Methodology for Flow and Salinity Estimates in the Sacramento-San Joaquin Delta and Suisun Marsh

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Chapter 7: Integration of CALSIM and Artificial Neural Networks Models for Sacramento-San Joaquin Delta Flow-Salinity Relationships

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7 Integration of CALSIM and Artificial Neural Network Models for Sacramento-San Joaquin Delta Flow-Salinity Relationships

7.1 Introduction

Determination of flow-salinity relationships in the Sacramento-San Joaquin Delta is critical to both project and ecosystem management. Project managers and planners require estimates of the flows required at specific peripheral locations in the Delta to satisfy salinity targets for municipal, industrial, agricultural, and environment uses at various interior locations. Likewise, ecosystem managers often want to control salinity at specific locations in the Delta to manage plant, fish, and bird species. DWR's Delta Simulation Model 2 (DSM2) is a 1-dimensional hydrodynamic and water quality model capable of simulating flow, stage, and water quality throughout the Delta. DSM2 requires input flows for the rivers that feed the Delta at the boundaries. DWR's CALSIM Model is a statewide planning model covering the entire State Water Project and Central Valley Project and is used for analysis of various structural and nonstructural alternatives. The upstream reservoir operations, as modeled in CALSIM, are often dependent on Delta salinity standards. Salinity in the Delta cannot be modeled accurately by the simple mass balance routing and coarse timestep used in CALSIM. Likewise, the upstream reservoirs and operational constraints cannot be modeled in DSM2. An Artificial Neural Network (ANN) has been developed (Sandhu et al. 1999) that attempts to faithfully mimic the flow-salinity relationships as modeled in DSM2, but provide a rapid transformation of this information into a form usable by the statewide CALSIM model. The ANN is implemented in CALSIM to constrain the operations of the upstream reservoirs and the Delta export pumps in order to satisfy particular salinity requirements.

7.2 Background

Prior attempts to develop flow-salinity relationships for statewide planning models were based primarily on operator experience or historical measurements. The first attempt to implement Delta outflow requirements for particular salinity targets was the Minimum Delta Outflow (MDO) curves and was primarily based upon operator experience. Curves were developed that specified required Delta outflow given a level of export, salinity target, and Delta Cross Channel gate position. The required Delta outflow increased in a nonlinear fashion as the export level increased. The MDO procedure was used in the first statewide planning models developed by DWR.

Contra Costa Water District's G-model (Denton and Sullivan 1993) relates salinity at various locations in the Delta to the net Delta outflow, as well as the prior history of net Delta outflow. The use of antecedent outflow conditions was a significant step in the development of flow-salinity relationships. The G-model is based on historical observations of flow and salinity in the Delta and uses an equation similar in form to the advection-dispersion equation for salinity transport. The parameters required for the solution of this equation, however, are determined by field measurements at the locations of interest. The equation may be solved for a required Delta outflow given a particular outflow history (G value) and desired salinity. The G-model is used in this form to estimate flow-salinity relationships in the current CALSIM model.

The MDO curves were developed to demonstrate that, at different levels of pumping, a nonlinear relationship of Delta outflow exists for the same salinity target. However, the curves did not account for antecedent conditions in the Delta. The G-model improved upon the prior model by including the antecedent outflow condition, but did not aggregate the flow patterns within the Delta. In reality, cross-channel gate operation, export levels, Sacramento River and San Joaquin River inflows, and channel depletions all affect the salinity regime in a slightly different way. For example, for a Delta outflow of 20,000 cfs, the export level could be 10,000 cfs with inflows of 30,000 cfs, or exports of 5,000 cfs with inflows of 25,000 cfs. The resulting salinity is the same in both cases when computed by the G-model, since the dependent flow parameter (Delta outflow) remains unchanged at 20,000 cfs. Similarly, a change in the cross-channel gate position would not affect the resulting salinity in the prior models since the Delta outflow is not affected.

