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HYD-242

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

PROGRESS REPORT DEALING WITH PROPOSED FIELD STUDIES IN THE SACRAMENTO-SAN JOAQUIN DELTA--CENTRAL VALLEY PROJECT

Hydraulic Laboratory Report No. Hyd-242

RESEARCH AND GEOLOGY DIVISION

BRANCH OF DESIGN AND CONSTRUCTION
DENVER, COLORADO

NOVEMBER 1947

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DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

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Research and Geology Division
Denver, Colorado
November 1947

Laboratory Report No. 242
Hydraulic Laboratory
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Subject: Progress report dealing with proposed field studies in the Sacramento-San Joaquin Delta—Central Valley Project.

INTRODUCTION

The need for field studies in the Sacramento-San Joaquin Delta, pertaining to the control of the tidal intrusion of ocean salinity, was pointed out in Hydraulic Laboratory Report No. 155. The model study reported therein, resulted in a recommendation that Sacramento River water be transferred across the Delta to the Tracy Pumping Plant through the natural channels of the Delta. This recommendation was predicated on the close control of salinity intrusion by the release of sufficient water from the Delta to accomplish such control. The rate of flow which constitutes sufficient water is subject to some controversy, and it is indicated that its evaluation to the satisfaction of all parties involved can be best accomplished by field studies. This report has been prepared to summarize the various factors involved in the complicated process of dynamic control of salinity intrusion by controlled releases of stored waters. The material contained in this report is not new, but is merely recapitulated from reports previously issued, to provide a background for the discussion of field studies.

OBJECTIVES

The ultimate goal of field tests in the Sacramento-San Joaquin Delta, is to supply the regional branch of irrigation operations and maintenance with the information and practical methods for controlling the intrusion of ocean salinity by regulated releases of stored waters from Shasta Dam. Many of the tests will be directed towards compiling the data required for constructing curves for steady-state conditions of salinity (mean tidal-cycle-surface-zone) versus net outflow at Collinsville or Antioch, Jersey and Webb Point or Central Landing. One such curve, at Collinsville, is shown in Hydraulic Laboratory Report No. 155, but it is based on only one reliable set of data which was obtained during retreat of ocean salinity in November 1929. The same data could not be used for a similar curve at Webb Point because there was enough residual salinity trapped from the preceding intrusion to affect the results seriously.

The point of having a curve of salinity versus net outflow is twofold. First, the necessity of accepting conditions as they occur requires a curve that can be used to interpolate for the desired salinity. Secondly, it is desirable in connection with planning of other related features of the Central Valley Project to know the salinity for discharges other than the widely discussed control flow.

Another relationship, which would be extremely valuable, and which might develop from the tests, is that which exists between the rate of increase in salinity, the corresponding salinity gradient and the related deficiency in net discharge. With such a relationship it would be possible to determine the prevailing net outflow and arrange accordingly for increasing it by the proper amount, when salinity conditions become critical. A more detailed discussion of this relationship together with the reasons for anticipating its existence will be given later.

METHODS

Steady-state Measurements

The simplest method for obtaining the data discussed previously, is to make measurements during steady-state conditions for different amounts of salinity. The rarity of the natural occurrence of such states and the difficulties of arranging them by regulated releases, make such a method highly impractical. Conceivably, one set of data for the salinity versus net-outflow curve might be obtained in some year when a shortage of water required that no water be wasted in excess of that amount necessary to hold the mean salinity at Antioch to 100 p.p. 100,000 of chlorine. The summer of this year (1947) was a very dry season and it is understood that the maximum value of the mean salinity at Antioch exceeded 100 p.p. 100,000 of chlorine. Either the maximum discharge available from storage was insufficient or it was decided that the control value of salinity could be exceeded without causing any material damage. The next intrusion will be even more critical because of the unusually dry season, and the conditions which develop should be noted and measured in more detail than usual. Data obtained under such conditions should prove valuable particularly when they are combined with other data that will be accumulated in the proposed field studies.

Evaluation of Diffusion Coefficients

A more practical method than that of awaiting the occurrence of ideal conditions would be to evaluate the diffusion coefficients of the natural channels by appropriate measurements under field conditions and, by means of the diffusion equation utilizing the coefficients, to construct a theoretical curve. A program of field tests to make such an evaluation would be difficult to carry out because of the large area involved. It would require a great deal of thought and planning without definite assurance that the results would be significant. The importance of the objectives would seem to warrant an attempt to make the field tests in at least enough detail to establish the possibilities.

