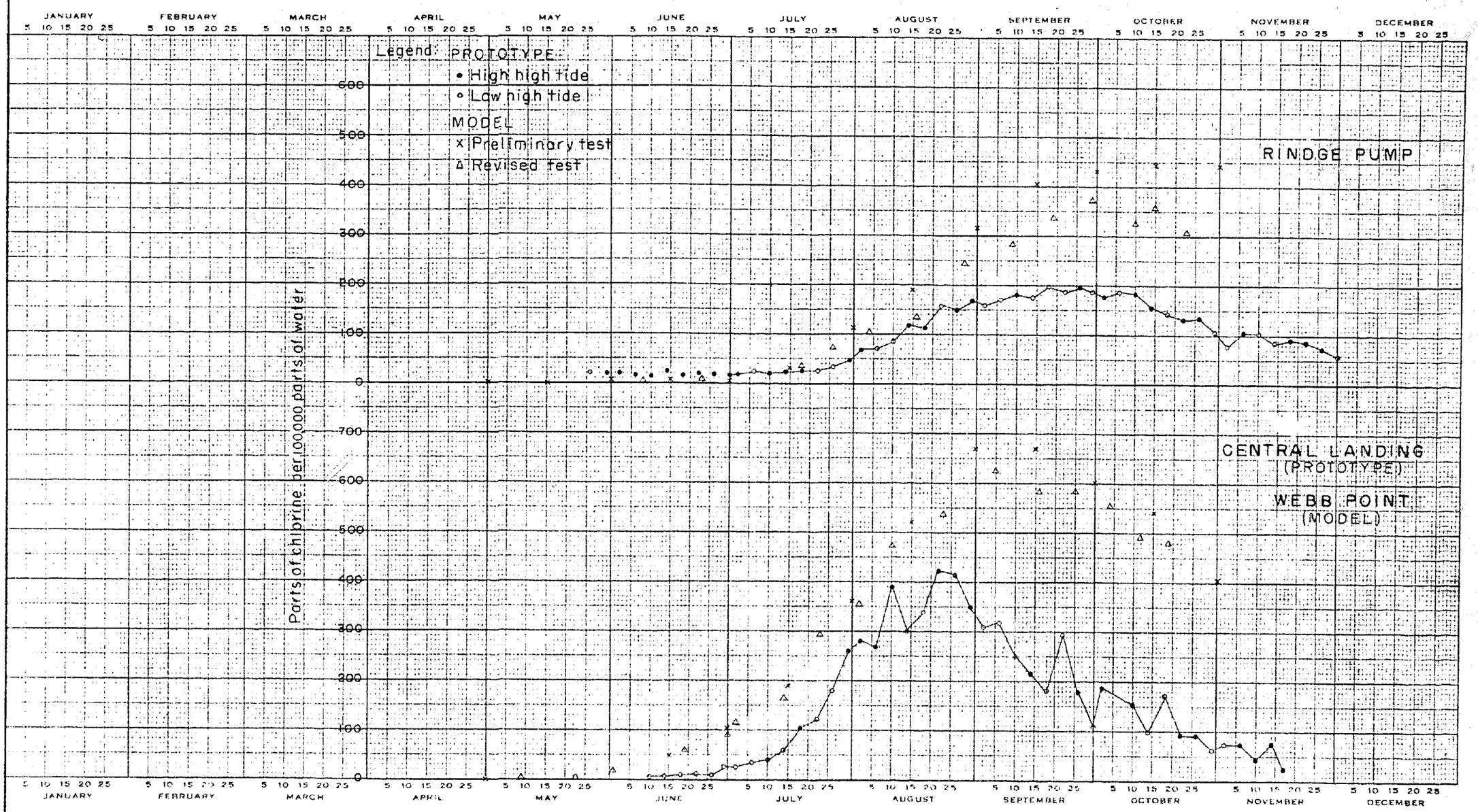
SACRAMENTO - SAN JOAQUIN DELTA
SALINITY CONTROL STUDIES 1:4800 MODEL
SEASON OF 1931

FIGURE 27



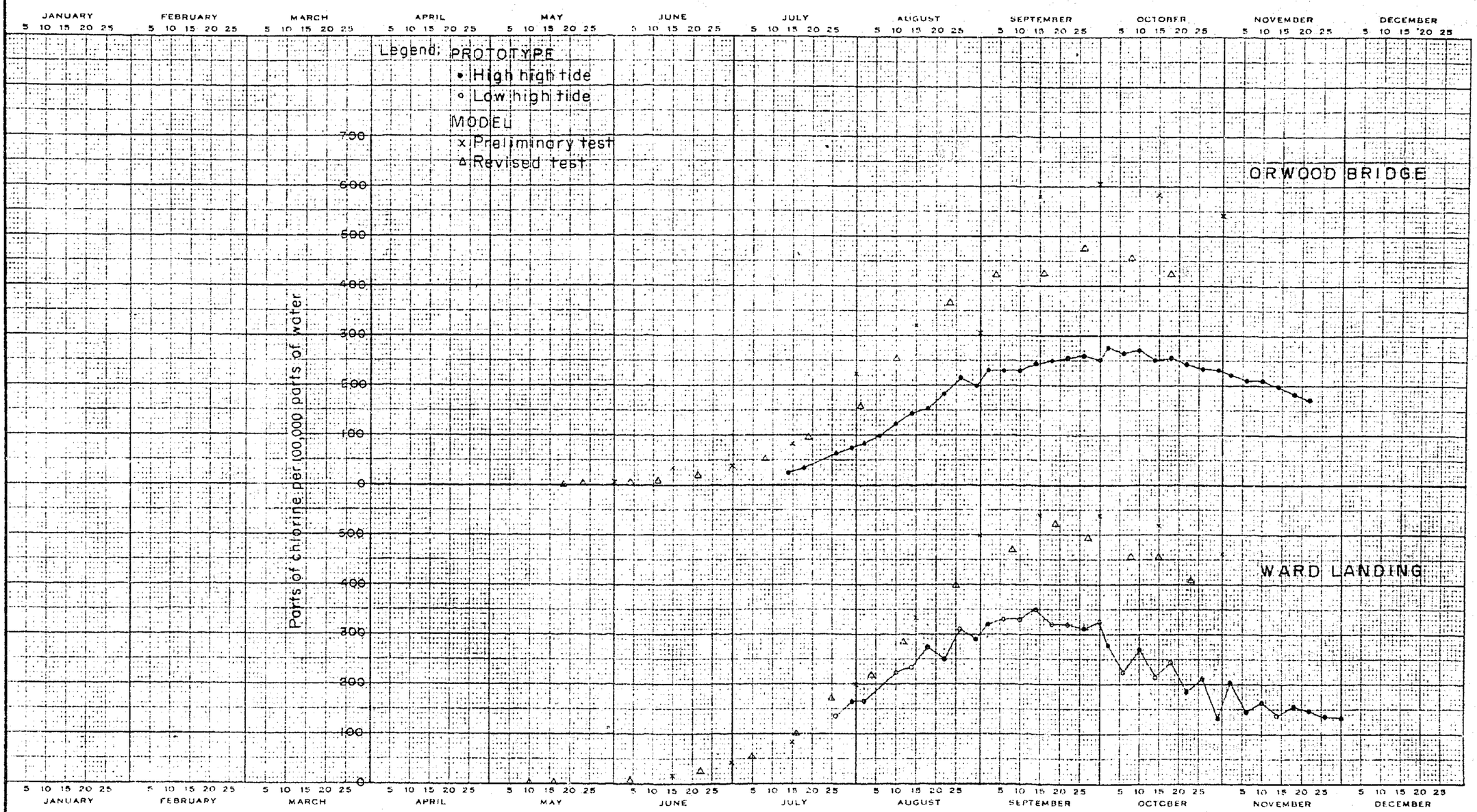
SACRAMENTO - SAN JOAQUIN DELTA
SALINITY CONTROL STUDIES 1:4800 MODEL
SEASON OF 1931

FIGURE 28



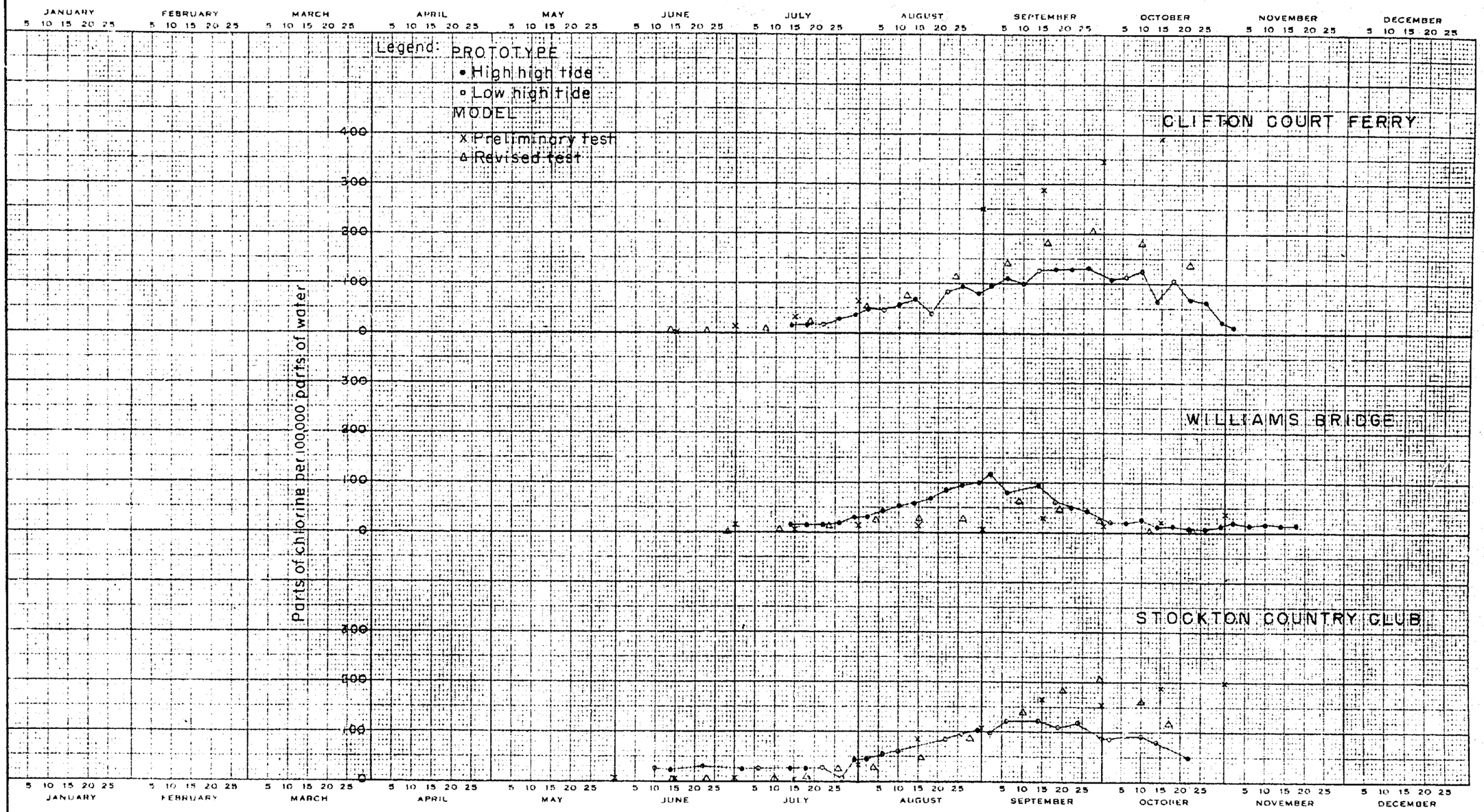
SACRAMENTO - SAN JOAQUIN DELTA
SALINITY CONTROL STUDIES 1:4800 MODEL
SEASON OF 1931

