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

Hydraulic Laboratory Report No. Hyd. 155

RESEARCH AND GEOLOGY DIVISION

BRANCH OF DESIGN AND CONSTRUCTION
DENVER, COLORADO

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APPENDIX I

Salinity distribution estimates for the Delta region - By R. E. Glover and W. H. Jurney 1-10

UNITED STATES
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Branch of Design and Construction
Engineering and Geological Control
and Research Division

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

1. Introduction. This report is a continuation of hydraulic laboratory report No. 142, "Progress report on model studies of the Sacramento-San Joaquin Delta - Central Valley, California," to which reference is made for details and background concerning the initiation of the hydraulic model studies as well as details of model construction. For the purposes of this report it is sufficient to summarize briefly the pertinent points of the earlier report.

After suitable adjustment of the model (figure 1) the tidal flow, as indicated by the variation of stage at numerous stations throughout the Delta, was similar in general to that of the prototype. Verification of salinity intrusion by duplication of historical tests was not successful, even after adjustment of consumptive use to account for its curtailment during periods of pronounced salinity intrusion. The apparent rate of diffusion in the model exceeded that of the prototype in all tests. In tests of steady state salinity distribution, called equilibrium tests in the report, a greater flow was required in the model to establish the estimated gradient than the control flow predicted in Bulletin 27.* The probable sources of

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

the discrepancies between model and prototype were discussed, and two possible methods of adjustment were suggested: (1) alteration of the rate of diffusion in the model by simplifying the channels and (2) distortion of the discharge scale to offset the high diffusion rate of the model.

Other possible explanations for the discrepancies between model and prototype were offered in a letter from Raymond Matthew, Supervising Hydraulic Engineer, Division of Water Resources, to Edward Hyatt, State Engineer of California, after Mr. Matthew returned from the conference relative to the model studies, held in Denver from January 27 to February 2, 1944. In this letter, a copy of which was sent to the Bureau, he suggested that the explanations might be:

> "1. Too large a tidal flow into the San Joaquin Delta and not enough into the Sacramento River Delta, for some reason so far unexplained.
>
> "2. Division of flow through channels connecting Sacramento and San Joaquin Deltas, not according to prototype.
>
> "3. Tidal cycle variation of salinity at Collinsville and Antioch not conforming with prototype."

In connection with the first of these suggestions, a memorandum written by Martin H. Blote, Associate Hydraulic Engineer, Division of Water Resources, was transmitted to the Chief Engineer by Mr. Hyatt, in which it was pointed out that by assuming a constant datum plane during construction of the model, the San Joaquin Delta was in general about 0.8 foot (0.008 foot, model) too low. This point was carefully considered, and it was decided that revision of the model would not be justified for the following reasons:

1. The revision would be one of shifting the bed levels and not the water levels; so the effect would be principally a change in channel resistance due to a change in cross-sectional area. Since the model resistance was artificially

adjusted in the tidal-verification studies, this effect was at least partially compensated.

2. Since the survey used in building the model dates back as far as 1913, it is probable that intervening changes in the channel bed which were necessarily neglected in the model would be of at least the same order of magnitude.

3. Any change of the order of 0.008 foot in the model would be at the limit of accuracy of the model construction.

With respect to the second of Mr. Matthew's suggestions, it developed in later tests, which will be discussed subsequently, that after certain other adjustments were made, the effect of an erroneous division of the Sacramento River flow became evident and was corrected in the model.

His third suggestion was based upon the lack of agreement between model measurements of tidal cycle variation of salinity for equilibrium (steady state) conditions compared to prototype estimates based on measurements made for nonequilibrium (transient) conditions. Unless the salinity gradients were similar for the two different conditions, which is unlikely, agreement could not be expected. Variation of salinity during a tidal cycle is a function of the salinity gradient and the amplitude of tidal flow, which is the distance traveled by the water during the cycle. Since the amplitude of tidal flow of the model was approximately correct as shown by the tidal-verification studies, the disparity between model and prototype tidal cycle variation of salinity was fundamentally one of salinity gradients. This point was illustrated nicely by the tests with the channels simplified to reduce diffusion. Due to the steepening of the salinity gradient, the tidal cycle variation of salinity was greatly increased.

2. Tests with simplified channel. As explained in the first progress report, tidal diffusion in the model was accomplished mainly by the mixing action of the vortices which, admittedly, are distorted

in the model. The vortices resulted from sharp changes in channel shape and alinement and were materially reduced in number when the San Joaquin River between Collinsville and Jersey was replaced by a smooth, uniformly tapering channel. No change was made in the Sacramento River above Collinsville, since the natural channel was practically uniform. The course of the rivers at their junction near Collinsville was straightened by removing parts of the islands in that section; and the connection with the approach channel was made with an easy curve. Several small islands, as well as the flooded area on Sherman Island, were eliminated.

The unbalance in the tidal adjustment resulting from these changes was expected and was not considered important because in these tests the tidal action was regarded only as a mechanism, in a qualitative sense, which caused the advance of salinity. As compared to the Sacramento River, occurrence of tidal phases was advanced in the San Joaquin River, but the shape and the amplitude were nearly correct. It was necessary to partially block Three Mile Slough to prevent excessively high flow to the San Joaquin River.

The results of equilibrium test No. 10, with a net flow of 3,300 second-feet, are shown in figure 2. Salinities at high-high tide for the various stations, referred to 100 at Antioch, were 180 at Collinsville, 5 at Jersey, and 15 at Emmaton. A comparison with a similar test for the original channel, equilibrium test No. 4, first progress report, shows that the salinity gradient was steepened enough to resemble the gradient predicted for 3,300 second-feet in Bulletin 27. As a result of the steepened gradient, the tidal variation of salinity was also increased. The salinity at Antioch varied from 180 at high-high tide to 20 at low-low tide, which is approximately the range measured in the prototype.

The magnitude of the change accomplished by the device of reducing the number and the size of vortices indicated that it could be

used as a tool for adjusting the salinity intrusion of the model. It had been planned originally to adjust the model diffusion on the basis of tests of historical intrusions. Historical tests were difficult to make at best, and when it is considered that in an historical test the intrusion was governed as much by the magnitude and the variation of net discharge as by diffusion, it is apparent that this type of test was not too desirable as a criterion for adjustment of the model. If sufficient prototype data were available for equilibrium or steady state salinity distribution, the model adjustments would have been reasonably straightforward because the variation of net flow would be eliminated. This type of data was not available except for one period ending November 15, 1929, during which time an average net flow of 6,000 second-feet prevailed. The salinity measurements indicated that a steady state had been reached. The only qualifying feature was the fact that the condition occurred after a period of retreat rather than after an advance of salinity, which might make the apparent control flow too high if, as claimed in Bulletin 27, the flow required to effect retreat of salinity of a given degree is greater than the flow required to contain salinity of the same degree.

Overlooking this point for the time, an equilibrium test was made with a net flow of 6,000 second-feet. It was found that the salinity would not advance much beyond Antioch although a high concentration was maintained at Collinsville. The steepness of the model gradient compared to that of the prototype indicated that the diffusion of the simplified channel was much too low. The amount of revision of the simplified channel required to increase the model diffusion and thus decrease the gradient to the correct value was indicated in equilibrium test No. 8, which was described in the first report. In this test it was found that with the original model channels and a net flow of 6,600 second-feet, the model gradient was quite similar to the prototype gradient of November 1929. Although the net flow was not quite right, it was definitely indicated that the diffusion of the original

model channels was nearly correct.

These conclusions relative to the model diffusion were based on the reliability of the November 1929 steady state as a criterion of model performance. The increasing importance of this prototype data made it necessary to establish whether or not its use must be qualified because it occurred during retreat of salinity. According to the eddy diffusion theory, which will be presented subsequently, the steady state values of salinity for a given steady flow are independent of the direction from which the condition is approached, provided sufficient time is allowed for establishment of a true steady state. A rough test in which the steady state for a net flow of 6,000 second-feet was established, after retreat from higher salinities, indicated that the gradient would be approximately the same as the one established during advance of salinity. The test was not conclusive, however, because the salinity gradient with the simplified channel was too steep for a reliable comparison. A more complete test of the same type was scheduled for repetition with the original channels.

Before the simplified channel was abandoned, an historical test was made to determine how much transient conditions were affected by the reduction in diffusion. For this purpose the season of 1929 was selected because abundant prototype data were taken during that season and it included the important steady state. In the first test, the model salinity advanced too far up the San Joaquin River despite the reduced diffusion of the model channel. Although part of the excess was due to the difficulty of controlling salinity at Collinsville, the large model intrusion indicated that the net flow was too low. This point was demonstrated by repeating the test with the net flow altered. The amount of alteration was obtained from the time graph of salinity, corrected to a common tide of 180 percent at Collinsville, a spring high-high tide, shown in figure 3. The marked decrease in the slope of the curve about August 10 was taken as an indication of an increase in net flow. As no appreciable change in river flow occurred at that time, the increase in net flow must have been caused by a decrease in

consumptive use. During the period from August 10 to September 1, the slope of the curve remained more or less constant with a constant river flow; so it was reasoned that the consumptive use was also constant. When a model test was made with the rate of consumptive use lowered by extending the September value forward to August 10, the advance of salinity closely resembled that of the prototype, and the retreat was equally good until November. During November the salinity in the model continued to retreat instead of stabilizing as in the prototype. Apparently the model was attempting to establish the condition which prevailed in the equilibrium test with 6,000 second-feet net flow. This was further proof that the steady state salinity distribution was not as dependent upon advance or retreat as was previously thought. The test also demonstrated that the net flow was a greater factor than diffusion in controlling an historical intrusion.

3. Comparison of advance and retreat. As soon as the original model channels were replaced, a special test was made to determine the effects of advance and retreat on the steady state salinity distribution. Regardless of whether or not the model diffusion is in proper similitude to the prototype, it is a similar phenomenon and would be governed by the same general laws. The general characteristics of the model diffusion would then be applicable to the prototype. Two model tests were made with all conditions the same, except that in the first test the salinity advanced upstream in channels which initially contained only clear water and in the second test the salinity retreated from values which were initially considerably higher than those reached in the steady state. In both tests there was a constant total net flow of 6,000 second-feet consisting of 5,000 second-feet of Sacramento River flow and 1,000 second-feet of San Joaquin River flow which approximates the net river flow of the October-November 1929 period. The estimated division of flow past Antioch was 2,500 second-feet in the Sacramento and 3,500 second-feet in the San Joaquin, although it was not important in this comparative

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test. Due to the variable nature of the tides, it was necessary to make measurements at a given station on identical tides and in general to use considerable care in conducting the tests.

The results, shown below in tabular form, indicate that the same steady state was reached whether the salinity was advancing or retreating. An extended period of time was allowed in each test to insure that a true steady state had been reached, because an apparent difference would exist if insufficient time were allowed.

Station	Prototype Nov. 1929 (Antioch = 100)	MODEL			
		Salinity advancing		Salinity retreating	
		Start	Finish	Start	Finish
Collinsville	150	0	170	520	173
Mayberry	-	0	100	416	93
Antioch	100	0	100	416	100
Emmaton	13	0	25	275	26
Three Mile Slough	7	0	3	300	9
Curtis Landing	50	0	43	300	43
Rio Vista	0	0	0	147	1
Jersey	23	0	22	218	18
Twitchell	-	0	2	60	5
Central Landing	-	0	1	30	4

The difference in the salinity at Three Mile Slough and at Jersey for advance and retreat was attributed to erratic readings and has no special significance. The slightly higher salinities for retreat at Twitchell and at Central Landing were significant because they demonstrated the manner in which salinity from an earlier intrusion can become trapped in the San Joaquin River above Central Landing. As the major portion of the transfer flow reached the San Joaquin River at or below Central Landing, through Georgiana and Three Mile Sloughs, any reduction of salinity in the San Joaquin River above Central

Landing had to be accomplished largely by dilution or negative diffusion. Elsewhere, as in the Sacramento River, the salinity was reduced more quickly by the direct displacement of a positive stream flow.

With the necessity for qualifying the indications of the November 1929 steady state eliminated by the comparative model tests, it was accepted as prototype evidence that for a steady state salinity pattern the total net stream flow required to maintain a mean tidal-cycle-surface-zone salinity of 100 parts of chlorine per 100,000 parts of water at Antioch is approximately 6,000 second-feet. The large discrepancy between this value and the control flow of 3,300 second-feet, which was the amount estimated in Bulletin 27 to accomplish the same purpose, suggested the possibility that the method of analysis used in Bulletin 27 was not complete. Discussion of this method of analysis is deferred until an alternate method of analysis is presented.

Although the prototype division of flow between the two rivers was not necessarily duplicated in the model, it was approximated sufficiently close to allow a comparison of salinity gradients. The fact that model and prototype gradients were similar was further evidence that the model diffusion was close to the correct value. This situation, together with the fact that changes in net flow were shown to have a much greater effect than changes in diffusion, indicated that, for reasons unknown, the net flow used in the previous historical tests was not correct.

4. Prototype data examined. In the light of the indications of the model tests, the prototype data were examined for corroborating evidence and for possible errors in the data used to obtain the values of net flow. These values of net flow were obtained by correcting gross inflow into the Delta for extractions such as consumptive use and additions such as return flow from upstream diversions. The gross inflow was determined from river gagings, with suitable adjustments for extractions and additions outside the Delta limits, and is open to little question. While the consumptive-use values were obtained from

use rates determined by the accepted method of tank measurements, it is estimated that their accuracy is no better than plus or minus ten percent. The schedule of consumptive use shows a variation from 500 to 3,700 second-feet, with the maximum occurring in August. In computing the net flow, it was assumed that consumptive use for any given time interval was supplied by diversion of an equal quantity from the river channels during the same interval. The point is that if, for reasons not clear at this time, there is a time lag between diversion from the river flow and consumptive use, it would explain some of the conflicting evidence.

An examination of Plate LXXX, page 227, Bulletin 27, shows that in the years 1924 and 1926 the maximum salinity at Collinsville occurred at a time when, according to the hydrographs of gross inflow and the consumptive-use curves in the lower portion of the plate, the net flow was practically zero. It hardly seems likely that the salinity intrusion was halted and retreat begun at a time when there was zero net flow. For the years 1920 and 1929, the net flow was positive downstream at the beginning of retreat but amounted to only 700 or 800 second-feet. In 1920 the rise in salinity was abruptly halted and nearly stabilized at a time preceding the occurrence of the maximum salinity, when there was a decreasing negative net flow. All of these indications point towards the probability of higher net flows than those shown.

Additional evidence was obtained by an entirely different approach. In place of the differential equation of eddy diffusion, which will be presented subsequently, a finite difference equation was developed by treating the entire body of water permeated by salt as a unit.

Consider this body of salt water upstream from a given section. The total salt contained in this water is the volume integral of the salinity distribution at any given time. Salt is added to the section more or less continuously by tidal diffusion while salt is being removed by net stream flow out of the section. The salt added by

diffusion is proportional to the salinity gradient $\frac{\Delta S}{\Delta x}$ and the salt removed is equal to the product of the net outflow and the mean salinity $Q_n \overline{S}$. The net change in total salt for an interval of time ΔT is equal to the difference between the two factors over the same interval, irrespective of the distribution of salt through the water prism.

$$\frac{\Delta (S_x V)}{\Delta T} = K \frac{\Delta S}{\Delta x} \pm Q_n \overline{S} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where

$S_x V$ = total salt of water prism,

$\frac{\Delta (S V)}{\Delta T}$ = change in total salt during interval ΔT,

K = diffusion coefficient for the section,

Q_n = average net discharge past section for interval ΔT,

$\overline{S}$ = mean salinity at section averaged over interval ΔT.

The total salt at any given time was evaluated by integrating the curve of measured salinity versus channel volume, and consistent results were obtained. Evaluation of the salinity-gradient term $\frac{\Delta S}{\Delta x}$ proved to be a much more difficult task. An approximation of the term was made by using the difference in salinity between the section under consideration and the next station upstream divided by the distance between the two stations. These values were erratic, and it was necessary to use considerable judgment in selecting the mean value. The mean salinity in the last term was taken from the curves of mean salinity shown in Bulletin 27. The diffusion constant K was evaluated from the steady state data of November 1929. With all the terms known for a given interval, the average value of net flow for the interval was computed by the equation for several months of 1926, with Bullshead Point as the base section, as shown in the following table. The value of K for this station was taken as 2.25×10^5 in miles times acre-feet per day.

Interval	$\frac{\Delta (S_x V)}{\Delta T}$ part per 100,000 times acre-feet per day	$\bar{S}$ parts per 100,000	ΔS	$K \frac{\Delta S}{\Delta x}$	Q (net)		Q (net) = Q (gross) minus consumptive use of Bulletin 27 (sec.-ft.)
					acre-feet per day	second-feet	
June	59.5×10^5	655	280	105×10^5	6,950	3,500	3,930
July	98.0×10^5	1,100	220	82.5×10^5	-1,410	-700	-1,070
August	47.1×10^5	1,430	240	90.0×10^5	2,880	1,440	-1,430

The most significant point shown by the above computation is the difference in the two net flows for August. The value obtained from the actual, measured, salinity intrusion is more than 2,800 second-feet in excess of the value obtained by subtracting the recommended consumptive use from measured gross flow. The two values can be reconciled only by decreasing the consumptive use from 3,700 to 1,000 second-feet. Similar computations were made for other years of record, and, though the values for any month were not consistent enough to warrant inclusion in this report, the same drop in the August consumptive use was indicated in every trial.

The main cause of the inconsistencies was undoubtedly the erratic nature of the values of the salinity gradient $\frac{\Delta S}{\Delta x}$. Probably the best data for evaluating the gradient were the measurements of tidal cycle variation of salinity shown in Bulletin 27. With more of this type of data and some knowledge of the amplitude of tidal flow, a more reliable evaluation of the salinity gradient might have been possible. One of the weaknesses of the method used to approximate the salinity gradient was the assumption that the amplitude of tidal flow was large enough to include the two stations used. If suitable means could be found for evaluating this term from prototype data, equation (1) offers a means by which net flow could be computed from measurements of

salinity intrusion and gross flow.

The data from the special model tests which were made in connection with appendix I, and which will be presented subsequently, were tried in equation (1) with little success. The model intrusion occurred so rapidly and the salinity gradient was so steep at the beginning of the model that it was difficult to select the mean values of the required factors.

5. Historical tests with adjusted net flow. The possibility of improving the model salinity intrusion by adjusting net flow had been apparent since the preliminary salinity verification tests, but it was not exploited until evidence supporting such an adjustment was found. The model tests showed that minor revisions in consumptive use and major changes in diffusion were not effective in reducing the exaggerated intrusion of the model; but when the net flow in the model was increased for the short period of one month, a considerable change in the model salinity intrusion was obtained. This indication was corroborated by the prototype data of Plate LXXX, Bulletin 27, which showed that the net flow obtained in the accepted manner was too low during the months of August and September. Changes in net flow were then considered justified, and a series of tests was made in which the net flow was adjusted to make the model and the prototype salinity intrusions agree. The accuracy of the values of net flow obtained in this manner depended upon the similarity between the model and the prototype diffusion. Similitude relationships, or scale ratios, for diffusion and salinity intrusion were not shown in the first progress report because they could not be developed until the eddy diffusion analysis was introduced into the study. The development of the scale ratios pertinent to salinity intrusion will be demonstrated subsequently when the eddy diffusion analysis is presented. The scale ratio controlling the time rate of change of salinity has the same dimensions as the time rate of discharge, provided the model was adjusted so that it duplicated a known steady state in the prototype. Since the model and the prototype agreed approx-

imately for the November 1929 steady state, at least in the region from Collinsville to and including Jersey, the discharge required to make the model intrusion duplicate the prototype intrusion in this region was approximately the net discharge which prevailed in the prototype.

As a first step in this series of tests, the 1929 historical test, with the simplified channel and the consumptive use decreased after August 10, was repeated with the original channel. Since this test was essentially qualitative, the testing procedure was not held in accordance with a planned schedule. Consumptive use was not taken from the drains but was accounted for by decreasing the river inflow. During the test, the roughness in Three Mile Slough and Georgiana Slough was adjusted several times when the salinity appeared to be advancing too rapidly up either river. It was observed that the amplitude of the tides was less than intended. For example, a 5-foot tide as indicated by the tide cam was only 4-1/2 feet in the model, but the condition was not corrected for this preliminary test.

The results, which were similar to those shown in figures 3 to 7, were sufficiently good to warrant a repetition of the tests under more carefully controlled conditions. A new discharge schedule was prepared by advancing the consumptive-use schedule 20 days. This change was made on the basis that there was a lag of 20 days between diversion from river flow and consumptive use. This appeared to be a more logical way of obtaining the desired net flow than merely lowering the consumptive use after August 10. Consumptive use was actually taken from the drains, although several drains were combined when they were located upstream from the point of greatest advance. In addition, the amplitude of the tides was corrected and the roughness in Three Mile and Georgiana sloughs was fixed.

In the first trial with these revisions, the salinity advanced too fast in the San Joaquin channels. After checking the model and finding nothing wrong, the tidal amplitude was adjusted so that a

5-foot tide was again 4-1/2 feet. The effect of reducing the tidal amplitude was a decrease in tidal flow and consequently a decrease in diffusion, although the change in diffusion was much smaller than the change in tidal amplitude. Since the tide cam was originally cut from the August 1941 records and was being used for other years, the change in tidal amplitude was not considered critical. The shape of the tides and the variation in tidal flow were still correct and could be even a closer approximation of the desired tide than the August 1941 tide. In any event, the adjusted diffusion could be accepted as being more nearly similar to that of the prototype if intrusion was improved by the change.

The adjustment in tidal amplitude improved conditions somewhat, but not nearly as much as was expected, and the salinity still advanced too fast in the San Joaquin channels. It was observed that there was practically no flow down Georgiana Slough. This would account for the obvious deficiency of net flow in the San Joaquin channels. To eliminate any question regarding the magnitude of the transfer flow through Georgiana Slough, which has been troublesome in many of the previous tests, the following procedure was adopted; the slough was blocked at its bifurcation with the Sacramento River, and the estimated transfer flow was added directly to the slough. The Sacramento River flow was decreased by the same amount. The estimated transfer flows were obtained from Plate XXVI, Bulletin 27, which shows the relationship between flow in Georgiana Slough and flow in the Sacramento River based on prototype measurements. This revision improved the model results considerably, and a fair agreement between model and prototype was obtained at all stations except Webb Point, where the salinity was too high (figures 3 to 7). Even at this station the salinity retreated properly, and it was nearly correct at the end of the test. The retreat stopped at all stations when it reached a pattern corresponding roughly to the November steady state of the prototype.