Experimental evidence, both model and prototype, was presented in Hydraulic Laboratory Report 155 to show that propagation of ocean salinity into the Delta is accomplished through a process of diffusion which is caused by tidal ebb and flood. The process had been recognized and named in Bulletin 27, published by the State of California in 1930, but it remained for the model study to establish the fundamental nature and mechanics of the process.

The fundamental equation according to which propagation of salinity occurs by tidal diffusion is written as follows considering only one direction (x):

$$\frac{\partial s}{\partial t} = \frac{\partial^2 (As)}{\partial^2 x} - V_x \frac{\partial s}{\partial x} \qquad (1)$$

where s = salinity or concentration

t = time

V_x = mean velocity

A = coefficient of mixing or diffusion

X = distance measured along the river

This equation is widely used in other branches of physics such as the flow of heat in a conductor, molecular diffusion, and the transportation of suspended sediment in streams. Although partial differentials have been used in Equation 1, its use in applying it to tidal diffusion will be restricted to changes that have occurred over a time interval which will include several tidal cycles. In other words, the interval "∂t" should really be written as " Δt", where Δt is the time interval from say slack after high-high tide to slack after an identical tide several cycles later. With such an interpretation, the variations due to tidal oscillation, that is, variations in the type and height of tide, would be eliminated. Then too, the term "V_x" would have a true significance as the velocity of the mean net outflow.

For the special case of steady state when $\partial s/\partial t = 0$, Equation 1 is relatively easy to solve. The solution as it was demonstrated in Hydraulic Laboratory Report 155 is:

$$S_x/S_o = e^{-V_x/K} \quad \text{———————————} (2)$$

This equation gives the relation between the mean salinity S_x, expressed as a ratio to the salinity at some reference point, and the velocity V_x which could as well be the discharge. Once the constant "K" is known, the equation can be used to construct the desired salinity curves at a given location showing salinity versus net outflow.

For cases other than steady-state, Equation 1 is much more difficult to solve. An approximate solution was obtained and used in the course of mathematical studies carried on in conjunction with the hydraulic model study. Application of the solution to certain selected model and prototype data is shown in the appendix to Hydraulic Laboratory Report 155. Since the time when this solution was worked out, another and more complete solution which appears to be applicable has been found. It was worked out for a problem in the analogous field of heat flow. If this more complete solution can be applied directly to the salinity intrusion, and if it can be reduced to a graphical procedure for use in analyzing prototype data, the following possibility exists: The data for historical intrusions could be reduced in terms of the two principal unknowns, diffusion coefficient and net outflow. The data from several intrusions could then be made to yield the numerical values of the coefficients and the net outflows. By subtracting the net outflow from measured gross inflow, the consumptive use schedule could be evaluated. Once the coefficients are known, the computations for steady-state can be readily made. In addition, any series of current data could be analyzed for the value of net outflow. Such an analysis of historical data would be difficult and time-consuming although at first thought it appears to be relatively simple. Computations of a similar mathematical nature involving tidal flow, which have been made in connection with certain problems in Holland, have required periods of over 2 years.

Finite Difference Equation

Another method by which an evaluation of the diffusion coefficients from prototype data taken during instrusion might be accomplished more quickly and simply by use of the so-called finite difference equation.

Considering any stretch of the river, the salinity being propagated into and out of the stretch is respectively:

into section $- A_1 \frac{\partial S_1}{\partial x} + V_2 \overline{S_2}$

out of section $- A_2 \frac{\partial S_2}{\partial x} + V_1 \overline{S_1}$

Where V = mean velocity of net flow

A = diffusion coefficient

and Section 1 is taken at the downstream end of the stretch.