FIGURE 29



SACRAMENTO - SAN JOAQUIN DELTA
SALINITY CONTROL STUDIES 1:4800 MODEL
SEASON OF 1931

FIGURE 30



SACRAMENTO - SAN JOAQUIN DELTA
SALINITY CONTROL STUDIES 1:4800 MODEL
SEASON OF 1931

FIGURE 31

1931 HISTORICAL TEST
JUNE 1

LINES OF EQUAL CONCENTRATION

Prototype - Water Supervisor's Report, 1931; Plate 7

Model - Preliminary test

Model - Revised test

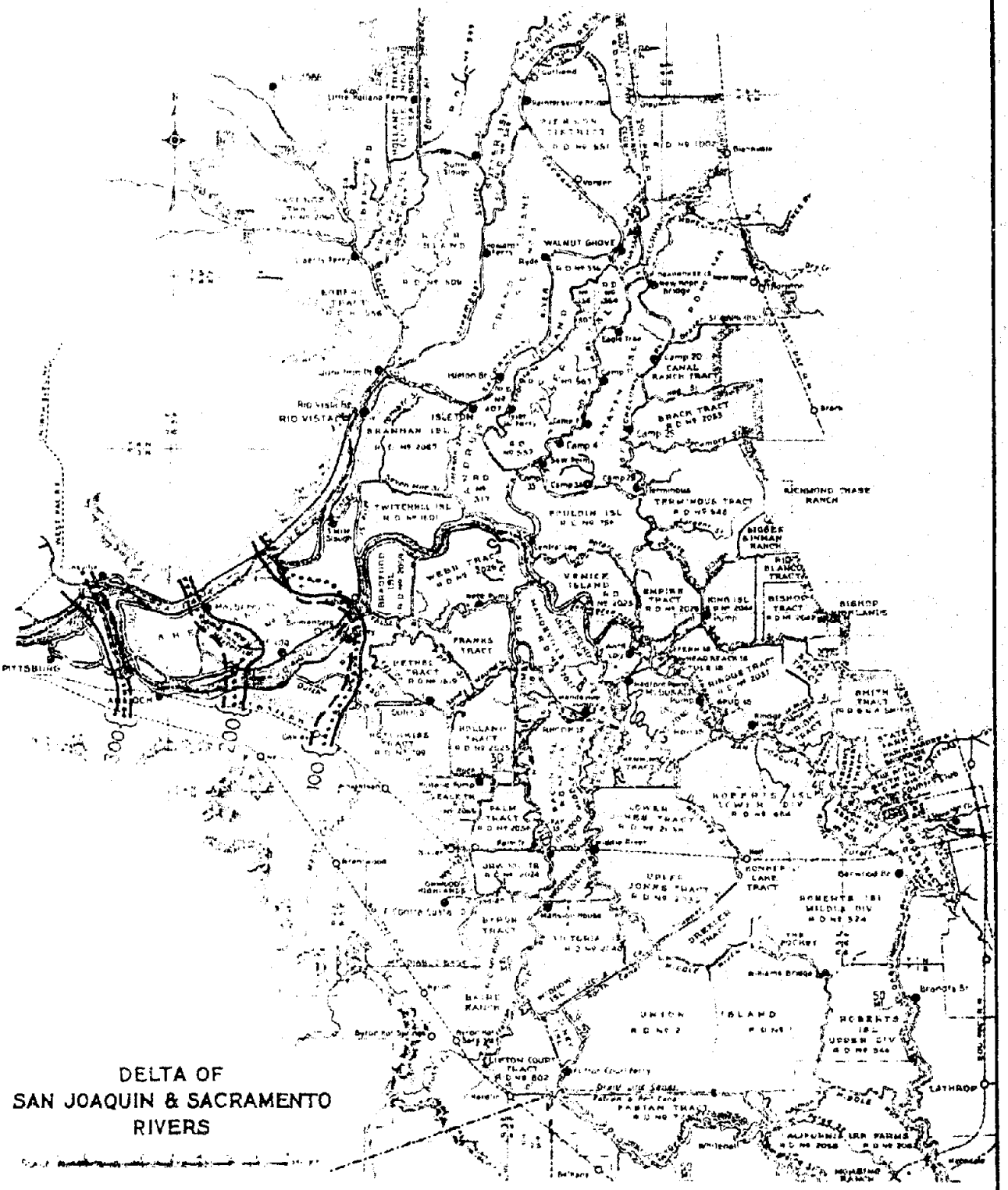


FIGURE 32

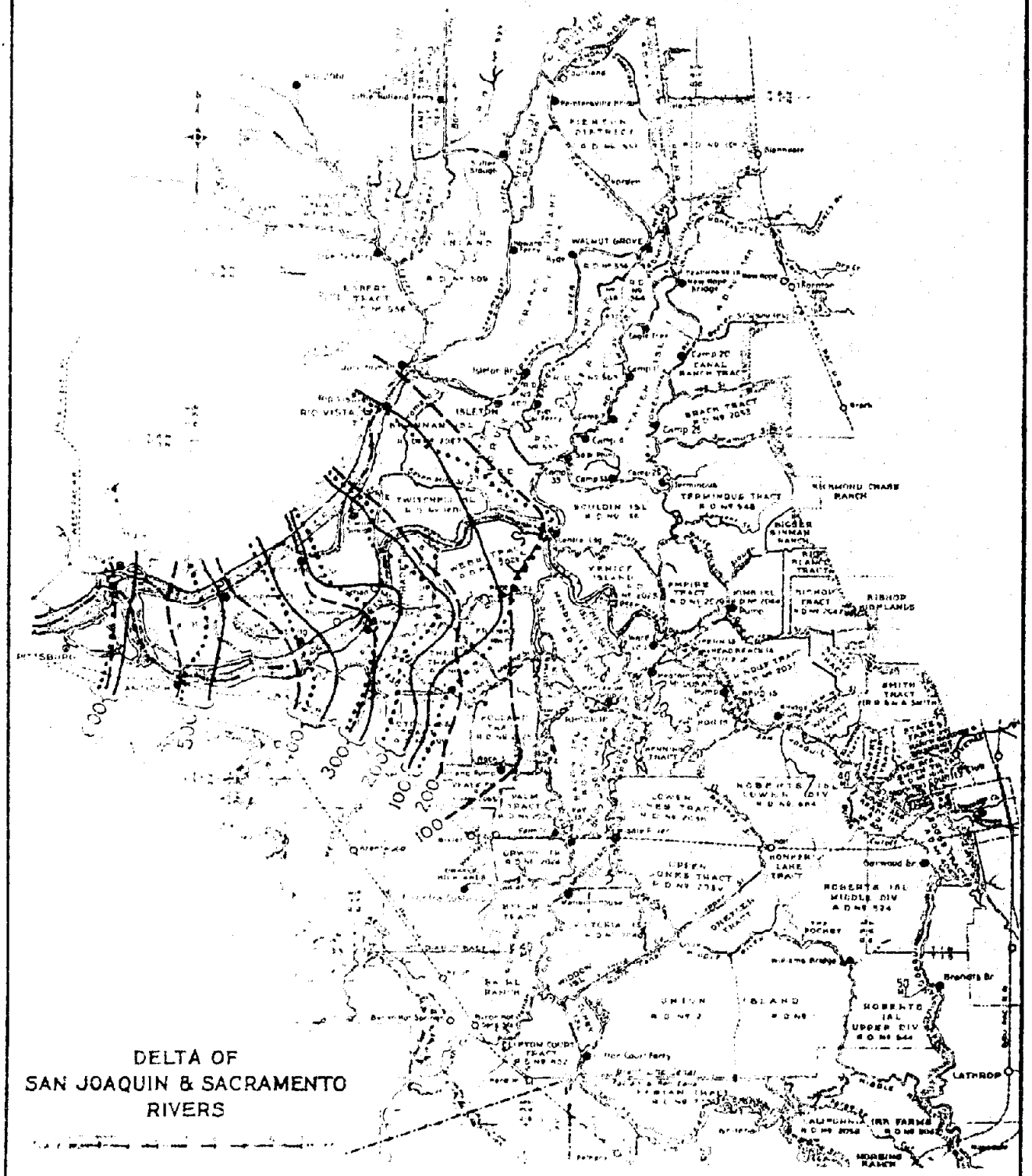
1931 HISTORICAL TEST
JULY 1

LINES OF EQUAL CONCENTRATION

Prototype - Water Supervisor's Report, 1931; Plate 7

Model - Preliminary test

Model - Revised test



DELTA OF
SAN JOAQUIN & SACRAMENTO
RIVERS

FIGURE 33

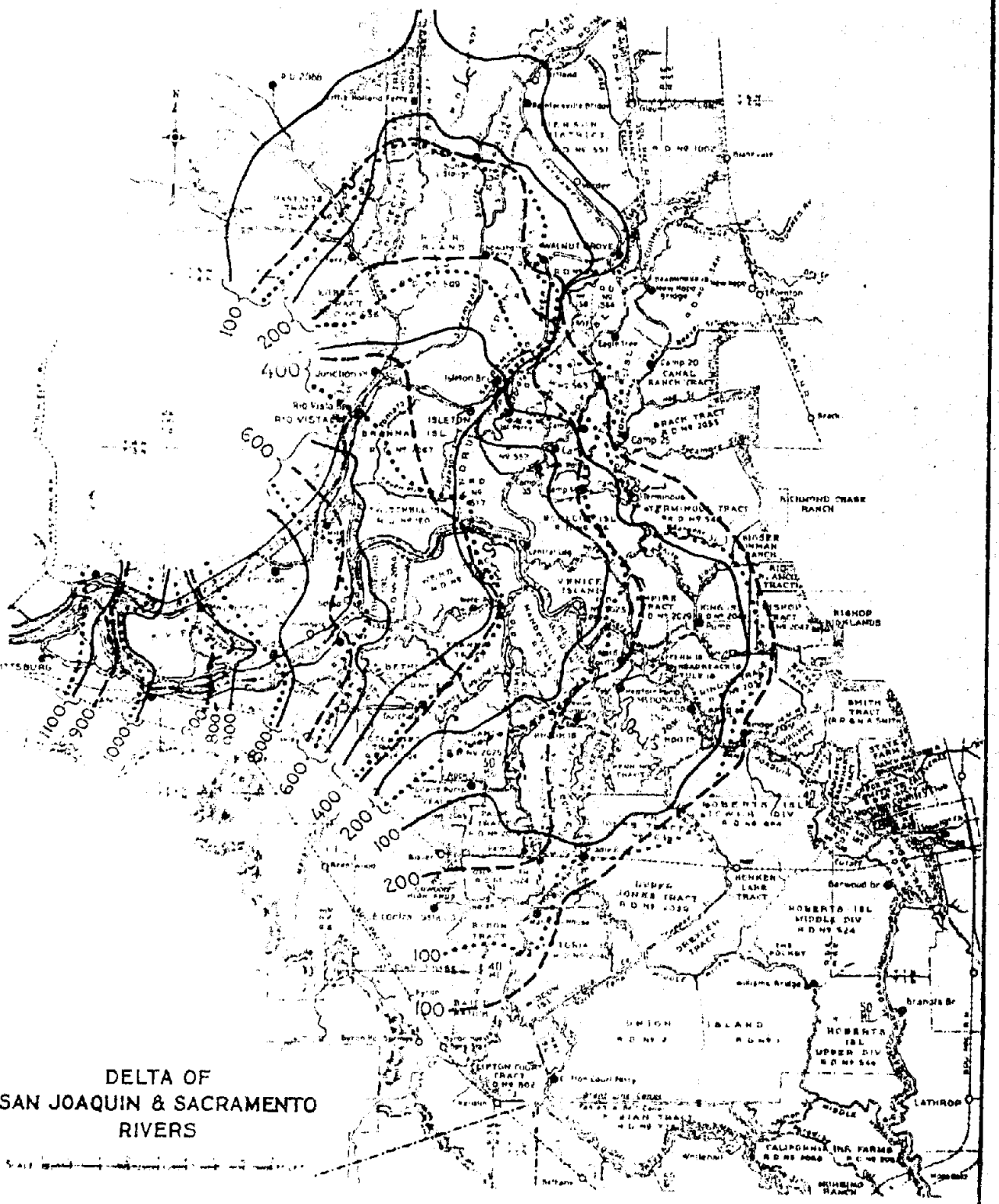
1931 HISTORICAL TEST
AUGUST 1

LINES OF EQUAL CONCENTRATION

Prototype - Water Supervisor's Report, 1931; Plate 7

Model - Preliminary test

Model - Revised test



DELTA OF
SAN JOAQUIN & SACRAMENTO
RIVERS

FIGURE 34

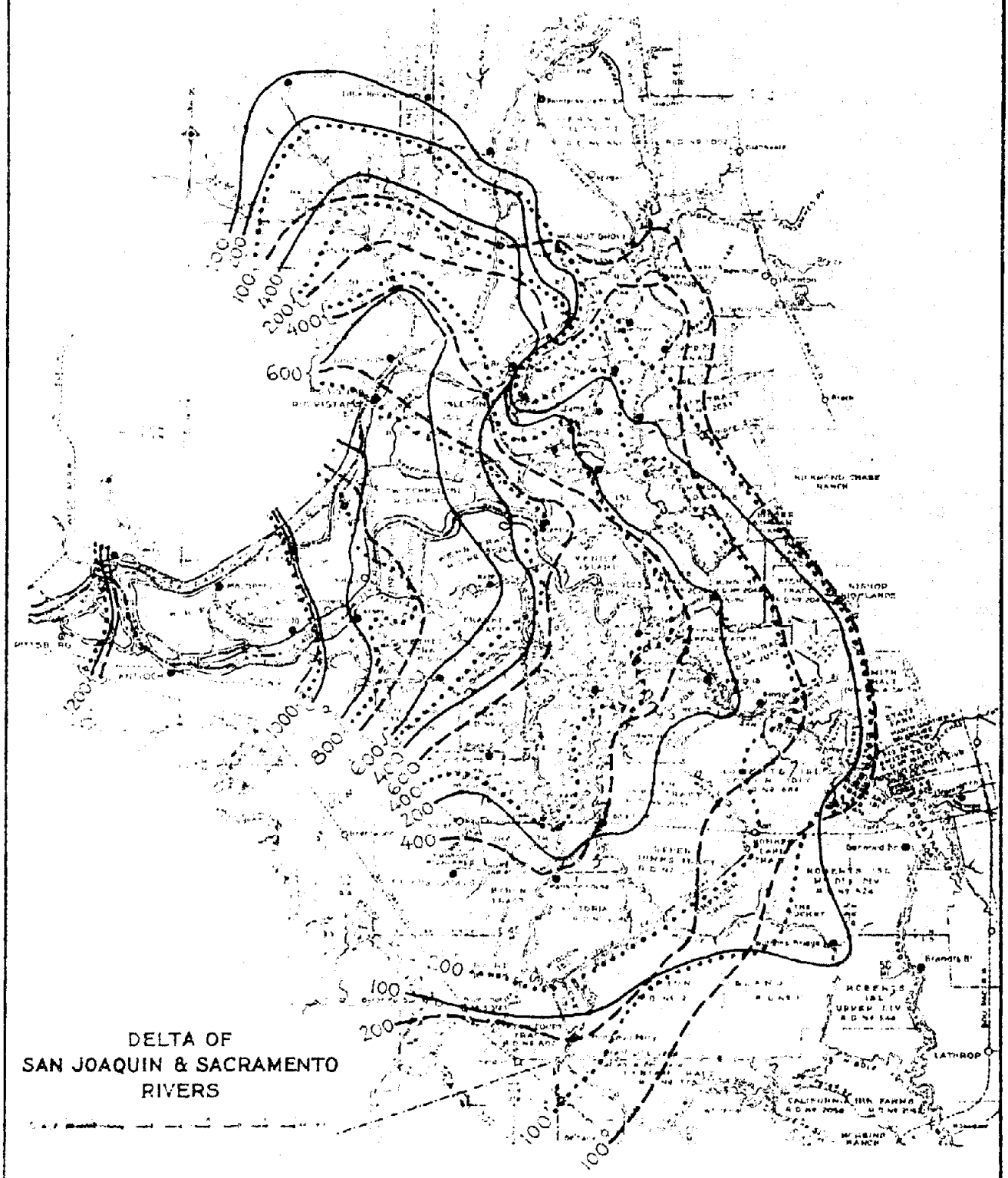
1931 HISTORICAL TEST
SEPTEMBER 1

LINES OF EQUAL CONCENTRATION

Prototype - Water Supervisor's Report, 1931; Plate 7

Model - Preliminary test

Model - Revised test



DELTA OF
SAN JOAQUIN & SACRAMENTO
RIVERS

FIGURE 35

