SOME SPECIALIZED INSTRUMENTATION FOR THE SOLUTION OF PROBLEMS IN TIDAL HYDRAULICS

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SUMMARY

The Bureau of Reclamation has developed over a period of years an instrument for continuous recording of ocean salinity in stream channels under tidal influence. It is designed to operate unattended for one to two weeks, and may be adapted readily to portable use in making traverses in channels and observations in depth to determine salinity variations. The meter consists of two main units: the sampling and standard conductivity cells as two legs of a self-balancing, alternative current Wheatstone bridge circuit, and a modified water-stage recorder.

Need for such a meter became apparent with the necessity for analyzing the factors which account for the intrusion and retreat of ocean salinity in the channels of the Sacramento-San Joaquin Delta of California. The success of the Central Valley Project which encompasses this area is to a great extent dependent upon good quality irrigation and municipal waters. The salinity meter has provided much useful information in the operation of the project. A network of measuring stations is described with a sample record and photographs. The results of several years of record from both fixed and portable recorders are briefly discussed in regard to their influence on the design of future facilities and the understanding of mechanics involved in the control of intrusions.

The electrical and recording equipment is fully described together with difficulties experienced in its development and use.

INTRODUCTION

The plan for development of the water resources of the large valley laying in the central part of the State of California includes storage of the runoff in excess of land needs in the northern portion of the valley and subsequent release of this water to the southern portion where land needs exceed the local water supply. Within the Delta a system of natural channels is utilized to conduct this water to the Tracy pumping plant where it is lifted into a canal for distribution to the land. The Delta extends for a distance of about 50 miles north and south and has a maximum width of about 25 miles.

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Figure 1. The Delta was formed by the Sacramento River entering from the north, the San Joaquin River from the south, and the north and south forks of the Mokelumne River from the east. The confluence of the Sacramento and San Joaquin rivers is near the west center of the area. From this point the flow is in a westerly direction through San Pablo, Suisun, and San Francisco Bay, and then to the Pacific Ocean.

In its original state almost the entire area was marshland interlaced with a network of meandering channels. Most of the land has now been reclaimed for agricultural use by construction of levees along the old water courses and drainage of the enclosed island areas. These channels are under the influence of the ocean tides, and therefore the direction of flow is periodically reversed. In reversing, during flood tide, ocean water is carried inland many miles, impeded only by water already present and natural downstream river flow. The resulting movement and mixing of fresh and saline waters provides a means capable of propagating ocean salinity into the Delta. The extent of propagation is directly dependent on the outflow in the streams. During periods of high outflow the salinity front recedes toward the ocean, but during low flows the front moves steadily upstream. Total tidal flow at flood stage is in the order of 150,000 cubic feet per second, while average summer river flow is less than 10,000 cubic feet per second, and spring flows can exceed 70,000 cubic feet per second.

The success of the scheme to develop the valley is to a great extent dependent upon the suitability of the water for irrigation and domestic use at the point of delivery. Excessive salinity must not be allowed to encroach on the channels being used to convey the water to the pumping plant or contamination to an unsatisfactory degree will occur. In order to resolve the problem of limiting the intrusion, it was necessary to establish the pattern and rate of fresh water flow required. Some streams which historically had flowed toward the ocean reverse to supply the pumping demand. Determination of the amount of fresh water needed to repulse the intrusion was of vital importance to the operation of the project.

Early in the planning phase of the project a program was initiated for obtaining samples of the water periodically at a number of locations throughout the area. Analysis of these samples provided data from which the general movement of salinity could be traced. To facilitate a more complete investigation of the factors which account for intrusion and retreat of ocean salinity, however, the need became apparent for continuous recording of the degree of contamination present at certain locations in the Delta.