The ANN developed by DWR (Sandhu et al. 1999) attempts to statistically correlate the salinity results from a particular DSM2 model run to the various peripheral flows and gate operations. The ANN is “trained” on DSM2 results that may represent historical or future conditions. For example, a reconfiguration of the Delta channels to improve conveyance may significantly affect the hydrodynamics of the system. In such a case, the MDO curves and G-model may not represent the new flow-salinity relationships since they are based on historical measurements or experience. The ANN, however, would be able to represent this new configuration by being retrained on DSM2 model results that included the new configuration. Thus, by accounting for the major flow and operational parameters as independent parameters rather than aggregated Delta outflow, and the ability to better represent future modified conditions in the Delta, the ANN is a significant improvement over the existing models.

The current ANN predicts salinity at various locations in the Delta using the following parameters as input: Sacramento River inflow, San Joaquin River inflow, Delta Cross Channel gate position, and total exports and diversions. Sacramento River inflow includes Sacramento River flow, Yolo Bypass flow, and combined flow from the Mokelumne, Cosumnes, and Calaveras rivers (East Side Streams). Total exports and diversions include State Water Project (SWP) Banks Pumping Plant, Central Valley Project (CVP) Tracy Pumping Plant, North Bay Aqueduct exports, Contra Costa Water District diversions, and net channel depletions. A total of 148 days of values of each of these parameters is included in the correlation, representing an estimate of the length of “memory” in the Delta.

7.3 Implementation of Artificial Neural Networks in CALSIM

7.3.1 Flow-Salinity Relationship

Implementation of Delta salinity standards in CALSIM, based on the ANN, requires a basic understanding of the flow-salinity relationship. In theory, the flow-salinity relationship is a multi-dimensional plot with all the previously listed flow parameters affecting salinity.

However, several of the parameters are either known or can be estimated in the CALSIM simulation. For example, Delta Cross Channel gate position is dictated by current Delta standards (SWRCB 1995); Yolo Bypass, channel depletions, and East Side Stream flows are input data in the current CALSIM version; the San Joaquin River system is operated independently of the Delta in CALSIM; and North Bay exports and Contra Costa Water District diversions can be estimated based upon demand. The major independent (and unknown) flow parameters that have a significant influence on salinity are Sacramento River flow and combined project exports (CVP Tracy and SWP Banks Pumping Plants). Sacramento River flow (Q_{SAC}) and combined project exports (Q_{EXP}) are the two decision variables used by CALSIM's LP solver to impose the ANN restrictions (discussed later in Section 7.3.2: *Operational Constraints*). The flow-salinity relationship at a location in the Delta can be found by computing the salinity values resulting from all possible combinations of these two parameters. An example salinity surface developed by this method is shown in Figure 7-1 for the Emmaton water quality location.

