ANTECEDENT FLOW-SALINITY RELATIONS:
APPLICATION TO DELTA PLANNING MODELS

by

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EXECUTIVE SUMMARY

This report presents a method for estimating the outflows necessary to control salinity at specified locations in the Bay-Delta estuary. The method provides a procedure for reducing errors and uncertainties resulting from the steady-state flow-salinity relationships often used in Delta operations analysis. It improves upon current practice by accounting for the salinity effects of antecedent flows. The method presented in this report is firmly based on field measurements of Delta salinity variations. Use of the method can significantly improve the accuracy of estimated water supply impacts resulting from alternative Delta operations and control strategies.

1. INTRODUCTION

Water supply impacts of alternative Delta operations and control strategies are frequently assessed using relations which relate flow and salinity in the Delta. Current methods are typically based on steady-state analysis, i.e., they relate present levels of salinity to present levels of flow. Recent work on Delta flow-salinity relationships (Denton 1993a; Sullivan, Denton & Gartrell 1993) has shown that the prior history of Delta outflow (antecedent outflow), not just the present Delta outflow, is important in determining salinity in the Delta. Delta operations analyses presently based on steady-state flow-salinity relations can now be significantly improved by taking account of antecedent flows.

The purpose of this report is to suggest a methodology which estimates Delta flows necessary to control salinity at specified locations in the Bay-Delta. The report is organized as follows: in section 2 a discussion is given of flow-salinity relations which estimate salinity at locations in the Delta given the prior history of Delta outflow; in section 3 a procedure to empirically determine parameters for the antecedent flow-salinity relations is given, and examples of "best-fit" parameters at several Delta locations are provided; in section 4 application of the antecedent flow-salinity relations to Delta operations simulations are discussed; and in section 5 the accuracy of estimates using the antecedent flow-salinity relations is examined and compared with the accuracy of estimates using steady-state flow-salinity relations.

2. ANTECEDENT FLOW-SALINITY RELATIONS

Empirical antecedent flow-salinity relations have been developed motivated by simple results from one-dimensional dispersion theory (Denton, 1993a). The relations can be used directly to predict salinity at locations in the Delta given the prior time-history of net Delta outflow, or inverted to predict the flow required over some time interval to produce a given salinity.

2.1 A simple flow-salinity relation

Consider the simple case of a one-dimensional estuary in which flow quantities vary only with longitudinal position and time. In this case the tidally-averaged advection-dispersion equation for salinity transport is given by

$$A\frac{\partial S}{\partial t} - Q\frac{\partial S}{\partial x} = \frac{\partial}{\partial x}KA\frac{\partial S}{\partial x} , \tag{1}$$

where A(x) is the estuary cross-sectional area, S(x,t) is the concentration of salt, Q(x,t) is the volumetric flowrate, K is the longitudinal dispersion coefficient, x is distance in the longitudinal direction (increasing in the upstream direction), and t is time (Denton 1993a). The problem may be further simplified by assuming that the area, A, longitudinal dispersion coefficient, K, and flowrate, Q, are independent of longitudinal position. Boundary conditions may be selected as constant ocean salinity, S_o, at $x=0$, and constant upstream river salinity, S_b, at $x=\infty$. For Q independent of time, the steady-state solution to this problem is

$$S = (S_o - S_b)e^{-Qx/KA} + S_b \,. \tag{2}$$

Of course in natural environments, such as the San Francisco Bay-Delta estuary, the above assumptions may need modification. In particular, the tidally-averaged flowrate, Q, can fluctuate significantly on time scales ranging from days to months, and the estuary geometrical configuration can be tremendously complex. Geometrical complexities notwithstanding, a modified form of equation (2) is considered for use in modeling unsteady salinity response to variations in Q. At a fixed position, a relationship of the form

$$S(t) = (S_o - S_b)e^{-\alpha G(t)} + S_b \tag{3}$$

is considered, where G(t) is a functional of the flow time-history (antecedent flow), and α, S_o, and S_b are empirically determined constants which can vary with position.

2.2 Antecedent outflow G(t)

Consider a relation for the functional, G, of the form

$$\frac{dG}{dt} = \frac{(Q - G)G}{\beta} \,, \tag{4}$$

where β is an empirically determined constant which can vary with position. (This formulation is similar to a relation used by Harder 1977.) In equation (4), β/G may be thought of as an effective time-constant, τ, which determines the rate of approach of G to Q; equation (4) implies that the system response is relatively quick when G is large and relatively slow when G is small.

3. PARAMETER ESTIMATION

Practical application of equation (3) and equation (4) requires that four constants be determined from field measurements for each Delta location of interest. In practice, the determination of empirical constants from measurements of Q and S may be done as follows. β may first be determined for arbitrary (but reasonable) S_o, S_b, and α by choosing the value which best moves the measurements of S onto a single line in the S-G plane. S_b can then be determined by locating the horizontal asymptote of the single line as $G \rightarrow \infty$. Here S_b represents the background salinity at high flowrates (large Q) from sources upstream and within the Delta, not from seawater intrusion. The remaining two parameters, S_o and α can then be determined by minimizing the deviation between model estimated S and measured S, subject to some defined weighting system (some range of S or G may be more important than another for a particular application). The parameter estimation procedure is illustrated in figures 1(a) and 1(b). In figure 1(a) 14-day average salinity is shown versus 14-day averaged net Delta outflow (Q). By selecting an appropriate value for β, the data from figure 1(a) can be moved onto a single line in the S-G plane as shown in figure 1(b). The parameters, S_o, S_b, and α, are determined from the "best-fit" line shown in figure 1(b).