In order to demonstrate that the agreement obtained in this test

was not unique, it was necessary to test the salinity intrusions of other years with the same adjustments. For this purpose the years 1936, 1933, and 1934 were selected and tested in the order listed.

The high flow of the 1936 season allowed only a minor advance of salinity into the Delta; so prototype observations were made only at Collinsville, Emmaton, Antioch, and Jersey. The model intrusion agreed quite well with the prototype, as shown in figure 8. It was observed further that no salinity advanced beyond Jersey.

The low flow season of 1933 was similar to that of 1929 but of shorter duration. The model results are compared to the prototype in figures 9 and 10. Good agreement was obtained at all stations except Central Landing, where the model salinity was similar to that at Webb Pump.

The season of 1934 was very dry with an abnormally large salinity intrusion which has been exceeded by only a few other years of record, such as 1931 and 1924. This season was selected in preference to 1931, which was studied previously, as the curtailment of irrigation would be smaller than in 1931 because of the lesser intrusion. The fact that the consumptive use was decreased substantially in these tests in a large measure compensated for the neglect of curtailment. The results shown in figures 11 to 16 were acceptable although minor improvements could be made. In this test a reasonably close control of salinity was maintained at Collinsville. In general, the advance and the retreat was good in the lower Sacramento River. Above Rio Vista, however, the retreat was somewhat too fast, as shown by the curves at Rio Vista, Junction Point, and Isleton Bridge. Indications were that the transfer flow through Georgiana Slough should have been increased by a small amount after September. The small lag in the retreat for the San Joaquin River indicated the need for a similar adjustment. Good agreement was obtained for Antioch, Curtis Landing, and Jersey, but for stations farther upstream, like Webb Pump, the salinity was somewhat high during retreat.

Model salinities were consistently high at two stations - Orwood Bridge and Central Landing. The high salinity at the first station, in the 1934 test, was the result of the action of a drain located in Old River just upstream from the station. The salinities at points near by, but beyond the effect of the drain, were much lower. The explanation for the high salinities at Central Landing is more uncertain. In all of the tests the model salinity at this station was the same as the salinity at Webb Pump, which was usually in good agreement with the prototype measurements. Observation of flow in the model indicated that there should have been no difference because the water was mixing continually between the two stations. Also, the quantity of water coming down the Mokelumne River and Georgiana Slough did not appear to be enough in a single tidal cycle to account for the difference. There was, however, a very steep salinity gradient in the Mokelumne River near its mouth, and the salinities at Southwest Point, which is only a relatively short distance above Central Landing, were nearly correct in the model. This condition suggests two possibilities: first, that the model location of the Central Landing station should have been moved upstream a short distance in the Mokelumne River; or second, that there was a separation of fresh and saline water in the prototype at the mouth of the river which would account for the lower prototype values. In any case it is interesting to note that model salinities at stations on all sides of Central Landing were in fair agreement with prototype measurements.

It was indicated in each historical test that further improvement could have been obtained by refining the adjustments of net flow. Most of the stations where further improvement seemed possible were located in that part of the Delta where multiple channels existed. For this portion of the Delta, the comparison of model and prototype diffusion on the basis of the November 1929 steady state was virtually impossible because in the prototype data there were too many different factors contributing to the measured salinity and the amount of ocean

salinity could not be segregated. Without such a comparison, the values of prototype net flow could not have been obtained from the model values. So no attempts to further refine the model net flow were made. Besides, the principal objective of this series of tests was to establish the source of the exaggerated model intrusion rather than to evaluate net flow of the prototype.

The possibilities offered by this method of using salinity intrusion as an index for determining net flow are worthy of note. If a model built to a larger scale and extended to San Pablo Bay were available, the method would be simplified and more effective because of the longer time intervals of a bigger model and because of the longer stretch of single channel in which steady state conditions could be studied and adjusted as required.

Despite the fact that no definite conclusions with regard to absolute values of net flow could be drawn from these tests, for the reasons explained previously, the general implications of the test results were valid. The agreement obtained in the four tests provided strong evidence that for the period from July through September, the variation of net flow required to give good model intrusions did not agree with the variation obtained by applying the consumptive-use schedule of Bulletin 27 to the measured gross flows. It was found that the required variation could be approximated by shifting the use schedule ahead in time, at least for the period covered by the tests.

No definite physical basis for such a shift of use schedule can be offered in this report, due to lack of precise information about irrigation practices in the Delta. It is suggested, based on a test described in the Water Supervisor's Report for 1929, that if the ground water is depleted and replenished as was done in this test, there is some basis in fact for a shift in the use curve for its application in computing net river flow. From the standpoint of net river flow, the accounting for consumptive use must be made at the time of diversion from the river channels. It is understood that a study of ground water

by means of wells situated in the Delta is now being made. The purpose of this study is not known to the laboratory, but the results should serve to clarify the question of time lag between diversion from river channels and actual use by the crops of the quantity of water labeled as consumptive use.

If the net flows used in the analysis, by which the control flow was estimated in Bulletin 27, were to be changed in value by virtue of a shift in the consumptive-use schedule, the values of control flow would also be changed. The change probably would not be very large because at the time salinity of 100 parts per 100,000 of water was passing Antioch, there would be only a small change in net flow due to a shift in the use schedule. There must be some other reason to explain the low figure of control flow presented in Bulletin 27, and it probably can be found in the method of analysis used to reduce prototype data.

6. Discussion of tidal-diffusion formula of Bulletin 27. The basic tidal-diffusion formula used in Bulletin 27 (page 209) to reduce prototype data for use in predicting control flows states that

$$C = D \pm S \quad \text{...(2)}$$

and

$$D = C \mp S \quad \text{...(3)}$$

where

C = the total amount of advance or retreat of salinity in a particular channel section, expressed as the volume of channel through which salinity of a particular degree advances or retreats during a particular time interval.

D = tidal diffusion, or the effect of tidal action on the total amount of advance or retreat of salinity (expressed in terms of channel volume) during the same time interval.

S = the net stream flow passing the particular channel section during the same time interval.

Determination of the flow required to control salinity was based upon computation of the quantity D, using data taken during the advance of salinity. When data taken during the retreat of salinity were used, it was found that the values of D were "somewhat greater during retreat than those computed for advance of salinity." At the same time, the shape of the diffusion curves was similar for both advance and retreat. Since the comparative model tests showed that the value of D or control flow for a given salinity was independent of retreat or advance, the variation in D computed by equation (3) must have been due to shortcomings in the equation. The fact that a quantity which should have been constant appeared as a variable suggested that some factor, which was a variable, was not specified in the equation.

Comparing the eddy diffusion equation given in the following section with equation (3), it is apparent that the principal difference is the inclusion, explicitly, of the salinity gradient term in the eddy diffusion equation. While the data used in the control-flow studies of Bulletin 27 must have included this factor, it is not explicitly specified in the equation (3). Unless the salinity gradient was a constant or some definite, repetitive function of the time since the beginning of advance, it would not be expected that correlation of prototype data would be obtained through application of this incomplete equation. The fact that fair correlation was obtained for data taken during advance of salinity indicated that the intrusions used in the analysis did follow more or less the same pattern. However, for retreat of salinity, the pattern changed enough to give an entirely different curve. If data for advance and retreat had been combined, there would not have been correlation. The question naturally arises as to whether the pattern for the steady state condition is approximated during advance or during retreat. As a first approximation it would seem reasonable to assume the steady state as the mean between advance and retreat. The control flow would then be the mean of the values determined during advance and retreat. Since the actual values

which were computed for the period of retreat were not included in Bulletin 27, this approximation could not be tried.

There is substantial prototype evidence which justifies the contention that the control flow as estimated in Bulletin 27 will hold the salinity to the desired maximum at Antioch if future hydrographs are similar to those used in its estimate. One required feature of such an hydrograph is that the low-flow period be of limited duration and that it be terminated before the corresponding steady state is reached. Hydrographs expected under Central Valley project operation will not satisfy this condition. The low-flow period may be very long, and there will no doubt be every opportunity for the steady state to be reached. The effectiveness of the control flow estimated in Bulletin 27 under the expected conditions is highly questionable.

An independent review of the Bulletin 27 control-flow analysis will be found in appendix I of this report.

7. Development of eddy diffusion analysis. As the model testing program developed and the discrepancies with regard to control flow appeared, it became evident that a more complete type of diffusion analysis would be extremely useful. Because it was definitely established by prototype studies that the movement of salinity in the Delta channels is accomplished by turbulence rather than by density flow, as in the case of a salt-water wedge, the turbulent mixing theory of modern fluid mechanics suggested itself as a possibility. During the last several years this theory has been applied with considerable success to problems of fluid stress, heat flow, and suspended load distribution in streams. Its use in analyzing the distribution of salinity in oceans was described by Sverdrup, Johnson, and Fleming,* but so far as is known it has not been used to study

*"The Oceans," by Sverdrup, Johnson, and Fleming, Prentice-Hall, Inc., 1942, p. 159.

the propagation of ocean salinity into tidal estuaries. In this

theory, it is assumed that as the small fluid masses are exchanged between sections of different concentrations, the concentration accompanies the fluid mass. The action can be treated mathematically as a flow of some entity, salinity in this case, which is proportional to the gradient of that entity. The factor of proportionality is a function of the intensity of the turbulence. The equation applied to a small cube of fluid, as given by Sverdrup, is

$$\frac{\partial S}{\partial t} = \frac{\partial}{\partial x}\left(\frac{A_x}{\rho}\frac{\partial S}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{A_y}{\rho}\frac{\partial S}{\partial y}\right) + \frac{\partial}{\partial z}\left(\frac{A_z}{\rho}\frac{\partial S}{\partial z}\right)$$

$$- \left(V_x \frac{\partial S}{\partial x} + V_y \frac{\partial S}{\partial y} + V_z \frac{\partial S}{\partial z}\right) \quad \text{.....(4)}$$

The last term accounts for the effect of stream flow. Neglecting all changes except those in the x-direction, the equation simplifies to

$$\frac{\partial S}{\partial t} = \frac{\partial}{\partial x}\left(\frac{A_x}{\rho}\frac{\partial S}{\partial x}\right) - V_x \frac{\partial S}{\partial x} \quad \text{.....(5)}$$

where

S = salinity,

t = time,

x = horizontal distance (in this case taken along the stream),

$\frac{A_x}{\rho}$ = kinematic eddy diffusion coefficient,

ρ = density of the fluid,

V_x = velocity in the x-direction.

This equation must be simplified before a ready solution can be found. One simplification is to assume that a steady state exists, that is, $\frac{\partial S}{\partial t} = 0$, which reduces the equation to

$$\frac{\partial}{\partial x}\left(\frac{A_x}{\rho}\frac{\partial S}{\partial x}\right) = V_x \frac{\partial S}{\partial x} \quad \text{.....(6)}$$

and if $\frac{A_x}{\rho}$ is assumed to be independent of x and equal to a

constant K, a known solution is

$$S_x = S_o\, e^{-\frac{V_x}{K}} \quad \text{(see appendix I)} \quad \ldots\ldots\ldots\ldots\ldots\ldots(7)$$

where the subscripts indicate the location of the sections, O being the origin and x any other section.

A similar expression can be derived without imposing the restrictions of constancy on the coefficient of diffusion. If it is assumed at any section under steady state conditions that the diffusion of salinity across the section $\frac{A_x}{\rho}\frac{dS}{dx}$ is equal to the salinity lost by reason of the flow across the section $Q_n \bar{S}$ where Q_n = net discharge and $\bar{S}$ = mean salinity, the equation can be written as follows:

$$-\frac{dS}{\bar{S}} = Q_n \frac{\rho\, dx}{A_x} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(8)$$

where the negative sign indicates that $\bar{S}$ decreases as x increases. $\frac{A_x}{\rho}$ can be assumed as some function of x which includes the effect of changes in cross-sectional area as well as the degree of mixing. Integration of the equation gives

$$-\log_e S_x = Q_n \int_o^x \frac{\rho\, dx}{A_x} + C$$

When $x = 0$,

$$\int_o^x \frac{\rho\, dx}{A_x} = 0 \quad \text{and} \quad C = -\log_e S_o$$

so

$$\log_e \frac{S_o}{S_x} = Q_n \int_o^x \frac{\rho\, dx}{A_x}$$

or

$$\frac{S_x}{S_o} = e^{-Q_n \int_o^x \frac{\rho\, dx}{A_x}} \quad \text{(which is a solution of equation 6)} \qquad \ldots\ldots\ldots\ldots\ldots(9)$$

Equations (7) and (9) are important because they apply to the steady state which, in the terminology of Bulletin 27, is the condition of controlled salinity. If sufficient prototype data for steady state conditions were available, the constants of these equations could be evaluated. Either equation could then be used to compute the flow required to control any desired salinity.

Application of a solution of equation (5) to prototype data as well as to certain model data is presented in appendix I, which comprises a memorandum by engineers R. E. Glover and W. H. Jurney of the Bureau's staff. The purpose of this study was the determination of the constants from transient conditions for use with the steady state equation (7). The difficulties inherent in analyzing transient conditions are evident in this study.

Equations (5) and (7) provided the functional relations of the various factors controlling salinity intrusion which were required in formulating the similitude ratios between model and prototype. The ratio of the time rates of change in salinity, prototype to model, according to equation (5), is

$$\frac{\frac{\partial S}{\partial t}_r = \left[\frac{\partial}{\partial x}\left(\frac{A_x}{\rho}\frac{\partial S}{\partial x}\right)\right]_m \left[\frac{\partial}{\partial x}\left(\frac{A_x}{\rho}\frac{\partial S}{\partial x}\right)\right]_r - \left(V\frac{\partial S}{\partial x}\right)_m \left(V\frac{\partial S}{\partial x}\right)_r}{\left[\frac{\partial}{\partial x}\left(\frac{A_x}{\rho}\frac{\partial S}{\partial x}\right)\right]_m - \left(V\frac{\partial S}{\partial x}\right)_m} \qquad \ldots\ldots\ldots\ldots\ldots(10)$$

where the subscript m represents model and the subscript r indicates the ratio, prototype to model, of the various quantities. If the model

and the prototype have similar steady states, equation (6) may be used as a ratio equation.

$$\left[\frac{\partial}{\partial x}\left(\frac{A_x}{\rho}\frac{\partial S}{\partial x}\right)\right]r = \left(V_x \frac{\partial S}{\partial x}\right)r \quad \ldots\ldots\ldots\ldots\ldots\ldots(11)$$

Substituting in equation (10) and clearing,

$$\frac{\partial S}{\partial t}\, r = \left(V_x \frac{\partial S}{\partial x}\right)r \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(12)$$

or

$$\frac{S_r}{t_r} = \frac{V_r S_r}{L_r} = \frac{S_r}{L_r V_r^{-1}}$$

Then $t_r = L_r V_r^{-1}$ which is the same time ratio as the one developed in the first progress report which was used to establish model discharges. If then, the steady state values of $\frac{A_x}{\rho}$ are in proper similitude, as indicated by the similarity of model and prototype gradients, the speed of intrusion and the rate of discharge have the same time ratio and when one is correct in the model, the other is perforce also correct.

8. Model tests to examine validity of eddy diffusion analysis. In order to demonstrate the soundness of the eddy diffusion analysis for both transient and steady state conditions and also to indicate the type of prototype data needed for a complete solution of the Delta salinity problem, a series of special model tests was made.

The first series of tests was made to check the method of computing transient conditions presented in appendix I. In these tests the San Joaquin portion of the Delta was isolated so that it alone was subject to tidal flow. With only one channel system, the uncertainties regarding division of flow between the Sacramento and the San Joaquin Rivers were eliminated and the velocity conditions were definite for any given discharge. Before the start of each test, the model channel

was blocked a short distance below Collinsville and the water below the block was brought to a uniform color. The tests were started by removing the block suddenly and starting the tide-generating machine. Measurements of color were made at the various stations at short intervals of time to determine the time variation of color concentration as shown in figures 1 to 3, appendix I. Tests were made with discharges, in prototype terms, of 2,200, zero, and negative 2,200 second-feet, respectively. The data and their treatment will be found in appendix I.

A second series of tests was made to check the validity of equation (9), which is a solution of the basic equation (5), for certain conditions which were easily arranged in the model. When a steady state of salinity distribution exists, the ratio of salinities at any two stations can be expressed as

$$\frac{S_x}{S_o} = e^{-Q_n K} \qquad \text{.....(13)}$$

since the integral in the exponent of e in equation (9) is a constant between two given stations. Therefore, if steady state conditions are arranged with different values of discharge Q_n the ratio of salinities should vary with discharge according to equation (13).

For this series of tests the model was further simplified by using only the San Joaquin channel. The Sacramento, Mokelumne, Old, and Middle Rivers were blocked to eliminate the uncertain transfer flows through interconnecting channels and to give some approximate semblance of the single prototype channel which exists downstream from Collinsville but which was not included in the model. The testing procedure consisted of establishing a constant discharge in the San Joaquin River, maintaining a constant rate of addition of concentrated color at the bay end of the model, and allowing the model tide to operate until salinities at all stations reached steady values. Careful measurements of color concentration were then taken at Collinsville,

Antioch, Curtis Landing, Jersey, Twitchell, and Webb Point. To eliminate any effect due to variation in tide height, these measurements were taken on identical tides.

Three sets of data were obtained for discharges of 50, 100, and 200 c.s. per 10 seconds, in the model. For each station, the ratio of the salinity at that station to the salinity at Collinsville for each discharge was used to determine three values of the constant K. These ratios were then averaged to obtain the mean value. If, by suitable measurements of the turbulence parameters, the value of K could have been determined independently, this step would have been unnecessary. With K evaluated and station 0 taken at Collinsville, a curve for each station showing $\frac{S_x}{S_o}$ against discharge was computed. The discharge was left in model terms because the values of K apply to the model only. The ratio $\frac{S_x}{S_o}$ is dimensionless and requires no further comment. The measurements of $\frac{S_x}{S_o}$ were then plotted at the corresponding discharge for comparison with the computed curves, as shown in figure 17. The agreement between measured and computed values, which is very close and in most cases within the accuracy of the measurements, constitutes a good check of the eddy diffusion equation.

9. Control of ocean salinity for protection of the Delta. After careful consideration of all the factors involved, the upper limit of acceptable ocean salinity intrusion was defined in Bulletin 27 as a mean tidal-cycle surface-zone salinity at Antioch of 100 parts of chlorine per 100,000 parts of water, with the salinities at points upstream materially less. In order to determine the net flow required to control ocean salinity at or below this limit, it was necessary to know the relationship between net flow and salinity for the steady state condition at Antioch or some nearby station. Such a relationship was determined for the model and is shown by the curves of figure 17. Similar curves could be constructed for the prototype if the required data were available.

Theoretically, the variation of steady state salinity at any station can be computed if measurements of just one steady state are available. For example, in the model tests described in the preceding section, the constant for each station could have been computed from the data for only one discharge without changing the curves appreciably. Since one reasonably well-defined steady state did occur in the prototype in November 1929, it was used to compute a curve of salinity against discharge for Collinsville. Collinsville was selected because it is downstream from the confluence of the two rivers and the problem of dividing the total net flow between the rivers is thereby eliminated. Also, it would serve just as well as Antioch for setting the control flow for protection of the Delta in accordance with the criterion of Bulletin 27. For the purpose of constructing the curve, the 0 station was taken at some indefinite but fixed point in San Pablo Bay where the salinity for the range of discharges used can be assumed as ocean salinity of 1,800 parts of chlorine per 100,000 parts of water. Using equation (12), the variation of salinity at Collinsville, with net discharge, can be expressed as

$$S_c = 1800\, e^{-Q_n K}$$

The constant K was evaluated by using the data from the November 1929 steady state when $S_c = 150$ for $Q_n = 6{,}000$ second-feet, as follows:

$$K = \frac{1}{6000} \log_e \frac{1800}{150} = 4.14 \times 10^{-4}$$

Substituting in the original expression, the equation becomes

$$S_c = 1800\, e^{-4.14\, Q_n \times 10^{-4}} \qquad \text{.....(14)}$$

The curve corresponding to this equation is shown in figure 18. In connection with the study reported in appendix I, a search of the records was made to collect enough prototype data approximating the steady state conditions to permit the construction of an empirical

curve similar to the theoretical curve of figure 18. These data as shown plotted in figure 18 give a reasonably good check of the theoretical curve, especially since they were obtained independently. The procedure used in selecting the data is fully discussed in appendix I.

A similar curve based on Plate LXXVIII of Bulletin 27 is also shown in figure 18. Although the two curves have the same general shape, their location with respect to the axis is considerably different. The two curves provide a graphical illustration of the difference in the control flows which has been discussed previously.

In a further attempt to reconcile the two curves, an entirely different set of data was used. These data were taken from Plate LXXII of Bulletin 27 which contained curves showing the time graph of mean surface-zone salinity at various stations for several years of record. The maximum salinity was reached at about the same time every year during the early part of September. For some of the years the salinity remained roughly constant for a short period before retreat began. When retreat started it seemed to occur more or less simultaneously at all the stations above Bulls Head Point. This would indicate that there may have been an approximation to a steady state salinity distribution at the time retreat started by virtue of an increase in net flow. If this were not the case, it would be expected that retreat would start at different times at each station. It must be remembered that the curves upon which these conclusions were based are averaged curves drawn through data which has been corrected to mean tide. Any selection of specific points, such as the maximum and the beginning of retreat, was at best an inexact method, but the data are presented because they seem to add to an understanding of the difference in the two control curves.