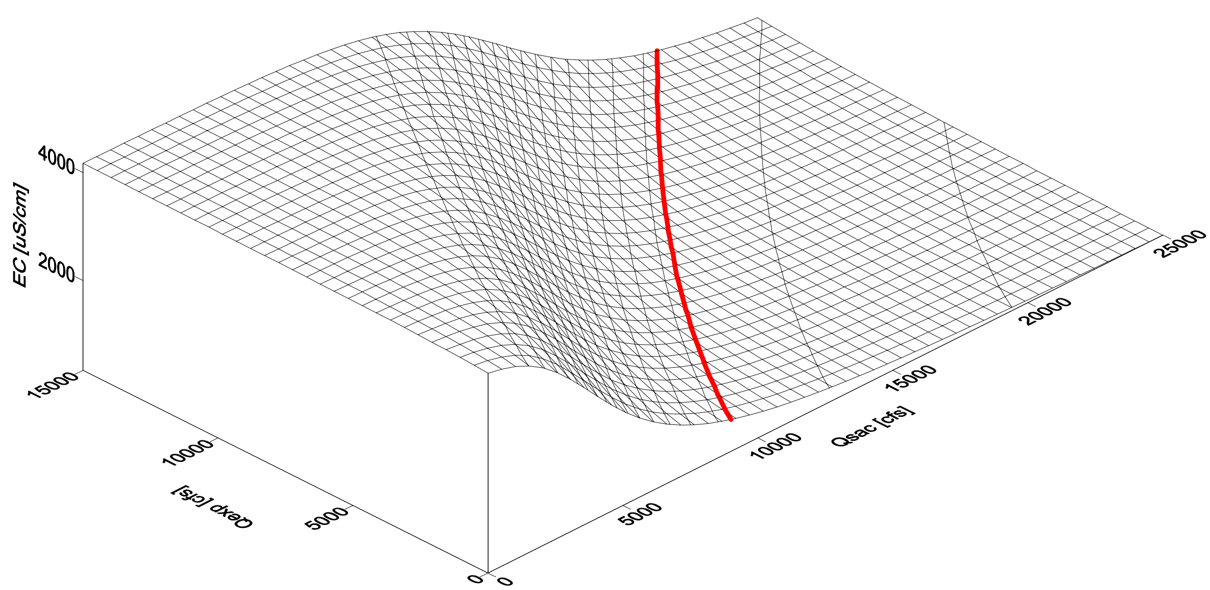

Figure 7-1: Salinity Surface Plot: Emmaton (Ex: October 1976) (uS/cm).

Development of a contour plot of this surface (Figure 7-2 – lines of equal EC) indicates that the relationship between Sacramento River flow and combined project exports at a constant EC is well behaved and approximately linear. A similar plot for Old River at Rock Slough in October 1976 is shown in Figure 7-3.

The combined project export – Sacramento River flow relationship represents the upper limit of potential flow combinations for the current period; any point to the right of this curve is considered a feasible operation in that it results in an equal or lower salinity than the given standard.

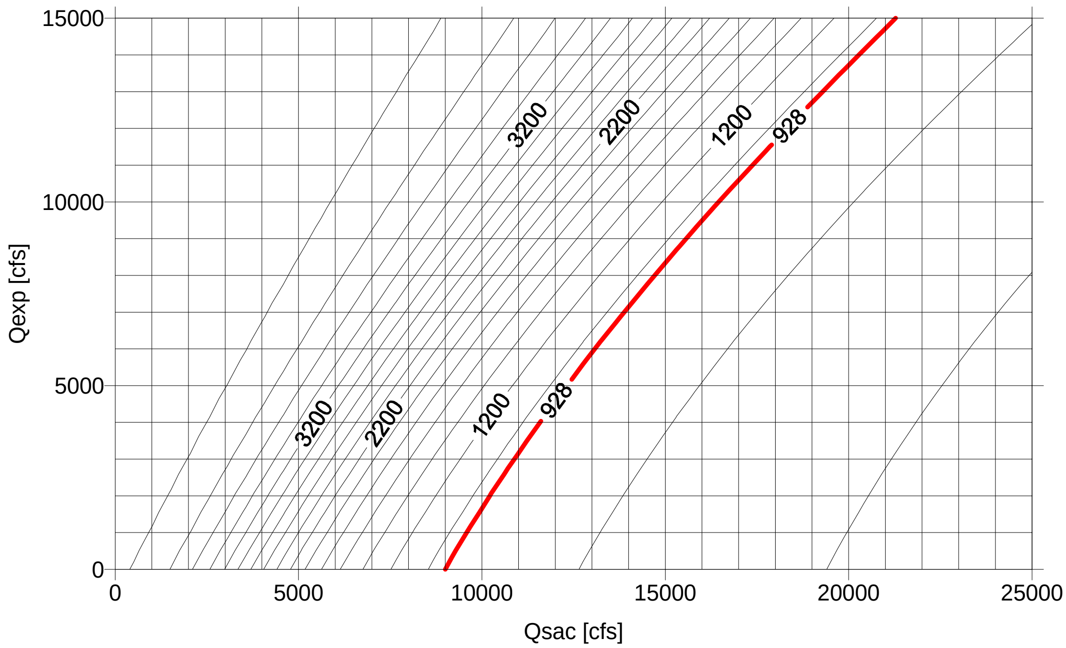

Figure 7-2: Salinity Contour Plot: Emmaton (Ex: October 1976) (uS/cm).

