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Simplified 1-D Hydrodynamic and Salinity Transport Modeling of the Sacramento–San Joaquin Delta: Sea Level Rise and Water Diversion Effects

William E. Fleenor*[1] and Fabián A. Bombardelli[1]

ABSTRACT

Long-term hydrodynamic and salinity transport modeling of the Sacramento–San Joaquin Delta is needed to evaluate the future Delta in terms of the California co-equal goals of ecosystem health and reliable water supply. While 2-D and 3-D hydrodynamic and water quality models are by definition better suited to modeling a complex network of tidally influenced flows under future conditions, a 1-D model is more computationally efficient in narrowing the large variety of multiple-year simulations required into a more manageable task. Still, a 1-D model of sea level rise in an estuary must account for the three-dimensional effects where increased depths will affect density driven (baroclinic) circulation and tidal dispersion of salt. In this paper, we use a simplified Delta network model with a tidally averaged computational approach to quickly perform multi-year simulations for sea level rise. The 1-D model uses tidal dispersion coefficients developed from 3-D hydrodynamic models. The resulting model is capable of performing very fast simulations over a wide range of conditions, providing guidance on what should be explored in depth with more detailed, but slower models.

Comparisons of unimpaired Delta inflow with the historical case show that the south Delta and San Joaquin River would be much fresher without exports, while the Sacramento River would be fresher in spring and more saline in the fall. Sea level rise will increase salinity throughout the Delta over time. With peripheral conveyance of export, water salinity will intrude upstream in the Sacramento River, be slightly lower up the San Joaquin River and increase in the south Delta. With sea level rise, peripheral conveyance will have similar trends to changes to the historical case, but export salinity will be improved by the peripheral conveyance component. A larger peripheral conveyance can benefit both the ecosystem and exports if managed properly.

KEY WORDS

Estuary modeling, sea level rise, salinity, water quality, Sacramento–San Joaquin River Delta, Water Analysis Module (WAM)

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INTRODUCTION

The California Sacramento–San Joaquin Delta (Figure 1) once included over 202,000 hectares (500,000 acres) of sub-tidal, intertidal marsh and seasonal floodplains (Thompson 1957; Whipple et al. 2012). Even before the current extensive management of upstream releases of water from dam construction and diversions, Delta hydrodynamics and water quality had experienced significant anthropogenic influences. Starting with the discovery of gold in 1848, the intertidal wetlands and floodplains of the Delta were diked and drained. As the Delta was being channelized, upstream hydraulic mining began sending large quantities of sediment into the Delta, thus reducing channel depths until the practice was banned in 1884 (CDWR 1995). Subsequently, dredging was undertaken to widen and deepen channels for shipping, and new channels were dug to straighten sinuous rivers (Thompson 1957).

Salinity intrusion into the Delta was an early problem as upstream irrigation diversions reduced Sacramento River flows (Young 1929). With the completion of Friant Dam on the San Joaquin River in 1942 and Shasta Dam on the Sacramento River in 1944 (CDWR 1995), upstream releases and diversions modified Delta inflows. Delta flow management was further increased and complicated with the early 1950s implementation of the federal Central Valley Project (CVP) to export water from the southern Delta to irrigate part of the central San Joaquin Valley. Some Sacramento River water entering in the north Delta was drawn down through the Delta by export pumps in the southern Delta. Exports from south Delta pumps expanded with the completion of the State Water Project (SWP) in the late-1960s to supplement Bay Area and southern California water supplies. The SWP pumps are also located in the southern Delta, further altering internal Delta flows. The combined changes produced a need to manage water quality in the Delta for agricultural and urban water uses. To help manage Delta water quality, multiple gates and barriers are permanently or annually installed, and dam releases controlled to reduce salinity intrusion (Lund et al. 2007).

Despite efforts to manage water releases for the native fish ecosystem, fish populations have continued to decline (Sommer et al. 2007; Moyle et al. 2010). The issue of ecosystem viability has become of increasing interest as five native fish species are now listed as endangered or threatened. A recent court decision to protect the delta smelt has ordered the reduction of some of the negative internal Delta flows produced by south Delta pumping (Wanger 2007a, 2007b).

The risks to dikes, which protect subsided Delta farmland up to 7.5 m (~25 ft) below sea level, are increasingly apparent. The seismic potential of the area could breach multiple islands. These issues will become more dramatic with sea level rise.

Sea level rise has occurred over the last 100 years, and the rate of increase is predicted to accelerate (IPCC 2007). The IPCC (2007) report also predicts increasing winter storms with more rain and reduced snow pack which increase the likelihood of higher winter and spring flood flows. Continued subsidence of the interior farm land increases stress on the dikes and compromises the ability to raise and reinforce the dikes to keep up with sea level rise and climate change.