The change in salinity per unit of volume is:

$$\frac{\overline{\Delta S}}{\Delta t} = A_1 \frac{\Delta S_1}{\Delta x} + V_2 \overline{S_2} - A_2 \frac{\Delta S_2}{\Delta x} - V_1 \overline{S_1} = \text{change in salinity}$$

If Section 2 is taken just upstream from the point where salinity equals zero, then $S_2 = 0$ and $\frac{\Delta S_2}{\Delta x} = 0$ and the change in salinity can be written as:

$$\Delta S / \Delta t = A_1 \Delta S_1 / \Delta X - V_1 S_1 \qquad (3)$$

Putting in volumes and areas, equation (3) becomes

$$\frac{\Delta(\Sigma \text{vol} \quad S)}{\Delta t} = A_1.\text{area}_1. \frac{S_1}{\Delta x} - V_1.\text{area}_1.X\overline{S_1}$$

or

$$\frac{\Delta(\Sigma \text{vol} \quad S)}{\Delta t} = A_1.\text{area}_1. \frac{\Delta S_1}{\Delta x} - Q_{n1}.\overline{S_1} \qquad (4)$$

Prototype records are available to evaluate the term (Σ vol S) which is the total ocean salinity upstream from any given section of the channel. Assuming for the minute that Q_n, the net discharge, and $\Delta S/\Delta x$, the salinity gradient as well as S_1, the mean salinity over the time interval Δt, are all known. The value of the diffusion coefficient A_1 could be computed and the requirements of a steady-state condition could be predicted.

$$A_1.\text{area} \frac{\Delta S_1}{\Delta x} = Q_n.\overline{S} \qquad (5)$$

If A were evaluated at many sections so that it would be known as a function of X, then equation 5 could be integrated to give the desired curve of salinity versus net discharge.

Let $\Delta S_1 = ds$ and $\Delta x = dx$

then $\frac{ds}{s} = \frac{Q_n}{area} \frac{dx}{f(x)}$ where

$A = f(x)$

This may be integrated to give

$$\log S = \frac{Q_n}{area} \int f(x)dx + c$$

At $X = 0$ let $S = S_o$

and $S/_{So} = e^{Qn \int f(x)dx / area} = e^{KQn}$

where $k = \frac{\int f(x)dx}{area}$.

Returning to a consideration of equation (4) it must be recognized that no direct measurements of Q_n or $\Delta S/\Delta x$ are available. The inaccuracies attached to the values of net discharge will be discussed subsequently. Assuming that data were available during periods of light consumptive use to give reasonably reliable values of net discharge an evaluation of A could be made, provided satisfactory values of the gradient $\Delta S/\Delta x$ could be obtained from the data.

Since no direct measurements of $\Delta S/\Delta x$ have been made, it must be evaluated indirectly. In the studies reported in Hydraulic Laboratory Report 155 the gradient was evaluated by taking the difference in salinity between two adjacent stations at high tide divided by the distance between stations. This method presumes that the tidal amplitude is greater than the distance between stations and further that very little diffusion occurs during the flood cycle. The values obtained by the method are approximate at best.

It is hoped that the use of the recently installed salinity meter will lead to the development of a better method of evaluating salinity gradient.

Every effort should be made to correlate gradient with some measurement included in the data taken in previous years so that the large mass of accumulated data can be used.

Assuming that better values for $\Delta S/\Delta x$ can be obtained and that the diffusion coefficients can be evaluated, it should be possible to compute a new consumptive use schedule.

Let Q net = Q_g(gross) - $Q_{c.u.}$ (consumptive use)

then $\frac{\Delta(\Sigma \text{vol } x^S)}{\Delta t} = A_1.\text{area}.\frac{\overline{\Delta S_1}}{\Delta l.c.} - (Q_g - Q_{c.u.}).\overline{S_1}$

Where all values are known but $Q_{c.u.}$ it can be computed as follows:

$$Q_{c.u.} = \frac{\left(\frac{\Delta(\Sigma \text{vol}.s)}{\Delta t} - A_1.\text{area}\frac{\Delta S_1}{\Delta x}\right)}{S_1} + Q_g$$

or

$$Q_{c.u.} = Q_g - \frac{A_1.\text{area}}{S_1}\,\frac{\Delta S_1}{\Delta l.c.} + \frac{\Delta(\Sigma \text{vol } xS)}{S_1 \Delta t}$$

Such a use of the diffusion equation would be similar to the accepted use of the salt-velocity method for measuring discharge. The value of a consumptive use schedule evaluated in this manner would depend entirely on the accuracy of the values of channel volumes, salinity concentration, salinity gradient and gross inflow.