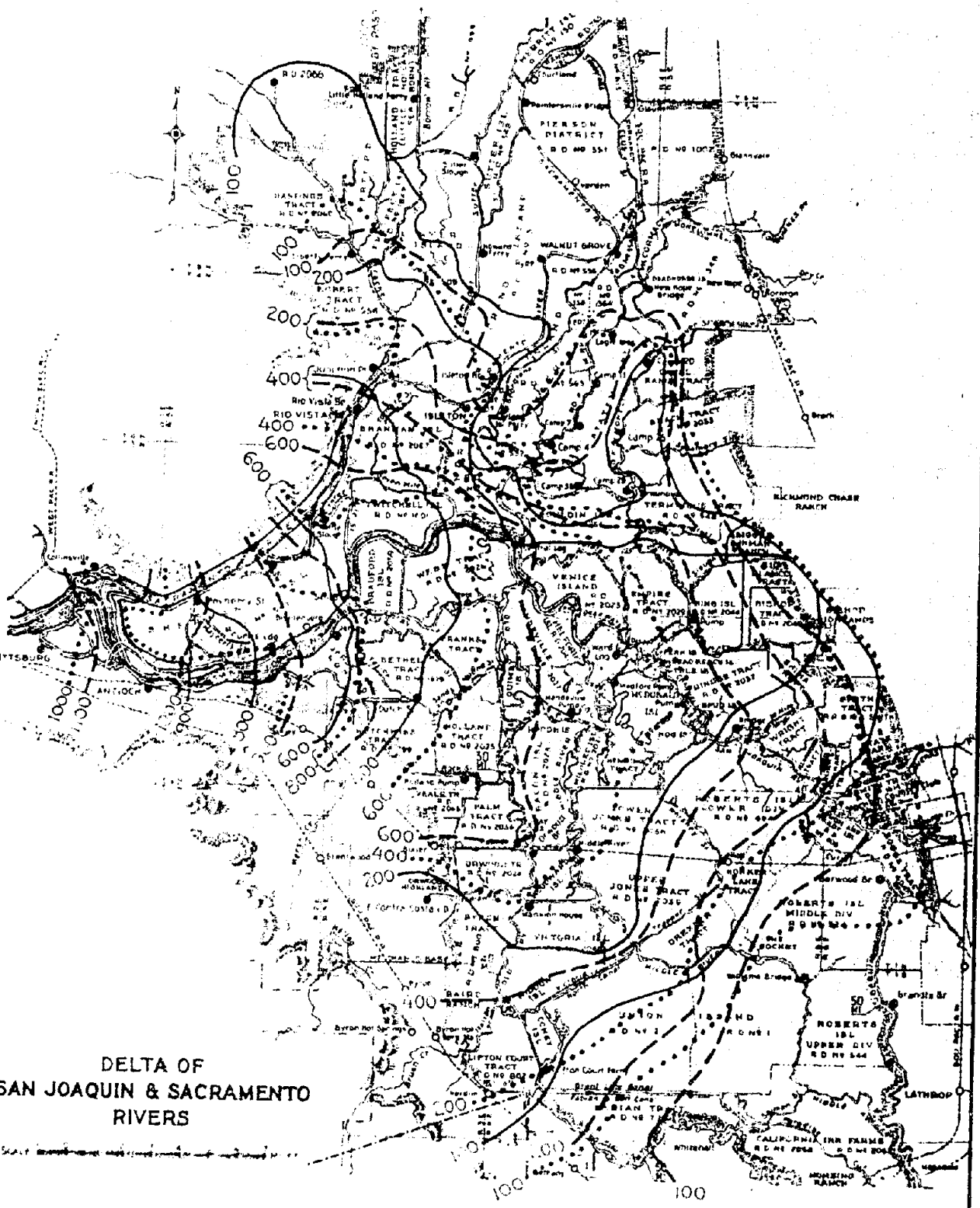
1931 HISTORICAL TEST
OCTOBER 1

LINES OF EQUAL CONCENTRATION

Prototype - Water Supervisor's Report, 1931; Plate 7

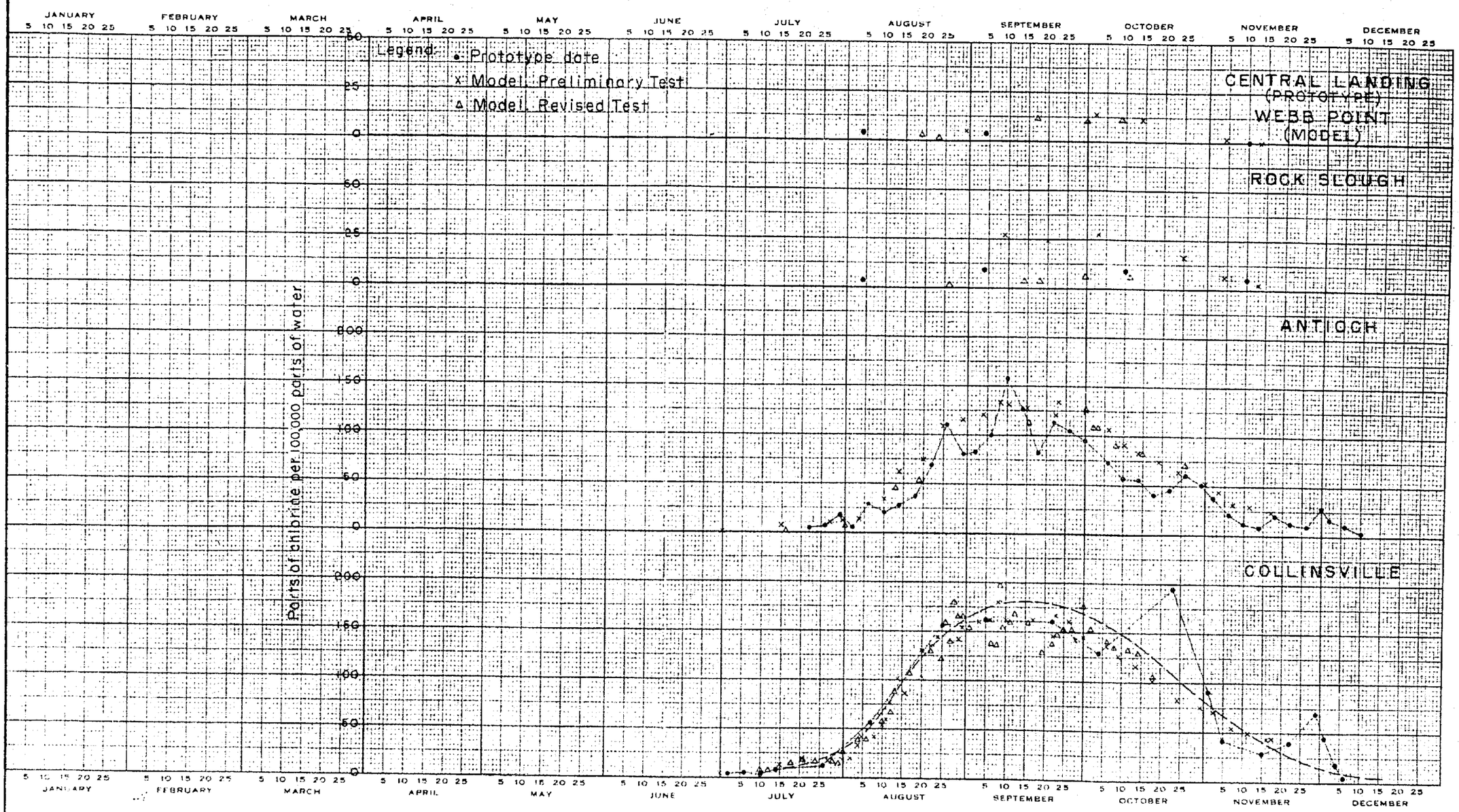
Model - Preliminary test

Model - Revised test



DELTA OF
SAN JOAQUIN & SACRAMENTO
RIVERS

FIGURE 36



SACRAMENTO - SAN JOAQUIN DELTA
SALINITY CONTROL STUDIES 1:4800 MODEL
SEASON OF 1941

FIGURE 37

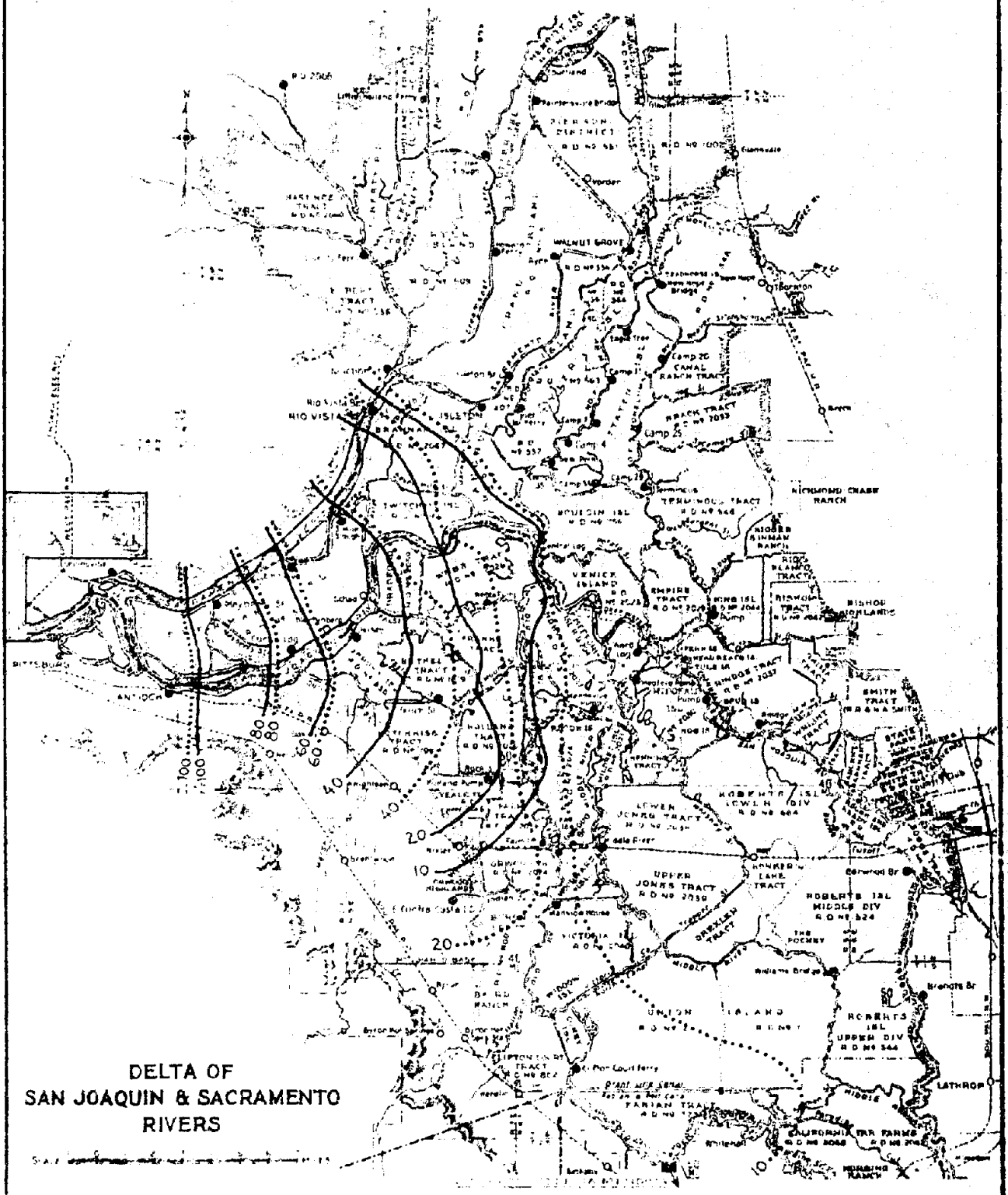
EXPLANATION

NO CONSUMPTIVE USE – NET FLOW = 3,300 C.F.S.
SAMPLES TAKEN AFTER HIGH HIGH TIDE

LINES OF EQUAL CONCENTRATION IN PERCENT – ANTIOCH = 100%

2,000 c.f.s. Down Sacramento River
1,300 c.f.s. Down San Joaquin River

7,900 c.f.s. Down Sacramento River
5,900 c.f.s. Diverted at Snodgrass Slough
4,600 c.f.s. To Delta Mendota
0 Down San Joaquin River



DELTA OF
SAN JOAQUIN & SACRAMENTO
RIVERS

EQUILIBRIUM TEST NO. 1

FIGURE 38

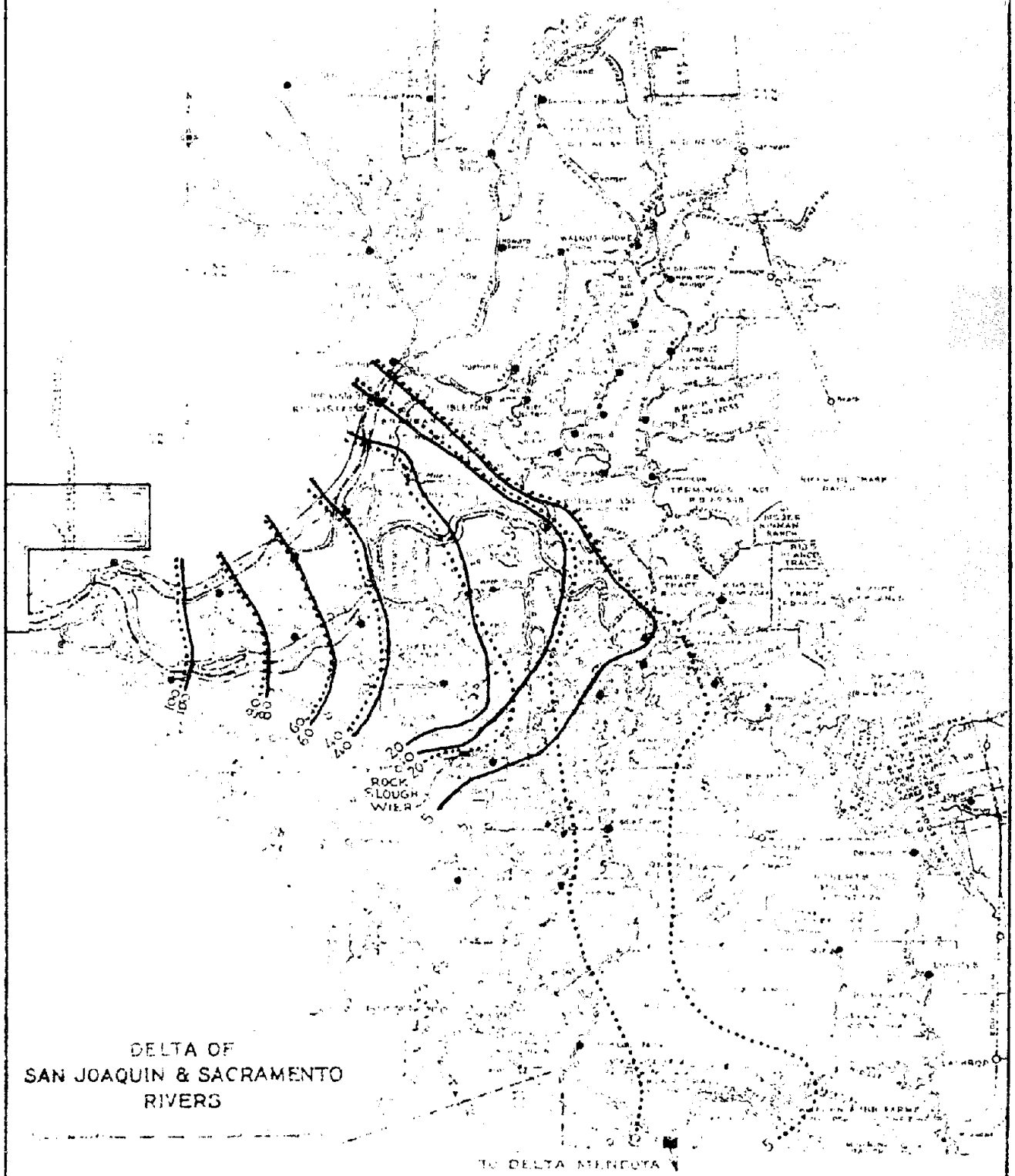
EXPLANATION

WITH CONSUMPTIVE USE - NET FLOW = 3,300 C.F.S.
SAMPLES TAKEN AFTER HIGH HIGH TIDE
ROCK SLOUGH WIER ADDED

LINES OF EQUAL CONCENTRATION IN PERCENT - ANTIOCH = 100%

3400 c.f.s. Down Sacramento River
3900 c.f.s. Down San Joaquin River
4000 c.f.s. Consumptive Use