The California Department of Water Resources' (CDWR) Delta Risk Management Strategy (DRMS) program assessed the current risks and produced strategies in dealing with future failures (DRMS 2006a). One of the projects developed to provide needed information was a simplified, one-dimensional (1-D) hydraulic and water quality model, the Water Analysis Module (WAM) (URS and JR Benjamin Assoc. 2007; Behrens et al. 2009), which was created to predict water quality (e.g., salinity) changes to the Delta for use by decision management systems (DRMS 2006b). The model results were used to determine how export pumping would need to be reduced or halted and how much additional upstream water might need to be released to hold back salinity intrusion or mix it out of the Delta if salinity were drawn in from the bay by levee failure. WAM was developed to integrate with other modules that predicted seismic risk, flood hazards, dike and levee fragility and emergency response planning to provide output

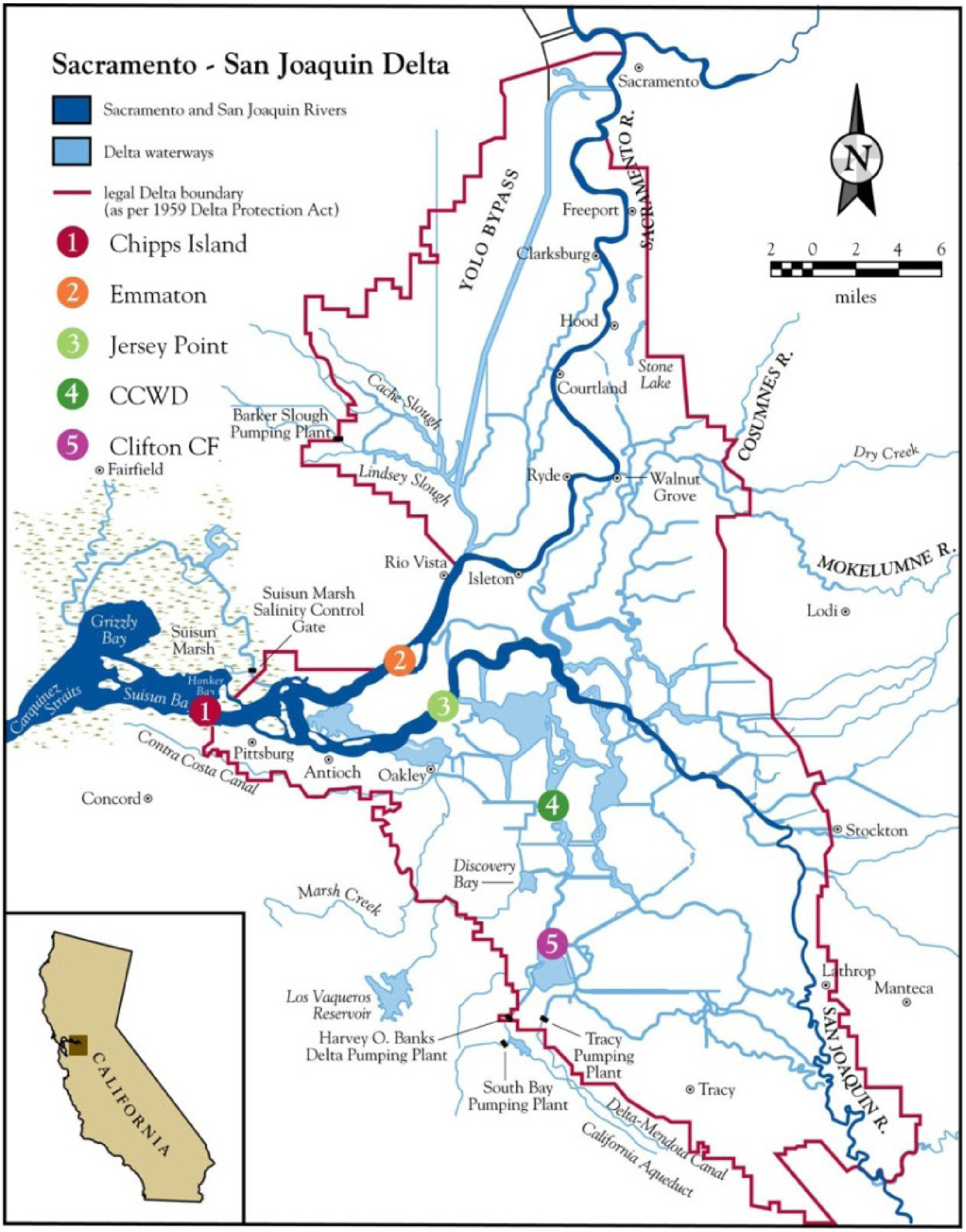

Figure 1 Sacramento–San Joaquin Delta: legal boundary in red and identification of 5 output locations by numbered and colored circles

which detailed economic and environmental consequences of failure scenarios.