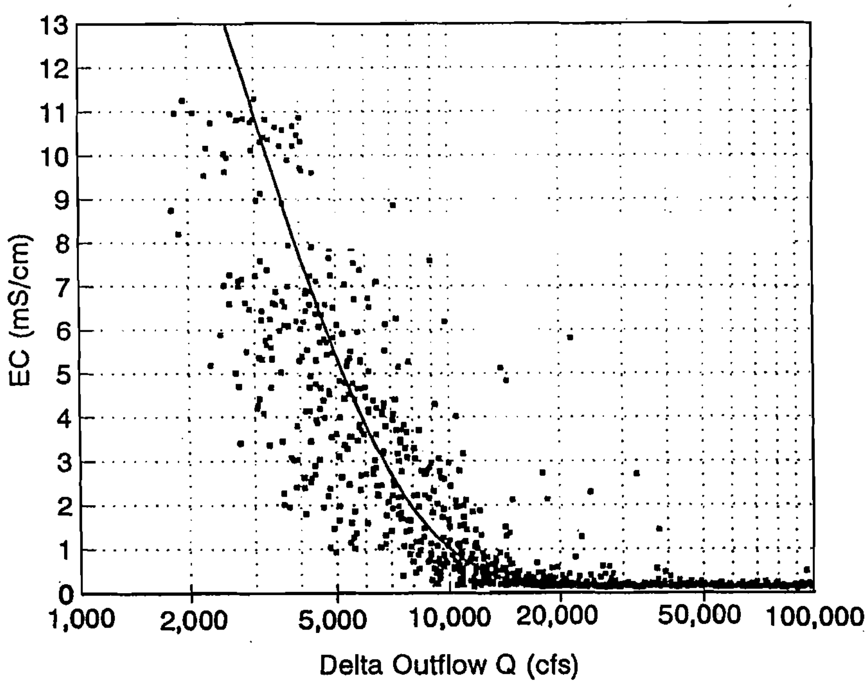

Figure 1(a). 14-day average salinity at Collinsville as a function of 14-day average net Delta outflow (Q). The data shown are for water years 1968 through 1986.

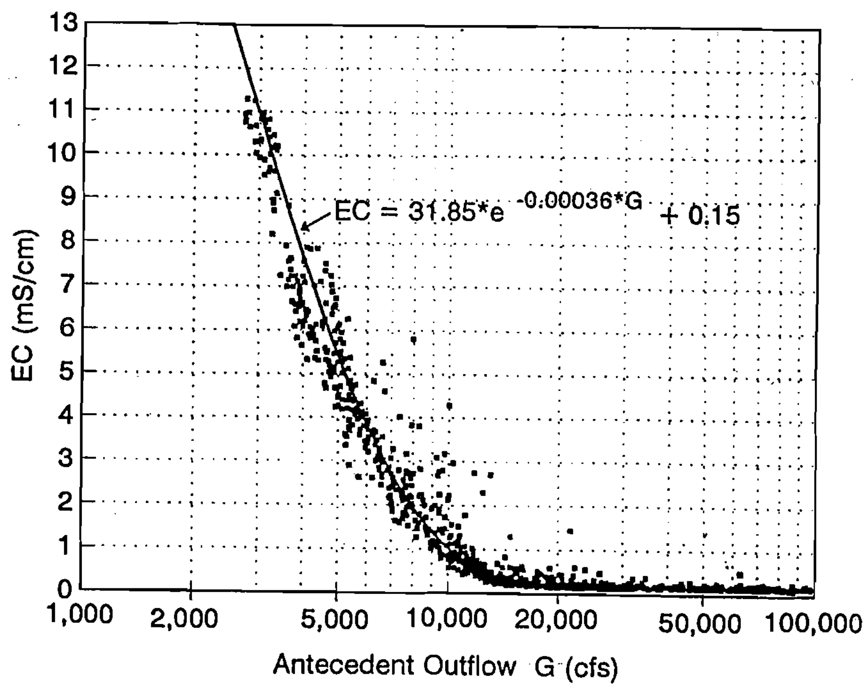

Figure 1(b). 14-day average salinity as a function of antecedent outflow (G). The data shown are for water years 1968 through 1986.

The parameter estimation procedure has been performed at a number of locations in the Delta. The "best fit" parameters at four sample locations are given in table 1 below.

Location	β (ft^3) ($x10^{10}$)	S_b ($\mu S/cm$) ($x10^2$)	α $(ft^3/s)^{-1}$ ($x10^{-4}$)	S_o ($\mu S/cm$) ($x10^4$)
Port Chicago	1.26	1.7	1.05	3.1
Chipps Island	1.50	1.8	2.5	3.6
Collinsville	1.50	1.5	3.6	3.2
Jersey Point	1.74	2.0	6.0	2.0

Table 1. Antecedent flow model constants.

4. APPLICATION TO PLANNING MODELS

The flow-salinity relations presented in section 2 can be used to determine salinities at points along both the Sacramento River (up to about Rio Vista) and the San Joaquin River (from Jersey Point to the Confluence) given the prior history of net Delta outflow. To determine salinity at points in the Delta interior a lagged salinity response scheme can be used in conjunction with the flow-salinity relations (discussed in section 4.2). At locations along both the Sacramento and San Joaquin Rivers and in the interior Delta the inverse problem of determining flows necessary to meet specified salinities can be solved (discussed in section 4.3).

4.1 Solution for G(t) for a Step Change in Q(t)

For the case of a step change in outflow from one level to a second constant level, equation (4) has the solution

$$G = \frac{\bar{Q}}{\left(1 + (\bar{Q}/G_0 - 1)e^{-\bar{Q}t/\beta}\right)}, \tag{5}$$

where G_0 is the value of G just before the step increase in outflow, and Q is the (constant) value of Q over the time interval.

Figure 2 shows a typical G response to a series of discrete changes in Q(t) using a monthly time-step. Note that G(t) continuously tends toward the steady state solution corresponding to the present value of Q, but may not reach steady-state before the time interval ends and a new value of Q is set.