11,900 c.f.s. Down Sacramento River
9,200 c.f.s. Diverted at Snodgrass Slough
4,000 c.f.s. Consumptive Use
7,600 c.f.s. To Delta Mendota



DELTA OF
SAN JOAQUIN & SACRAMENTO
RIVERS

EQUILIBRIUM TEST NO. 2

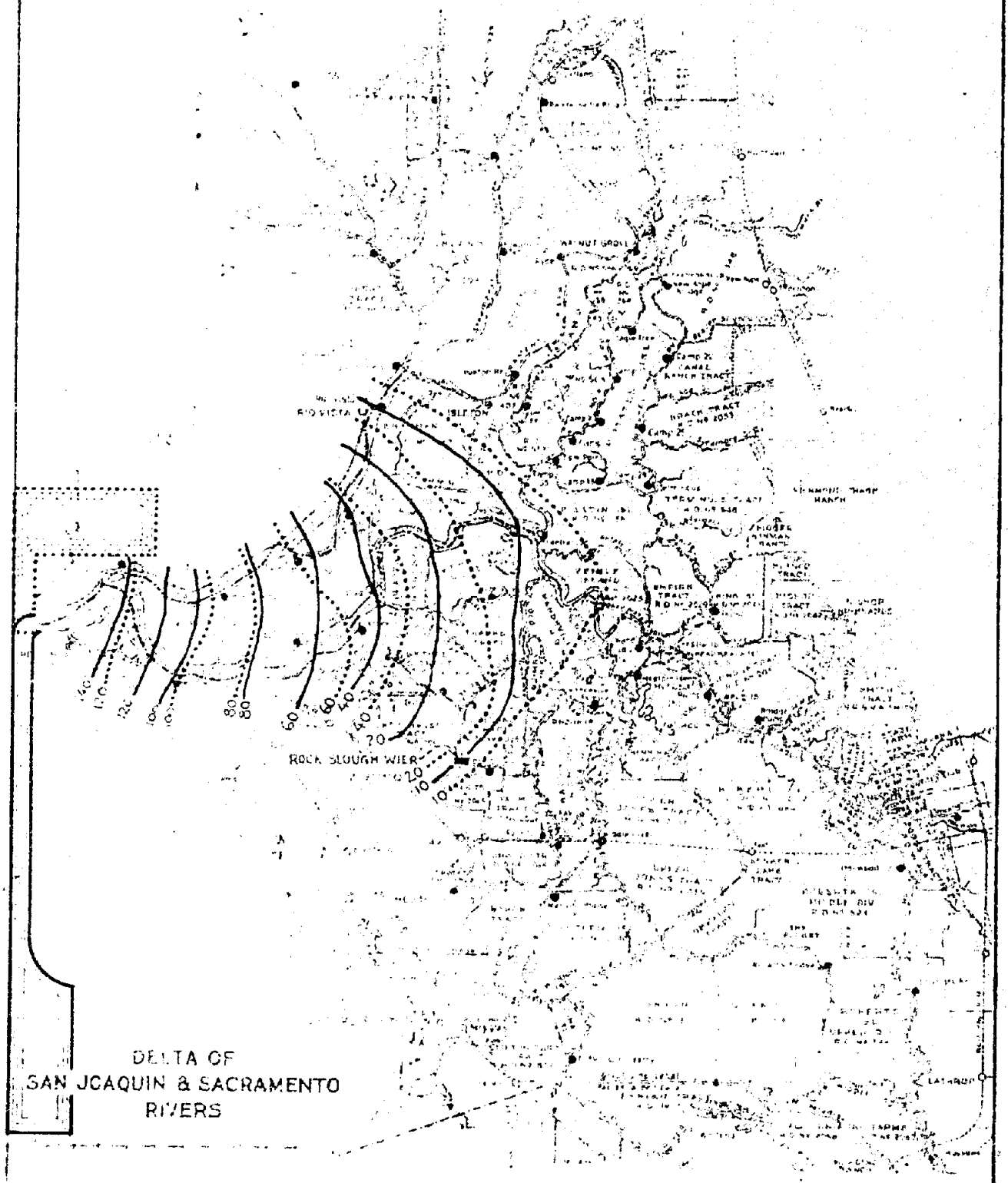
FIGURE 39

EXPLANATION

MODEL EXTENDED BY RELOCATING PLUNGER BASIN
WITH CONSUMPTIVE USE - NET FLOW = 3,300 C.F.S
SAMPLES TAKEN AFTER HIGH HIGH TIDE.

3,400 c.f.s. Down Sacramento River - 3,900 c.f.s. Down San Joaquin River - 4,000 c.f.s. Consumptive Use
LINES OF EQUAL CONCENTRATION IN PERCENT - ANTIOCH = 100%

Without model extended — With model extended



EQUILIBRIUM TEST NO. 3

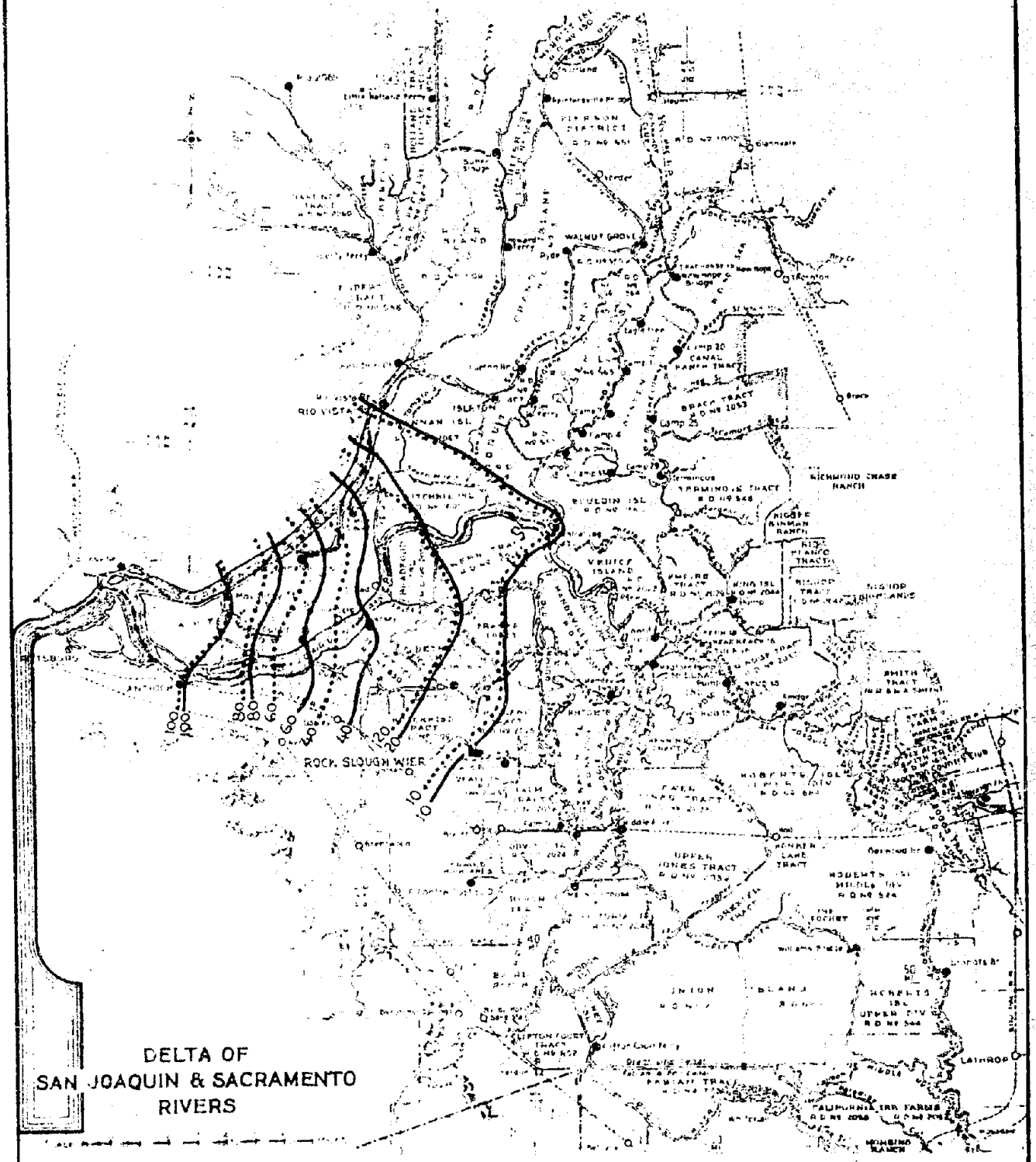
FIGURE 40

EXPLANATION

COMPARISON OF READINGS AT HIGH HIGH TIDE AND MEAN TIDE
WITH CONSUMPTIVE USE - NET FLOW = 3,300 C.F.S.

3,400 c.f.s. Down Sacramento River - 3,900 c.f.s. Down San Joaquin River - 4,000 c.f.s. Consumptive Use
LINES OF EQUAL CONCENTRATION IN PERCENT - ANTIOCH = 100 %

High high tide — Mean tide



EQUILIBRIUM TEST NO. 4

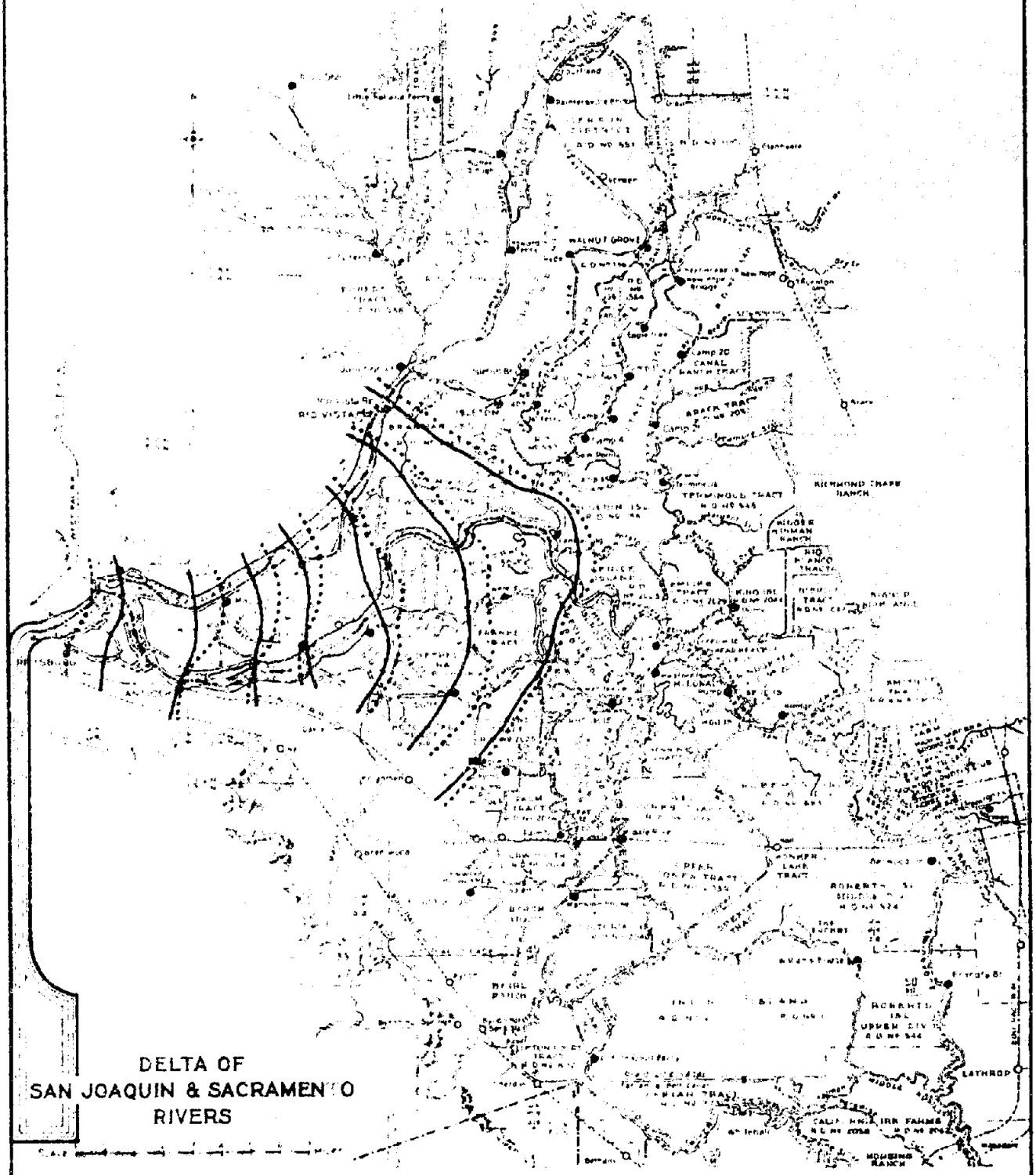
FIGURE 41

EXPLANATION

EFFECT OF CHANGING CONCENTRATION AT ANTIOCH
WITH CONSUMPTIVE USE – NET FLOW = 3,300 C.F.S.