What the preceding computation actually amounts to is an evaluation of the net outflow which should be extremely useful in itself to guide the operators in scheduling releases. The consumptive use is then obtained by combining net outflow and gross inflow.

Evaluation in a Larger Hydraulic Model

Another possible method for determining salinity control flow is by using a larger hydraulic model. The method would be similar to that used in the smaller model but it could be carried out in more detail and more accurately in a larger model. A series of verification tests of duplications of historical intrusions would be made. The model diffusion coefficients as well as the model discharges would be varied to accomplish duplication. If the model with adjusted diffusion and discharge scales could be made to reproduce several historical intrusions it would then be valid for establishing the pattern and speed of any future intrusion based on any predicted flow hydrograph. Although this procedure would be in a sense a duplication of the previous studies in the small model, the larger model would yield much more reliable results in a quantitative sense. Unless the model could be justified on the basis of uses other than evaluation of control flow, this procedure would be quite expensive.

FIELD TESTS

Factors

The major factors involved in the process of salinity intrusion into the Delta, which have been indicated in the preceding discussion, will be developed in more detail with particular reference to field measurements.

Tidal Diffusion

The force contained in and occasioned by the tidal ebb and flood acts to propagate ocean salinity into the Delta by a process of diffusion. This force acts usually in an upstream direction but in more general terms it acts in the direction of decreasing salinity.

The field tests required to evaluate this force consist principally of measurements of salinity gradient. Direct measurement of the diffusion coefficients is not possible by any means now known. The methods by which salinity gradient would be evaluated are not completely clear at this time. The proper method would have to be developed by preliminary tests. A general approach which appears to offer possibilities is that of making continuous recordings of salinity and velocity at several stations in a selected stretch of river. Selection of an appropriate stretch could be based on observations of the movement of floats. A proper stretch would be one which is completely traversed by a float during an average tide.

The recordings of salinity and velocity could be evaluated in terms of salinity gradient in two ways. First, the salinity records averaged at each station when combined with the distances would supply values of average salinity gradient. Secondly, the rate of change of salinity during flood tide at any station taken together with the velocity variation during the same period could be interpreted in terms of salinity gradient if no appreciable mixing occurred during the period. The worth of each method would be judged by the consistency of the results with the data inserted in the diffusion equation. Measurements of the same general type were taken as a part of the comprehensive studies made by the state engineers. However, complete data, including both salinity variation and velocity variation recorded simultaneously, were not obtained.

Net Outflow

The directly opposing force of net stream outflow from the Delta tends to sweep all saline waters downstream. The various elements that comprise net outflow are important and deserve special mention and listing.

Gross Inflow

The total or gross inflow into the Delta is well defined by measurements at rating stations on the rivers feeding into the Delta. The stations are located upstream from the tidal effects. The sum of the flows as measured at the various stations or the gross delta inflow is open to question only to the extent of diversions and accretions between the rating stations and the Delta proper.

Diversions and Accretions

Some of the water diverted and used above the Delta returns to the Delta by seepage flow. The amount of this flow is very difficult to evaluate and for the present the estimates resulting from the studies made by the state engineers as reported in Bulletin 27 must be accepted.

Consumptive Use

Consumptive use by transpiration and evaporation is a major factor in determining net outflow especially at the time of maximum salinity encroachment when the net outflow is low. The use has been estimated to reach a maximum value in August of 3,700 second-feet. This value compared to the magnitude of the control flow which is of the order of magnitude of 5,000 second-feet is a numerical measure of its importance. Evaluation of the rate at which water is consumed in the Delta is based on data obtained from tank experiments. Samples of the different types of crops were grown in tanks located in various spots in the area. The use of water was measured throughout the growing season. The difficulties and limitations of such tests is well illustrated by an example. One tank had a pin-hole leak and this was enough to cause a large error in the results. The possible error of the method is estimated at 25 percent which, applied to the maximum value of consumptive use or 3,700 second-feet, amounts to more than 900 second-feet.