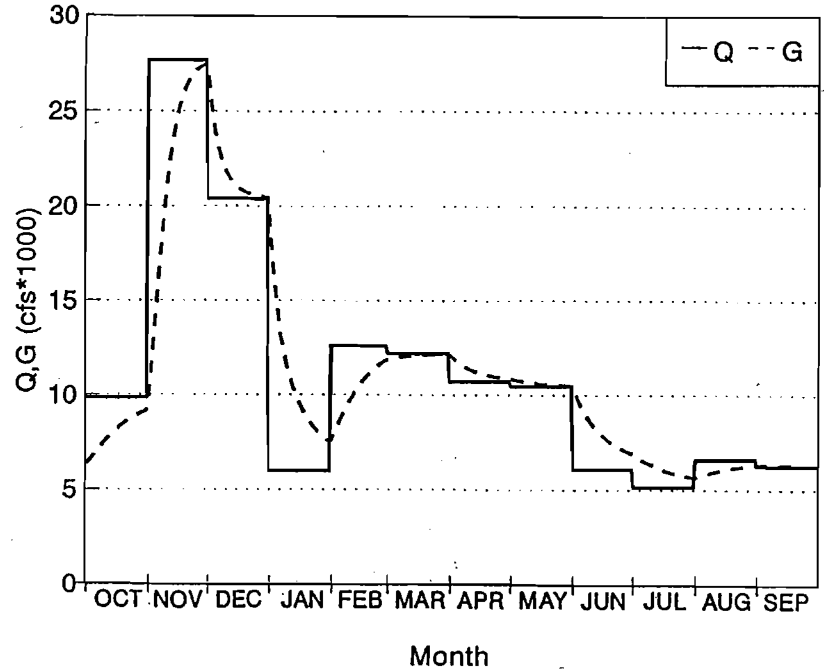

Figure 2. Response of G(t) to a series of step changes in Q(t).

If monthly-averaged salinities are used in a particular application, monthly-averaged values of G should also be used. From equation (5), the average value of G(t) over a time interval Δt is given by

$$\bar{G} = \bar{Q} + \frac{\beta}{\Delta t} LN\left(\frac{1 + (\bar{Q}/G_0 - 1)e^{-\bar{Q}\Delta t/\beta}}{\bar{Q}/G_0}\right). \tag{6}$$

4.2 Predicting Salinity at points in the Delta interior

The methodology described in section 2 can be extended to estimate salinities at locations in the interior Delta. To predict salinities at Delta interior points a time-lagged salinity weighting scheme can be used in conjunction with the antecedent flow methodology. For example, salinity at Rock Slough can be determined from the prior history of net Delta outflow using a two step approach (Denton 1993b). First, the antecedent outflow method can be used to determine salinity at Jersey Point; second, Jersey Point salinity can be related to salinity at Rock Slough using a simple lagged weighting scheme. The lagged weighting scheme is given here by

$$RS = 0.11 * WJP, \tag{7}$$

where RS is chloride concentration at Rock Slough in mg/l and WJP is the weighted electrical conductivity (EC) at Jersey Point in μS/cm given by

$$WJP = 0.55 * JP(t) + 0.45 * JP(t-\Delta t), \tag{8}$$

where JP(t) is EC at Jersey Point averaged over the present month and JP(t-Δt) is the average EC at Jersey Point for the previous month. The weighting coefficients in equation (8) correspond to a salinity transport time lag of about 14 days between Jersey Point and Rock Slough.

It should be noted that the method above estimates salinity due to sea-water intrusion. It does not account for periods of high agriculture return flow; however, periods of high agricultural return flow correspond generally to periods of high precipitation and low ocean salinity intrusion (Jersey Point EC $<$ 0.4 mS/cm), and in practical applications such as Delta operation simulations salinity requirements at points in the Delta interior are typically met during these periods without intervention by project operations.

4.3 The inverse problem: flow required to meet specified salinities

In simulations of Delta operations for purposes such as estimating water supply impacts of proposed Delta salinity standards, it is typically necessary to estimate the monthly-average flow required to meet water quality standards at various locations in the Delta. At points along the Sacramento River up to about Rio Vista and on the San Joaquin River from about Jersey Point to the Confluence this can be done by reversing the procedure discussed in section 2. This involves determining the value of G from equation (3) required to meet a specified salinity and then determining from equation (6) the corresponding value of required Q.

The procedure at an interior point in the Delta is slightly more involved. For example, at Rock Slough the procedure to estimate flow required to meet a specified salinity would be as follows. Given the required monthly-averaged salinity at Rock Slough the corresponding weighted monthly Jersey Point EC (WJP) is calculated using equation (7). The required Jersey Point EC for the present month is then calculated from equation (8) and the average value of G for the present month is calculated using equation (3). Net Delta outflow, Q, for the current month is then determined from equation (6) using an iterative method such as Newton-Raphson (an iterative scheme is necessary since equation 6 is implicit in Q). Equation (5) is then used to determine the value of G at the end of the month, giving G_0 for the next month's calculation.

A Fortran program, GREVERSE, has been developed based on the methodology discussed above as a tool for use in planning model simulations. GREVERSE is presently configured to handle salinity standards at a single Delta interior point, Rock Slough, but can be extended to include additional locations in the Delta where water quality standards are specified. GREVERSE compares the predicted Delta outflow required to meet a salinity standard with QOUT, a minimum outflow set by either uncontrolled runoff (large storms) or another controlling standard and increases the outflow above QOUT, if necessary, but does not decrease it.

5. MODEL ACCURACY

5.1 Uncertainty in predictions along Sacramento and San Joaquin Rivers

Predictions of salinity at three sample locations along the Sacramento and San Joaquin Rivers are shown alongside field measurements in figures 3-5. The salinities shown have been averaged over 14-day intervals to remove spring-neap tide-induced salinity variations since net Delta outflow (Q) estimates do not account for spring-neap variations.