**DESIGN CONSIDERATIONS**

The primary problem was to provide an instrument that would produce a continuous record of the degree of salinity present in the flow. Spot sampling had shown that the base salinity of natural downstream flow entering the Delta was in the range 150-250 parts per million (ppm) total dissolved
solids (TDS) as compared to about 35,000 ppm for the ocean; thus ocean salinity would be the principal contaminant in most of the channels under consideration. This being true, in addition to the fact that the chemical mixture comprising ocean water varies a negligible amount, a reasonably constant relationship exists between TDS and conductivity. An empirical expression for the relationship as determined experimentally by an International Commissioner from samples collected in the Baltic Sea, is:

\[
\text{Salinity (TDS in ppm by weight)} = 0.3 + 1.805 \times \text{chlorinity (in ppm by weight)} \tag{1}
\]

for a given temperature. 3/

The program of water sampling spoken of earlier was integrated with observations being made by a network of water stage recorders. The accumulated data showed that salinity from the ocean entered the subject channels in a diffused state rather than by means of a density wedge as has been found in some estuarine channels. Passage of the ocean water through a series of embayments and defiles along the main stream from the Pacific Ocean to the Delta causes a mixing of the saline and fresh waters. At certain locations samples showed the salinity content to be distributed quite evenly throughout the cross sections; therefore, continuous measurement of salinity at points on or near the shore could be relied upon to give reasonably reliable indices of salinity.

The principle expressed in equation (1) permitted consideration of a conductivity instrument to determine salinity since conductivity could be related to the total dissolved solids content of the water and calibrated accordingly. Initially, the average salinity of the surface waters was of primary importance. During the sampling program, samples were taken at a depth of 1 foot below the water surface. In order to relate the records to the samples, it was considered necessary to maintain the sampling conductivity cell at this depth by a float arrangement to automatically adjust for changes in tide levels. The same cell should also be of the type through which water could pass since a continuous record was desired.

For the purpose of obtaining stability a reference cell was considered necessary. The probability of rapid changes in temperature was considered remote so it was not deemed necessary to compensate for errors which might be introduced by a thermal lag in such an arrangement. This condition obviated the need for simultaneous measurement of conductivity and temperature in determination of salinity.

3/BERICHTE ÜBER DIE KONSTANTENBESTIMMUNGER ZUE AFSTELLUNG DER HYDROGRAPHISCHEN TABELLEN, C. Forsh, M. Knudsen, S. P. S. Sorensen, Kongelige Danske Videnskabernes Selskab, Skrifter 6 Raekke, Naturvidenskabelig og Mathematisk Afdeling (Copenhagen, Denmark), Volume XII, Number 1, 1902.
The apparatus was expected to operate unattended for a period of one week, or longer if it were found practicable. To fulfill this requirement a stable and dependable recorder with ample record chart capacity was necessary.

DESCRIPTION OF THE INSTRUMENT

The basic components of the salinity meter developed to meet the requirements are: a Wheatstone bridge circuit, an amplifier, a phase controlled drive motor, and a continuous recorder, Figure 2. A circuit diagram is shown in Figure 3.

The Wheatstone bridge consists of one conductivity cell, in which is sealed a sodium chloride solution of known concentration for temperature compensation and reference; one sampling cell, which is in contact with the water to be tested and is open to allow free passage of the water through it; and two variable resistances, one of which keeps the bridge in balance as the resistance in the testing cell varies. This variable resistance, or ten-turn potentiometer, is controlled by a two-phase alternating current induction motor, which in turn is driven by the amplified off-balance voltage from the bridge. The other variable resistance is used to establish the limits of variation in salinity and once established is locked in place. The fixed resistors are incorporated with a switching arrangement to replace the cells for circuit testing.

The bridge output amplifier is a conventional three-stage resistance-capacitance coupled unit with a 6L6 beam power amplifier tube to energize the "balance-recorder" motor stators. A small amount of adjustable negative feedback is used to stabilize the output.

A commercially available water stage recorder was adapted to the apparatus to provide a continuous and permanent record of salinity. The recorder pen is driven from a gear attached to the induction motor previously mentioned. The normal gear-train ratio produces one inch deflection on the chart for each 500 ppm change in total dissolved solids. This scale may be varied to correspond to the range of salinity expected at the point of installation.