The salinity at the beginning of retreat was selected from the Collinsville curve of Plate LXXII, and the gross inflow into the Delta at the same time was taken from the discharge tables in the back of

Bulletin 27. The net flow required for plotting these data in figure 18 was obtained in two ways. First, the consumptive use was assumed as 1,200 second-feet, which is the value required to make the data agree with the theoretical curve. Secondly, the values of consumptive use were taken from the schedule shown in Bulletin 27. These latter values resulted in points which fell between the two curves, but closer to the Bulletin 27 curve. Assuming that the data apply to conditions which approach those for steady state conditions, these points bear a certain significance. In the first case, it was necessary to assume a consumptive use of only 1,200 second-feet, which represents a greater reduction than the one used in the model intrusion tests. However, when it is considered that the adjusted model consumptive use, which gave fair duplication of the prototype intrusion, was an average of only 2,000 second-feet in September and that even better duplication could have been obtained with a further lowering of consumptive use, the value of 1,200 second-feet does not seem unreasonably low. In the second case, where the consumptive-use values of Bulletin 27 were used, the nearness of the points to the Bulletin 27 curve indicated that if a curve had been drawn based on retreat and then averaged with the one based on advance, it might be close to the location indicated by the points. If this were found to be true, it could be said that the difference between the two curves is a combination of the effect of basing control-flow estimates on advance only and the effect of using a net flow which was too low.

The net flow required to maintain any desired salinity at Collinsville may be selected from the theoretical curve shown in figure 18. If it had been important to estimate the salinities at other stations, similar curves could have been constructed to show the relation between the salinity at Collinsville and any other station, provided sufficient data were available. From the standpoint of controlling ocean salinity according to the criterion in Bulletin 27, this was not considered necessary because the November 1929 steady state was very close to the desired condition. The salinities during this period were approximately

150 at Collinsville, 110 at Antioch, and materially less at stations farther upstream. If the effect of residual salinity trapped in the San Joaquin River were eliminated, it is estimated that the salinity at Antioch would have been very close to 100 parts of chlorine per 100,000 of water. The total net flow in both rivers, required to maintain a mean salinity at Antioch of 100 parts of chlorine per 100,000 parts of water, would then be the same as the net flow which prevailed during the November 1929 period, or approximately 6,000 second-feet. This value compares favorably with the value of 5,500 second-feet obtained in the independent study reported in appendix I.

10. Control of ocean salinity for protection of the Delta-Mendota water. The criterion for determining the flow required to protect the Delta-Mendota pumping plant intake against contamination by ocean salinity is the "Contract for Exchange of Waters." The terms of this contract require that the total pollution added to the water which is transferred from the Sacramento River be held to 35 percent of the average original pollution of said water. When it is considered that the original pollution of the Sacramento River water is expected to be 120 parts per million of total dissolved solids, or less, it is apparent that the added pollution must be less than 42 parts per million total dissolved solids. Of the total pollution which might be added to the transfer water other than from the San Joaquin River, which will be treated separately later, some portion of it would no doubt originate in the drainage water from irrigation in the Delta. Therefore, the amount of pollution from ocean salinity must be held below 42 parts per million total dissolved solids.

To forestall any confusion arising from the use of two different methods of expressing pollution, the methods were correlated. In the preceding pages the method used in Bulletin 27 has been followed. Pollution was expressed as so many parts of chlorine per 100,000 parts of water. If the origin of the pollution is ocean water, there is a definite relationship between chlorine content and total dissolved

solids. This relation was given by Sverdrup, et al.,* as:

$$\text{salinity} = 0.03 + 1.805 \times \text{chlorinity}$$

*Loc. cit., page 51.

Neglecting the constant, which is not important in this study, the total dissolved solids in parts per million equals approximately 18 times the chlorine content in parts per 100,000 when the source of the dissolved load is ocean water. The equivalent of 42 parts per million is then 2.3 parts of chlorine per 100,000. The allowable ocean salinity at Delta-Mendota pumping plant, in the absence of pollution from any other source, is only approximately 2 percent of the allowable salinity at Antioch.

It was demonstrated by model tests that operation of the State Plan changed conditions in the Delta in only one respect for net flows varying from 3,000 to 6,000 second-feet. This change occurred along the route by which the bulk of the Delta-Mendota supply was conveyed to the pumping plant intake. This route comprised the stretch of Old River from the mouth of the Mokelumne River to the intake. The negative average flow in this reach resulted in a uniform salinity for all stations located thereon, including Webb Point, Webb Pump, Contra Costa Canal intake, and the Delta-Mendota pumping plant intake. This uniform salinity had a value approximately equal to the salinity which existed at Webb Pump for the same net outflow under natural conditions. In the first progress report the reference station for predicting the amount of ocean salinity in the Delta-Mendota water was taken at the mouth of the Mokelumne River because most of the mixing of transfer water and water contaminated with ocean salinity occurred at this point. The salinity station closest to this point was Webb Point, but for some unknown reason only very few records were taken at this station. The next closest station was Central Landing on the Mokelumne

River. The historical tests with adjusted net flow showed that while the agreement between model and prototype was poor at Central Landing, which is only one-half mile up the Mokelumne River from its mouth, it was good at Webb Pump where the model salinity was equal to that at the mouth of the Mokelumne River. Because of the better agreement at Webb Pump, it was selected as the reference station instead of Webb Point or the mouth of the Mokelumne River.

To determine the flow required to protect the Delta-Mendota intake against contamination by ocean salinity, it was necessary to know the relation between net flow and steady state salinity at Webb Pump. An attempt was made to construct a curve for Webb Pump similar to the one shown for Collinsville in figure 18. The attempt was unsuccessful because very little reliable prototype data could be found, particularly for periods when low salinity prevailed at Webb Pump. It was impossible to segregate ocean salinity from the various factors contributing to these low salinities, such as pollution from river water, from drainage water, and from previous intrusions of ocean salinity. The rough estimate which was obtained indicated that the net flow required to hold the ocean salinity at Webb Pump, and thus at Delta-Mendota, below the tolerable value may be less than the flow required to maintain 100 parts of chlorine per 100,000 parts of water at Antioch. The theoretical value of 4,650 second-feet given in appendix I corroborates this finding. Because of the approximations involved in this finding and the fact that pollution by drainage water would be additive to any ocean salinity at Webb Pump, it is suggested that the control flow be established on the basis of allowable salinity at Antioch.

11. Pollution from San Joaquin River. A few preliminary tests which showed that San Joaquin water reaches the Delta-Mendota pumping plant intake northwest of Tracy in appreciable quantity were reported in the first progress report. The seriousness of this situation became evident when predictions of the quality of this water were re-

ceived from the Branch of Project Planning. These estimates showed discharges varying from 600 to 2,000 second-feet and pollutions varying from 1,000 to 2,000 parts per million of total dissolved solids. It requires only a small amount of this type of water to raise the dissolved load of the Delta-Mendota water above the maximum allowed by the contracts which specify its quality.

It had been planned originally to determine Delta-Mendota pollution by ocean salinity and by San Joaquin water concurrently by using dyes of different color to identify each source of pollution. Since each source constituted an entirely separate and distinct problem, each was studied and tested by itself. To determine the amount of San Joaquin water likely to reach the pumping plant, it was colored with the "Patent Blue" dye which had been used previously to assimilate ocean salinity. With the San Joaquin water held to a constant concentration and all other water originally clear, the proportion of San Joaquin water at any point was determined with the spectrophotometer which was described in the first progress report. After a few preliminary observations, it was evident that the model tests could be simplified without introducing any appreciable error by eliminating consumptive use and concentrating entirely on local conditions from the San Joaquin River through Old River to the pumping plant intake. The difference between the Delta-Mendota discharge and the San Joaquin flow was supplied by transfer of water from the Sacramento River; so there was no net flow from the model. The contemplated dredging of Old River from Grant Line Canal to the pumping plant was not assimilated in the model, because hydraulic losses in the model are not accurate enough to warrant it and because, as shown by the test results, the benefit of the dredging would not offset or materially change the high proportion of San Joaquin water reaching the pumping plant. The test conditions and the results are shown in the following tabulation.

Discharge in second-feet		Portion of San Joaquin going to Delta-Mendota (in percent)	Part of total pumping represented by San Joaquin water (in percent)
San Joaquin River	Delta-Mendota pumping		
600	4,600	100	13
1,000	4,600	100	22
2,000	4,600	78	34
500	2,500	100	20
1,000	2,500	88	35
2,000	2,500	65	52

In every case, all or nearly all of the San Joaquin flow was drawn into the pumping plant. In those cases where less than the entire flow entered the pumping plant, that part which continued down the San Joaquin River would have eventually found its way back, in part, to the pumping plant by mixing with the transfer water from the Sacramento River. This would have taken some time to develop, and, since the tests were not continued over a long interval of time, the measured values were conservatively low. The large portion of the San Joaquin flow entering the pumping plant is not surprising when it is considered that for low flows with no draft head from a pumping plant to assist it, approximately 25 percent of the San Joaquin flow, as estimated by Army Engineers, travels down Old River past the site of the proposed pumping plant. This percentage would be increased greatly under the influence of the draft head for a pumping load of 4,600 second-feet.

The seriousness of this situation can be illustrated best by an example. Assuming a quality of the San Joaquin River water of 1,000 parts per million and of the Sacramento River water of 150 parts per million, with the lowest ratio listed in the table, the quality of the Delta-Mendota water would be:

$$0.13 \times 1{,}000 + 0.87 \times 150 = 130 + 130 = 260 \text{ p.p.m.}$$

exclusive of any contamination added by ocean salinity or water of

the Delta channels. An increase of 90 parts per million occurs under the most favorable condition tested. In view of the fact that under the terms of the water exchange contract increases of only 30 to 50 parts per million may be critical, the importance of pollution by San Joaquin River water is evident.

In an attempt to relieve this situation, a dam was installed in Old River just downstream from its bifurcation with the San Joaquin River. In theory, the dam, which prohibits direct access to the pumping plant, would constrain the San Joaquin River until it reached the Stockton ship channel where there would be an opportunity for it to mix with the total transfer flow. Under these conditions the portion of the transfer flow which provides the net outflow for controlling ocean salinity would carry with it some part of the San Joaquin flow.

The effect of the dam was tested under model conditions which included river flows, in prototype terms, of 11,100 second-feet in the Sacramento and 1,000 second-feet in the San Joaquin. The disposition of these river flows was: salinity control, 5,500; Delta-Mendota pumping, 4,600; and consumptive use, 2,000 second-feet. Transfer of water from the Sacramento River to the San Joaquin River was made up of 7,680 second-feet through Snodgrass and Georgiana Sloughs and 900 second-feet through Three Mile Slough.

The San Joaquin River flow was colored with a definite concentration of blue for identification. Color appeared in the Stockton ship channel 4 days (prototype) after the start of the test, and in the Delta-Mendota water 20 days after the start, but it did not reach its maximum concentration at the latter point until 1-1/2 months later. When the maximum steady concentration was finally reached, 55 percent of the San Joaquin flow was contained in the Delta-Mendota water. A large portion of the colored water appeared to be taking advantage of a short cut from the Stockton ship channel to Middle River through Turner Cut. When a dam was installed in Turner Cut, the improvement was only temporary; so it was removed. The numerical value of the

measured ratio (55 percent) indicated that the Sacramento River water being transferred through Georgiana and Snodgrass Sloughs (7,680 second-feet) and the San Joaquin flow, less the consumptive use upstream from the mixing zone (800 second-feet), were mixing nearly 100 percent. Assuming 100 percent mixing, the percentage of the total San Joaquin water going to Delta-Mendota would equal the ratio of the pumping load of 4,600 second-feet to the total available mixed water of 8,480 second-feet (7,680 + 800) or 54 percent. The balance of the San Joaquin flow was carried from the Delta with the net outflow. For estimating purposes it can be assumed that the dam in Old River reduced by 50 percent the percentage of San Joaquin water in the Delta-Mendota water and resulted in nearly the optimum quality of Delta-Mendota water which may be obtained by mixing the San Joaquin flow, corrected for extractions upstream from the mixing zone, roughly upstream from Rindge Pump, with the transfer flow through Georgiana and Snodgrass Sloughs.

The idea of using dams to control flow in the Delta was carried to an extreme in the model. The transfer flow of Snodgrass Slough was forced by a series of dams to flow down the South Fork of the Mokelumne through White and Fourteen Mile Sloughs into the ship channel at a point upstream from Rindge. From there the portion required for net outflow passed downstream and the Delta-Mendota water flowed up the San Joaquin River to a pumping plant on the San Joaquin just downstream from its bifurcation with Old River. A dam just upstream from this site forced the San Joaquin River flow to pass down Old and Middle Rivers. The points where the two flows crossed the ship channel were far enough apart and the net outflow great enough that no mixing occurred and all the San Joaquin flow passed out of the Delta. When some of the dams controlling the transfer flow were removed, there was some mixing and part of the San Joaquin water reached the Delta-Mendota intake. The control dams need not necessarily be complete obstructions of flow and could probably perform their function of training the flow even though an opening for navigation were provided

thorugh them. It is apparent that the southwest portion of the Delta would receive undiluted San Joaquin water, which might be objectionable.

12. Conclusions. Subject to confirmation by prototype tests of certain critical data and to the model limitations, the following conclusions are drawn:

1. Diversion and transfer of Sacramento River water through natural channels according to the so-called State Plan affected conditions in the Delta in only one respect. The ocean salinity at Webb Pump remained unchanged, but the entire stretch of Old River from its mouth to the Tracy pumping plant assumed a salinity equal to that at Webb Pump, due to the negative average flow in this reach. The ocean salinity at Contra Costa Canal intake was approximately the same as that at Webb Pump.

2. With the ocean salinity at Antioch controlled by stream flow to 100 parts of chlorine per 100,000 parts of water, the salinity at Webb Pump will be limited to a fraction of a part per 100,000 and may be completely absent.

3. The net stream flow in both rivers past Antioch required to maintain 100 parts of chlorine per 100,000 parts of water over an extended period of time was indicated to be 6,000 second-feet instead of the 3,300 second-feet predicted in Bulletin 27.

4. When ocean salinity was controlled by the required net stream flow and the proper division of it between the two rivers, the quality of the Delta-Mendota water was principally determined by the quality and the quantity of San Joaquin River flow.

5. When no preventative measures were taken, practically

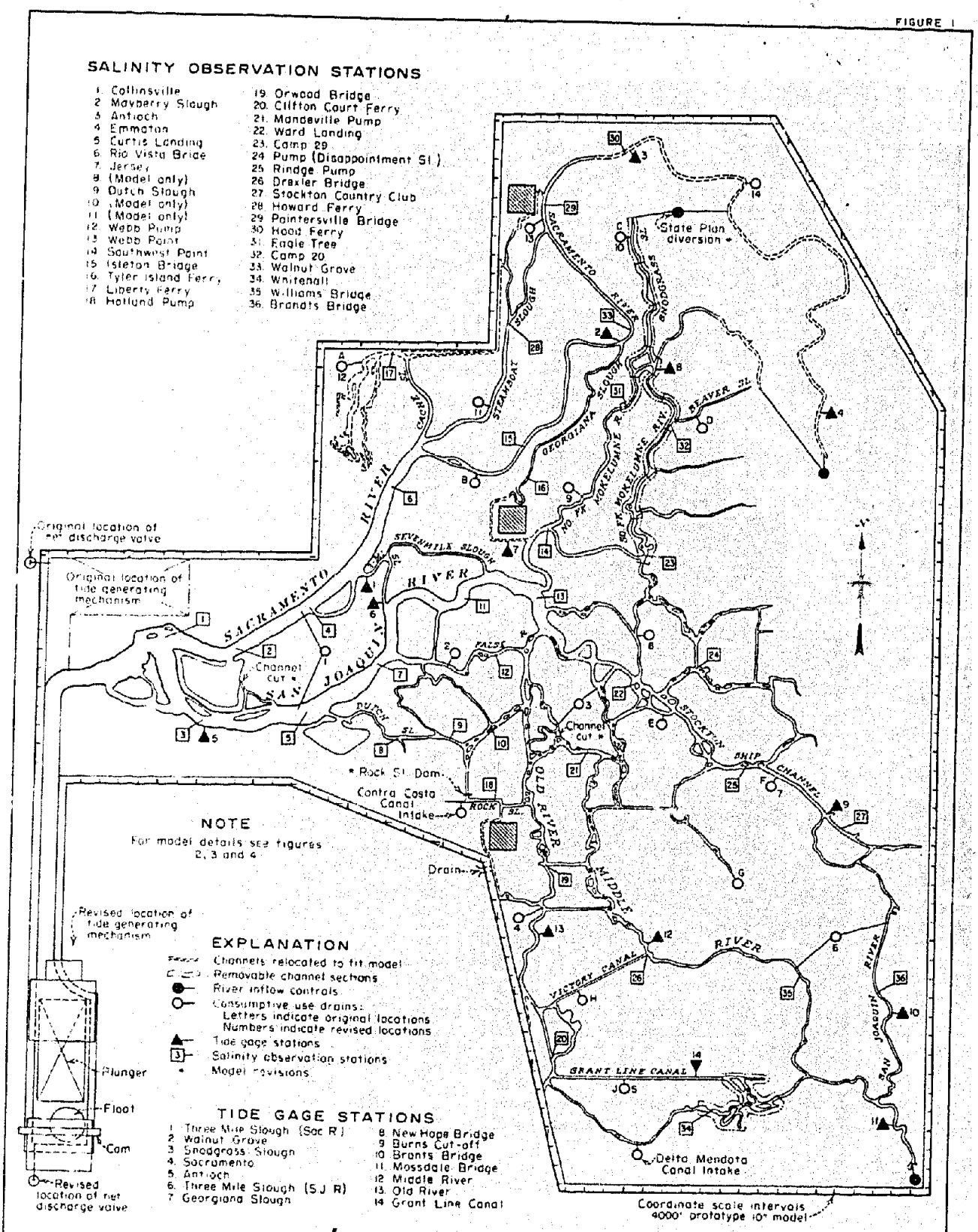
all the San Joaquin flow was drawn into the Delta-Mendota pumping plant by reason of the draft head induced by pumping.

6. With the State Plan in operation, approximately one-half of the San Joaquin flow was eliminated from the Delta-Mendota water by constructing a dam in Old River below its bifurcation with the San Joaquin River.

13. Proposed prototype test. Of the conclusions stated in the preceding section, the second and third are the most controversial. Their importance at the present time depends entirely upon the value of water which will be great enough eventually, if not now, to require confirmation of the amount of water necessary to control ocean salinity both for protecting Delta use and for insuring that no adverse contamination of Delta-Mendota water occurs under operation of the State Plan.

Because of the discrepancy between the control flow estimated from prototype studies in Bulletin 27 and that predicted in this report, the most satisfactory method for confirming the true value would be certain prototype tests. The reasons for questioning the results based on previous tests as given in Bulletin 27 have been fully discussed. As contrasted with prototpye tests made in the past, the proper confirmation of control-flow value can be supplied only by prototype tests made under conditions closely resembling those expected during project operation when the net flow required to control salinity may be held constant for an extended period of time. It is essential that the net flow during the period of test be known with some degree of certainty. This type of prototype test can be made only when the inflow to the Delta can be controlled while a steady state salinity pattern develops. Heretofore it would have been impossible to arrange such a test, but with Shasta Dam on the Sacramento River and Friant Dam on the San Joaquin River, it would seem that the necessary control of stream flow is available.

FIGURE 1



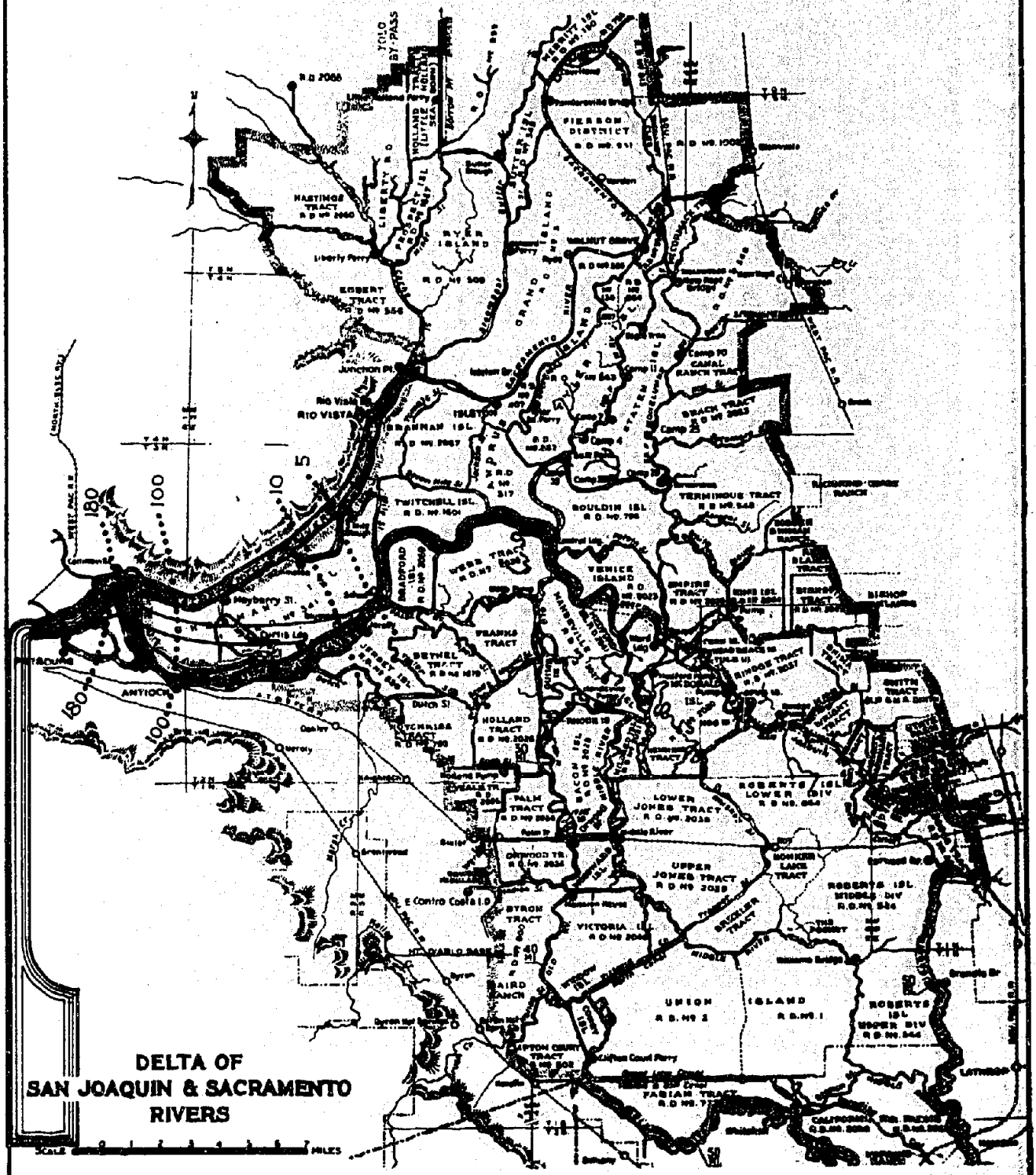
HYDRAULIC MODEL OF SACRAMENTO - SAN JOAQUIN DELTA