Natural Transfer

Natural transfer of flow from the Sacramento River to the San Joaquin River through Georgiana and Three Mile Sloughs is another factor of considerable importance. In the low flow season the major portion of the gross inflow is contributed by the Sacramento River. During this period the flow of the San Joaquin River in the section which is critical with respect to salinity intrusion is determined largely by flow transferred from the Sacramento River. The division of flow between the two rivers must be known in the evaluation of the diffusion coefficients. Because there is a definite uncertainty as to the division of total net outflow all estimates of control flow in Hydraulic Laboratory Report No. 155 were related to Collinsville where the two rivers have joined and the division of flow is not a factor.

The transfer flows in Georgiana and Three Mile Sloughs were measured during the studies by the state engineers. The characteristics of the flows in both sloughs make a flow measurement using current meters a difficult operation and the results are open to question. The flows are widely variable throughout a tidal cycle and in the case of Three Mile Slough the flow varies in direction also. The average net flow for a tidal cycle must be obtained by integrating the discharge over an entire tidal cycle and a more significant result would be obtained if a period of several cycles were used. The longer period does not adapt itself well to the limitations of current meters A recording flow meter would be much better adapted.

Since these flows have an important bearing on the subject tests, it is recommended that new measurements of the flows in both sloughs be made utilizing the most recently developed equipment. For such specialized tests it might be necessary to develop some equipment. Recently reported is a new meter developed for wartime use which will measure and record velocities from 1/20 foot per second to several feet per second. Such an instrument would be very useful in recording velocity variation over a period of time that could include many tidal cycles. Another new technique which might prove useful is the echo-sounding method for obtaining quick depth measurements.

Timing of Tests

The influence of a few of the factors which have been discussed previously can be minimized by proper timing of the tests. Consumptive use of water is known to vary through the growing season from an estimated maximum of 3,700 second-feet in August to a minimum of 500 to 700 second-feet in November. Measurements made in November when the consumptive use is low would be subject to a possible error in the value of consumptive use of 25 percent of 600, or 250 second-feet, compared to a possible error of 900 second-feet when the use is high. However, tests made in November may incur certain restrictions such as occurred in the November 1929 data. If, as in the case of the 1929 data, the intrusion should develop to a point beyond the mouth of the Mokelumne River, a certain amount of saline water becomes trapped because of the very complicated flow conditions. Under such conditions, the concentrations measured at points within the influence of entrapped salinity are not significant for use in analyzing the mechanics of intrusion.

The magnitude of return flow is also reduced in the later part of the year because of the decrease in diversions. In December the inflow usually increases to such an extent that the ocean salinity is swept completely out of the Delta. Once the saline waters have been moved much beyond Collinsville no salinity tests are contemplated.

SUMMARY AND RECOMMENDATIONS

Although no definite program has been proposed in the preceding discussion, it is evident that a great deal of work can be done to explore the many possibilities that have been discussed. It is felt that any definite program must be developed by cooperation with regional forces. To this end the following procedure is recommended. The procedure recognizes that the current restrictions on funds, personnel, and time are serious handicaps.

1. Establish by correspondence with the Regional Director the priority of any salinity control studies.

2. If low priority is established no major studies would be started. But, there are certain steps that should be taken soon which will help materially when active studies are renewed. These steps include among other things:

   a. Meeting of hydraulic laboratory and regional personnel to formulate a general schedule.

   b. Completion and installation of instrumentation which will provide data for interim control of salinity and for more extensive studies to be carried on at some later date.

   c. Decision should be made relative to construction of a new and larger hydraulic model of the Delta. This will require a statement from the laboratory relative to cost and possible technical benefits that could be realized in such a model. Other benefits, such as publicity and training, should be apprised by the region. The cost of a larger model has been roughly estimated to be about $150,000. Such a cost would no doubt preclude any possibility of activating it this fiscal year. In any event the Regional Director should be given the opportunity of accepting or rejecting the proposal to construct a larger Delta model.

d. A limited amount of study and field testing might develop a method for utilizing data acquired in previous years leading to a determination of the controversial value of salinity control flow and consumptive use. Certain steps along this line were initiated about a year ago as mentioned in Field Trip Report No. 191 from D. J. Hebert to the Chief Engineer, dated October 30, 1946, a copy of which was sent to the Regional Director. No report on the work accomplished or the results obtained has been received. Since the matter was initiated on a rather vague and informal basis, any information will have to be obtained by direct contact with the regional personnel.