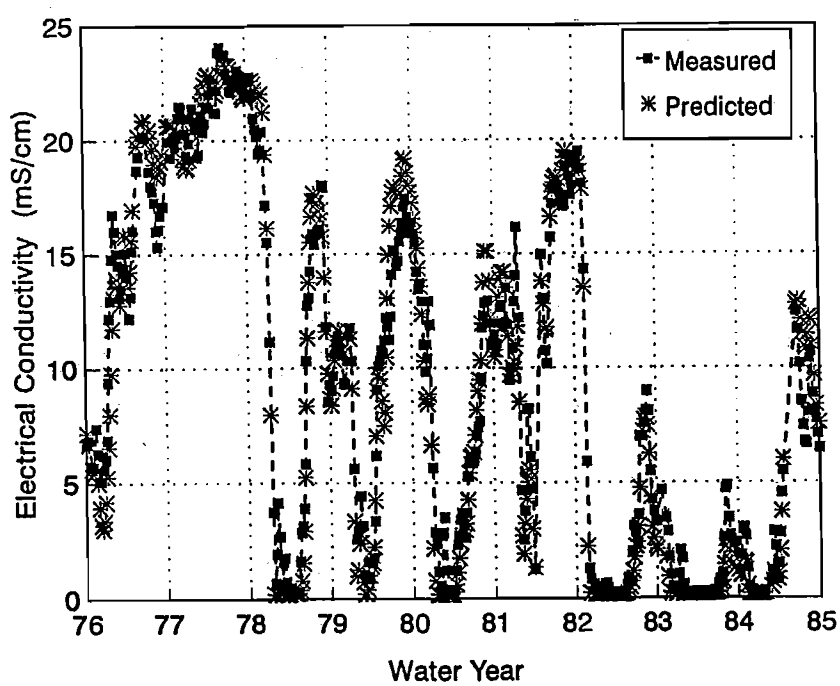

Figure 3. Measured and predicted 14-day average salinity at Port Chicago.

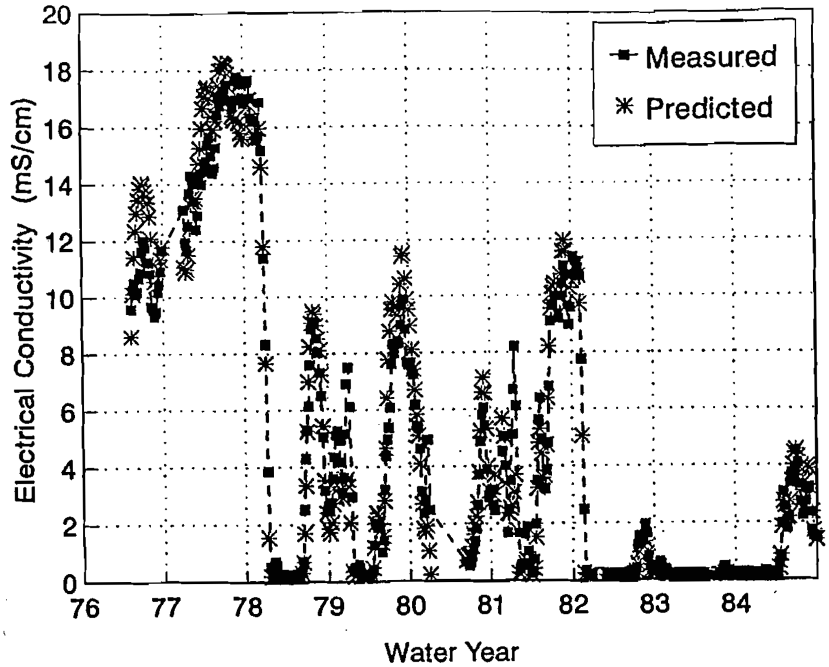

Figure 4. Measured and predicted 14-day average salinity at Chipps Island.

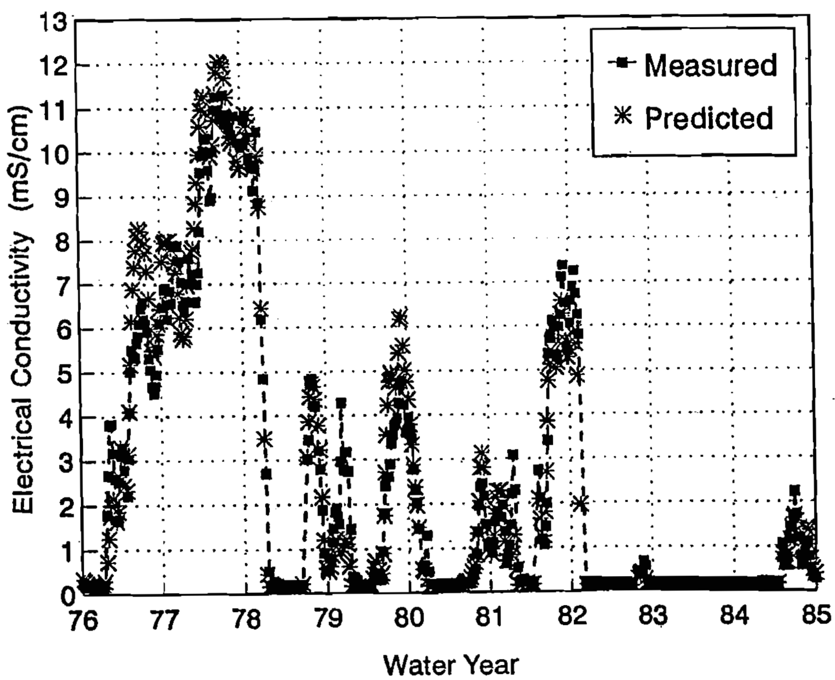

Figure 5. Measured and predicted 14-day average salinity at Collinsville.

A quantitative estimate of uncertainty in a single 14-day average salinity prediction may be determined from the standard deviation of the difference between predicted and measured salinity values. For the period shown in figure 4, water year 1976 through 1984, the standard deviation of the salinity error at Chipps Island was about 970 μS/cm. The average salinity over this period was about 4950 μS/cm so that the fractional error in a single 14-day average salinity prediction at Chipps Island was about 20%.

5.2 Uncertainty in predictions at interior Delta locations

Figure 6 shows predictions of salinity at an interior Delta point, Rock Slough, using two methods: (i) the antecedent flow methodology discussed in this report, and (ii) the steady-state relations from the California Department of Water Resources' planning model DWRSIM (module MDO).