MODEL SCALES 1:4800 Horizontal
1:100 Vertical

EXPLANATION

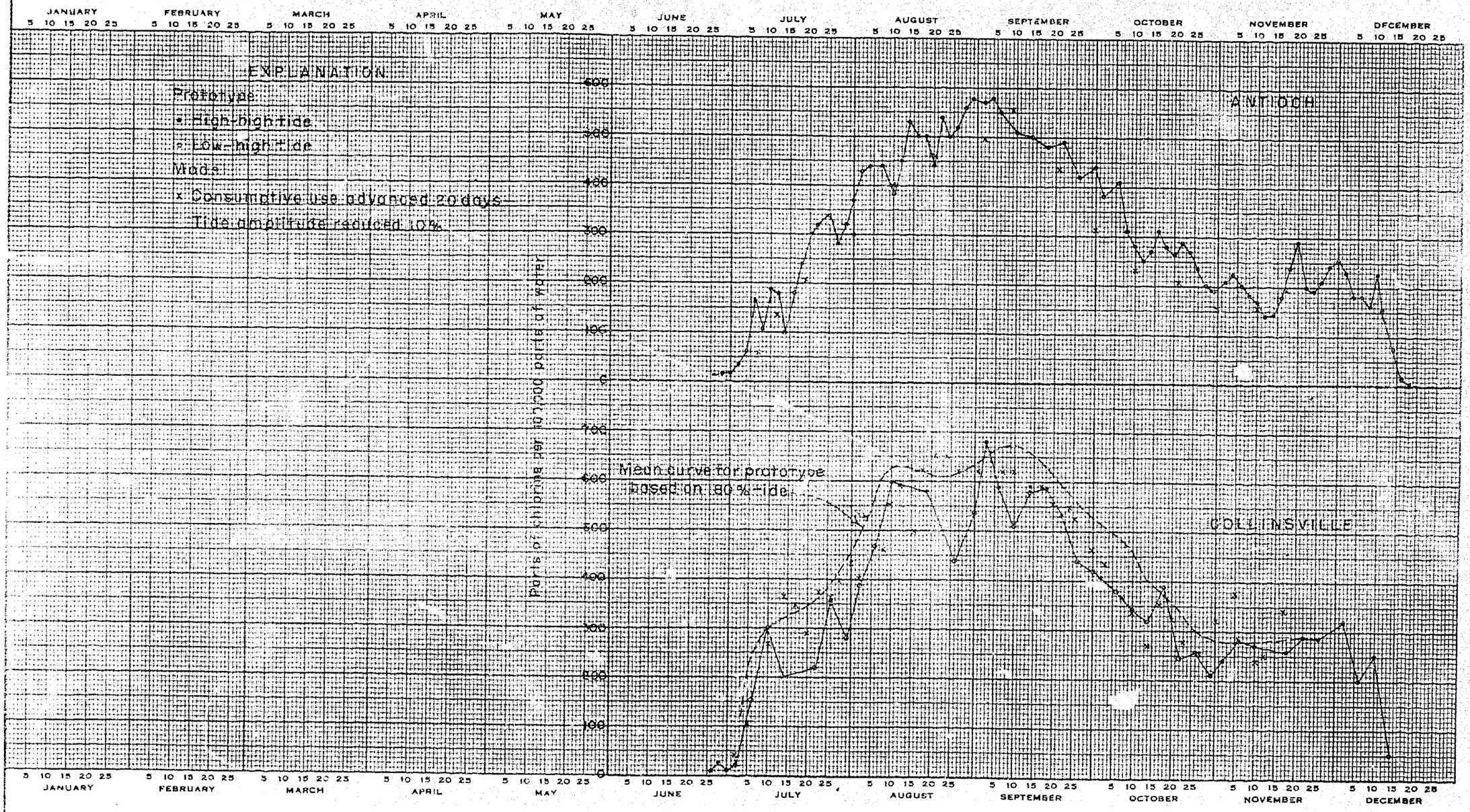
EFFECT OF SIMPLIFIED SAN JOAQUIN CHANNEL
NO CONSUMPTIVE USE - NET FLOW = 3,300 C.F.S.

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



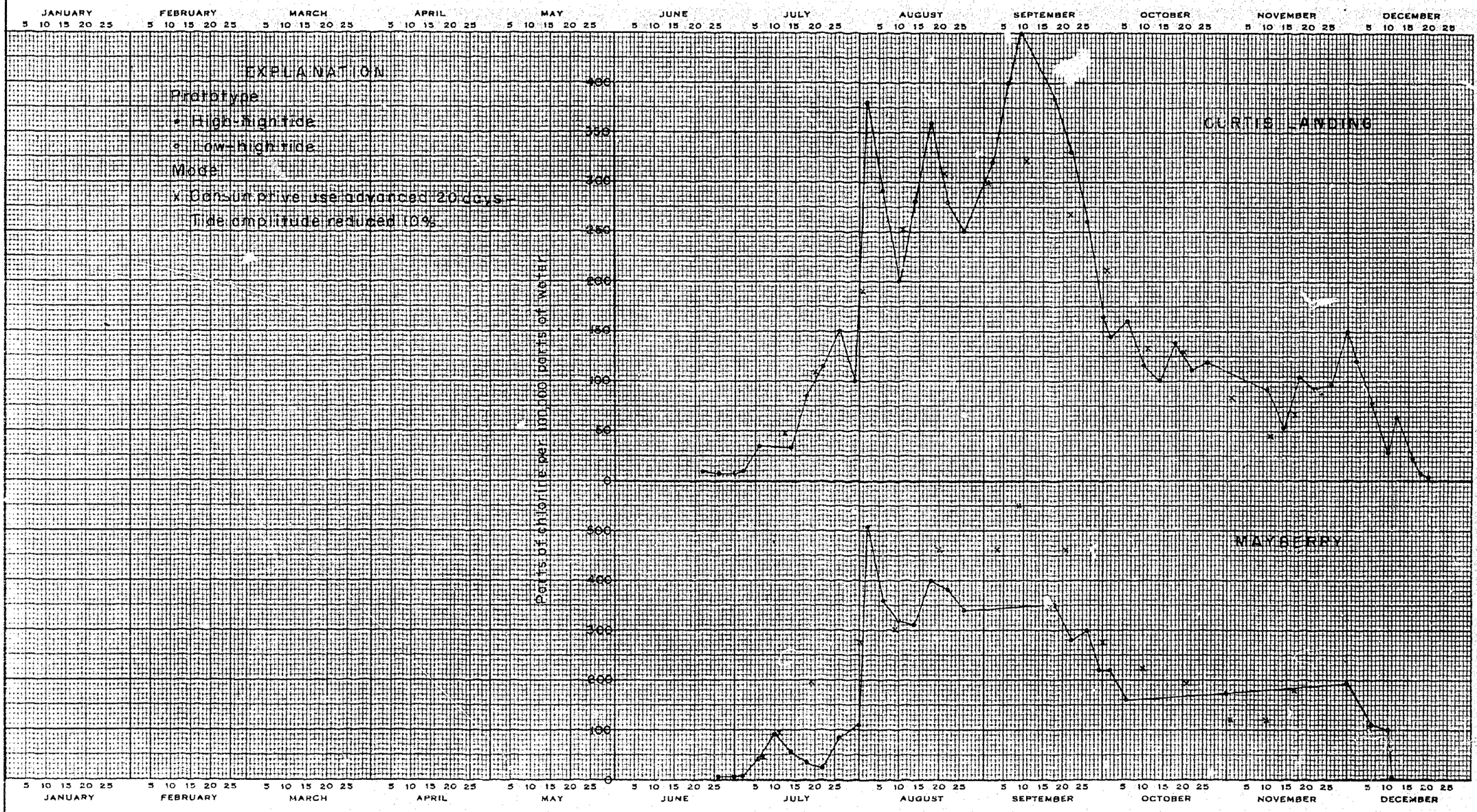
EQUILIBRIUM TEST NO. 10

FIGURE 3



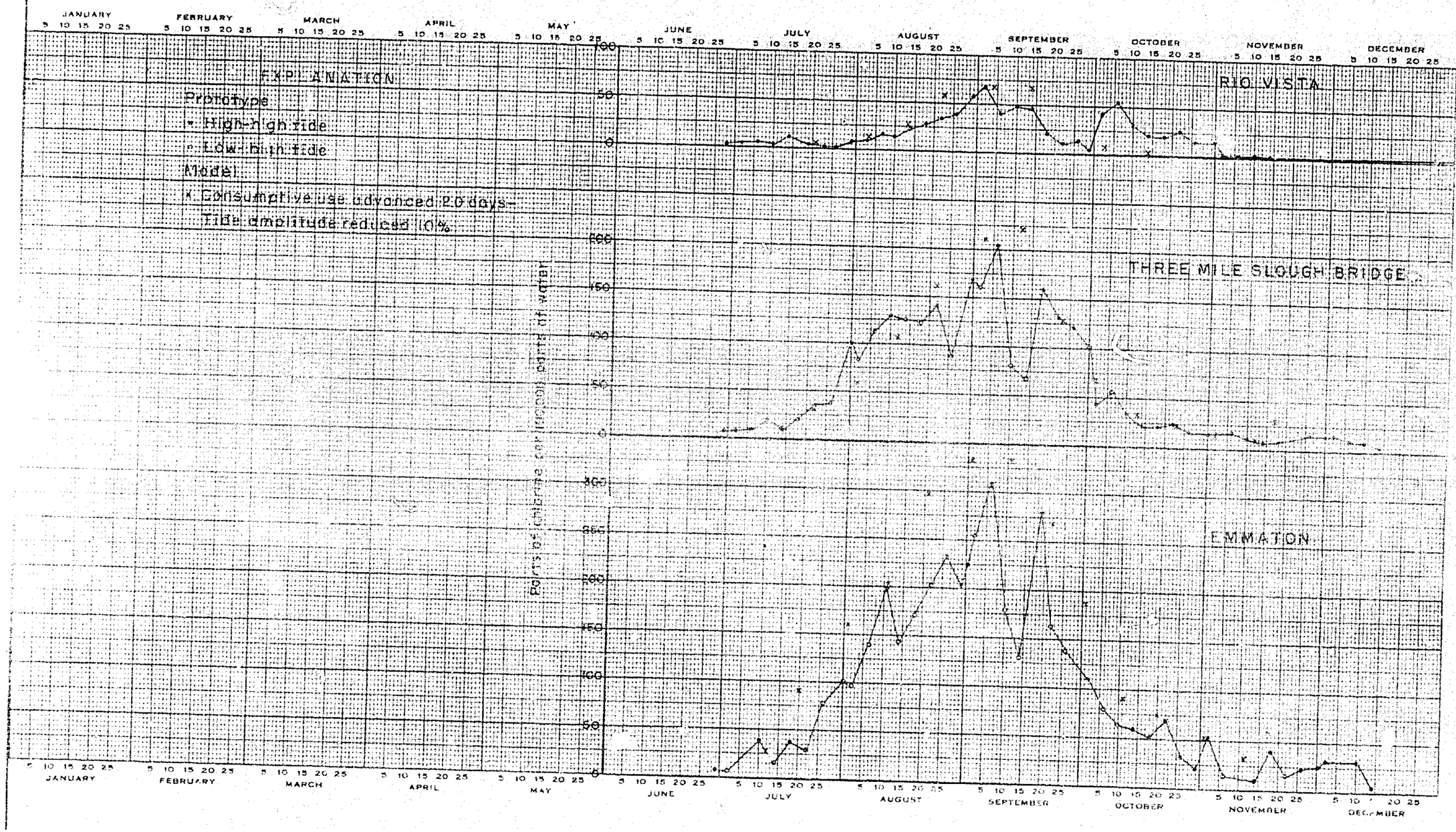
SACRAMENTO - SAN JOAQUIN DELTA
SALINITY CONTROL STUDIES 1:4800 MODEL
SEASON OF 1929

FIGURE 4



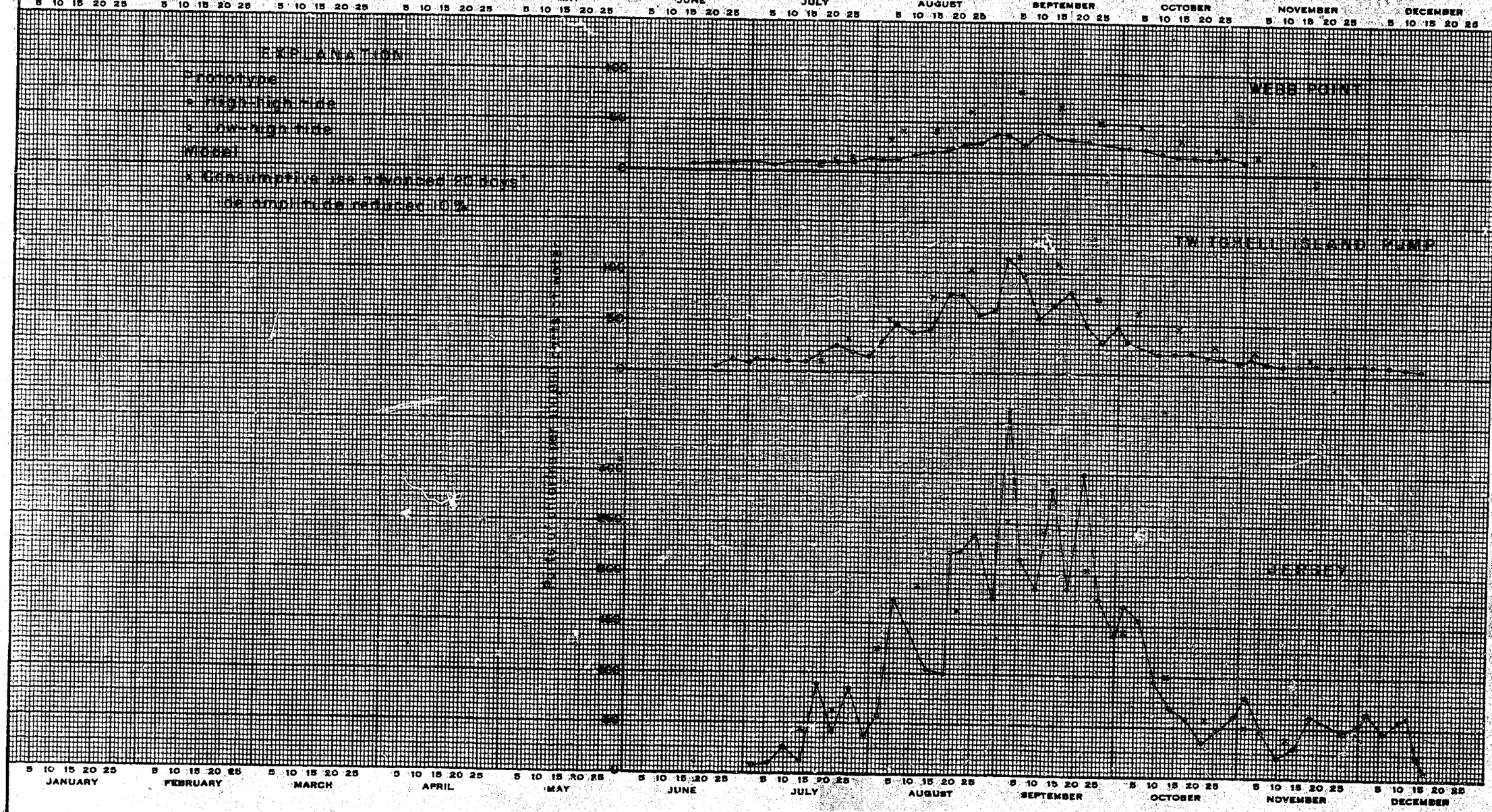
SACRAMEN[illegible]-SAN JOAQUIN DELTA
SALINITY CONTROL STUDIES 1:4800 MODEL
SEASON OF 1929

FIGURE 5



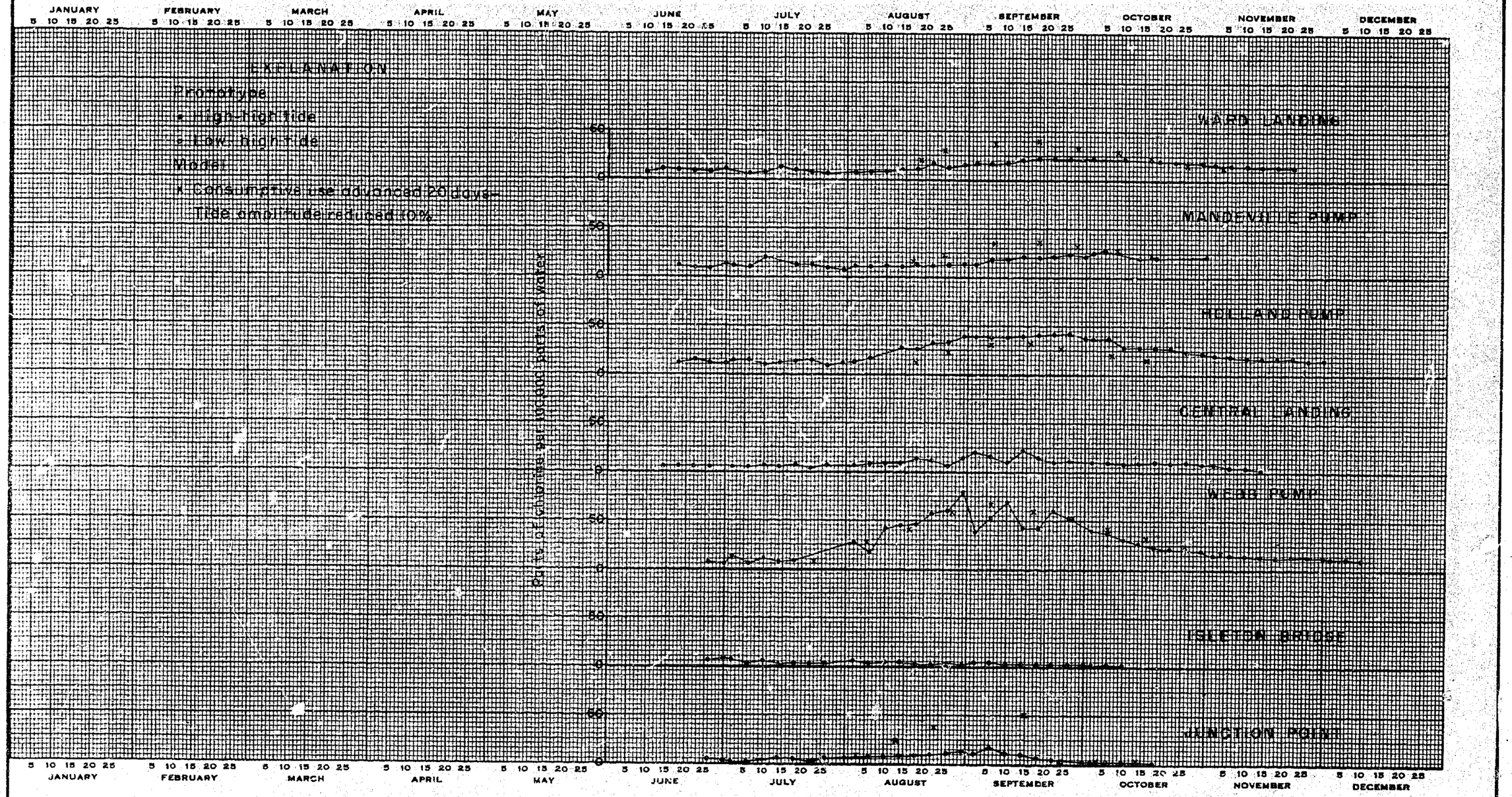
SACRAMENTO SAN JOAQUIN DELTA
SALINITY CONTROL STUDIES 1:4800 MODEL
SEASON OF 1929

FIGURE 6



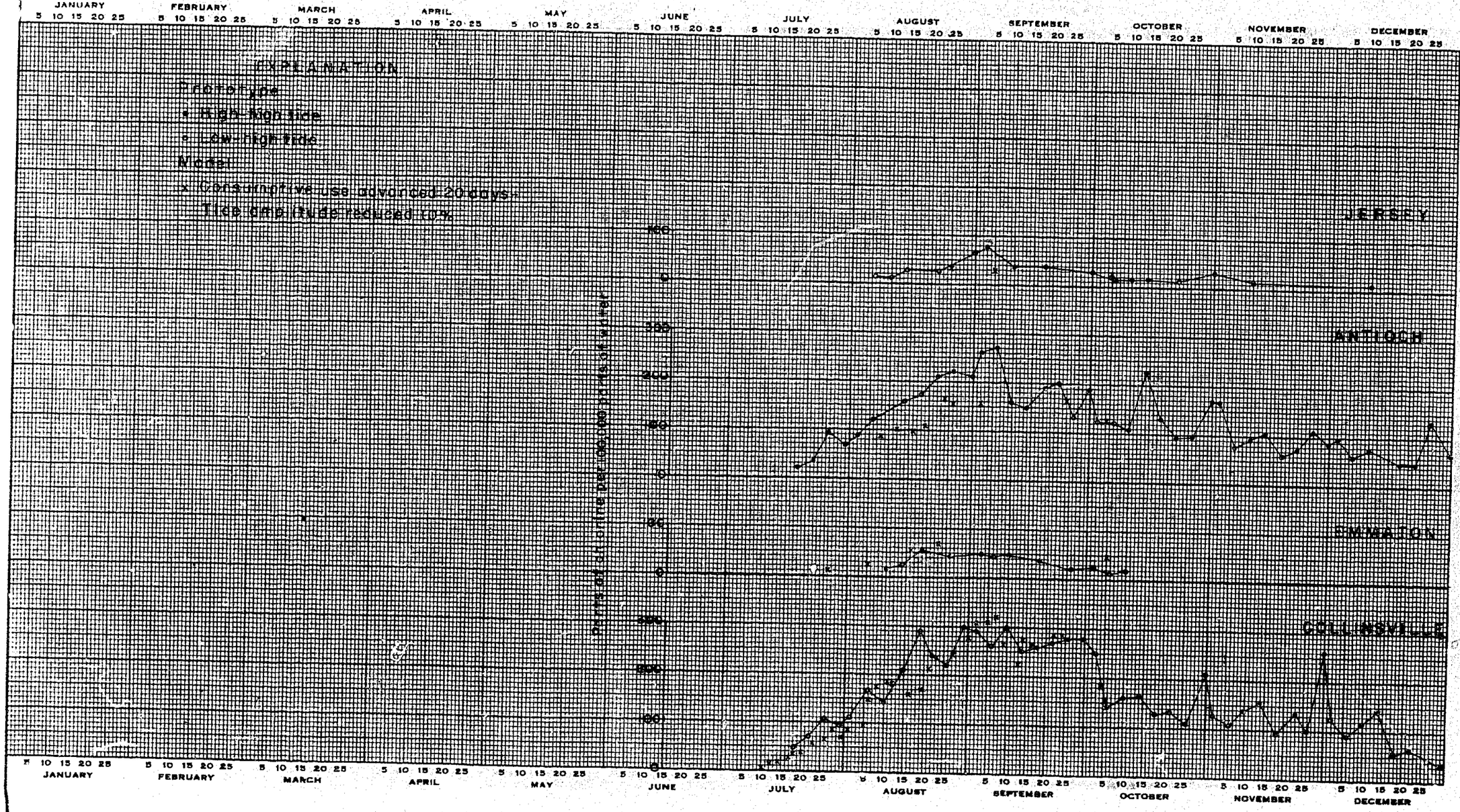
SACRAMENTO - SAN JOAQUIN DELTA
SALINITY CONTROL STUDIES 1:4800 MODEL
SEASON OF 1929