3,400 c.f.s. Down Sacramento River – 3,900 c.f.s. Down San Joaquin River – 4,000 c.f.s. Consumptive Use
LINES OF EQUAL CONCENTRATION IN PERCENT – ANTIOCH = 100% AT MEAN TIDE

——— 100% at Antioch = 0.1% of base solution
····· 100% at Antioch = 0.9% of base solution



EQUILIBRIUM TEST NO. 5

FIGURE 42

EXPLANATION

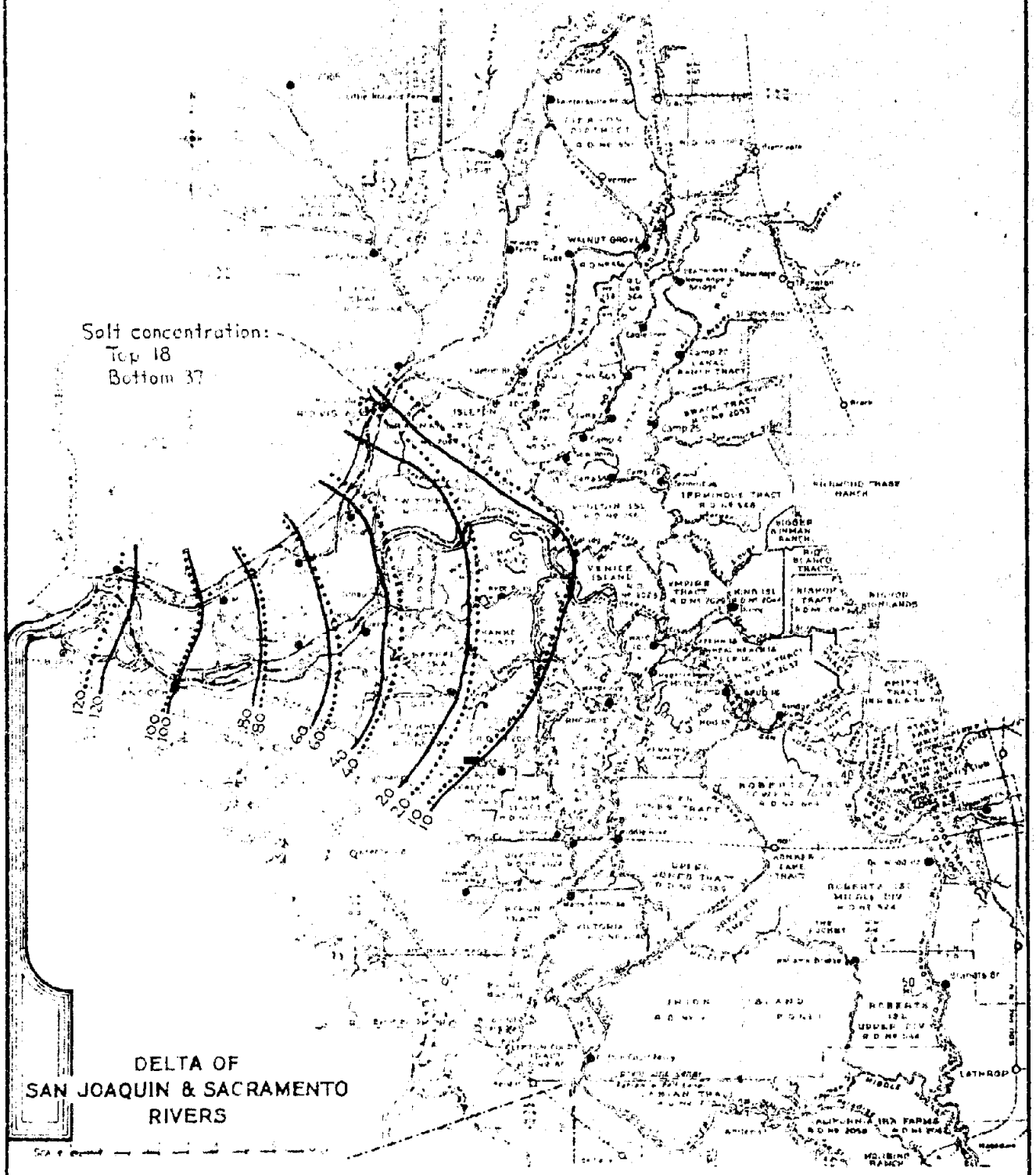
SALT VERSUS COLOR
WITH CONSUMPTIVE USE — NET FLOW = 3,300 C.F.S.

3,400 c.f.s. Down Sacramento River – 3,900 c.f.s. Down San Joaquin River – 4,000 c.f.s. Consumptive Use

LINES OF EQUAL CONCENTRATION IN PERCENT - ANTIOCH = 100% AT HIGH HIGH TIDE

····· Salt (100% at Antioch = 3,650 p.p.m of NaCl)

——— Color



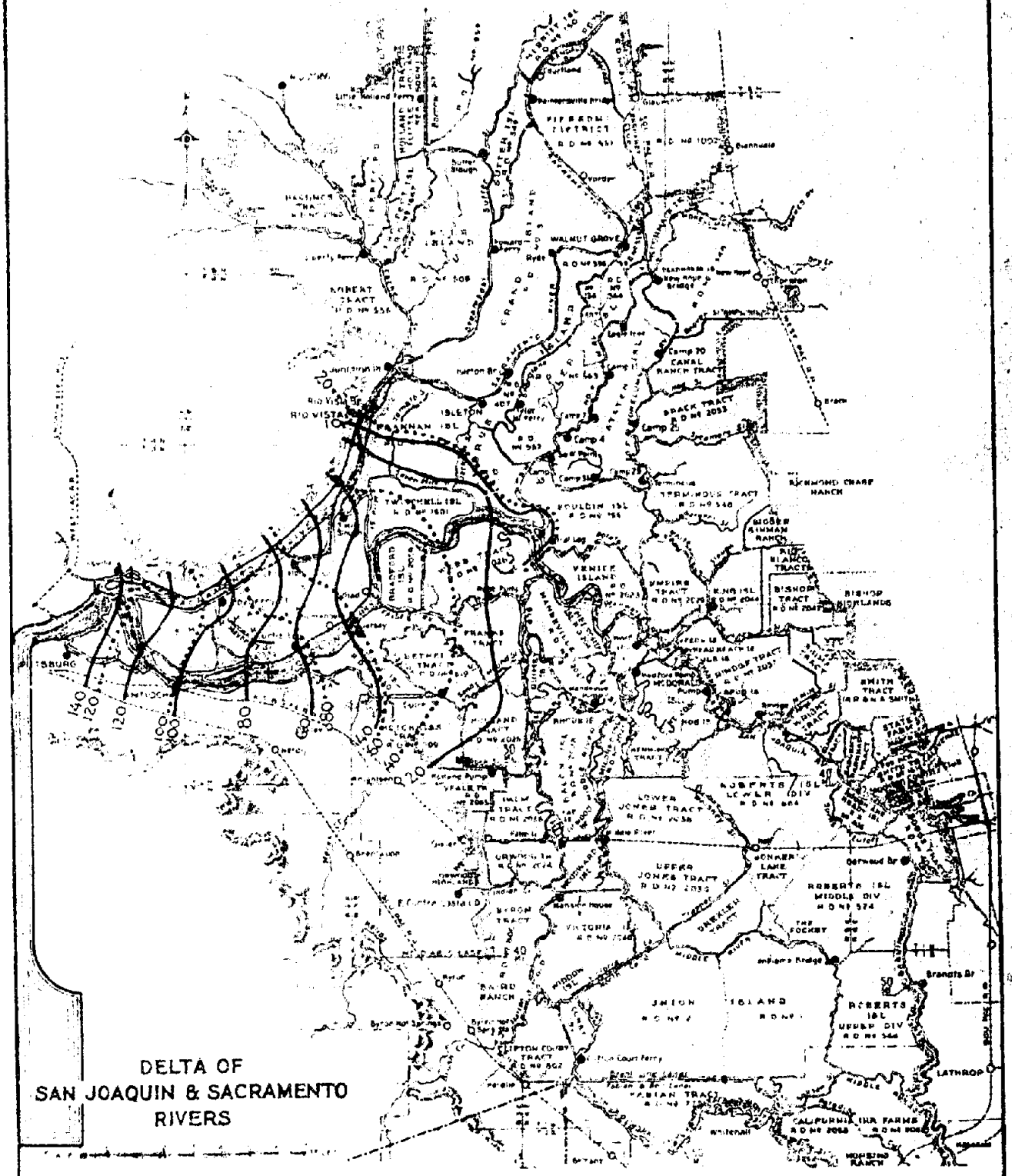
EQUILIBRIUM TEST NO. 6

FIGURE 43

EXPLANATION

EFFECT OF BLOCKING GEORGIANA AND THREE MILE SLOUGHS
NO CONSUMPTIVE USE — NET FLOW = 3,300 C.F.S.

LINES OF EQUAL CONCENTRATION IN PERCENT - ANTIOCH = 100% AT HIGH HIGH TIDE
——— Channels open (3,300 c.f.s. Down Sacramento River, 0 Down San Joaquin River
····· Channels blocked (1,100 c.f.s. Down Sacramento River, 2,200 c.f.s. Down San Joaquin River



EQUILIBRIUM TEST NO. 7

FIGURE 4

EXPLANATION

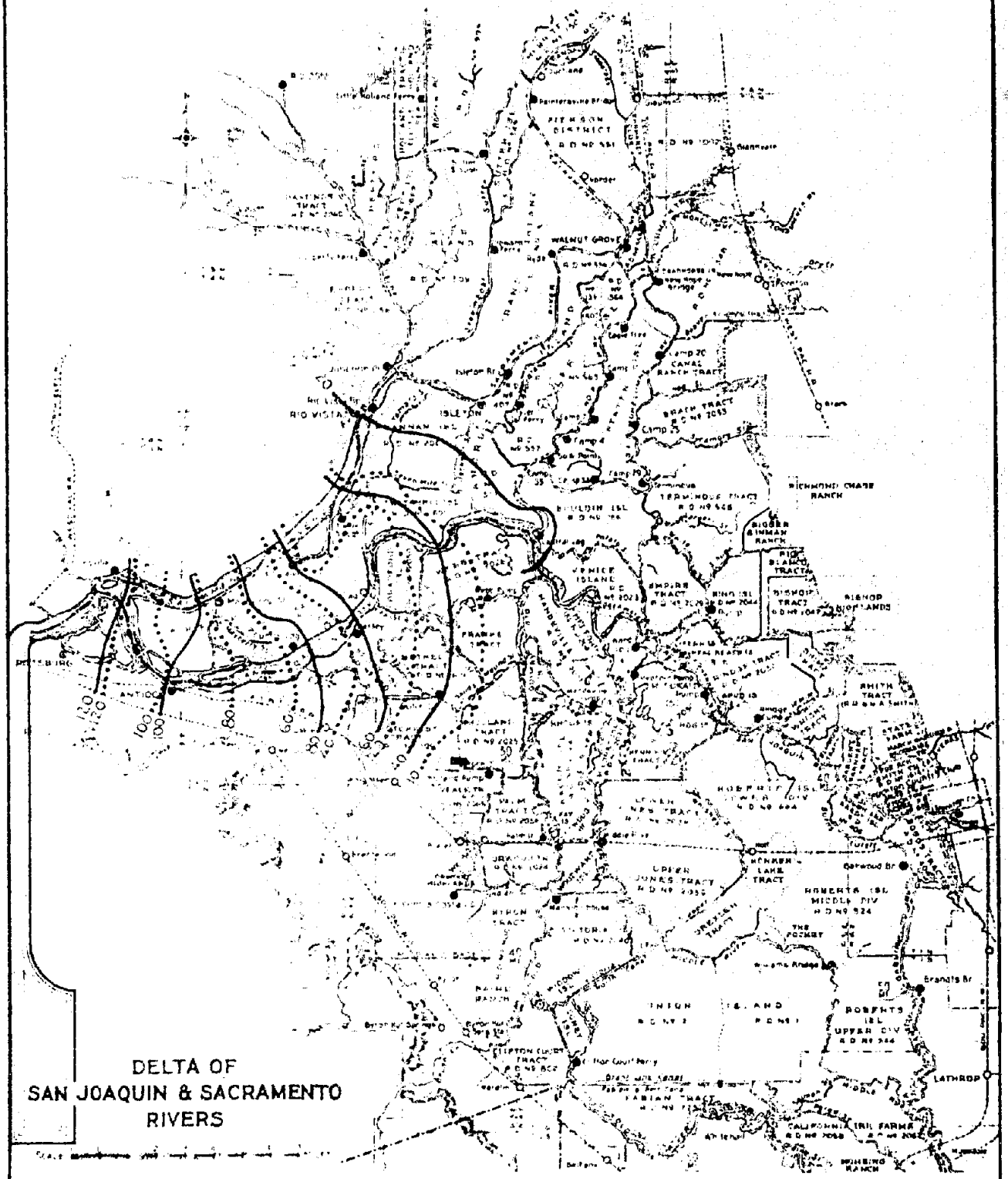
EFFECT OF CHANGING NET FLOW

NO CONSUMPTIVE USE - GEORGIANA AND THREE MILE SLOUGHS BLOCKED

LINES OF EQUAL CONCENTRATION IN PERCENT - ANTIOCH = 100% AT HIGH HIGH TIDE

——— Net flow = 3,300 c.f.s. (⅓ Sacramento River, ⅔ San Joaquin River)

····· Net flow = 6,600 c.f.s.