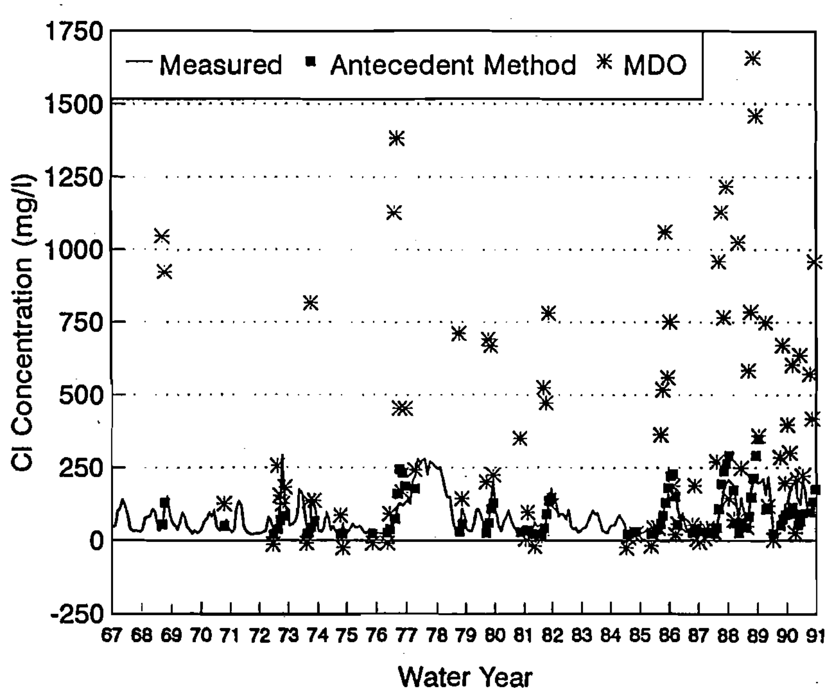

Figure 6. Measured and predicted monthly-averaged salinity at Rock Slough. Predictions are based on: (i) the antecedent flow method discussed herein, and (ii) steady-state relations from California Department of Water Resources' planning model DWRSIM (module MDO).

For periods in the interval, water year 1967 through 1990, where DWRSIM MDO was able to predict salinity at Rock Slough (requires that net flow in the lower San Joaquin River is eastward) errors were determined for salinity predictions using the antecedent flow methodology and using MDO's steady-state relations. The standard deviation of the salinity error using the antecedent flow methodology from this report was about 50 mg/l; the standard deviation of the salinity error using MDO was about 380 mg/l. The average salinity at Rock Slough over the time interval studied was about 100 mg/l so that the fractional uncertainty in a single monthly-average salinity prediction using the antecedent flow methodology was about 50%, and the fractional uncertainty using MDO was about 380%.

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Attachment 1

Accounting for Filling and Draining of the Delta in the G-Model

Figure 1 shows the prediction of Chipps Island EC when the original DAYFLOW estimates of Delta outflow are used as input to the G-Model. The example shown is February through June of 1988 (corresponding to figure 6 in Progress Report No. 2). The predicted EC values do not show the fluctuations in daily Chipps EC that occur with periodicities ranging from several days to two weeks but does follow the trend of the observed data remarkably well.

Accounting for Delta filling and draining

Figure 2 shows the greatly improved prediction if the draining and filling of the Delta is included in the estimate of Delta outflow. Observed tidal elevations at Antioch were filtered using a Godin filter to remove hourly fluctuations in the tide and used to compute dH/dt, the rate of change in tidal elevation for each day, midnight to midnight. The modified Delta outflow was calculated using the equation

$$\text{Modified NDO} = \text{DAYFLOW NDO} - 62500 * dH/dt$$

where NDO is in cfs and dH/dt is in feet/day. The coefficient value of 62,500 is a calibration coefficient fitted to the salinity data and may not necessarily represent the fit of actual daily Delta outflows. In fact, Delta outflows simulated using the Fischer Delta Model, using a real tide, are best fit using a coefficient of approximately 42,000.

The prediction of daily Chipps Island EC using the modified Delta outflow does a good job of reproducing the details of the salinity fluctuations caused by the filling and draining of the Delta for the period February through June of 1988.

Errors caused by the consumptive use estimates

Figures 3 and 4 show the G-Model predictions of daily salinity over a longer period, January 1988 through January 1989. Even when filling and draining of the Delta is taken into account, there are some major departures from the observed EC values from July onwards. These may be due in part to the use of long term averaged channel depletion data in the DAYFLOW estimates of Delta outflow (i.e. the same channel depletions are assumed every year independent of actual rainfall patterns).

During the summer periods, the Delta outflows are relatively low and small changes in the assumed channel depletions can represent a significant percentage change in outflow, and a correspondingly large change in predicted salinity. If, for example, the channel depletions are reduced to 60% of the DAYFLOW values from July through mid October, the predicted salinities reduce and fall into line with the observed values. Note that once this adjustment is in consumptive use is made, the range of salinity variations over the spring-neap cycle also agree well with the observed data through October.

DAYFLOW assumes that all the precipitation in the Delta area contributes to the Delta outflow with a built-in time delay. However, the precipitation that occurs after a prolonged dry period may infiltrate, evaporate, or otherwise be lost and not contribute to outflow. It is not unreasonable to reduce the contributions of local precipitation from the first major storms of the season.

Figure 5 shows the salinity predictions assuming only 60% of the DAYFLOW channel depletions from July 1 through mid October and neglecting the contribution of local precipitation until January 1. None of the other DAYFLOW parameters (Sacramento River inflow, Delta exports, etc.) were changed, only the consumptive use adjustments shown in Figure 6. These relatively minor consumptive use adjustments lead to major changes in the predicted salinities.