FIGURE 7



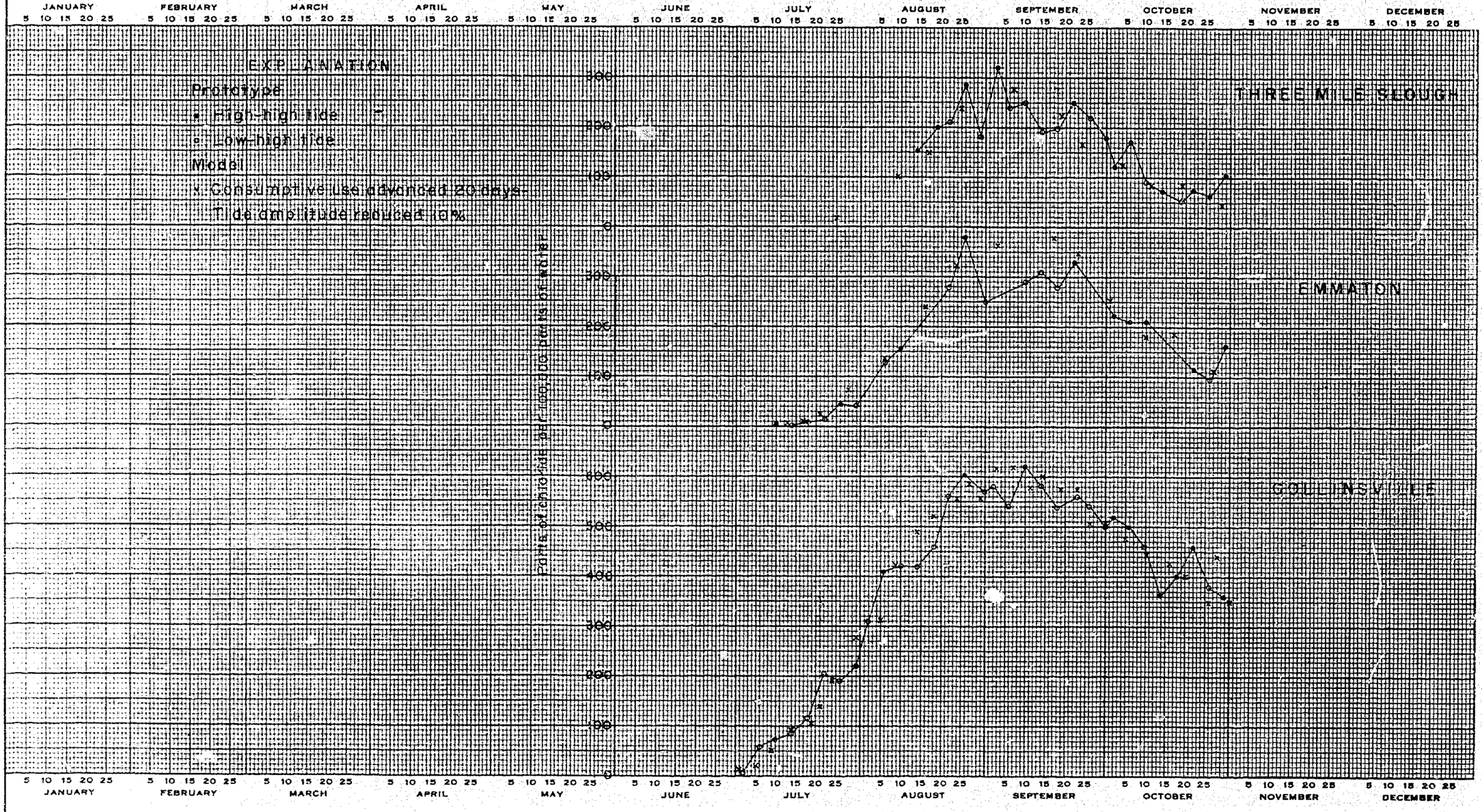
SACRAMENTO - SAN JOAQUIN DELTA
SALINITY CONTROL STUDIES 1:4800 MODEL
SEASON OF 1929

FIGURE 8



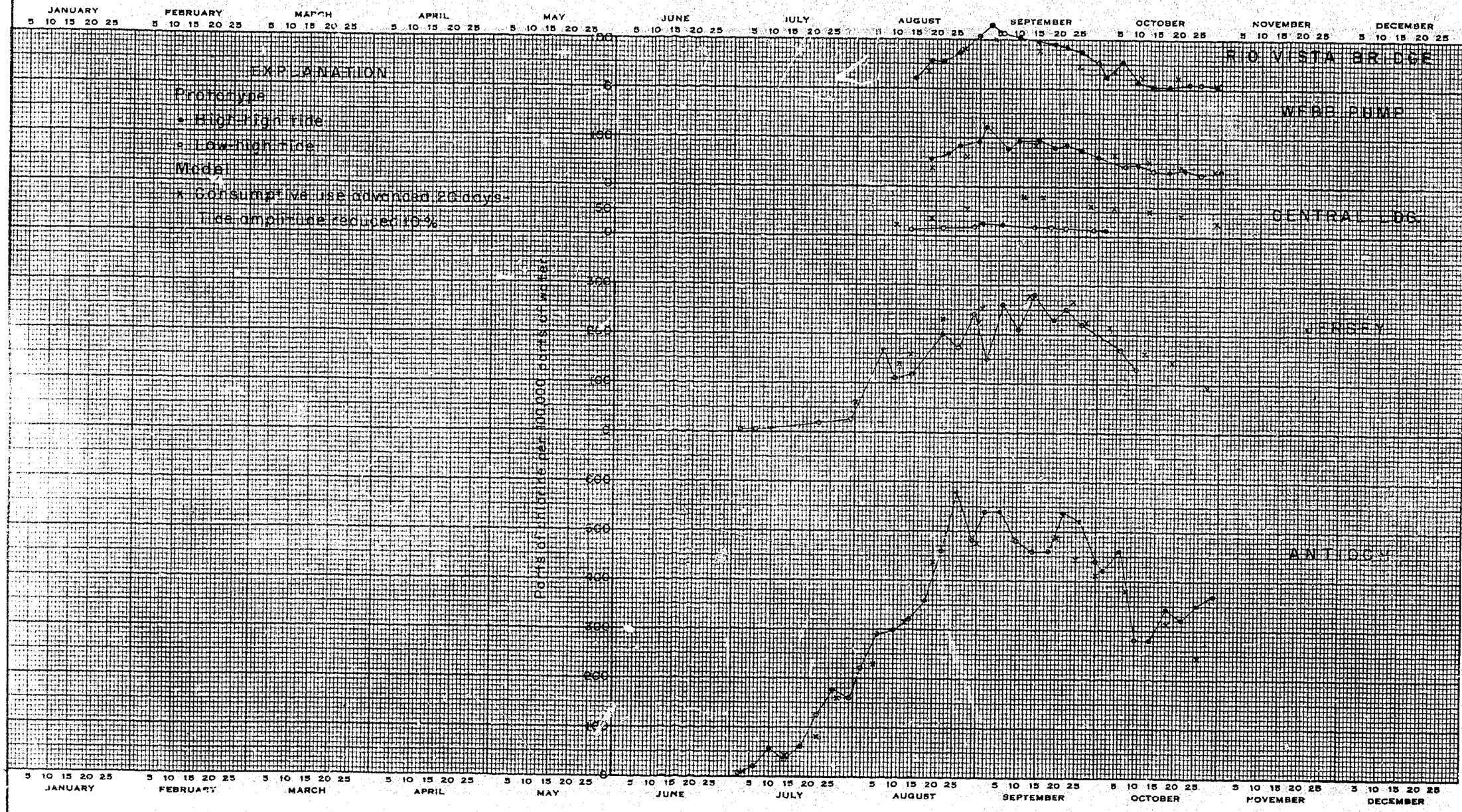
SACRAMENTO - SAN JOAQUIN DELTA
SALINITY CONTROL STUDIES 1:4800 MODEL
SEASON OF 1936

FIGURE 9



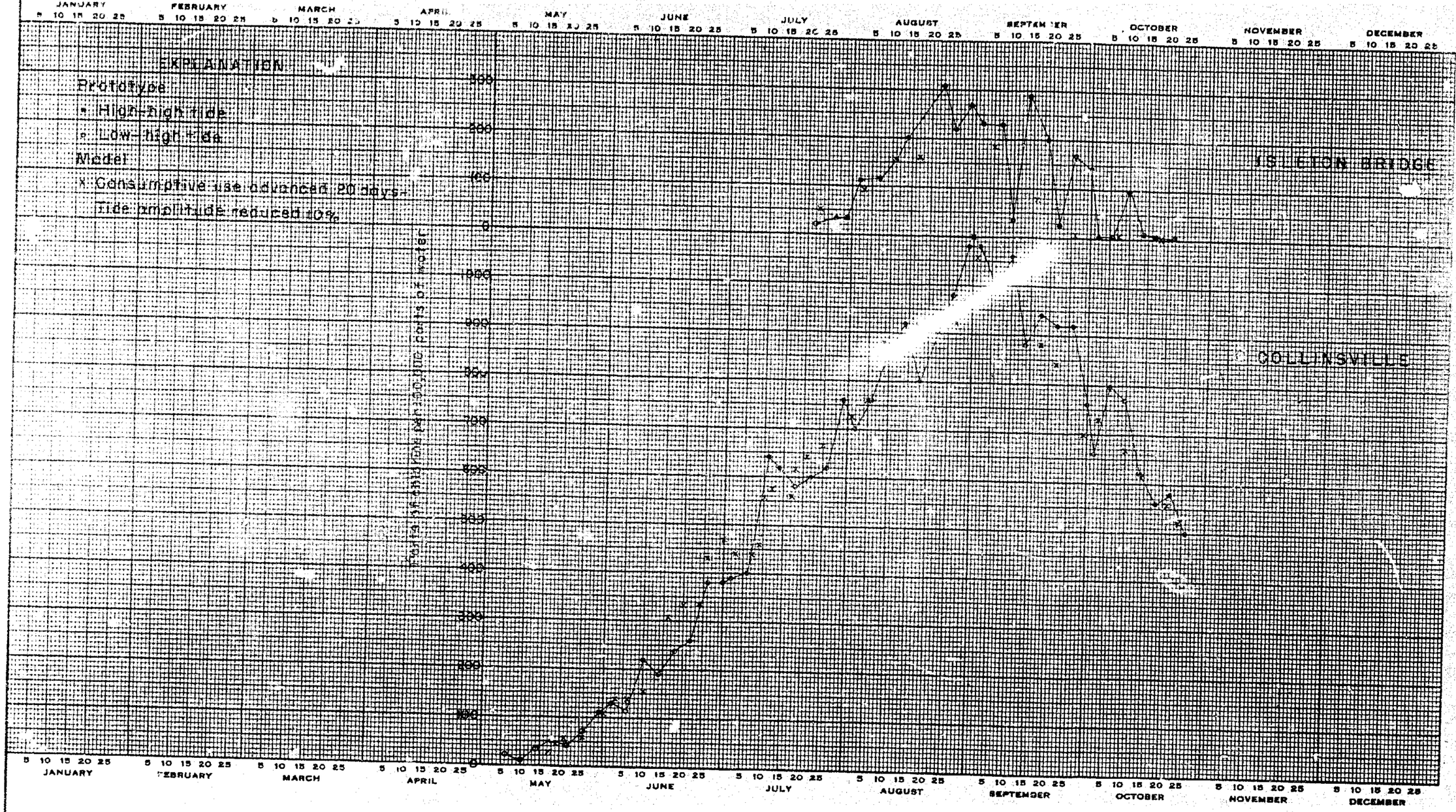
SACRAMENTO – SAN JOAQUIN DELTA
SALINITY CONTROL STUDIES 1:4800 MODEL
SEASON OF 1933

FIGURE 10



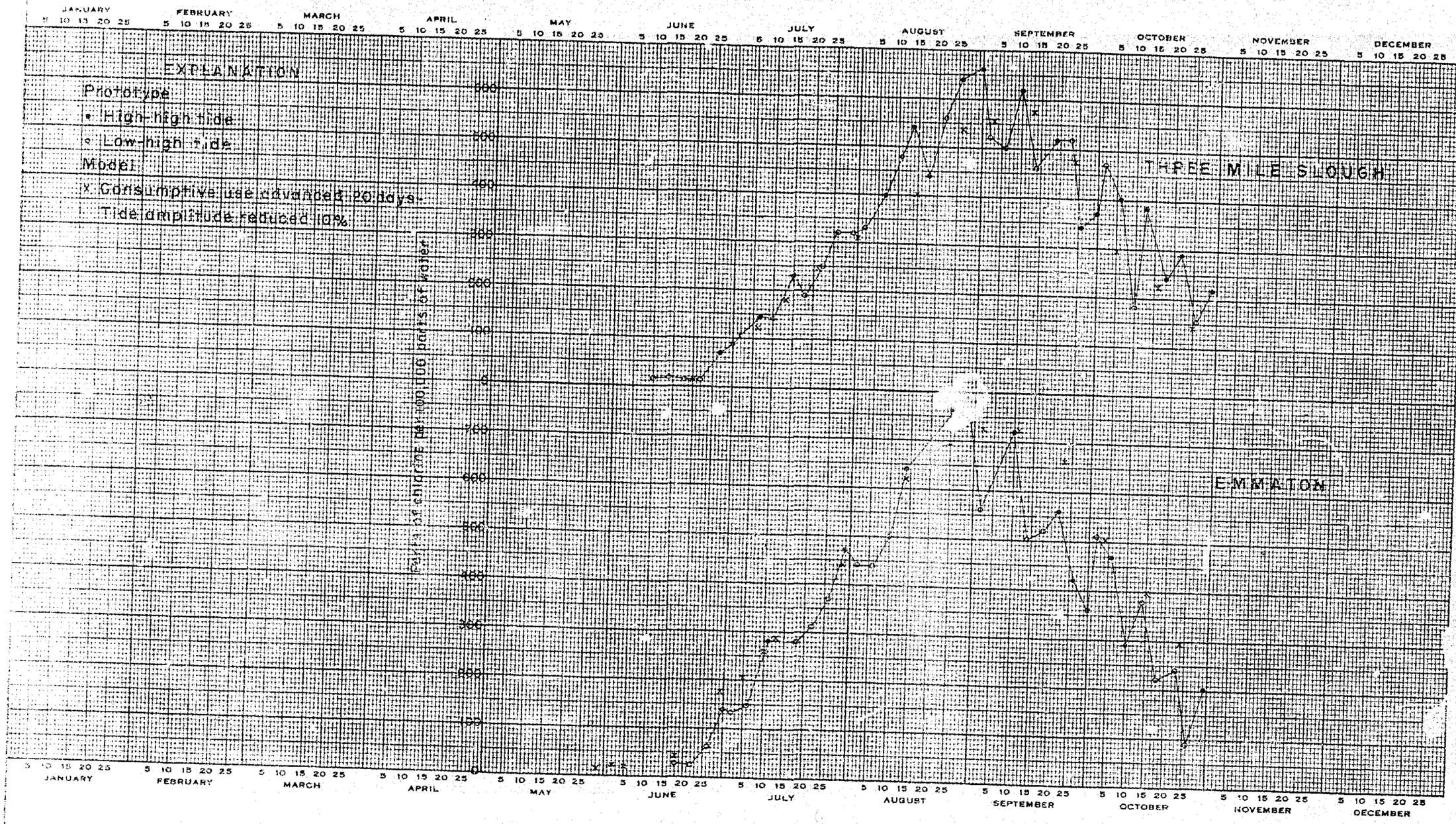
SACRAMENTO – SAN JOAQUIN DELTA
SALINITY CONTROL STUDIES 1:4800 MODEL
SEASON OF 1933

FIGURE 1



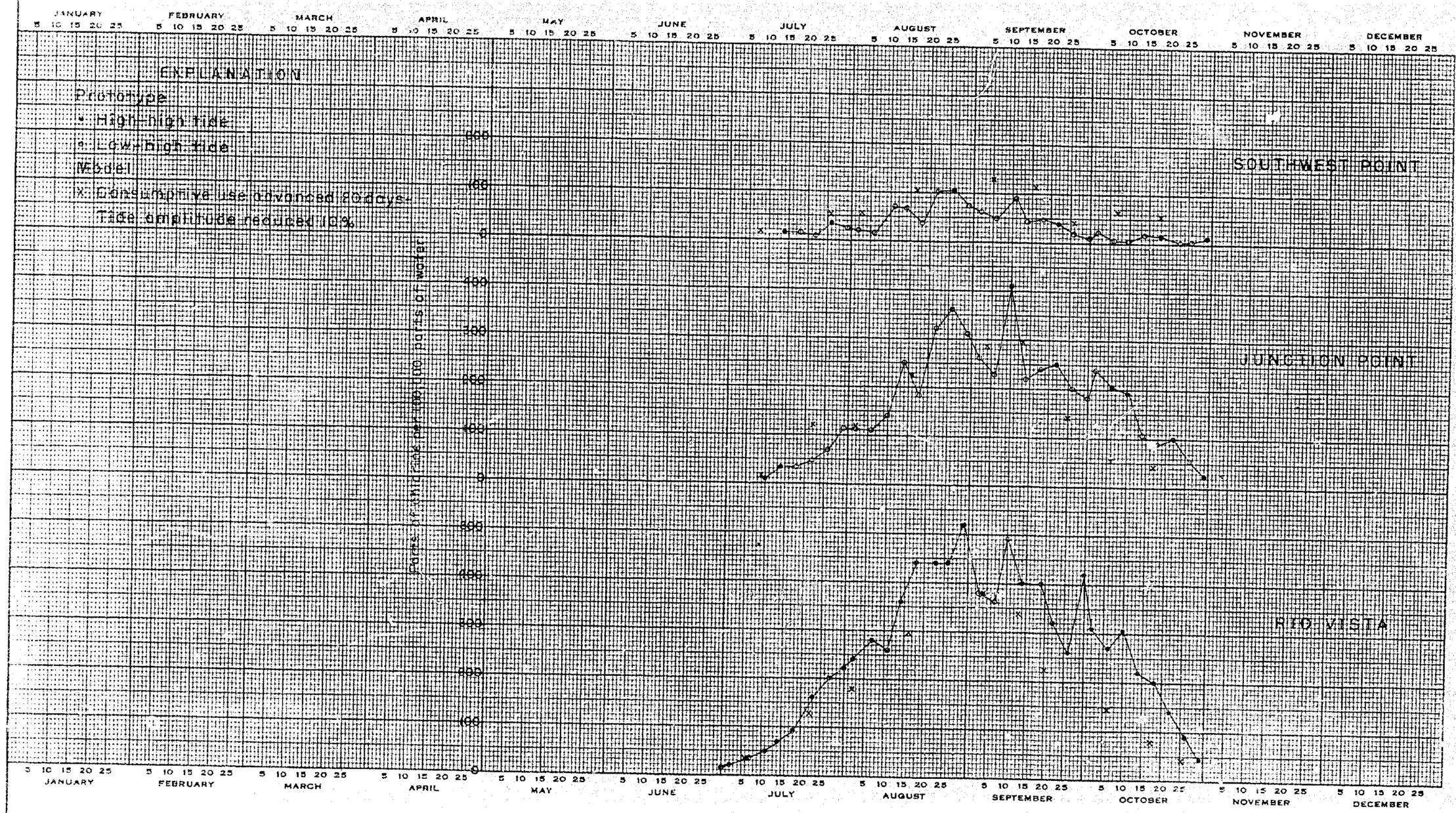
SACRAMENTO - SAN JOAQUIN DELTA
SALINITY CONTROL STUDIES 1:4800 MODEL
SEASON OF 1934