EQUILIBRIUM TEST NO. 8

FIGURE 45

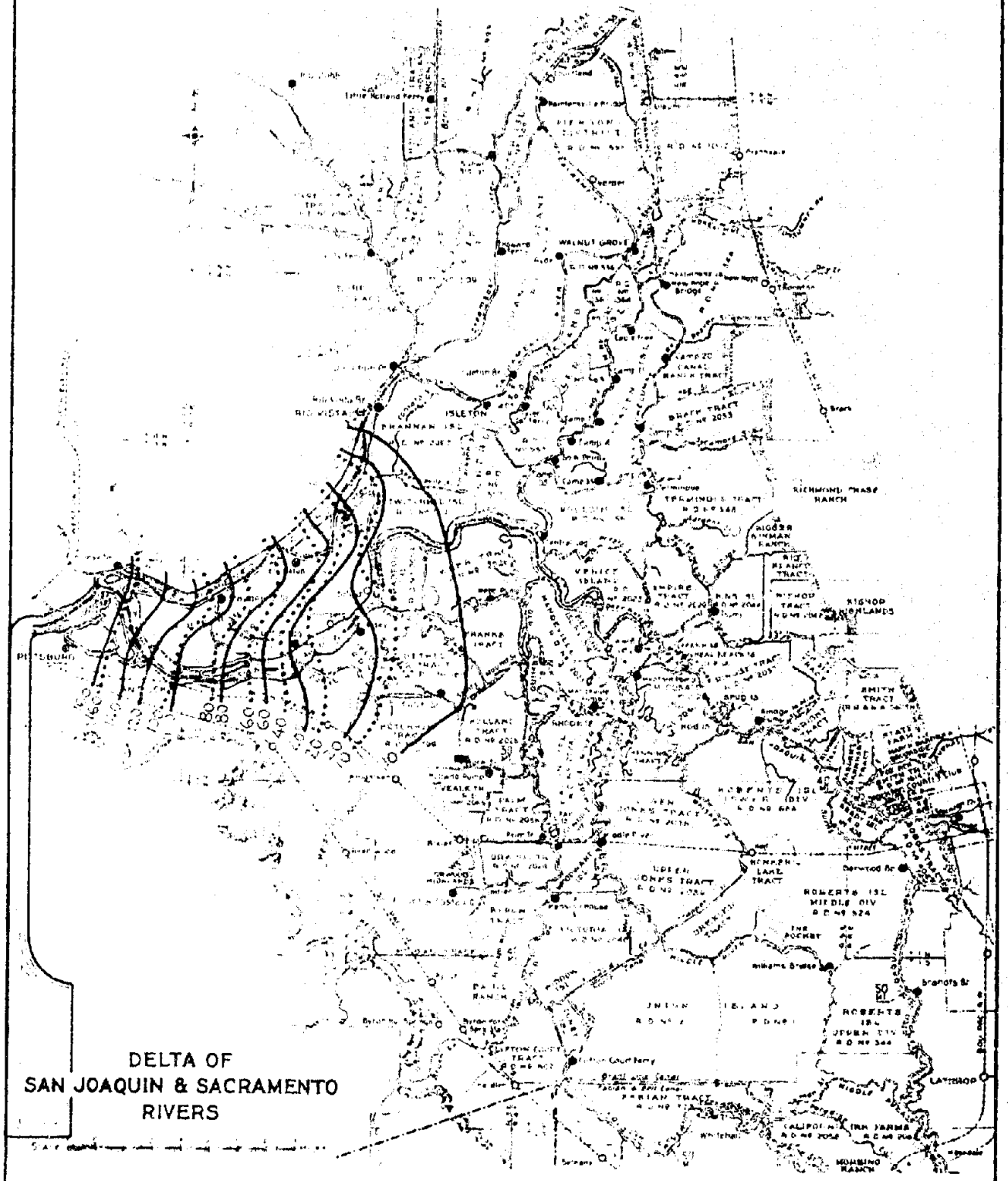
EXPLANATION

EFFECT OF CHANGING DIVISION OF FLOW
WITH CONSUMPTIVE USE - NET FLOW = 6,600 C.F.S.

LINES OF EQUAL CONCENTRATION IN PERCENT - ANTIOCH = 100% AT HIGH HIGH TIDE

——— 1/3 Sacramento River, 2/3 San Joaquin River

..... 2/3 Sacramento River, 1/3 San Joaquin River



EQUILIBRIUM TEST NO. 9

DISCHARGE SCHEDULE FOR RIVER FLOW

PRELIMINARY 1931 TEST

Date		DISCHARGE									
		Prototype in c.f.s.						Model in cc. per 10 sec.			
		Sacramento R.		San Joaquin R.		Mokelumne R.		Consumptive use		Net flow(2)	
From	To	Proto(1)	Model	Proto	Model	Proto	Model	Proto	Model	Proto	Model
5- 1	5-10	6,410	580	444	26				152		254
5-11	5-31	3,620	214	444	26				152		88
6- 1	6-16	1,620	95	392	23				158		-35
6-17	6-25	3,320	197	392	23				155		+67
6-26	6-30	1,350	80	392	23				153		-50
7- 1	7- 8	600	35	233	14				221		-172
7- 9	7-31	7	0	233	14				221		-207
8- 1	8-21	300	17	228	14				237		-206
8-22	8-31	850	50	228	14				237		-173
9- 1	9-10	1,670	99	320	19				162		-44
9-11	9-30	3,640	216	320	19				162		+73
10- 1	10-23	3,650	216	478	28				93		151
10-24	10-31	6,250	370	478	28				95		305

(1) Average Prototype discharge for period.
(2) Net flow - River flow less consumptive use.

REVISED 1931 TEST

Date		DISCHARGE									
		Prototype in c.f.s.						Model in cc. per 10 sec.			
		Sacramento R.		San Joaquin R.		Mokelumne R.		Consumptive use		Net flow	
From	To	Proto	Model(1)	Proto(2)	Model(3)	Proto	Model	Proto	Model	Proto	Model
5- 1	5-10	6,408	382	521	37				167		244
5-11	5-20	3,998	239	521	37				167		101
5-21	5-31	3,030	181	521	37				167		43
6- 1	6- 4	3,030	181	497	35				171		+37
6- 5	6-16	1,367	83	497	35				171		-61
6-17	6-24	3,434	209	497	35				171		+65
6-25	6-30	1,475	89	497	35				171		-55
7- 1	7- 5	709	44	349	27				226		-163
7- 6	7-10	340	22	349	27		Less than 1		226		-185
7-11	7-16	+47	+5	349	27				226		-202
7-17	7-25	-80	-3	349	27				226		-210
7-26	7-31	+56	+5	349	27	309	18		226		-184
8- 1	8- 3	+56	5	325	25	309	18		169		-129
8- 4	8-21	341	22	325	25	309	18		169		-112
8-22	8-31	850	52	325	25	309	18		169		-82
9- 1	9-11	1,760	106	407	30				119		+9.
9-12	9-30	3,700	221	407	30				119		+124
10- 1	10-23	3,655	218	555	39				79		+170
10-24	10-31	6,261	373	555	39				79		-325

(1) 2 cc./10 sec. added for leakage of model.
(2) Includes return flow between Vernalis and Mossdale Br.
(3) 6 cc./10 sec. added for leakage of model.

APPORTIONMENT OF CONSUMPTIVE USE TO DRAINS

PRELIMINARY TEST

The total consumptive use, as given in Water Supervisors Report, 1931, is apportioned to each drain according to the irrigated area represented

* Drain designation	A	B	C	D	E	F	G	H	J
Irrigated tracts represented	1/2 R.D.999 Little Holland Liberty Hastings R.D.536 1/2 R.D.501 R.D.1667	1/2 R.D.501 Grand Island 1/2 R.D.551 R.D.556 R.D.407 R.D.317 R.D.2067	1/2 R.D.999 Merritt Island R.D.755 1/2R.D.551 R.D.349 R.D.113	R.D.1002 McCormack R.D.348 Canal Ranch Staten Island Tyler Island R.D.2033	McDonald Medford Bradford Island Webb Tract Mandeville Is. Quimby Franks Tract Bethel Tract Jersey Hotchkiss Holland Veale Tract Palm Fay Bacon Mildred Henning	Bouldin Island Terminous Island Venice Island Empire Tract King Island Rindge Bigger & Inman Bishop Shima Wright Smith Elmwood Sargeant-Barnhart Fox	Lower Roberts Middle Roberts Rough & ready Boggs-Statton Pocket Honker Lake Drexler Jones Lower Jones	Byron Baird Clifton Orwood Woodward Victoria Is. 1/2 Union Coney	Calif.Irr.Farms Moreing Fabian Fink & Winkler 1/2 Union Upper Roberts
Irrigated acreage	38,500	37,500	24,500	34,100	39,200	38,500	38,900	30,300	28,800
Percent total	12.4	12.1	7.9	11.0	12.6	12.4	12.5	9.8	9.3

*See figure 1 for drain location.

Table 3

DISCHARGE SCHEDULE FOR CONSUMPTIVE USE DRAINS

PRELIMINARY 1931 TEST

DISCHARGE												
	Prototype in c.f.s.						Model in cc. per 10 sec.					
	May		June		July		August		September		October	
Drain	Proto	Model	Proto	Model	Proto	Model	Proto	Model	Proto	Model	Proto	Model
A		19		19		27		29		20		12
B		12		12		17		19		13		7
C		18		19		26		29		20		11
D		17		17		25		26		18		10
E		19		19		27		29		20		12
F		19		19		28		30		20		12
G		19		19		28		30		20		12
H		15		15		22		23		16		9
J		14		14		21		22		15		8
TOTAL	2,560	152	2,580	153	3,730	221	4,000	237	2,790	162	1,590	93

REVISED 1931 TEST

with allowance for curtailment of irrigation

DISCHARGE												
	Prototype in acre-feet per month						Model in cc. per 10 sec.					
	May		June		July		August		September		October	
Drain	Proto	Model	Proto	Model	Proto	Model	Proto	Model	Proto	Model	Proto	Model
1	9,140	9	10,100	10	10,900	11	10,400	10	8,490	8	5,680	6
2	11,500	12	12,000	12	13,700	14	11,700	12	9,550	9	6,950	7
3	15,600	16	16,600	17	21,800	22	14,500	14	11,400	11	9,120	9
4	* 2,030 8,210	10	7,180 13,200	14	7,940 13,200	20	5,710 6,140	11	4,480 2,930	7	1,560 4,070	5
5	* 9,070 15,700	25	9,320 9,220	19	15,160 16,500	33	11,790 9,620	23	6,920 4,720	12	2,840 4,190	7
6	* 6,160 12,000	17	5,940 12,000	15	12,000 13,300	23	8,740 14,600	22	4,380 11,200	16	1,760 4,950	6
7	14,300	14	11,000	11	15,300	15	11,700	12	7,820	8	6,110	6
8	10,600	11	11,500	12	16,200	16	12,500	13	10,100	10	7,800	8
9	7,060	7	8,290	8	13,100	13	10,900	11	6,290	6	4,380	4
10	9,750	10	7,860	8	10,440	10	12,000	12	7,800	8	4,580	5
11	8,870	9	10,800	11	11,700	12	6,350	6	5,740	6	4,830	5
12	7,858	8	8,802	9	9,570	10	4,100	4	3,850	4	3,420	3
13	7,830	8	9,610	10	11,400	11	4,910	5	3,850	4	3,390	3
14	11,000	11	14,800	15	16,000	16	13,600	14	9,780	10	5,440	5
TOTAL		167		171		226		169		119		79

*85 percent upland diversions to allow for return flow.

DISCHARGE SCHEDULE FOR 1941 TEST

Table 4

PRELIMINARY TEST

Date		DISCHARGE									
		Prototype in.c.f.s.(1)				Model in cc. per 10 seconds					
		Sacramento R.		San Joaquin R.		Mokelumne R.		Consumptive use (2)		Net flow(3)	
From	To	Proto	Model	Proto	Model	Proto	Model	Proto	Model	Proto	Model
7-1	7-15	11,040	652	13,600	804	316	19		221		1254
7-16	7-31	6,900	408	4,920	291	316	19		221		497
8-1	8-31	4,530	268	2,095	124	210	12		237		167
9-1	9-30	5,170	306	1,686	100	254	15		165		256
10-1	10-31	7,010	415	2,199	130	347	20		93		472
11-1	11-30	9,580	566	2,329	138	358	32		49		687

(1) Average discharge for period.
(2) The consumptive use same as in preliminary 1931 test table 3.
(3) Net flow = River flow - consumptive use.

REVISED TEST

Date		DISCHARGE									
		Sacramento R.		San Joaquin R.		Mokelumne R.		Consumptive use (4)		Net flow	
From	To	Proto	Model	Proto	Model	Proto	Model	Proto	Model	Proto	Model
7-1	7-15		652		804		19		246		1229
7-16	7-31		408		291		19		246		472
8-1	8-31		268		124		12		255		149
9-1	9-30		306		100		15		174		247
10-1	10-31		415		130		20		97		468
11-1	11-30		566		138		32		48		688

CONSUMPTIVE USE FOR 1941 REVISED TEST (4)

DISCHARGE

Drain	July		August		September		October		November		December	
	Proto	Model	Proto	Model	Proto	Model	Proto	Model	Proto	Model	Proto	Model
1	13,890	14	15,927	16	12,369	12	7,823	8	2,974	3	2,033	2
2	18,226	18	18,182	18	12,433	12	7,213	7	4,009	4	2,661	3
3	22,832	23	20,648	21	13,562	14	7,928	8	5,035	5	3,345	3
4	13,743	20(5)	13,941	18	8,262	12	3,581	5	2,539	3	1,736	2
5	16,504	32(5)	19,140	31	12,465	20	6,339	9	3,515	4	2,463	2
6	13,340	23(5)	14,657	22	11,251	16	4,935	6	2,884	3	1,955	2
7	15,743	16	15,268	15	10,438	10	5,703	6	3,452	3	2,390	2
8	16,464	16	16,695	17	11,466	11	7,602	8	4,276	4	2,662	3
9	13,591	14	16,051	16	11,517	12	7,532	7	3,116	3	2,248	2
10	10,906	11	13,333	13	9,837	10	5,646	6	2,937	3	2,065	2
11	14,945	15	17,958	18	12,816	13	7,812	8	3,477	3	2,389	2
12	14,472	14	17,682	18	12,388	12	8,095	8	3,514	4	2,567	3
13	13,592	14	15,260	15	10,430	10	5,709	6	2,929	3	2,075	2
14	15,685	16	16,462	16	11,434	11	6,181	6	3,302	3	2,362	2