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Chipps Island Salinity
February - June, 1988
Using Delta Outflow from DAYFLOW

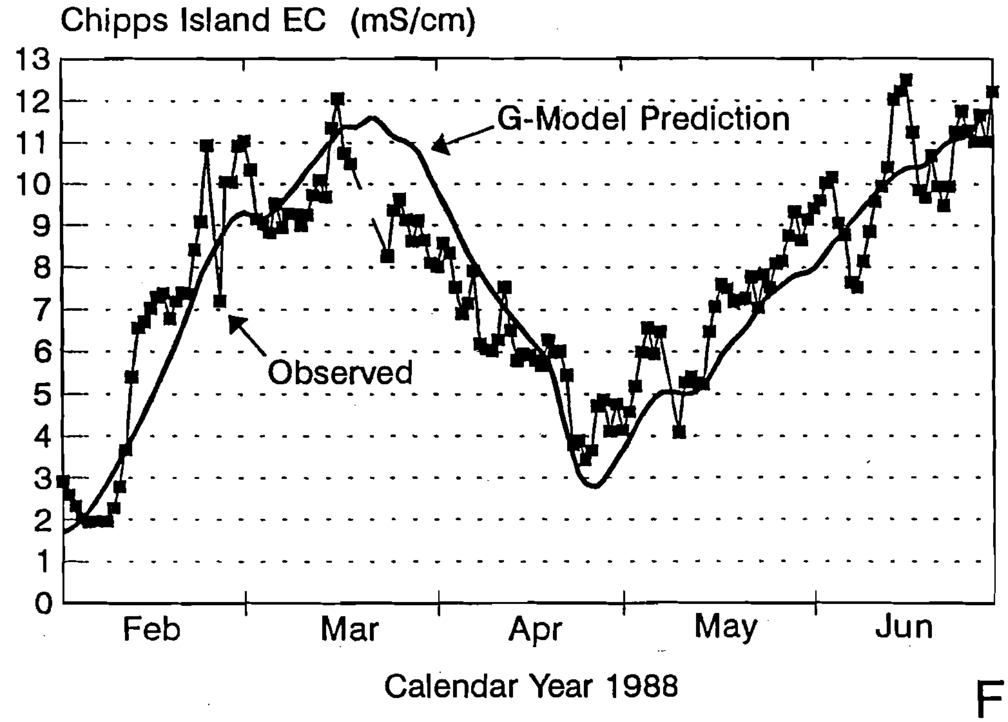

Figure 1

Chipps Island Salinity
February - June, 1988
Accounting for Filling and Draining of the Delta