FIGURE 12



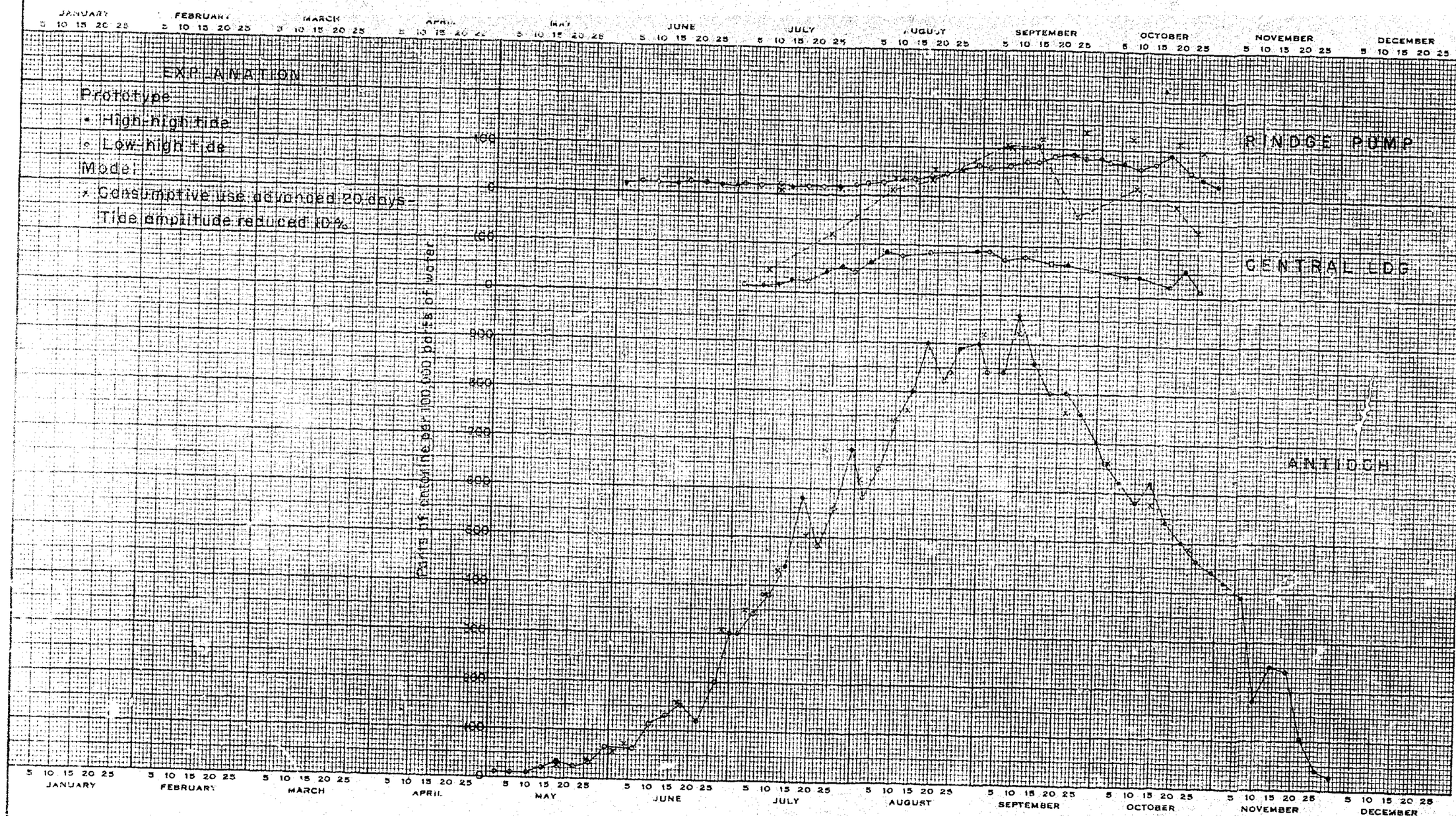
SACRAMENTO - SAN JOQUIN DELTA
SALINITY CONTROL STUDIES 1:4800 MODEL
SEASON OF 1934

FIGURE 13



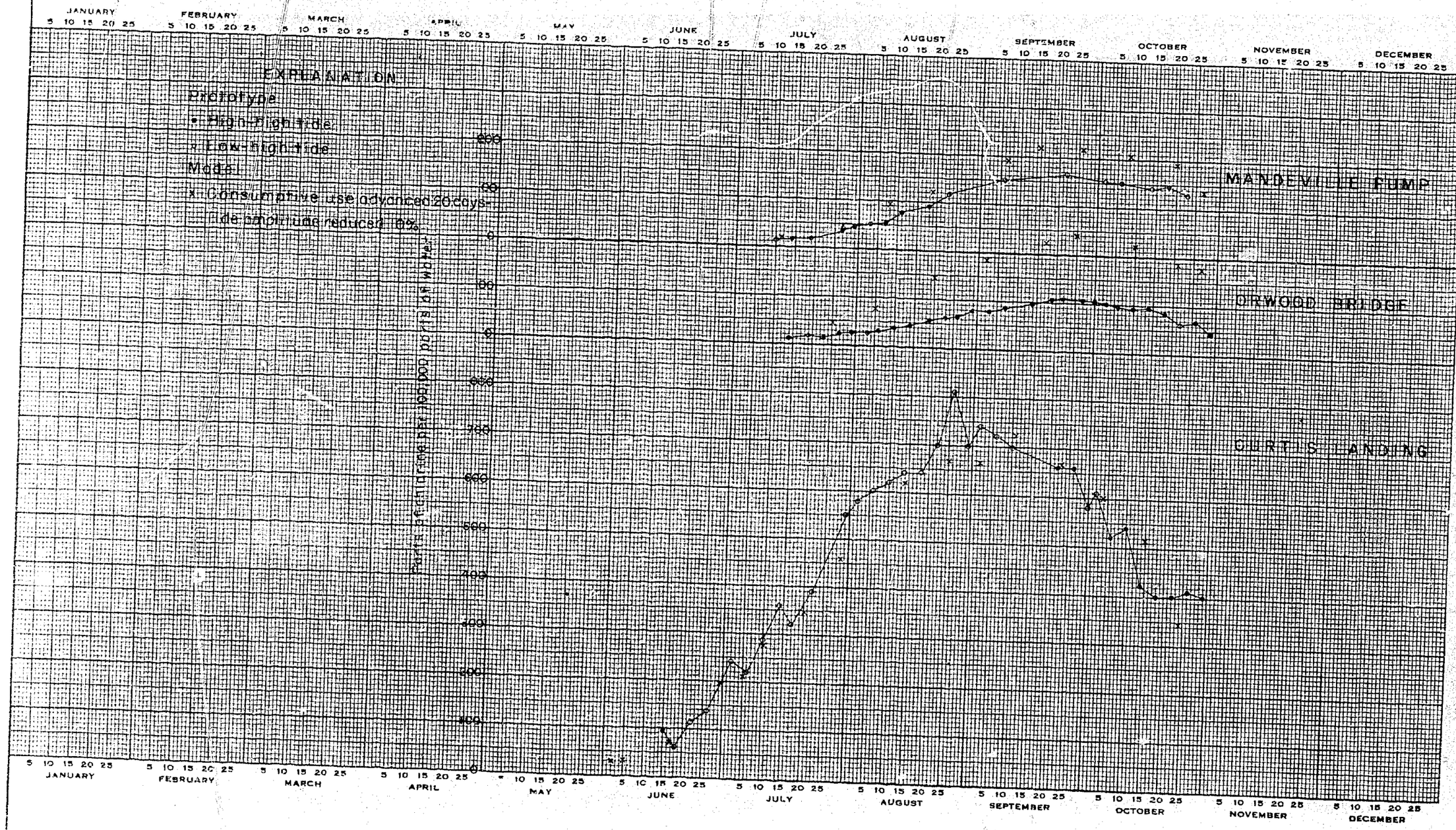
SACRAMENTO - SAN JOAQUIN DELTA
SALINITY CONTROL STUDIES 1:4800 MODEL
SEASON OF 1934

FIGURE 14



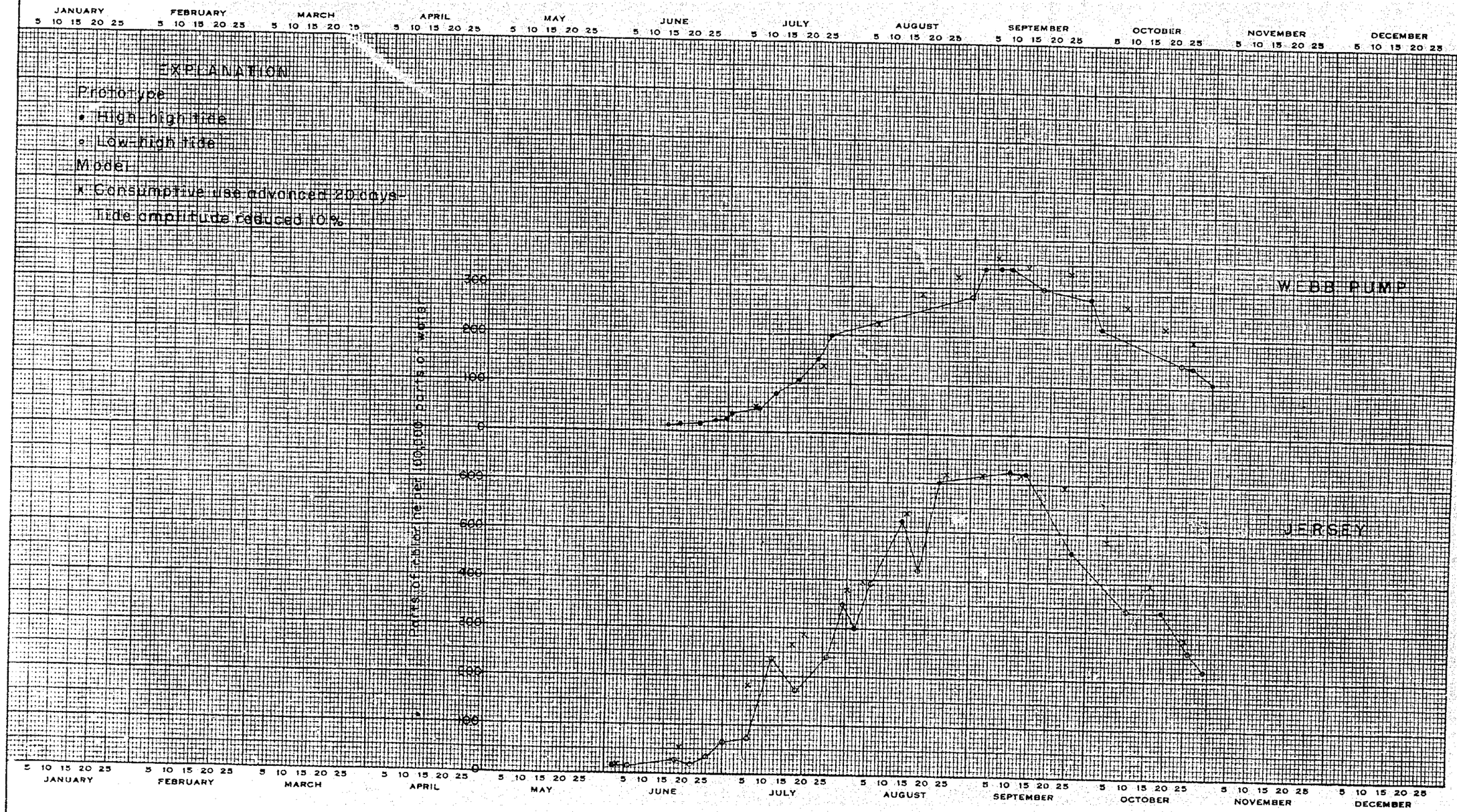
SACRAMENTO - SAN JOAQUIN DELTA
SALINITY CONTROL STUDIES 1:4800 MODEL
SEASON OF 1934

FIGURE 15



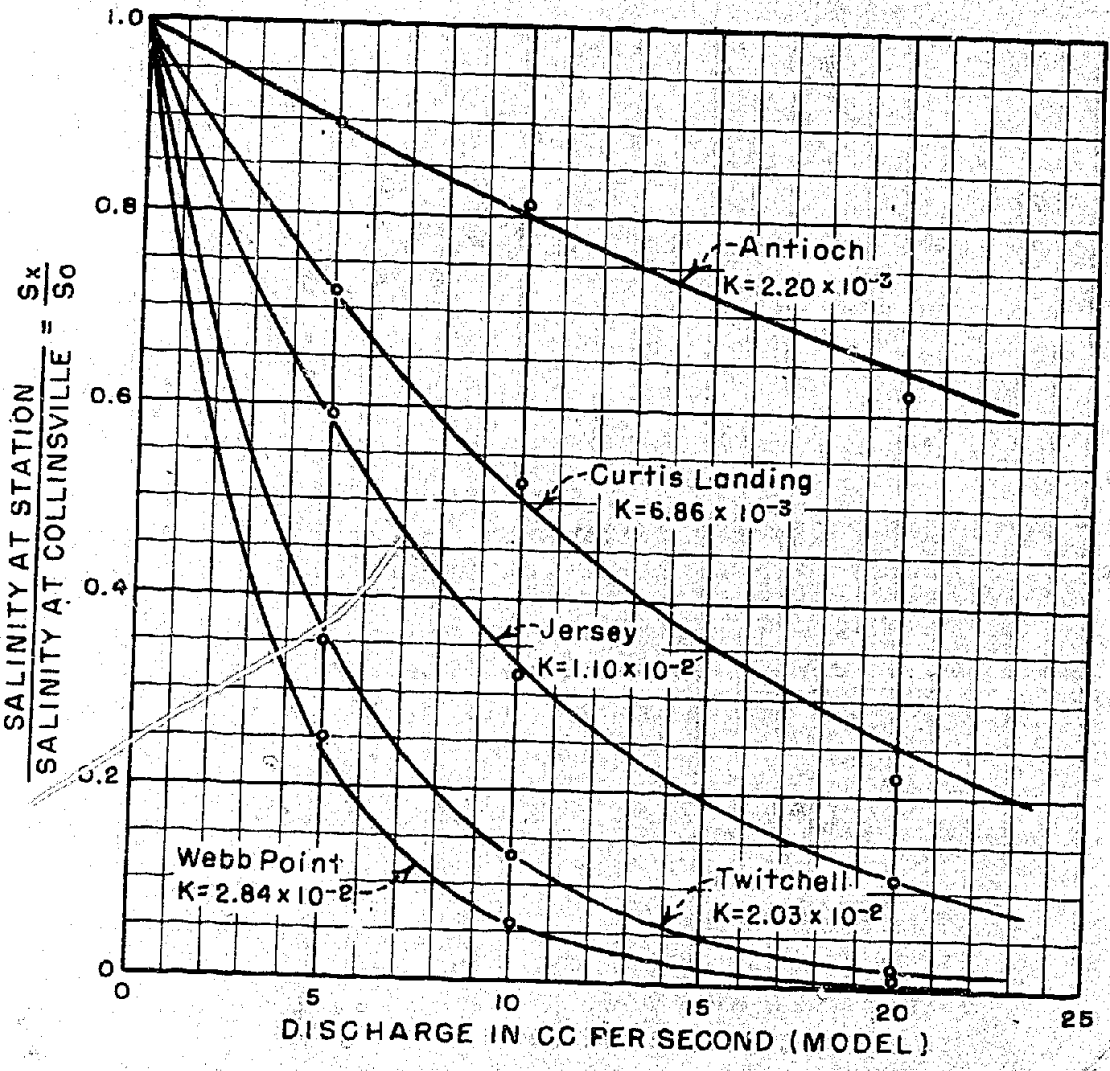
SACRAMENTO – SAN JOAQUIN DELTA
SALINITY CONTROL STUDIES 1:4800 MODEL
SEASON OF 1934

FIGURE 16



SACRAMENTO – SAN JOAQUIN DELTA
SALINITY CONTROL STUDIES 1:4800 MODEL
SEASON OF 1934

FIGURE 17

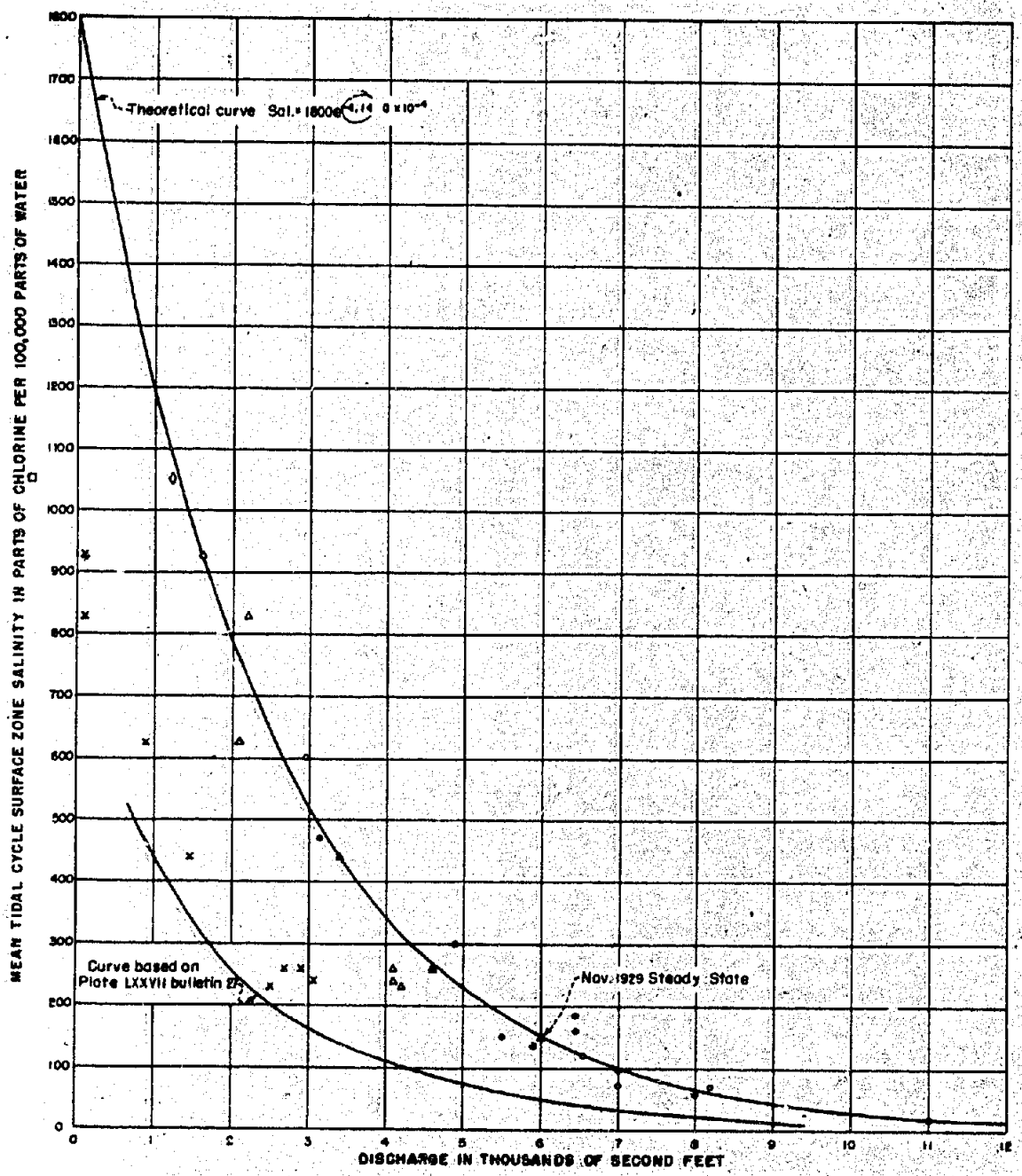


NOTES

1. The curves are based upon the relation $\frac{Sx}{So} = e^{-QK}$.
2. Points represent model data.

RELATION OF SALINITY TO DISCHARGE
IN ISOLATED SAN JOAQUIN CHANNEL OF MODEL

FIGURE 18



EXPLANATION

• Data from figure 7 Appendix I.

Based on data from Plate LXXII - Bulletin 27
× Consumptive use from Bulletin 27.
△ Consumptive use 1200 sec.ft. for September.

1931 data (September).
□ Consumptive use from Bulletin 27.
◇ Consumptive use 1200.

MEAN TIDAL CYCLE SURFACE ZONE SALINITY AT COLLINSVILLE FOR VARIOUS CONTROL FLOWS

APPENDIX I

Denver, Colorado, September 14, 1944.

MEMORANDUM TO MR. J. E. WARNOCK
(R. E. Glover and W. H. Jurney)

Subject: Salinity-distribution estimates for the Delta region - Central Valley project - California.

1. References

Reference is made to the following publications:

(a) State of California, Department of Public Works Bulletin No. 27, "Variation and Control of Salinity in Sacramento-San Joaquin Delta and Upper San Francisco Bay," 1931.

(b) State of California, Department of Public Works. Reports of Sacramento-San Joaquin Water Supervision for the years 1929, 1931, 1933-34-35-36-38 and 1939.

(c) Memorandum to the Chief Engineer by D. J. Hebert and F. C. Lowe dated April 10, 1944. Subject, "Progress report on model studies of the Sacramento-San Joaquin Delta, Central Valley, California."

(d) Memorandum dated September 27, 1943, by J. L. Honnold entitled, "Operation Studies Shasta Reservoir, Central Valley Power Plants, with Supporting Data."

2. Contents

The following paragraphs contain the results of a study of methods of estimating salinity distributions in the Delta region. The formula proposed in the Bulletin No. 27 of reference (a) is first studied and a new procedure is then set up to serve as a check. Curves showing a comparison of observed data and values computed by the new procedure are shown. Finally, an estimate of the salinity at the mouth of the Mokelumne in terms of the salinity at Collinsville is made for a series of control flows, and a minimum control flow is estimated.

3. The formula of Bulletin No. 27

This formula is described in a paragraph on "Tidal Diffusion" beginning on page 208 of Bulletin No. 27 on "Variation and Control of Salinity" of reference (a). This formula is of the form

$$C = D \pm S \quad \text{..} (1)^{+}$$

where the quantities as defined in the Bulletin No. 27 are:

C = the total amount of advance or retreat of salinity in a particular channel section, expressed as the volume of channel through which salinity of a particular degree advances or retreats during a particular time interval.

D = Tidal diffusion, or the effect of tidal action on the total amount of advance or retreat of salinity (expressed in terms of channel volume) during the same time interval.

S = the net stream flow passing the particular channel section during the same time interval.

+See page 209 of reference (a).

On plate LXXIV the tidal diffusion is expressed in terms of thousands of acre-feet per day, and it is presumed that the two other quantities in the formula would be expressed in the same units. The observed data were reduced by use of the formula by the method explained in the paragraph on "Tidal Diffusion" and the results are shown on plates LXXIV, LXXV, LXXVI, and LXXVII, where it will be noted that the diffusion is treated as a function of salinity.

When an effort was made to judge the suitability of an expression of this type for the purpose of estimating the control flow necessary to hold the salinity in check, certain questions arose. In the plates mentioned above, for example, the diffusion will be seen to decrease with increasing salinity, whereas, if other factors were absent, it would be expected that the rate of propagation would be independent of it, since the tidal ebb and flow would doubtless be unaffected by the amount of salt present. (The expression "rate of

propagation" as here used refers to a velocity of propagation of a salinity pattern by tidal action which is the author's interpretation placed upon the term "diffusion" as used in the Bulletin No. 27. It is assumed that its expression in terms of acre-feet per day was adopted as a matter of convenience to permit comparison with stream-flow data. On this basis the actual velocity of propagation could be obtained by dividing the diffusion by the cross-sectional area of the channel.)