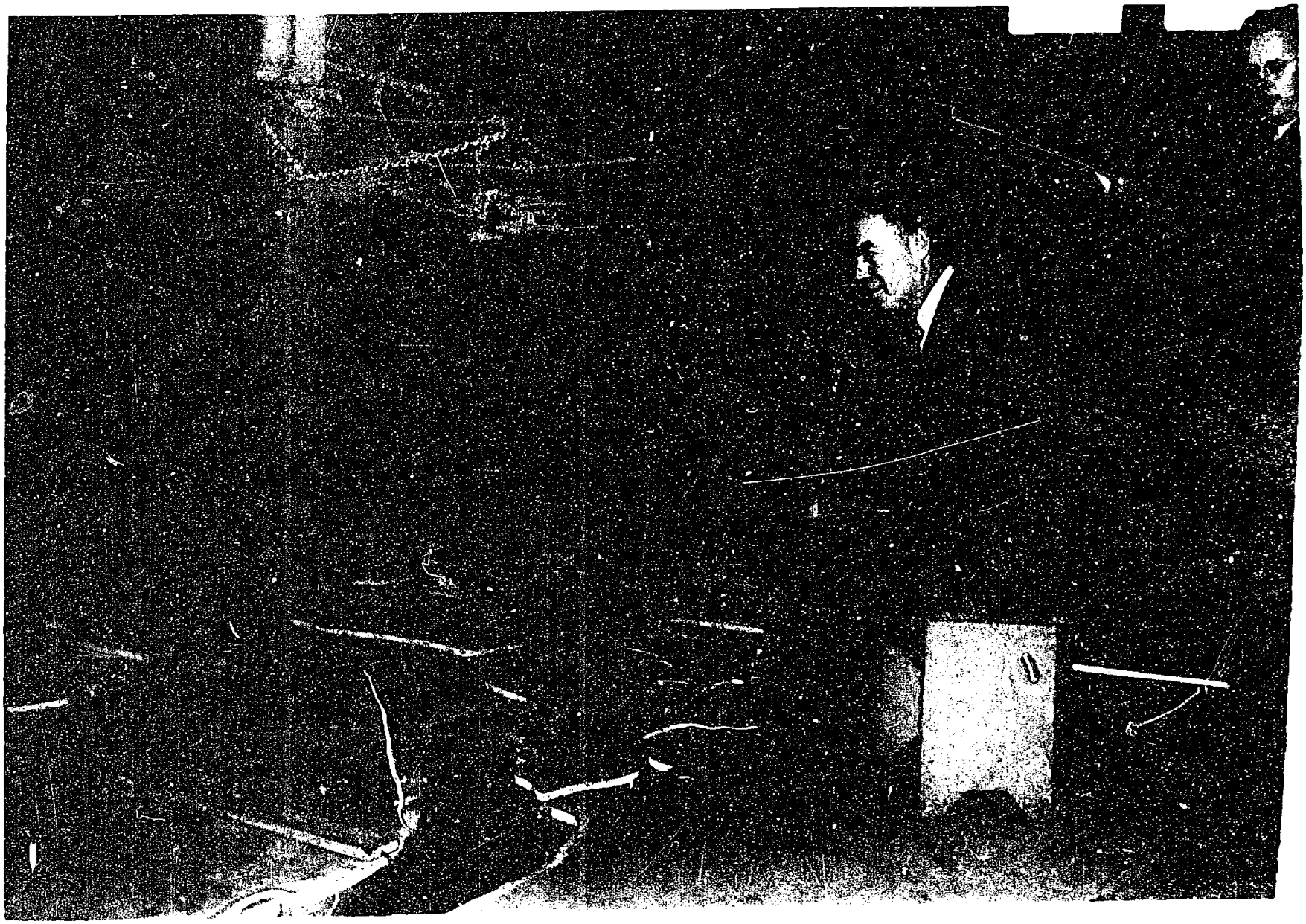
(4) Consumptive use based on 1931 crop survey without any restrictions of flow.
(5) Consumptive use at drains 4, 5, and 6 includes upland diversions.

APPORTIONMENT OF CONSUMPTIVE USE TO DRAINS - REVISED

The total consumptive use for any year was computed for each tract according to crop survey of 1931

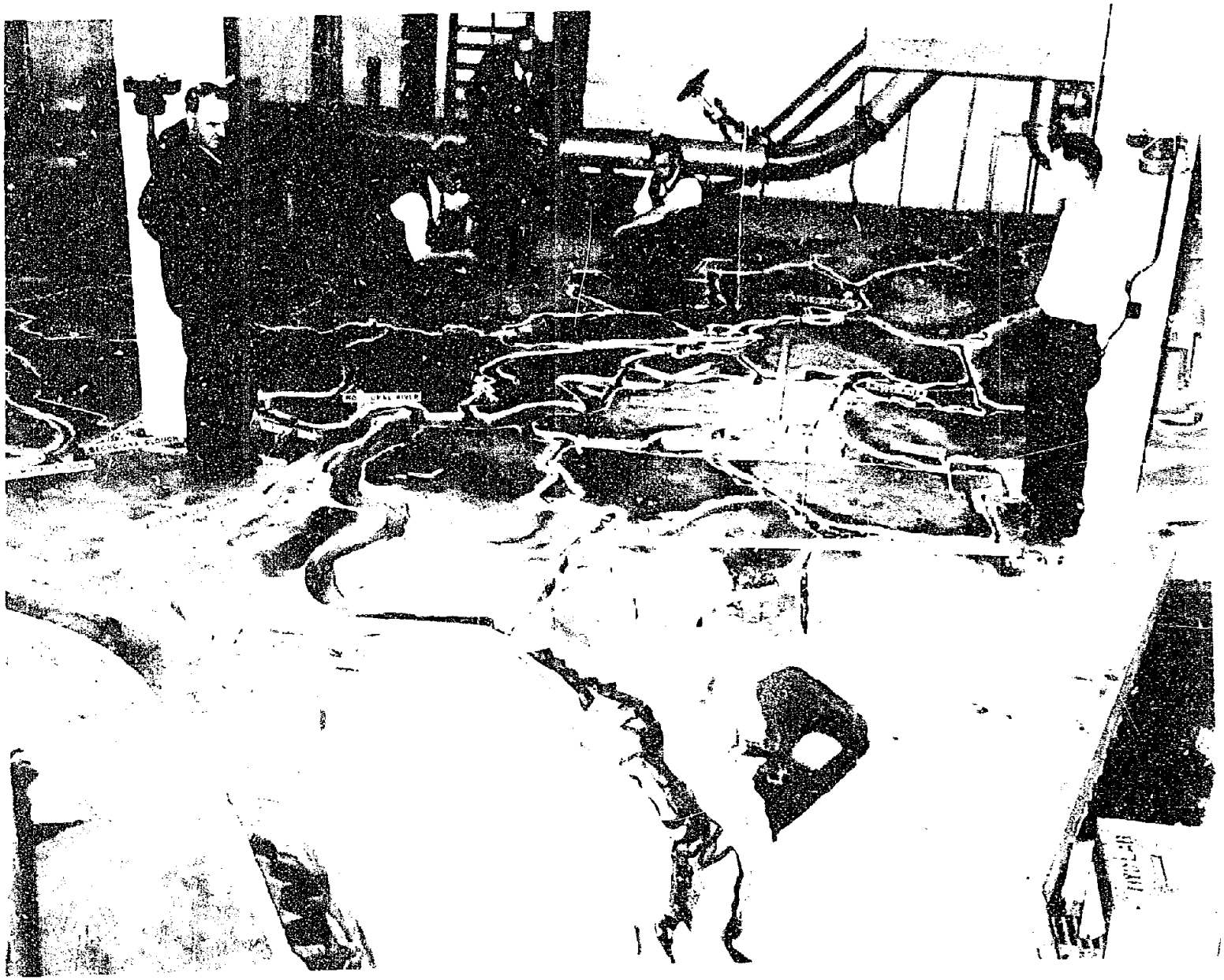
*Drain designation	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Water consuming tracts	Sherman Is. Twitchell Is. R.D.50 Dontan Is. West Is. Kimball Is. Horseshoe Is. Black Point Collinsville Manor)	R.D.2059 R.D.630 R.D.1619 Franks Tr. Hotchkiss +) R.D.799) R.D.2025 Webb Tr. Porter Est.	R.D.2065 R.D.2036 R.D.2028 Henning Quimby Is. Mandeville Is. Medford Is. McDonald Is. Orwood Tr. Woodward Is. Headreach Is. Hog Is. Mildred Is. Orwood Highlands) Rhode Is. Lower Jones	Byron Tr. Victoria Is. Baird Ranch Drexler Tr. Upper Jones	Coney Is. Union Fabian Tr. Clifton Ct. Tr. Widdow Is.	Middle Roberts Upper Roberts Boggs Tr. The Pocket Calif. Irr. Farms Fink & Winkler Moreing Ranch	Lower Roberts Rough & Ready Stockton Acres Smith Tr. Sargeant Barnhart) State Farm Fox Ranch March Card. &) Brookside Tr.) Elmwood Tr. Shima Tr. Wright Tr. Rindge Tr. R.D.1614 Honker L. Tr.	Venice Is. Empire Tr. King Is. Bishop Tr. Bishop Highlands) Rio Blanco Bouldin Is. Terminous Is. Bigger & Inman Tulie Is. Spud Is. Fern Is. Fay Is.	Staten Is. Tyler Is. Brack Is. 1/2 Andrus	R.D.348 Canal Ranch Deadhorse Is. McCormack R.D.1002 R.D.554 1/2 R.D.813 R.D.369 Shardt Club 2/3 Pierson	Brannan 60/83 Grand Is. 1/2 Ryer 1/2 Andrus	Prospect Is. Liberty Little Holland) 1/2 Ryer Hastings R.D.536	Suffer Is. Randell Is. Merrill Is. 1/2 R.D.999 1/2 R.D.813 1/3 Pierson 23/83 Grand Is.	R.D.535 R.D.744 R.D.900 Content Edinger-Johnson) Ida Is. R.D.673 R.D.746 R.D.824 R.D.765 R.D.307 1/2 R.D.999
Exterior acreage: Water	7,325	3,961	4,520	929	1,393	974	1,851	2,636	1,973	598	2,875	1,018	882	1,880
Exterior acreage: Tulies	70	679	1,811	404	174	13	778	705	160	323	45	154	0	0
Exterior acreage: Willows	0	0	10	10	706	769	16	10	9	0	19	55	0	0
Upland diversions				East Contra Costa	Byron Bethany	San Joaquin uplands								

*See figure 1 for drain location.



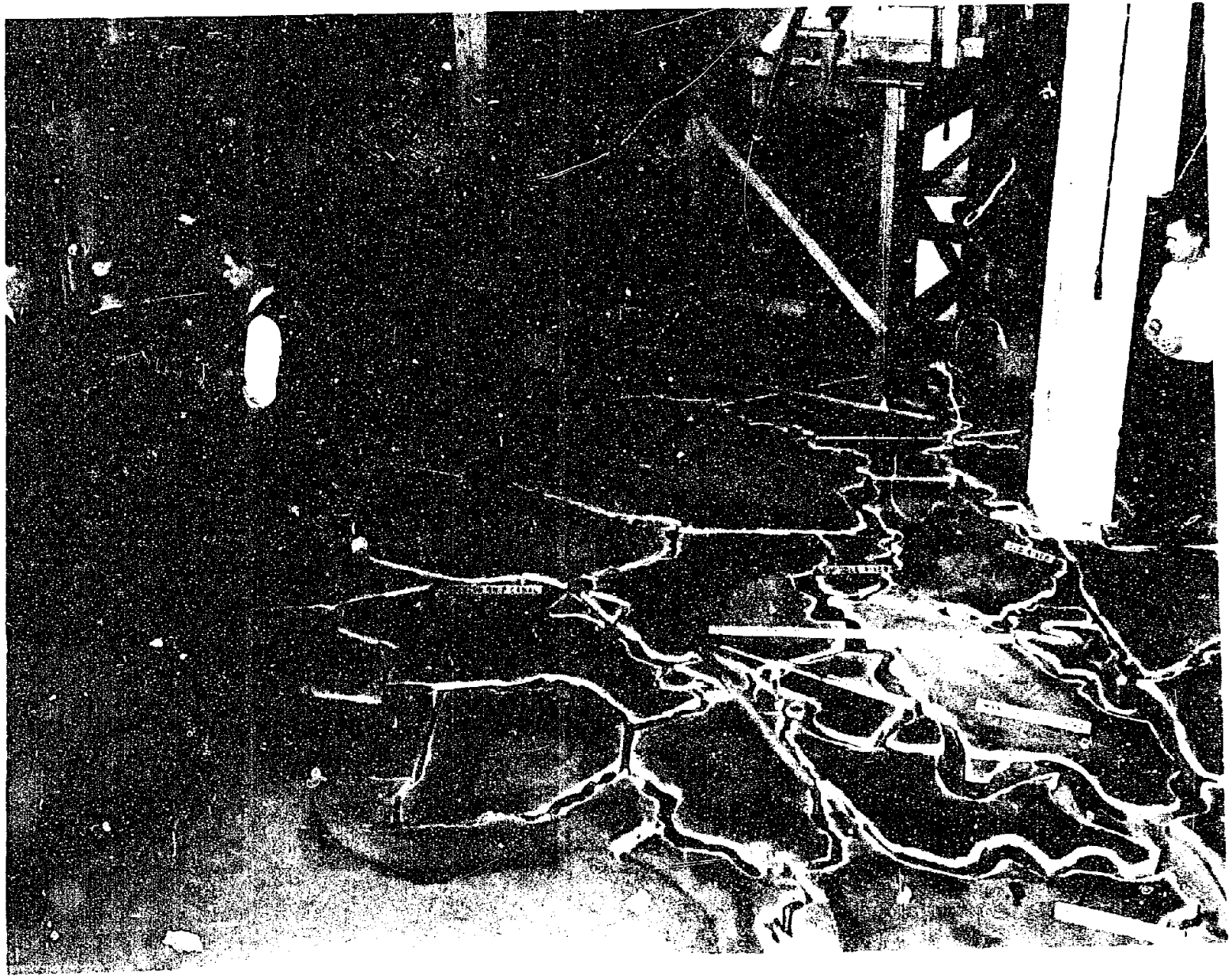
MODEL OF SACRAMENTO-SAN JOAQUIN DELTA.

Close-up of Sherman and Jersey Islands showing one end of consumptive use siphon.