Unlike the DRMS work, this paper presents work based on results from WAM on multi-year simulations of potential operational solutions to the future changes in the Delta, including sea level rise. The Delta with its complex estuary of branching channels with strong tidal flows, variable tributary inflows and complex operations is indeed a challenging system to model.

METHODS

Model Selection

The most commonly applied 1-D model for the Delta, DSM2, was developed by CDWR and is widely and successfully used for planning work. However, sea level rise, flood flows that exceed the calibration range, and multiple breached islands constitute challenges for any 1-D model without adequate modification. Additionally, a DSM2 analysis of sea level rise would suffer from the downstream boundary condition (located at Martinez) being insufficiently downstream to avoid boundary salinity changes; further, upstream boundary conditions are so close to the central Delta that tidal signals would be reflected. The Resource Management Associates (RMA) 2-D model, RMA2, along with the RMA11 water quality model, has also been widely and successfully used for both Delta and Bay–Delta modeling. Although the RMA model applications extend some of the boundary conditions, model simulation times are much greater than DSM2, and salt transport from increased sea levels would still require modification of dispersion terms. Both the DSM2 and RMA models have been applied by CDWR and others to examine various planning efforts.

To control some of these problems and essentially to reduce computational costs, a simplified and faster model was needed to simulate the many possible scenarios in the Delta. The simplified model is a tidally-averaged flow model solved along with an advection–diffusion transport equation with net flow toward the ocean, and tidal dispersion coefficients derived from multi-dimensional models. The objective was to deliver a model with the necessary geometry and physics to produce reasonable predictions without being so complicated that it compromised the computational efficiency.

WAM Features

The hydrodynamic module of WAM was developed from the RMA suite of higher-dimensional, finite-element models as part of a larger DRMS study (CDWR 2007b). The WAM downstream boundary condition is in the north San Francisco Bay (see Figure 2) where salinity would be nearly constant with sea level rise, and tidal averaging eliminated any reflection issues from upstream boundaries. These are clear improvements over DSM2 for sea level simulations.

To properly provide an adequate representation of transport processes in the Delta, the model was equipped with the following features:

1. the simplified geometry was given appropriate volume and conveyance area;
2. net flows were checked for appropriate distribution across the channel network; and
3. tidally-averaged mixing coefficients were provided to be representative of dynamic tidal flows.

Channel cross-sections are represented in WAM by trapezoidal sections with consideration given to matching area, volume and wetted perimeter of the actual channels. Some parallel channels are aggregated with cross-sectional areas, and perimeters are adjusted accordingly (Figure 2). Other minor cross-flow channels that transfer water between major conveyances are represented with regressions derived from stage or flow differences between the connected channels. Delta Island Consumptive Use (DICU) is represented by five diversions and returns internal to the Delta, aggregating as many as 258 points used in the more detailed models of the Delta (Figure 2). The total volume of the net returns is small compared to the large inflows and tidal flows. Since overall long-term seasonal changes—not localized short-term values— are of interest, we considered the error introduced by minimizing the number of internal input locations to be acceptable.

Transport and dispersion of salt in an estuary is a three-dimensional problem. There are three main salinity transport consequences of sea level rise. The first is for the ocean to force its higher salinity (denser) water farther into the Delta for any given upstream Delta inflow, a process sometimes referred to as "barotropic" flow, that results directly from water elevation (pressure) differences (Fischer et al. 1979; Kundu and Cohen 2008). The second consequence comes from increases in density-driven, or "baroclinic" flow (Fischer et al. 1979; Kundu and Cohen 2008). Baroclinic effects increase with sea level rise because the deeper water depths cause more strongly stratified water (i.e., the estuary has a lower ability to mix vertically, because of wind events, for instance). A third dynamic effect of deeper water depths is the retardation of vertical mixing, because the resistance of the bottom exerts less overall vertical influence (Hansen and Rattray 1965). Parts of the Delta system are already deepening, regardless of sea level rise—the result of net erosion (Krone 1979; Wright and Schoellhamer 2004; Cappiella et al. 2005).