In the comments on "Variation of Tidal Diffusion with Salinity" appearing on page 212 of the Bulletin No. 27, the behavior described might be explained on the assumption that the rate of propagation is primarily dependent upon the salinity gradient and that the curves relating salinity and diffusion acquire their validity through a relation existing between the salinity and the salinity gradient wherein the gradient decreases with an increase of salinity. Since there is some uncertainty in regard to the stability of the relations between salinity and diffusion under the proposed changed conditions, produced by controlling the river flow through reservoir operation, it was desired to provide an independent check of the estimated control flow necessary to hold the salinity in check. This estimate was based upon a set of simple assumptions whose suitability was judged by using a test of extremes. This test is applied by determining whether the assumed relations will hold up under the most extreme conditions imaginable. The results of computations based upon assumptions so chosen should be reasonable even though they may not represent the actual conditions exactly.

4. New procedure

The new procedure is based upon the assumption that the propagation of salt by tidal action and stream flow depends primarily upon the salinity gradient. If the test of extremes is applied to this assumption in the manner described in the preceding paragraph, it will be found to give the expected result in all cases. For example, if the

salinity is the same everywhere, then the salinity gradient or the variation of salinity with distance as measured along the stream channel will be zero. In this case no change of salinity can occur due to tidal action. This result would be obtained if the propagation were assumed to be proportional to the salinity gradient. If the transition from fresh to salt water were abrupt so that the salinity gradient would be steep, then a rapid propagation of salt by tidal action would be expected. This result would also be compatible with the assumption that the rate of propagation is proportional to the salinity gradient.

In a uniform channel the stream flow would tend to move a salinity distribution along bodily so that with respect to a point on the bank, the rate of change of salinity with respect to time would be proportional to the stream velocity and the salinity gradient. This assumption would also stand the test of extremes.

These relations can be expressed in mathematical form in the following manner:

Let

- x represent a distance measured along the bank - positive upstream,
- t, the time,
- S, the salinity at the point x and the time t,
- V, the stream velocity - positive if downstream, and
- K, a constant such that $-K \frac{\partial S}{\partial x}$ represents the rate of salt propagation past the section at the point x due to tidal action. The propagation is considered to be positive if salinity is propagated upstream or in the direction of x positive.

Then the time rate of increase of salinity in the length dx is

$$\frac{\partial S}{\partial t} dx = -K \frac{\partial S}{\partial x} + K\left(\frac{\partial S}{\partial x} + \frac{\partial^2 S}{\partial x^2} dx\right) + V \frac{\partial S}{\partial x} dx$$

or

$$\frac{\partial S}{\partial t} = K \frac{\partial^2 S}{\partial x^2} + V \frac{\partial S}{\partial x} \quad \text{.....(2)}$$

An important special case is that of the steady state. To obtain this, set $\frac{\partial S}{\partial t} = 0$. Then the differential equation becomes

$$K \frac{d^2 S}{dx^2} + V \frac{dS}{dx} = 0 \quad \text{.....(3)}$$

A solution of this equation, having the salinity gradient everywhere negative and a maintained salinity S_o at $x = 0$, is

$$S = S_o e^{-\frac{V}{K}x} \quad \text{.....(4)}$$

This equation is useful for estimating the final salinity distribution in a channel after the control flow has been maintained constant for a considerable time.

5. Determination of the constant K

The constant K was determined by trial from selected prototype and model data. The data for the prototype were obtained from the Bulletin No. 27 of reference (a). The Delta model is described in the report of reference (c). After several trials, a value of $K = 900$ ft.^{2}/sec. was obtained for the portion of the San Joaquin channel between Collinsville and Jersey. As a check, four cases obtained from the model and one case for the prototype were worked out. The model data were converted to equivalent prototype data by the laboratory and the computations were made on a prototype basis. These cases are shown on figures 1 to 5, inclusive. In all cases the observed salinity at Collinsville was used as a basis for computing the salinity at other points. The distances from Collinsville to the various stations were read from Plate LXXI in Bulletin No. 27.

6. Estimate of control flow required

It is required that the total dissolved solids be kept within 135 percent of that of the Sacramento River water. Model studies show that the salinity of the water at the Delta-Mendota intake will be about the same as is observed in the San Joaquin channel at the mouth of the Mokelumne River. The relation between total dissolved solids and chlorine content of ocean water is such that about 20 parts of chlorine would represent about 35 parts of total solids per 100,000 parts of water. If the dissolved solids in the Sacramento River water are 100 parts per million, and if all other waters entering the Delta are assumed to be of a quality as good as the Sacramento waters, it would suffice to provide a control flow which would hold the ocean salinity to 2 parts per 100,000 at the mouth of the Mokelumne River. Since the mathematical work previously described gives a relation between the salinities at Collinsville and points upstream from it, a relation between the control flow passing Collinsville and the salinity at Collinsville is required. A search was made of the records [references (a), (b), and (d)] to find periods in the fall months when the inflow into the Delta was nearly constant. At this time the salinity should be receding, so the values thus obtained may be expected to be somewhat higher than those maintained by a constant control flow and therefore slightly on the safe side for the present purpose. The result of this study is shown on figure 6.

To get the values of the control flow shown on figure 6, Honnold's averages [reference (d)] were used for the years 1936, 1938, and 1939. These are averages for the month and could not be used when there was a rapid rise in the control flow in the latter part of the month. In this case the flow at the end of a period of fairly constant flow was obtained from Bulletin No. 27, when possible. This was done for the years 1920, 1921, 1922, 1925, 1926, 1928, and 1929. For the four years 1931-33-34 and 1935 the flow was read in the Water Supervisor's Report from a graph representing the combined flows of the

Sacramento River at Sacramento and the San Joaquin River at Vernalis. All other flows except the last four represent total flows from all sources. The use was read from the consumptive-use curve on page 227 of Bulletin No. 27. In no case was this curve shifted. The control flow was computed by deducting the consumptive use in the Delta from the total inflow into the Delta.

To obtain the values of the salinities shown on figure 6, the values were read in Bulletin No. 27 and in the Water Supervisor's Report at the end of the period of fairly constant flow. These salinities were changed to mean tidal-cycle surface zone salinities by the use of Plate LXII in Bulletin No. 27 [reference (a)]. The tide data for 1929 was obtained from Plate LXX in this bulletin. For other years the tide data was not available and so the readings taken 1-1/2 hours after the high high tide were changed to mean surface zone salinities by the use of the 160-percent curve, Plate LXII. In drawing this curve considerable weight might be placed on the point for 1929 because in this year there was a fairly long period of approximately constant flow and also because for this year the tide data was available.

A comparison was made to the Collinsville curve, which was obtained in the main body of this report and shown in figure 17 thereof, by making the curve

$$S = 1800\, e^{-\frac{Vx}{K}}$$

go through the 1929 data as used therein (control flow 6,000, salinity, 150). This curve, which is reproduced in figure 6, fitted the data well enough to be used here also.

The corresponding salinities at the mouth of the Mokelumne are shown on figure 7. The salinities at the Mokelumne River were computed from those at Collinsville in the following manner. For a given control flow, it was assumed that two-thirds of it went down the

San Joaquin. The cross-sectional area A was taken as 79,200 sq. ft. Then the velocity was obtained from the relation

$$V = \frac{Q}{A}$$

where Q is the control flow in the San Joaquin. The salinity at the Mokelumne River was obtained from the formula

$$S = S_o e^{-\frac{Vx}{K}}$$

where

S represents the salinity at Mokelumne River,

S_o, the salinity at Collinsville (obtained from figure 6),

K = 900 ft.^{2}/sec.

x = distance in feet from Collinsville to Mokelumne River = 110,880 ft. (Plate LXXI, Bulletin No. 27).

Figure 7 shows that a control flow of 4,650 ft.^{3}/sec. will hold the salinity at the mouth of the Mokelumne at 2 parts chlorine per 100,000 parts water, or 20 parts per million.

It may be noted that the Collinsville curve (figure 6) may be varied to some extent without affecting the Mokelumne curve (figure 7) a great deal.

The estimated salinity distribution for Antioch is shown in figure 8, together with a curve representing a series of check points obtained from the records and plotted in the manner described in connection with the Collinsville curve of figure 6. It will be noted that the estimated curve for Antioch is too low. This is considered to be due to the effect of flow through the New York slough and the increased mixing due to eddy formation at the junction of the Sacramento and the San Joaquin rivers. The control flow needed to hold the salinity at Antioch to 100 parts per 100,000 would therefore be nearer 5,500 cubic feet per second instead of the 4,500 cubic feet given by the estimated curve. This discrepancy is considered to be due to local conditions

which are not present elsewhere. The estimated salinity distribution for intermediate points is shown on figure 9. These latter values were computed by use of equation (4). For this purpose it was assumed that two-thirds of the total control flow would come down the San Joaquin channel either naturally or through artificial control exerted to cause it to do so.

It will be noted from figure 7 that a flow of 4,650 cubic feet per second passing Collinsville is estimated to be required to hold the ocean salinity at the mouth of the Mokelumne to 2 parts per 100,000 or 20 parts per million of chlorine. This would represent a minimum value since, if the other waters entering the Delta carry more solids than the Sacramento River water, some extra diversion might be necessary to dilute them. It is believed that the quality of other waters entering the Delta may not be as good as that of the Sacramento River water due to the large proportion of return flow in the former. Because of the uncertainties involved, the above figure should be considered as a reasonable estimate of minimum requirements rather than an exact value.

7. Summary and conclusions

(a) The formula of Bulletin No. 27 [reference (a)], taken together with the supplemental data prepared for use with it, are understood to be based upon data obtained during periods of variable stream flow and for this reason may possibly give too small values for a net flow to hold the salinity in check under a controlled regimen.

(b) An alternative method of computation is devised to provide a check and is applied to estimate the new flow required to hold the salinity in check under controlled conditions. A minimum value of 4,650 cubic feet per second is the value obtained by this method.

8. Computations

Computations were made by Mrs. V. M. Kingston and checked in part by the authors.

- - -

R. E. Glover

W. H. Jurney

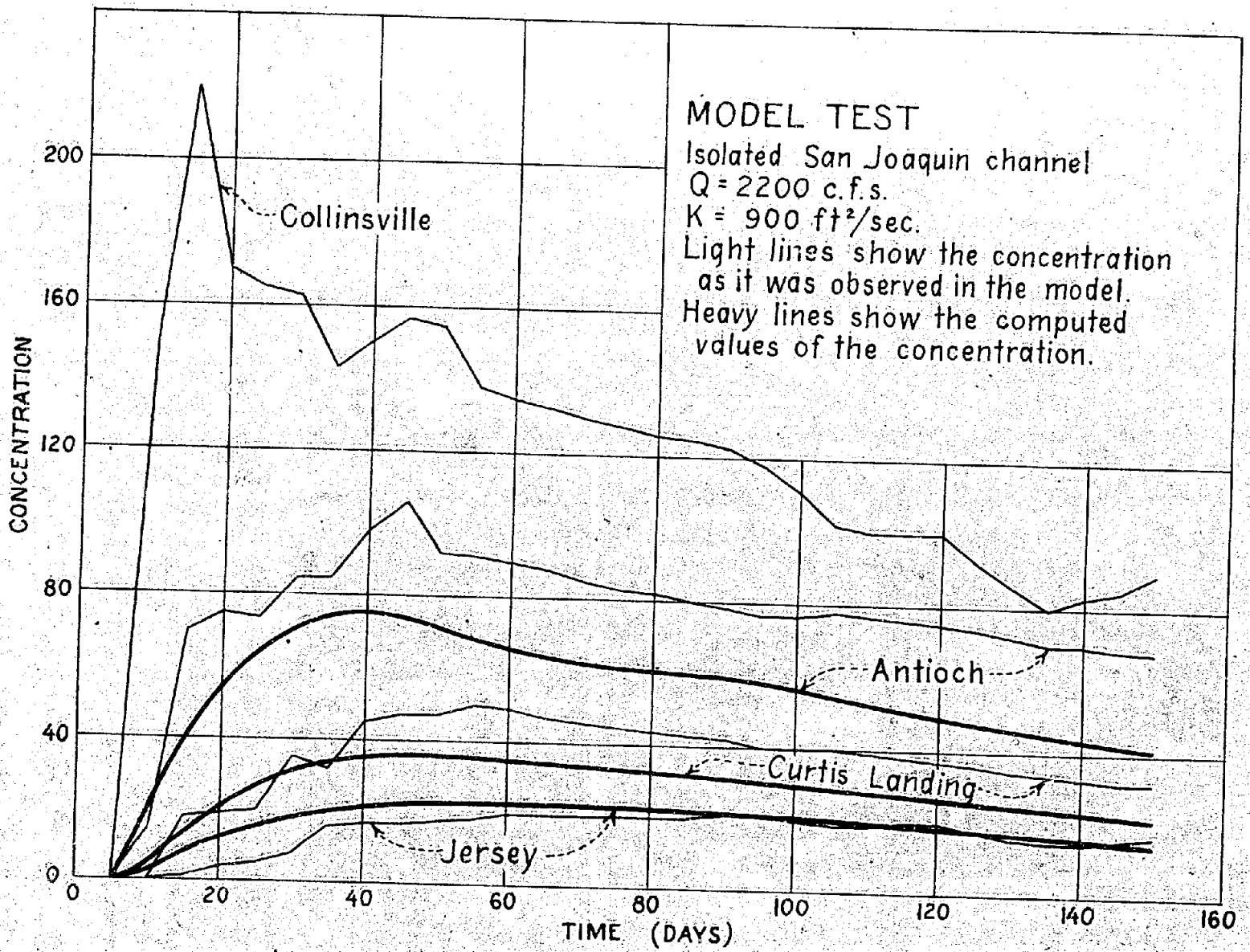
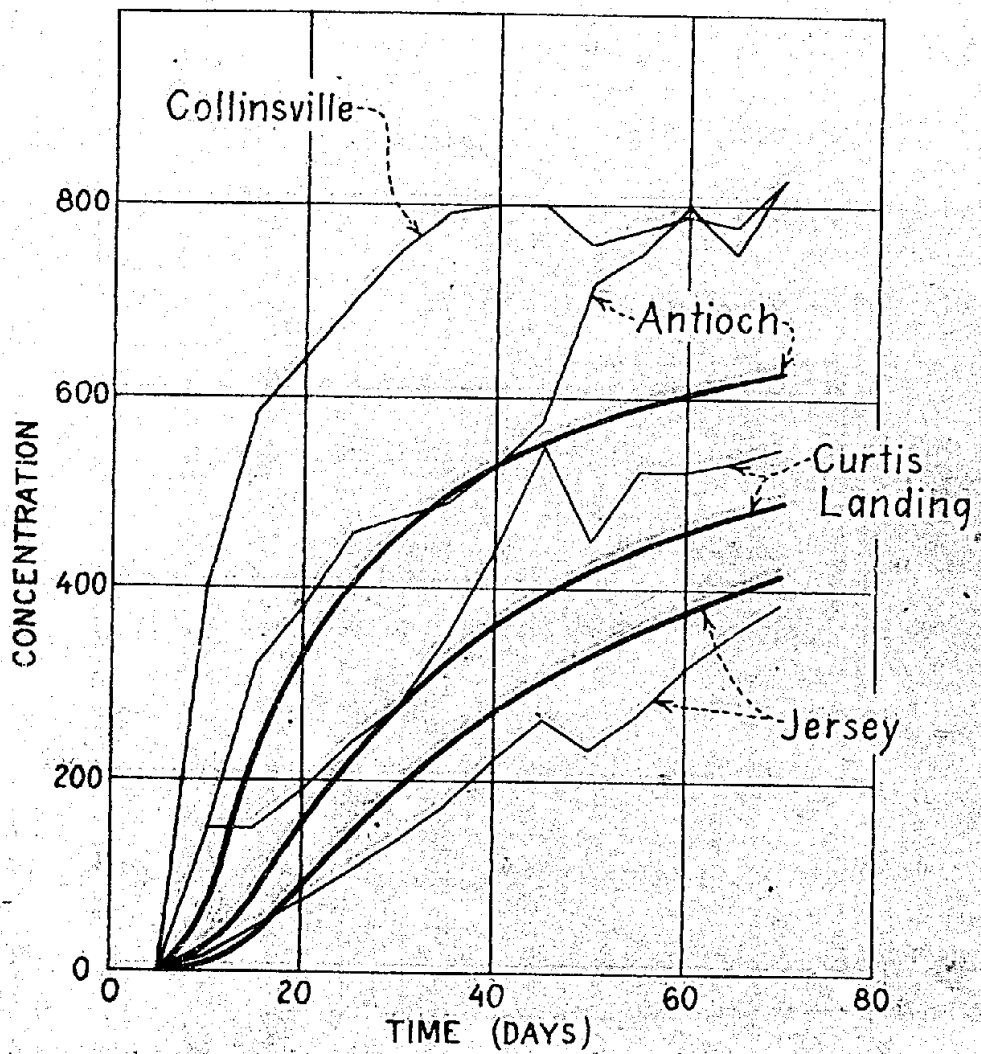


Fig. 1

214-R.E.G.-588

V. M. KINGSTON



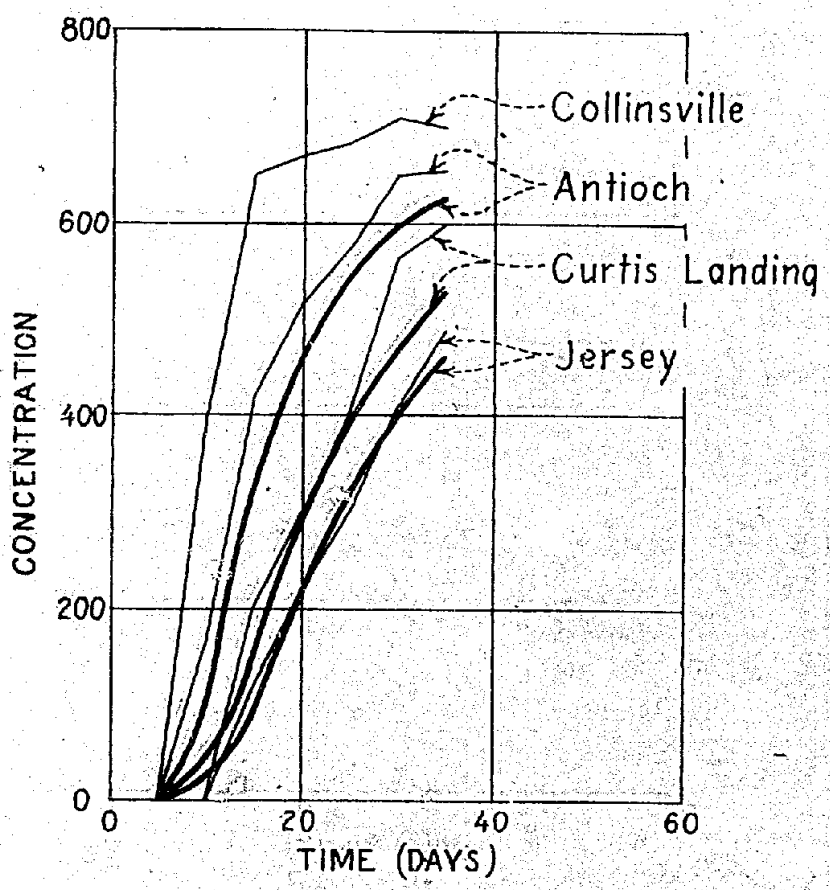
MODEL TEST

Isolated San Joaquin channel.
No flow
$K = 900\ ft^2/sec.$
Light lines show the concentration as it was observed in the model.
Heavy lines show the computed values for the concentration.

Fig. 2

21A-R.E.G.-589

V. M. KINGSTON



MODEL TEST
Isolated San Joaquin
Negative flow
Q = -2200 c.f.s.
K = 900 ft²/sec.
Light lines represent observed values.
Heavy lines represent computed values.

Fig. 3

MODEL TEST

Flow into the delta = 3300 c.f.s. K = 900 ft²/sec.
⅔ of the flow was assumed in the San Joaquin. In the model test 1300 c.f.s. were put into the Mokelumne river. It was assumed that 900 c.f.s. went across Three Mile Slough. If this amount actually were less than 900 c.f.s. a better check would have been obtained.
Light lines show the concentration as it was observed in the model.
Heavy lines show the computed values of the concentration.