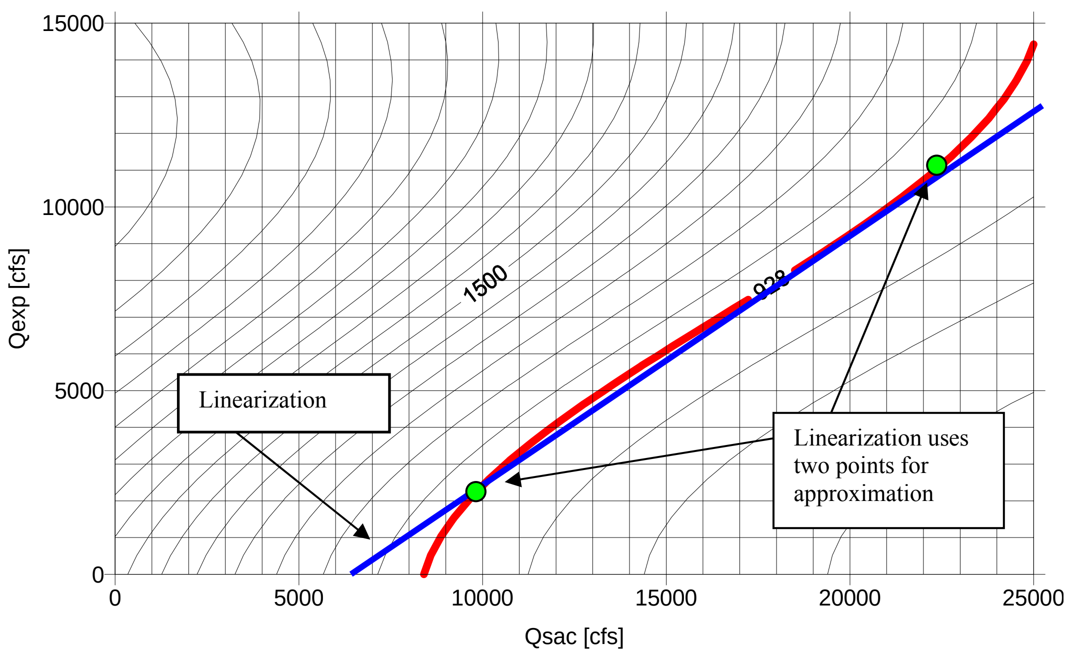

Figure 7-3: Salinity Contour Plot with Linearization: Old River at Rock Slough (Ex: October 1976) (uS/cm).

7.3.2 Operational Constraints

CALSIM utilizes a linear programming solver for determining routing of water throughout the statewide network and therefore requires all constraints to be in a linear form. This necessitates approximation of the ANN combined project export – Sacramento River flow relationship such that a linear constraint may be formulated. The constraint that represents the approximated linear relationship between flows for a given salinity target is:

$$Q_{EXP} \leq m\, Q_{SAC} + b \qquad \text{[Eqn. 7-1]}$$

where m and b are the slope and intercept, respectively. The slope and intercept are based on a prior month's Sacramento River inflow, San Joaquin River flow, total exports, and Delta CrossChannel gate operation, and on the current month computations of the Delta Cross Channel gate, Yolo Bypass, channel depletions, East Side Streams, San Joaquin River, and North Bay and Contra Costa diversions.

The method used to linearize (as is shown in Figure 7-3) the ANN representation uses two points from the combined project export – Sacramento River flow plot: exports at 2,000 and 11,000 cfs. These two points were selected because they represent the probable range of exports and avoid the extreme areas where the relationship may deviate from linear and there is less confidence in the ANN. The current CALSIM-ANN studies of 73 years of simulation have approximately four months each above the 11,000 cfs and below 2,000 cfs export level. The slope and intercept of Equation 7-1 are determined from these two points. The Sacramento River flows corresponding to these two export levels are found using the ANN. The greatest inconsistencies between the linearized and original ANN curve are due to the nonlinearity at low and high exports. At high export levels, the linearized form will require more Sacramento River flow than the original ANN. Conversely, the linearized form will require less water at low export levels.

The linear constraint (Equation 7-1) is normally directly implemented in CALSIM as a limitation on project operations such that the salinity target is met. However, three cases exist that affect how Equation 7-1 is implemented. The solution field under which Equation 7-1 is valid is within a range of exports up to15,000 cfs and a range of Sacramento River flow up to 25,000 cfs.

7.3.2.1 Case 1: Basic Implementation

Under the basic implementation, there exists a combination of combined project exports and Sacramento River flow within the valid solution field. The slope and intercept are determined in CALSIM by calling the ANN subroutine with the prior month's parameter values as well as the current month values for the known parameters. The constraint (Equation 7-1) is activated in CALSIM and project operations are adjusted accordingly. In general, the Sacramento River flow is increased by upstream reservoir releases in order to support exports for South of Delta demand and storage targets.