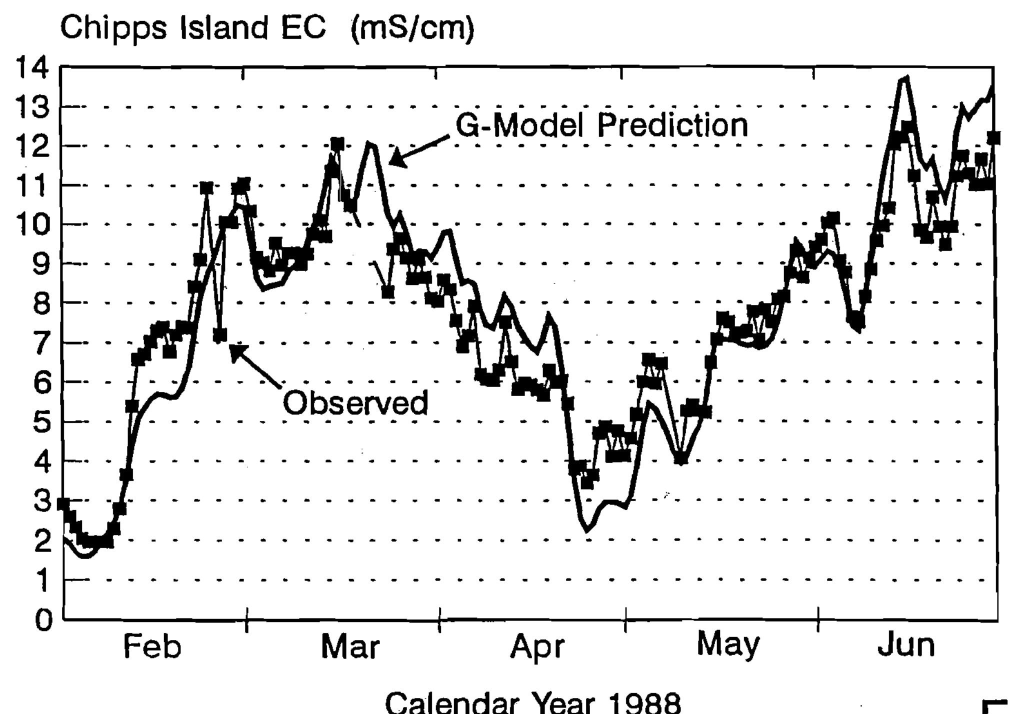

Figure 2

Chipps Island Salinity
January - December, 1988

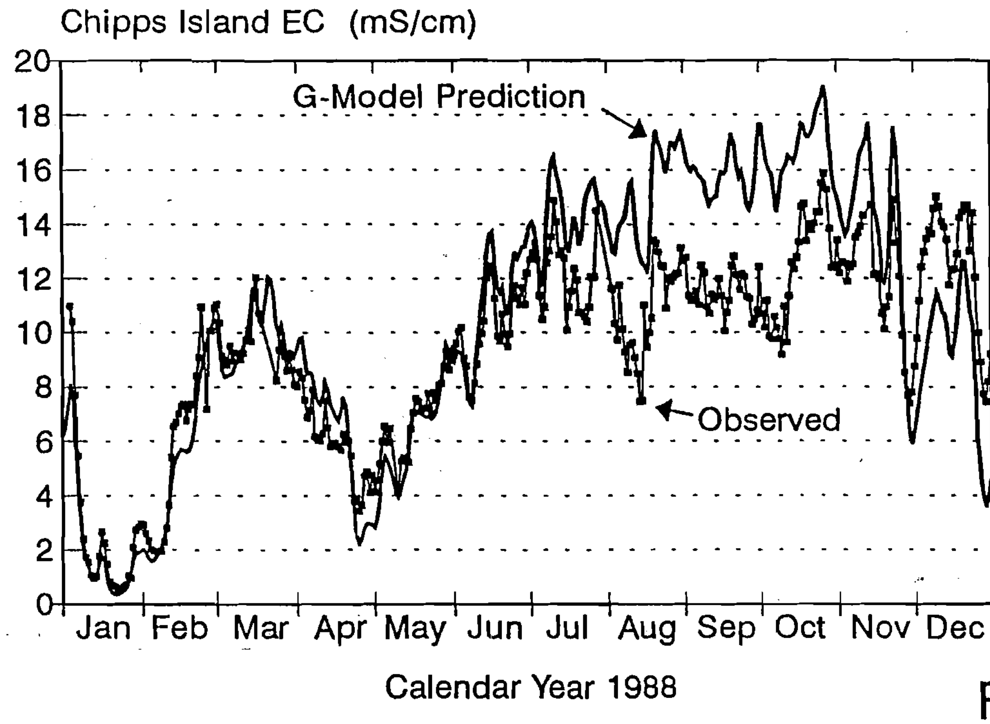

Figure 3

Chipps Island Salinity
July 1988 - January 1989

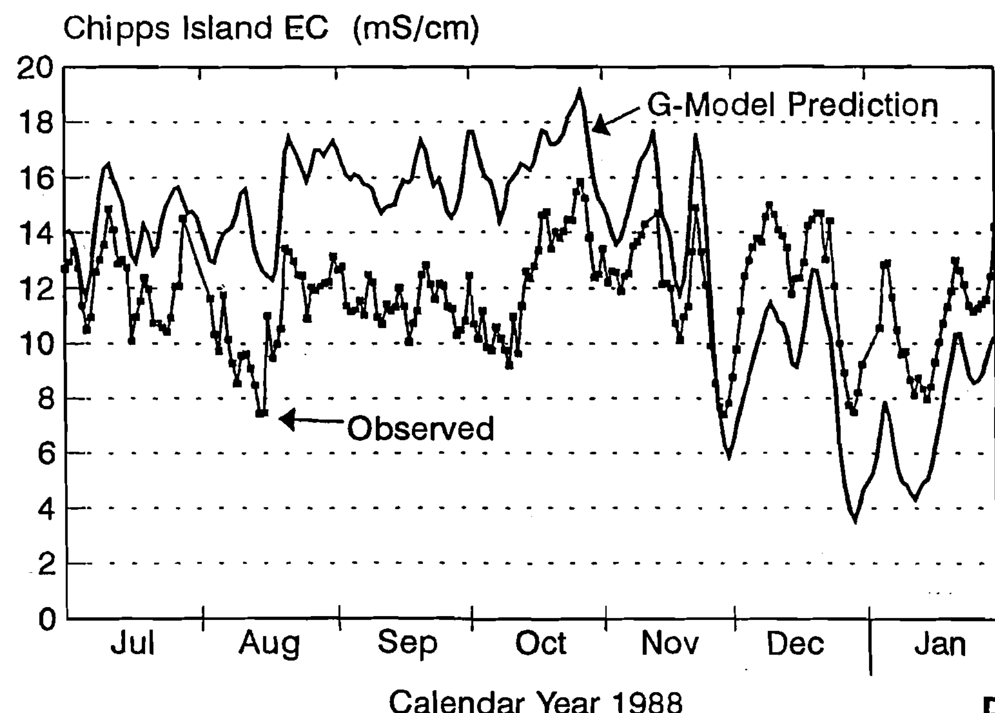

Figure 4

Chipps Island Salinity
July 1988 - January 1989

Adjusting Channel Depletions and Precipitation

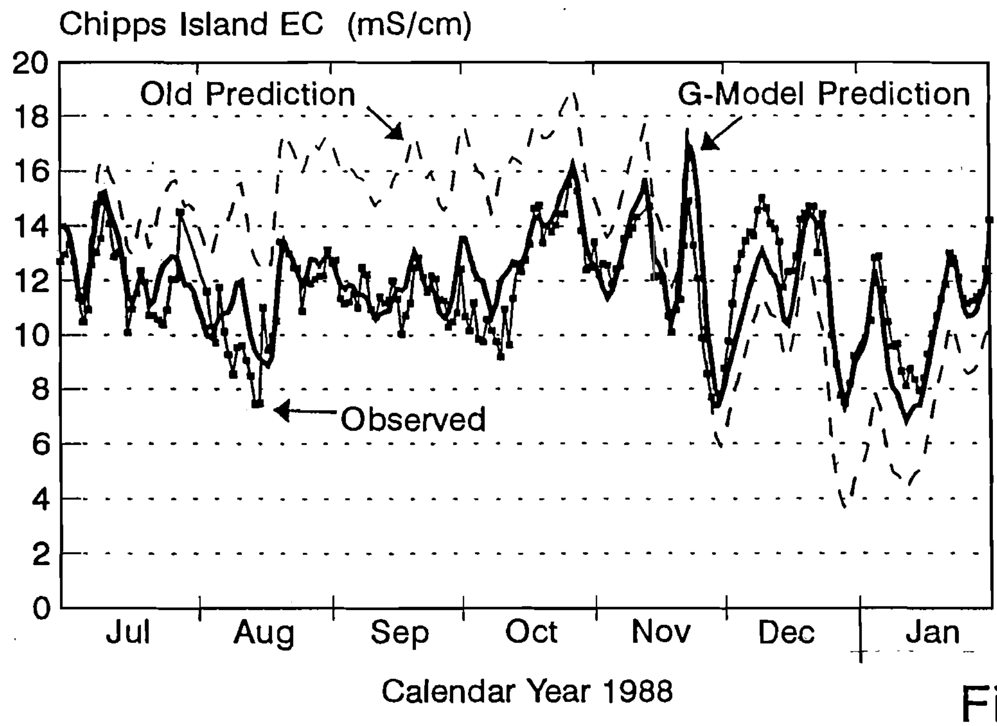