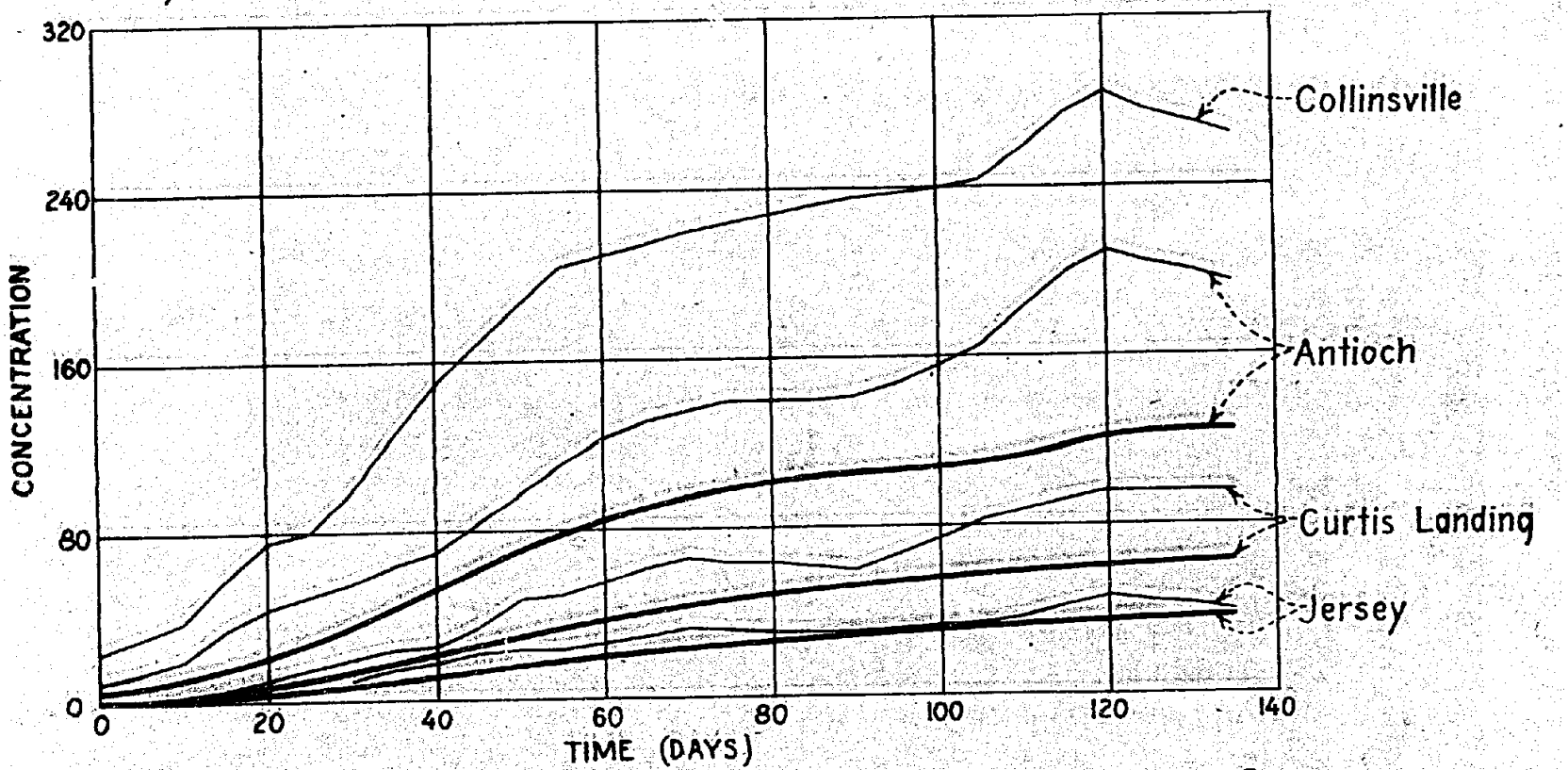


Fig. 4

V.M. KINGSTON

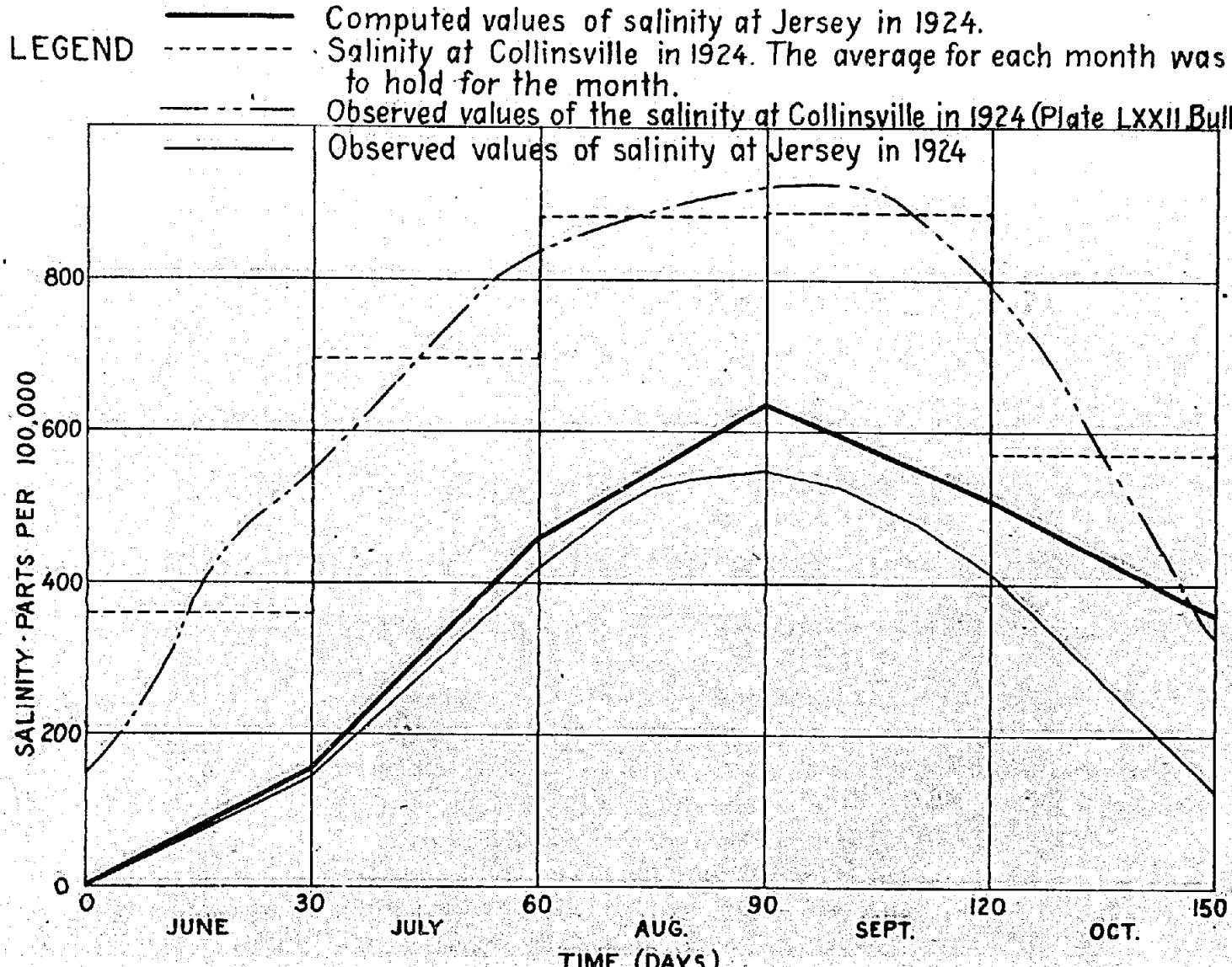


Fig. 5

214-R.E.G.-592

V.M.KINGSTON

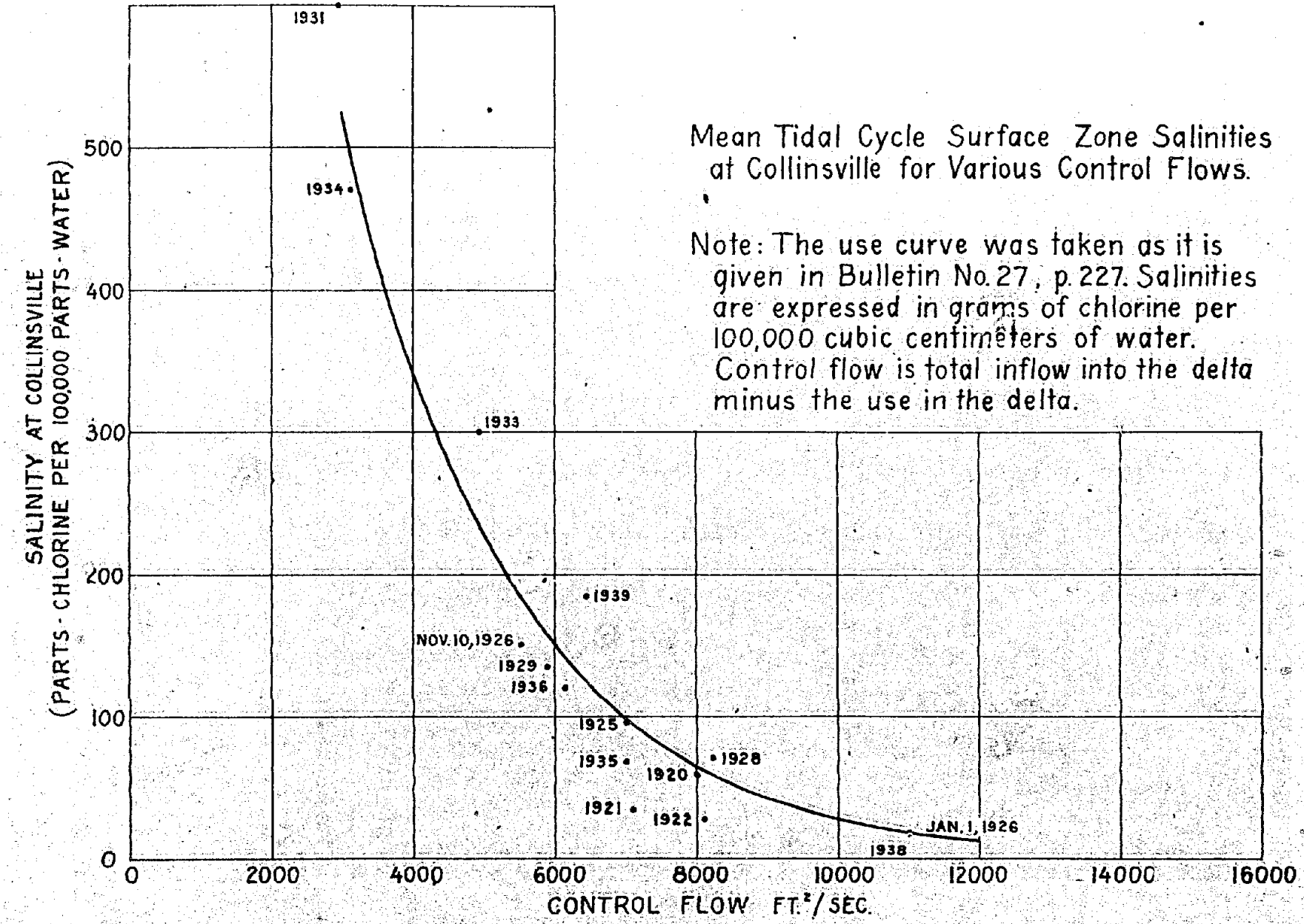
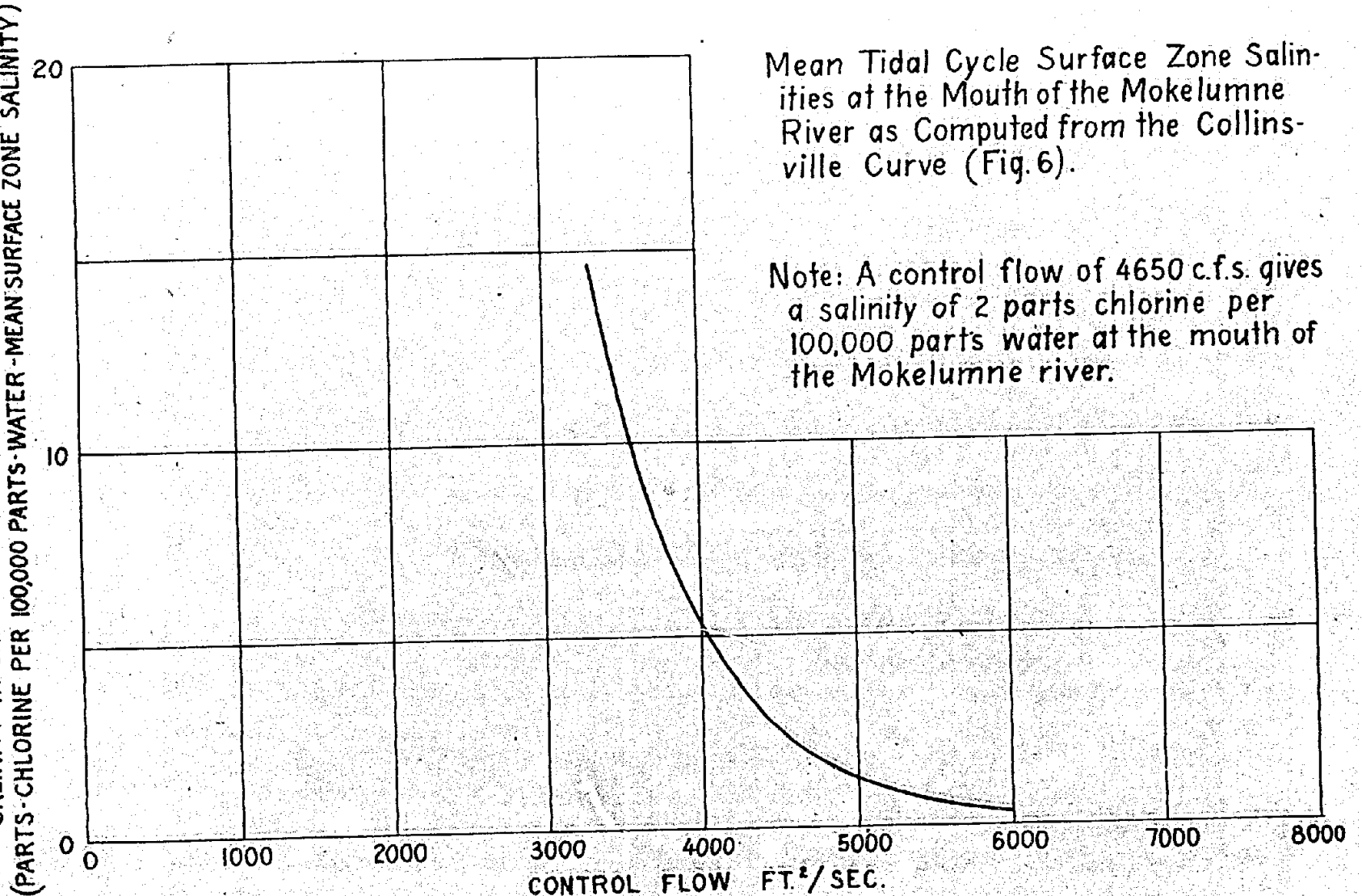


Fig. 6

V.M. KINGSTON

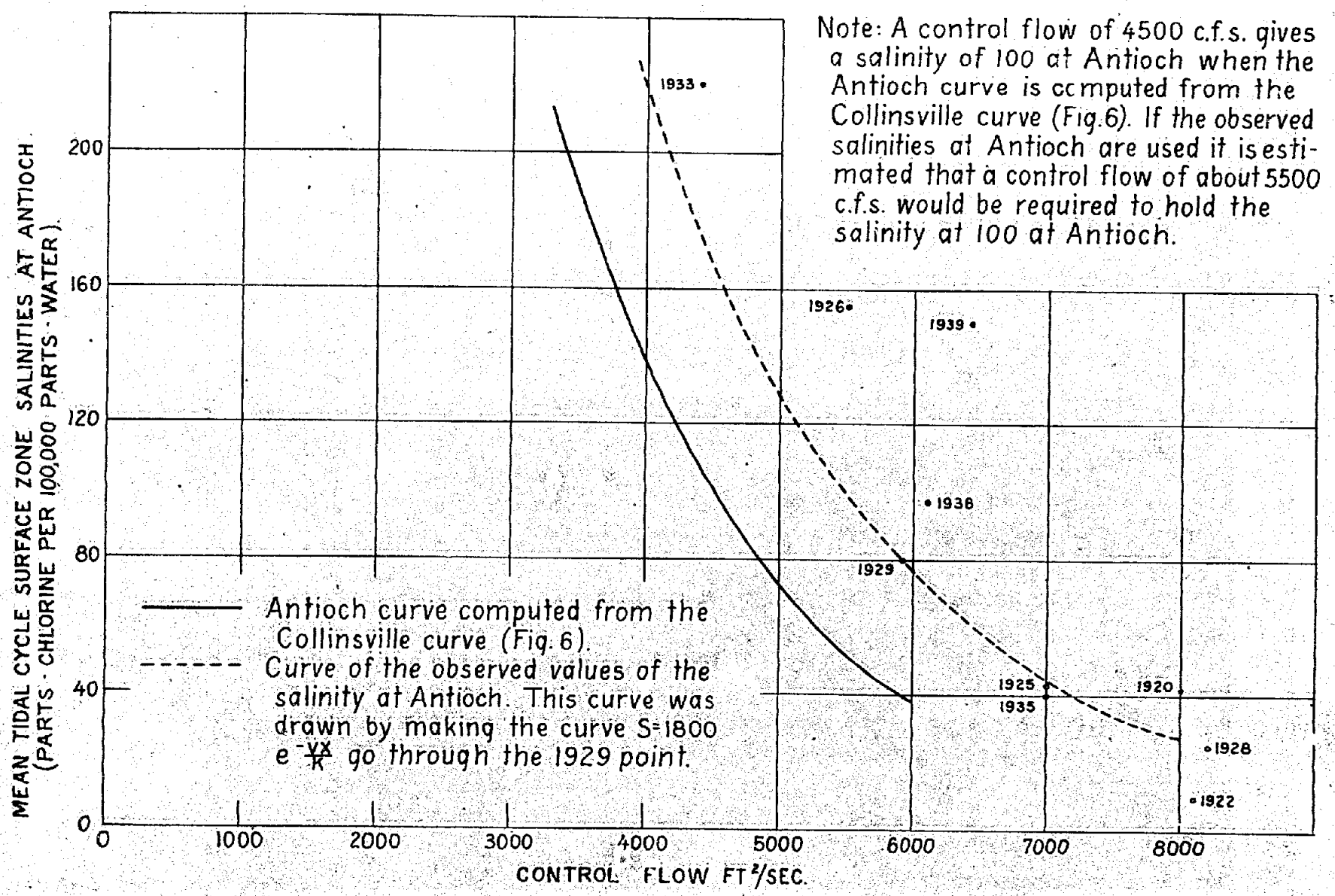


Mean Tidal Cycle Surface Zone Salinities at the Mouth of the Mokelumne River as Computed from the Collinsville Curve (Fig. 6).

Note: A control flow of 4650 c.f.s. gives a salinity of 2 parts chlorine per 100,000 parts water at the mouth of the Mokelumne river.

Fig. 7

214-R.E.G.-594



Note: A control flow of 4500 c.f.s. gives a salinity of 100 at Antioch when the Antioch curve is computed from the Collinsville curve (Fig. 6). If the observed salinities at Antioch are used it is estimated that a control flow of about 5500 c.f.s. would be required to hold the salinity at 100 at Antioch.

Fig. 8

214-R.E.G.-595

V.M. KINGSTON

Estimated Steady State Salinity Distribution
S denotes the salinity at distance x ft. from Collinsville.
(Distance taken from plate LXXI, bulletin No. 27)
S_o The salinity at Collinsville.
The flow, Q down the San Joaquin was assumed to be $\frac{2}{3}$ of the flow into the delta minus $\frac{2}{3}$ of the use in the delta.
The cross sectional area, A was taken as 79,200 sq. ft.
Then $V = Q/A$ ft. per sec.
K was taken as 900 ft.^{2} per sec.
The formula used for computing the salinity was $S = S_o e^{-\frac{VX}{K}}$.

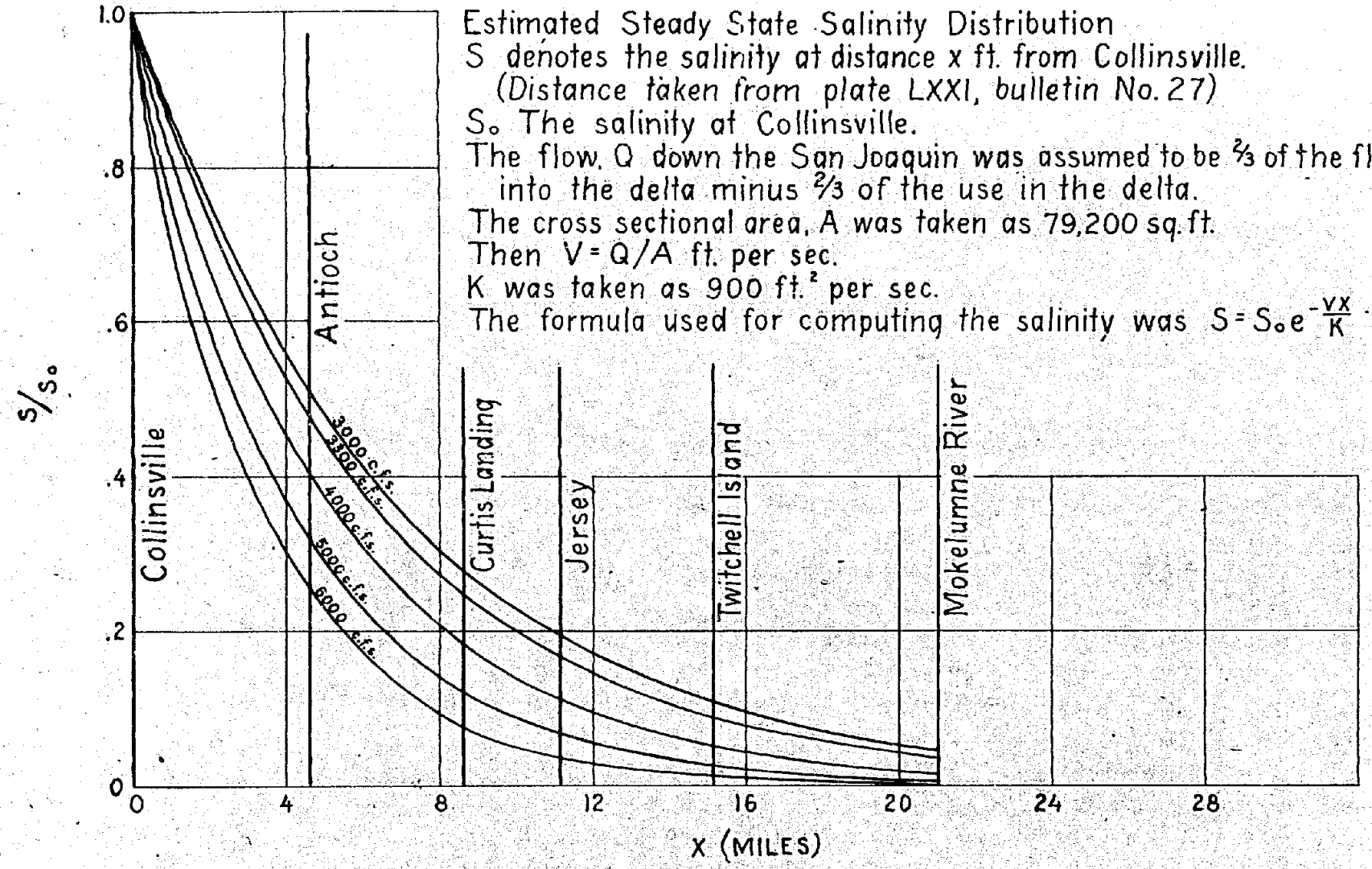


Fig. 9

V. M. KINGSTON