The graph is made on a strip chart 10 inches wide and 75 feet long. In operation the strip chart moves forward at a rate controlled by a clock while the pen moves laterally across the chart in proportion to the salinity present in the flow, thereby producing a graphic record of salinity against time. The pen in its lateral movement reverses at each margin of the chart to accommodate unusually high or low concentrations, thus insuring against loss of record and continuing the record with no reduction in scale. The standard time scale is 2.4 inches per day but accessory parts to produce scales varying from 1.2 inches to 72 feet per day are available from the manufacturer.
The two conductivity cells are located in close proximity to each other to avoid temperature difference. In the initial installations these cells were maintained at a depth of one foot below the water surface at all times by means of a float which moved up and down with the tide. The float was guided by two fixed rods. In later installations, floats are not used because of excessive maintenance necessary on the guides. The cells are positioned in the flow at such a level that they are always at least one foot below the low water surface. The electrical leads from the cells to the instrument are sealed in "Tygon" tubing for water tightness.

The motor, variable resistor for salinity limits, potentiometer, and gear train are mounted on the front of the recorder, Figure 2. The amplifier is built in a separate chassis.

The operation of the apparatus is as follows: The resistance in the sampling cell varies as the salinity of the contaminated water passing through it changes. Likewise, the resistance in the reference cell changes slowly with the rise or fall of the temperature of the surrounding water. As the conductivity in the sampling cell varies the bridge circuit becomes instantaneously unbalanced. The off-balance potential is applied to the amplifier, the output of which activates the motor driving the potentiometer. The function of the potentiometer is to restore bridge balance. The motor is made reversible by reversing the phase of the field windings. The phase of the correction voltage is automatically reversed through 180 degrees as the adjustment of the balance potentiometer passes through the balance point.

Since the recorder pen is mechanically connected to the drive motor, a record is maintained of all of its movements. A sample record is shown in Figure 4.

Calibration of the instrument is effected by filling the sampling cell with sodium chloride solutions of known concentration. The concentration of the solutions used exceeds the range of salinities anticipated at the installation site. Concentration of the solution sealed in the reference cell is approximately mid-range of the concentrations that the instrument is expected to cover. Extreme care must be exercised to keep the equipment and the calibration solutions at the same temperature during the calibrating procedure.

ADAPTATION TO PORTABLE OPERATION

In order to coordinate some of the readings that were taken at the fixed stations near shore and to investigate the area immediately surrounding them, one of the meters was adapted for use in a boat.

The clock chart drive was replaced with an electric motor to provide flexibility and increased chart speed. To permit coverage of a wider range of salinity variations, two standard cells are used instead of one and each can be chosen at will by use of a switch. Three fixed resistors with
switches are connected into one leg of the bridge circuit in lieu of one variable resistor. Thus three ranges of operation are available for each standard cell giving a total of six scales. The value of the resistors was selected to give an almost linear variation of salinity with conductivity. Calibration curves were established for each of the six scales.

Figure 5 shows the arrangement for testing for distribution of salinity with depth and Figure 6 shows the recorder installed in a boat.

THE SHORE STATIONS

As has been stated previously, salinity in the channels under study was relatively well distributed throughout the cross section. The instruments could therefore be installed near shore. Figure 7 shows one of the shore installations. The present network consists of 15 recorders, Figure 1. Some of them are located in existing structures along the water courses.

The cross-sectional area of the channel at the recorder station is normally determined by use of echo-sounding equipment. Periodic checks with the portable salinity meter are made to determine distribution of salinity in vertical and transverse sections at the sites.

OPERATING CHARACTERISTICS

The meter attains its greatest accuracy in waters in which ocean salinity is the principal constituent of contamination, and a reasonably constant relationship exists between total dissolved solids and conductivity. At locations where ocean salinity is not present and total dissolved solids vary as to amount and composition, the accuracy of the instrument is considerably reduced. With frequent calibrations and maintenance, the meters have produced results that are quite consistent with those obtained by analysis of check samples.