Figure 5

Adjusting Consumptive Use Estimates
July 1988 - January 1989

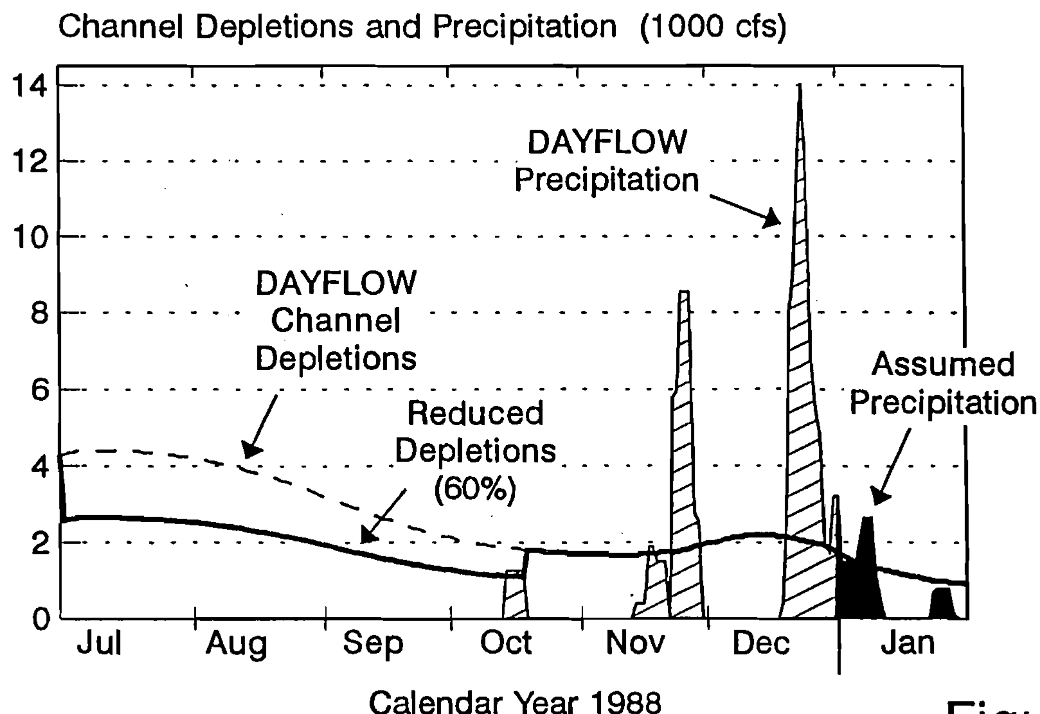

Figure 6

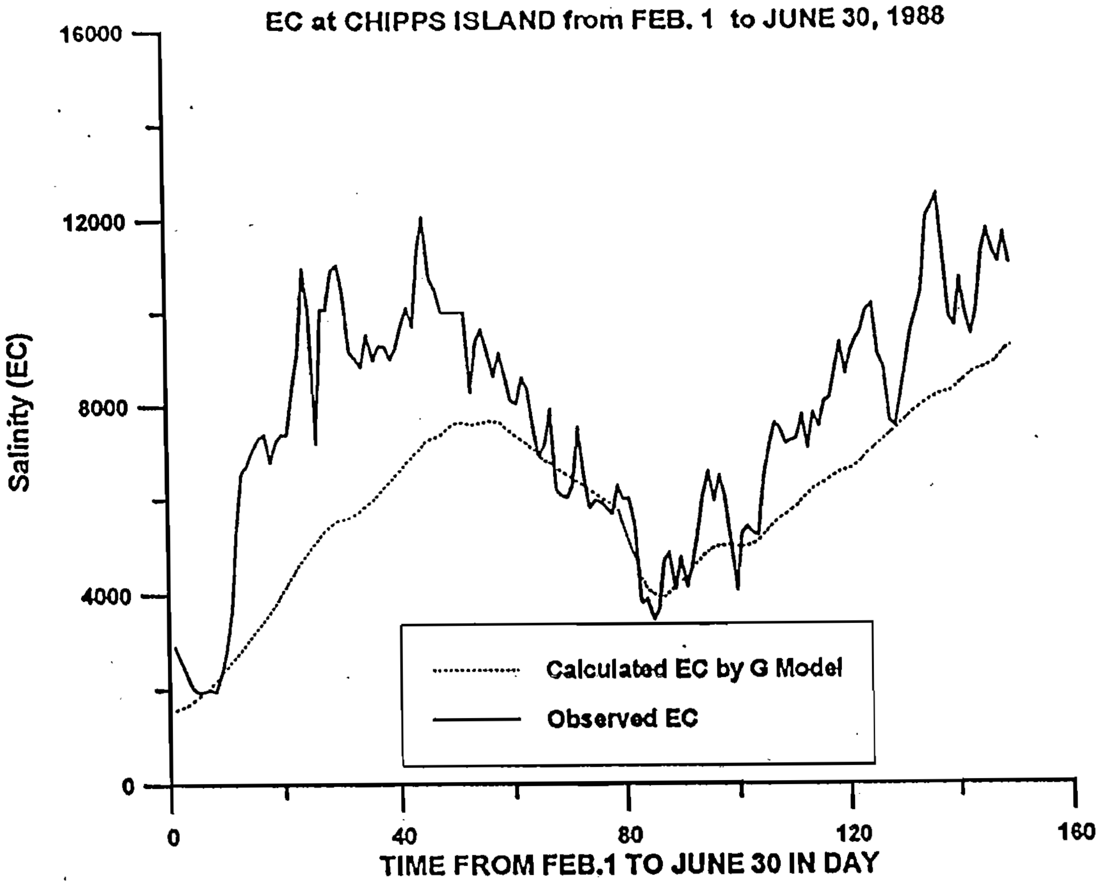

Figure 6. EC Time Series At Chipps Island In 1988

From: "Evaluation of San Francisco Bay/Sacramento-San Joaquin Delta Salinity Standard" by Hsieh Wen Shen *(Progress Report No. 2 to MWD, August 31, 1994)*