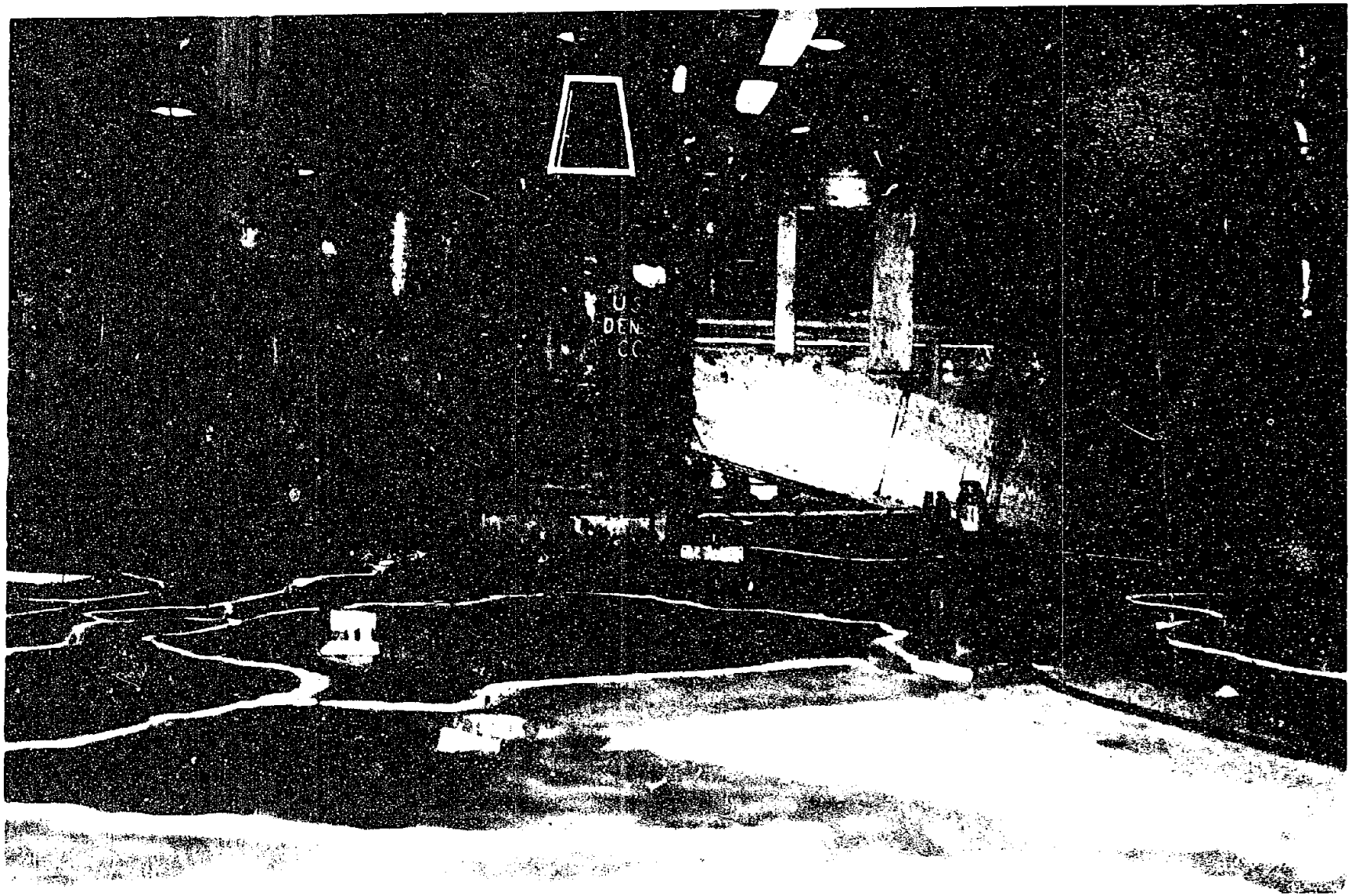
MODEL OF SACRAMENTO-SAN JOAQUIN DELTA.

View looking east. Apparatus for adding Sacramento River flow can be seen in left background. Screens in channel in foreground represent hydraulic resistance of natural channels.



MODEL OF SACRAMENTO-SAN JOAQUIN DELTA.

View looking south. Board across the various islands are protective devices for siphons which represent consumptive use.

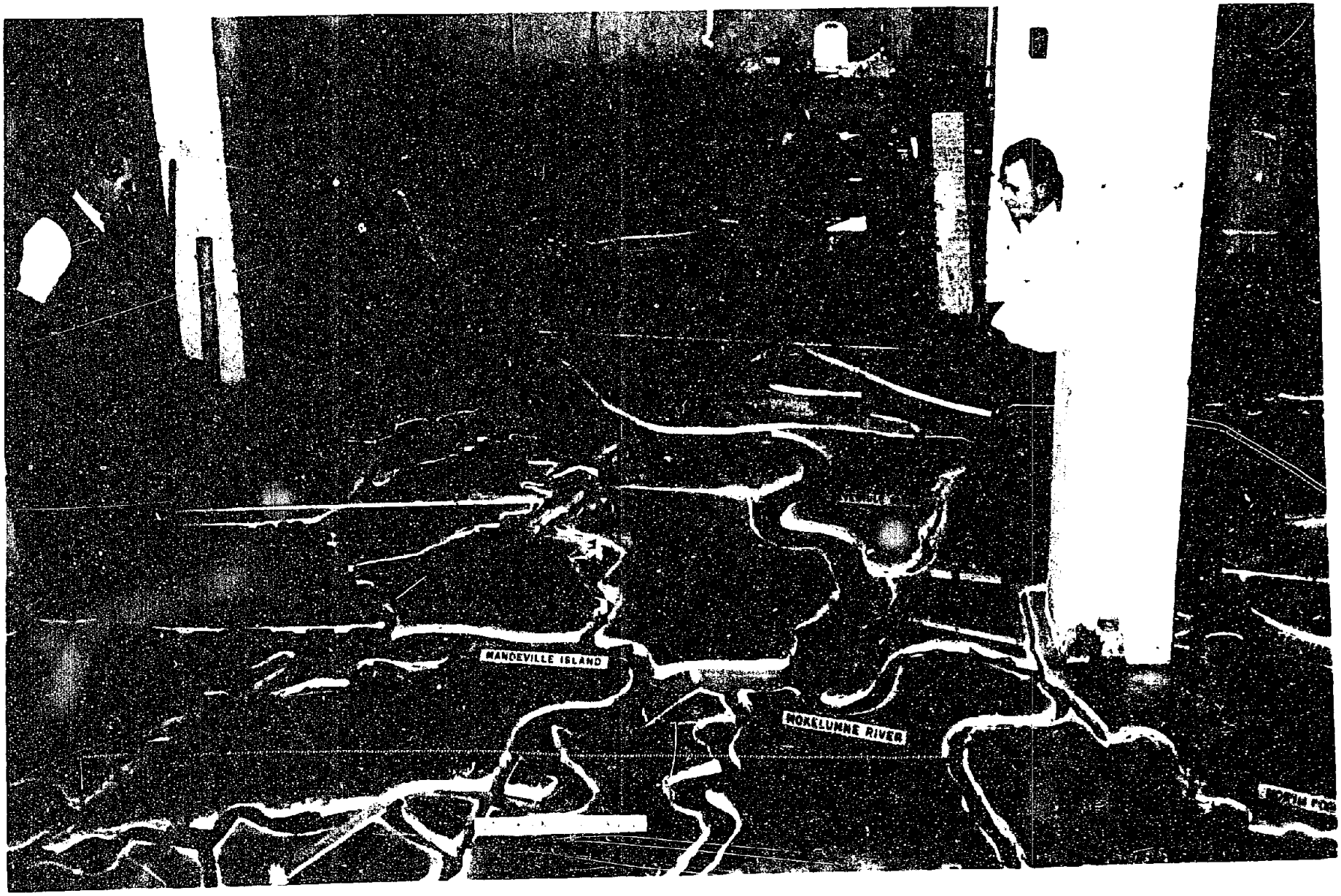


MODEL OF SACRAMENTO-SAN JOAQUIN DELTA.

View looking north. Showing method of diverting into Snodgrass Slough. Supply at left of tank discharges into Snodgrass Slough and one at right into Sacramento River which appears at right of picture because it was relocated to fall within model limits. Bottle on top of tank contains concentrated sloution of dye which drips slowly into tank. Tube at right center represents Mokelumne River supply.

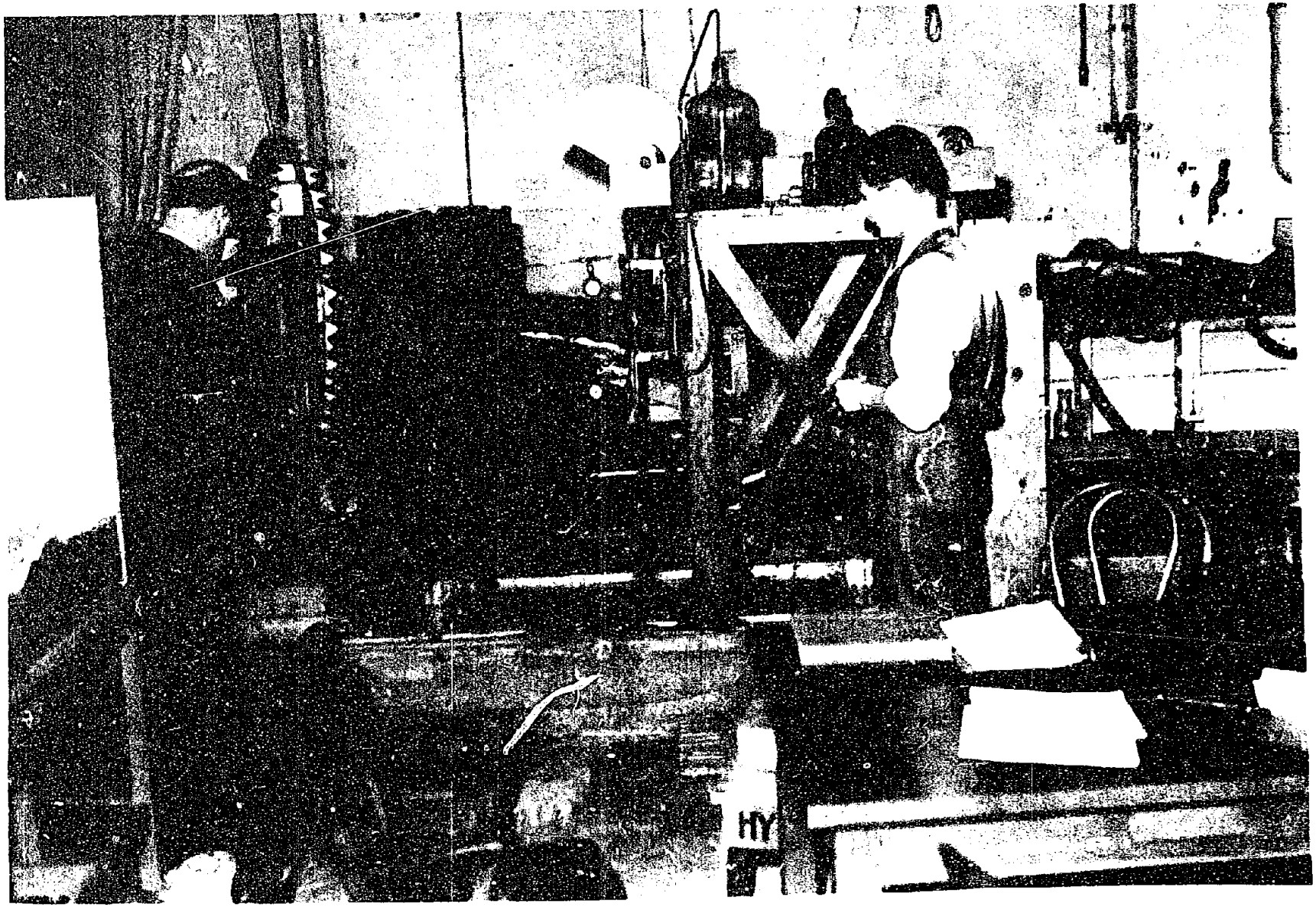
MODEL OF SACRAMENTO-SAN JOAQUIN DELTA.

Showing spectrophotometer used in color analysis.



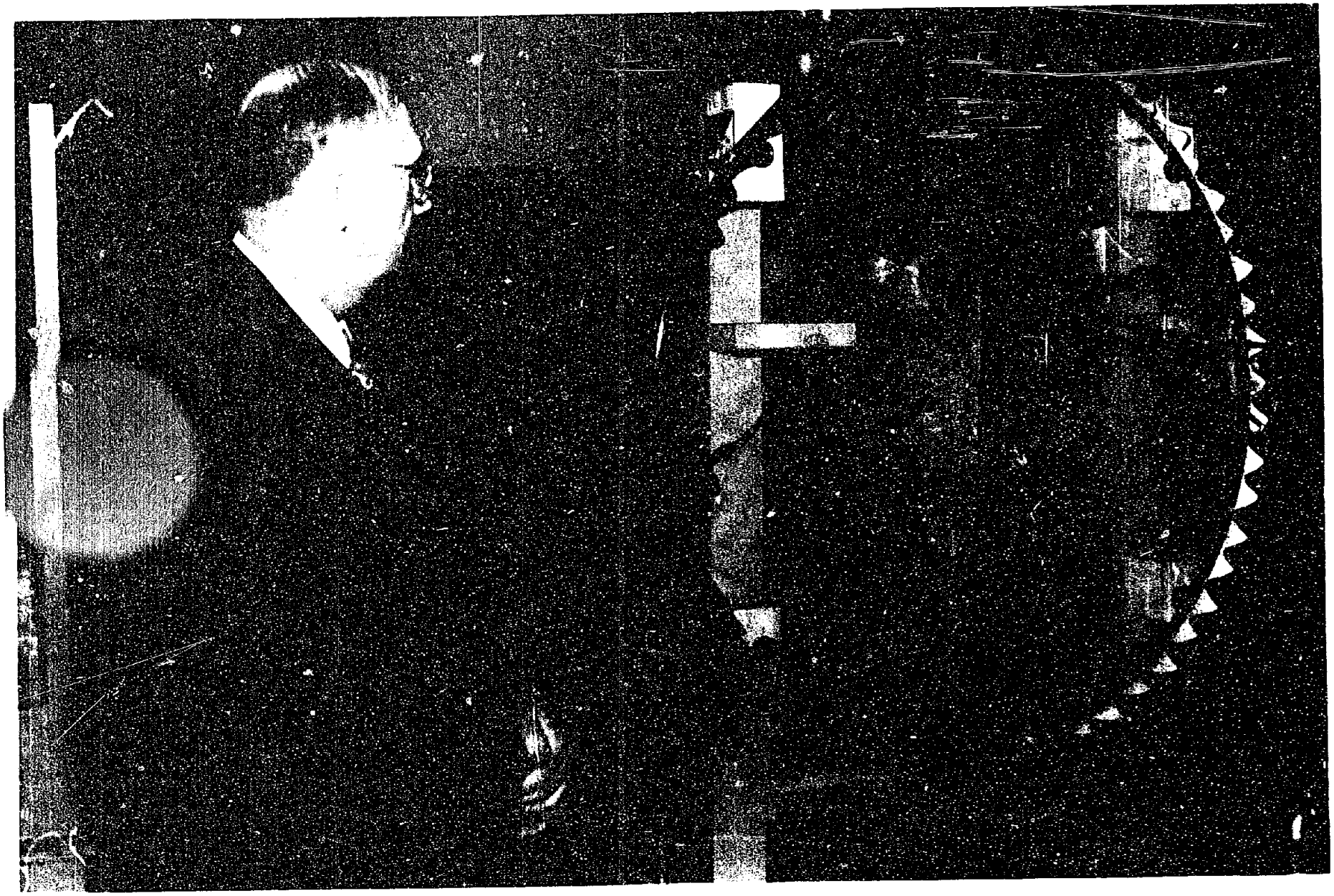
MODEL OF SACRAMENTO-SAN JOAQUIN DELTA.

Looking west towards Pittsburg. Channel extending south connects with tide generator seen in background at left.



MODEL OF SACRAMENTO-SAN JOAQUIN DELTA.

Details of tide generator reading left to right: tide cam and controls with half of float showing below; pressure leads from control valve to hydraulic cylinder which operates plunger shown below; counter-balancing device for plunger. Tank in background represents net inflow from ocean for periods of negative outflow from delta.



MODEL OF SACRAMENTO-SAN JOAQUIN DELTA.

Close-up of tide cam and controls.