7.3.2.2 Case 2: Salinity Standard Has No Possible Control on Project Operations

The second case arises from the possibility that, for the given salinity standard, Equation 7-1 has no controlling effect on exports or Sacramento River flow. Determining the salinity at maximum exports and minimum Sacramento River flow performs a check for this case. If the resulting salinity is less than the target, project operations are considered to have no controlling effect on Delta salinity. Under this scenario, the slope is set to zero and the intercept is set to 999,999. This results in Equation 7-1 having no impact on the solution ($Q_{EXP} \leq$ 999,999). The Sacramento River flow and the Delta exports are unrestricted according to the ANN requirements.

7.3.2.3 Case 3: No Project Operations Will Meet Salinity Standard

The third case exists when Equation 7-1 cannot be met for any combination of combined project exports and Sacramento River flow. This case is determined by predicting the salinity when the Delta exports are reduced to zero and Sacramento River flow is set to 25,000 cfs. If the resulting salinity is greater than the target, project operations are considered to be unable to satisfy the current salinity standard. To prevent the ANN requirements from releasing large volumes of water from storage while not meeting the salinity requirements, caps are placed on the required Sacramento River (25,000 cfs) and on the combined project exports (1,500 cfs). Also, the requirement of satisfying Equation 7-1 is relaxed.

7.3.3 Modeled Locations

The current CALSIM-ANN integration allows the simulation of flow-salinity relationships at three locations: (1) Emmaton, (2) Jersey Point, and (3) Contra Costa Canal Pumping Plant #1 (CCC PP#1). The Emmaton and Jersey Point standards are modeled directly at their respective locations in the Delta. However, the CCC station salinity standard is translated into an equivalent salinity standard at Old River at Rock Slough due to difficulties in accurately representing water quality by DSM2 in this slough. The current transformation of the standard is:

$$\text{Old River at Rock Slough EC} = (\text{CCC PP\#1 Chloride} + 23.6)/0.268 \quad (\text{uS/cm}) \qquad [\text{Eqn. 7-2}]$$

The CCC PP#1 salinity standard in the current Water Quality Control Plan (SWRCB 1995) specifies the number of days each year that the chloride concentration will be lower than 150 mg/l. The number of days required for this standard is based on the water year type (Wet = 240 days; Above Normal = 190; Below Normal = 175; Dry = 165; Critical = 155). A maximum chloride standard of 250 mg/l applies at all times. Buffers are applied to each of these standards due to the fact that CALSIM uses a monthly time step. These buffers are conservative in nature, such that the 250 mg/l field standard becomes 225 mg/l in CALSIM and the 150 mg/l standard becomes 130 mg/l. The model determines the timing of the 130 mg/l Contra Costa Canal standard by waiting until the last possible month before it requires this stricter standard to be satisfied. The model determines the number of days on which the 130 mg/l standard needs to be met based on water year type. During all months, beginning in February, the code will test the previous month's actual salinity concentration for meeting the 130mg/L standard. If the stricter standard is satisfied, 30 days credit is applied toward meeting the standard. This continues until the number of days required to meet the lower standard equals the number of days left in the year. When this occurs, the 130 mg/l standard applies for the remainder of the year.

7.3.4 Partial Month Standards

Occasionally, salinity requirements change within a month or are specified for time periods less than a full month. This may occur due to the actual written standards (Emmaton and Jersey Point) or due to the implementation procedure (Contra Costa Canal). This causes difficulty in simulating these standards in CALSIM because it uses a monthly time step. To compensate for this difference in time step, partial month standards are averaged according to an exponential function (Figure 7-4) that attempts to mimic the flow-salinity relationship shown in the G-model development (Denton and Sullivan 1993). A monthly average standard is developed by integrating the function and weighting the areas under the curve for the higher and lower standards according to their respective number of days. In general, the average standard is weighted more towards the lower standard since the required flow increases exponentially with a unit reduction in the salinity standard. For example, if 15 days remain to meet the Contra Costa Canal 130 mg/l standard (with the remaining 16 days standard at 225 mg/l) the area under the curve between 0 and 15 days is 5.68 and the area between 15 and 31 is 0.52. The salinity standard averaging is calculated as (130*5.68 + 225*0.52) / (5.68 + 0.52), which results in a monthly standard of 138 mg/l. If a salinity standard is specified for less than a full month and no other standard exists for the remainder of the month, then the highest salinity standard is selected as the target for the remainder of the month.