Some difficulty has been encountered in operation of the equipment in the field. For the sampling cell to operate efficiently and accurately, periodic cleaning is necessary to remove silt and slime accumulations within the cell, particularly on the electrodes. During periods of low flow in the channels, barnacles and other marine growth have, at times, coated the cell and clogged the water passages.

Some electrolysis of the standard solution in the reference cell has been experienced, even though a 60-cycle alternating current at 12 volts is applied to the bridge. This causes formation of bubbles which may collect between the electrodes in the cell and introduces errors in results. Orienting the cell in such a manner as to locate the electrodes on the sides rather than on the top and bottom has alleviated this condition somewhat. In this position the bubbles collect above the electrodes and do not alter the cell constant.
Excessive maintenance on the float and guides was eliminated by fixing the cells in position below the low water surface. Initially, some difficulties were encountered in the electronic circuits but these have been almost entirely eliminated by minor alterations.

Temperature changes during calibration of the equipment has also caused some discrepancies in results. This has been corrected by carefully controlling temperatures of solutions and equipment during the calibration period.

DATA OBTAINED FROM THE RECORDERS

The salinity meter has provided much information useful in operation of the project. Following the installation of a trial meter station, a network of measuring stations was established, Figure 1. The primary function of this network is to give warning of increasing salinities in sufficient time to schedule releases from storage upstream, and to trace the advance of the salinity front. Measuring stations were built at points on the Sacramento and San Joaquin rivers far enough inland to be above the limit of ocean contamination. These are used to judge the quality of water as it enters the Delta. Another station was constructed about 25 miles upstream from the ocean to give early warning that ocean salinity is beginning to propagate into the Delta. Within the region itself stations are located at points of diversion for domestic and irrigation uses, and other points important to the study of salinity propagation mechanics.

In 1944 a model of the Delta was tested in the Hydraulic Laboratory of the Bureau of Reclamation. The scale ratios used made it possible to operate the model until steady states of salinity distribution existed for certain net downstream river flows. The equation expressing such steady state conditions is:

\[ \frac{S_x}{S_0} = e^{-QnK} \]  

where \( \frac{S_x}{S_0} \) is the ratio of salinities for two river sections, \( S_0 \) being the downstream and higher salinity; \( Q_n \) is the net river flow to the ocean in cubic feet per second; \( K \) is a factor which considers the distance between the two sections and the average cross-sectional area of the channel; and \( e \) is the base of natural logarithms.

Though a steady state condition has not been fully realized in the Delta since the network was completed, the patterns of several intrusions as indicated by salinity meters have served to strengthen the \( K \) factor determined by the model. A method of computing transient salinity states recently completed is dependent upon evaluation of a reliable coefficient \( K \). A means for determining in advance the effects of changing flow regime on salinity values was thus aided by the network of meters.
At the two principal points of delivery of water from the Delta, salinity meters have been used to record the quality of water diverted. Written contracts specify the average amount of total dissolved solids allowed in the water; hence, salinity meters fulfill a need in contract administration by giving a continuous record of the quality of water available.

CONCLUSIONS

The equipment as developed and described above has met the requirements of providing a continuous record of the degree of salinity of the water at a number of sites in the channels of the Delta. The graphic records of salinity versus time are permanent and may be studied when convenient.

With normal maintenance and calibration, carried on concurrently with spot sampling and analysis, the accuracy has been quite good, especially in areas where ocean salinity is the principal constituent of contamination.

The data obtained from the salinity records, when combined with information from many other sources included in the overall study, have yielded results that have proved to be very valuable in the step-wise development and the operation of the project.

Present plans include transport of additional water across the Delta to extend the area now being benefited. The salinity recorders should play an important part in providing data for this expansion.
FIGURE 1 - SACRAMENTO - SAN JOAQUIN DELTA
Fig. 2 - Salinity Meter
FIGURE 3 — SALINITY RECORDER CIRCUIT DIAGRAM
FIGURE 4 - SAMPLE RECORD
Fig. 5 - Arrangement of Cells for Measuring Salinity Distribution in Depth
Fig. 6 - Salinity Meter Mounted in Boat