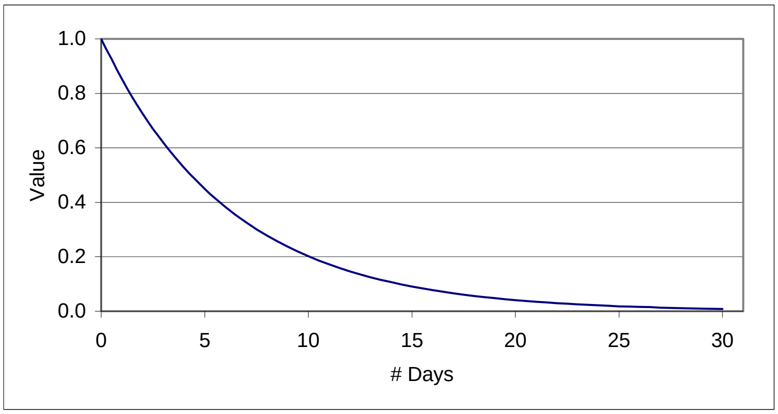

Figure 7-4: Exponential Averaging Function for Partial Month Salinity Standards.

7.4 Limitations

As with all attempts to capture the flow-salinity relationship in the Delta, there are limitations to the Artificial Neural Network implementation in CALSIM. First, it needs to be noted that CALSIM implements an *approximation* to the true ANN by linearizing the combined project export – Sacramento River flow relationship at a given salinity target. At the Emmaton and Jersey Point locations, this relationship is fairly linear such that the approximation does not introduce significant error. For most periods at the Old River at Rock Slough station, the relationship remains fairly linear. However, there exist several months for which the combined project export – Sacramento River flow relationship is linear in the mid-range of flows, but nonlinear at the extremes. At these extremes, the current CALSIM implementation will deviate from the true ANN solution and errors in implementing ANN into CALSIM will occur. It remains unclear whether the nonlinear relationship at the extremes is due to the actual salinity dynamics of the Delta or to inherent errors in the “training” of the ANN from DSM2 results.

Another possible limitation is directly linked to the ability of the ANN to faithfully capture the dynamics of the Delta under conditions other than those under which it was trained. Presumably, the ANN does not require retraining when export or inflow patterns or magnitudes change. However, it is possible that the ANN will exhibit errors in flow regimes beyond those in which it was trained. In addition, change in operation of the Delta Cross Channel gate requires a new training of the ANNs. A clearer picture of the robustness of the ANN and magnitude of errors will be developed when the “full circle” (DSM2-ANN-CALSIM-DSM2) analysis is performed with the newly calibrated DSM2 model.

7.5 Recommendations

The current implementation of the ANN in the CALSIM statewide planning model represents a major improvement in determining salinity standard water costs and impacts to the projects. In addition, the flow-salinity relationships are dynamically represented by taking into account numerous peripheral flows and operations as well as antecedent conditions. The ability of the ANN to be retrained when the configuration of the Delta has changed represents a significant enhancement over prior models. However, the robustness of the ANN and the capability of the DSM2 model to predict salinity at the locations of interest needs to be measured. It is recommended that once the new DSM2 calibration is complete, a full circle analysis of the CALSIM-ANN implementation should be performed in which errors are quantified in each step of the process.

The CALSIM implementation of the ANN has been rigorously tested. CALSIM, like any other planning model, would require iteration of the entire network solution in order to solve the nonlinear export-flow-salinity relationship that exists at extreme export levels at specific locations. The iteration of the entire network is unacceptable for the solution and use of CALSIM as a planning tool. The linearization of this relationship within the mid-range of exports represents the best attempt to capture the system dynamics within the range of expected operations of the export facilities. Further investigation may provide insight into whether the nonlinearites at the export extremes, only present at the Old River at Rock Slough location, are real or are a result of the ANN training.

7.6 References

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