All 1-D models—including WAM—and 2-D models use either cross-sectionally or vertically averaged

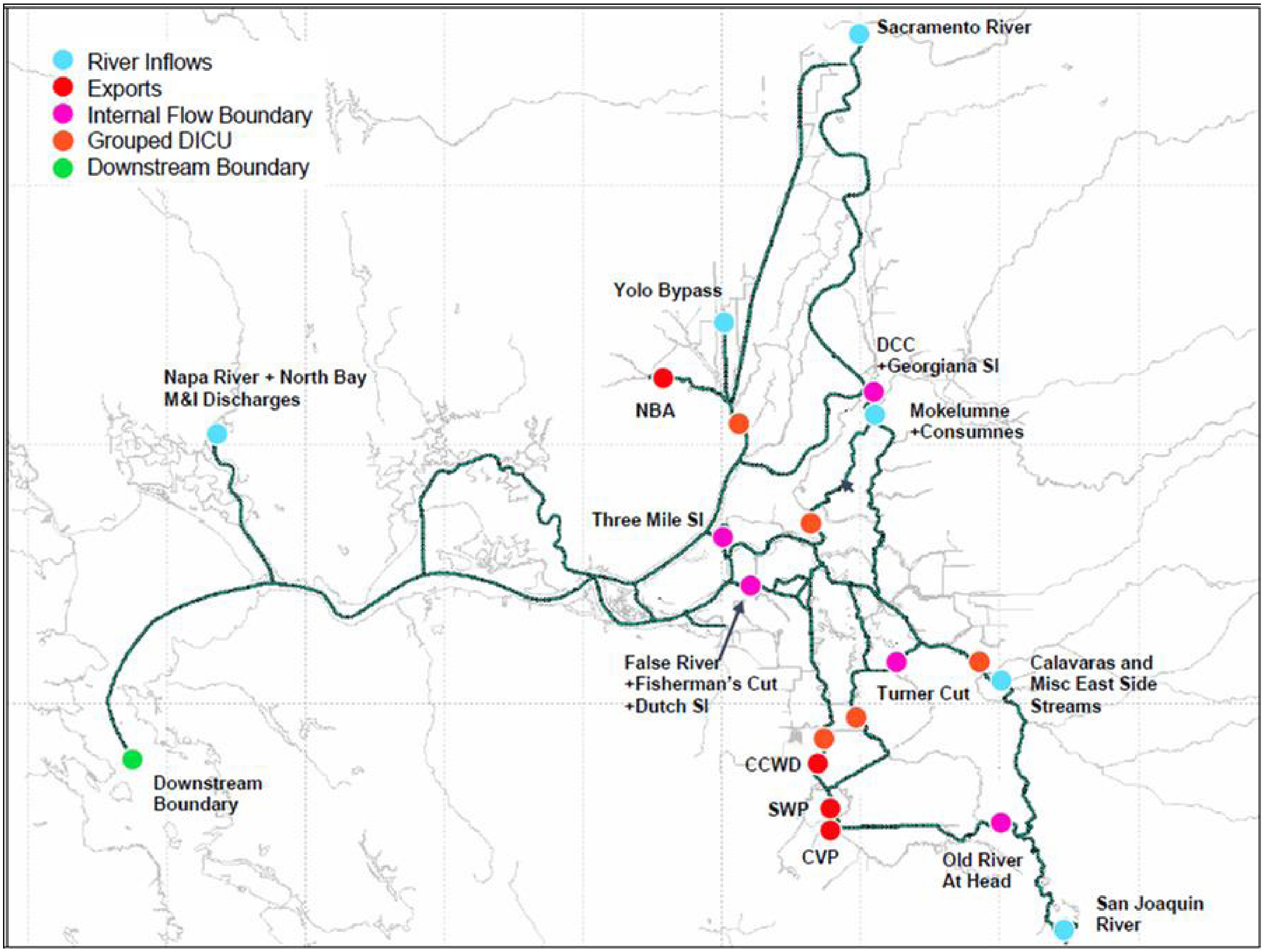

Figure 2 Simplified WAM network superimposed over Delta network showing boundary conditions, internal flows, export locations and DICU sites

variables and most of them do not account for baroclinic influences. To incorporate these 3-D effects into the 1-D WAM model, dispersion coefficients were developed by running a 3-D model to capture the processes involved with landward transport and dispersion of salt (CDWR 2007b; MacWilliams and Gross 2007; Gross et al. 2007a, 2007b, 2012).

Details of the dispersion coefficient development can be found in Gross et al. (2007a), where four different increases in sea level rise were simulated including 20 cm, 50 cm, 90 cm, and 140 cm in addition to the baseline scenario with a 3-D model. With each scenario simulated to a near steady-state condition, the dispersion coefficient could be calculated for each reach with the equivalence given by (see Fischer et al. 1979),

$$K = -Q\,S \,/\, (A\,dS \,/\, dx), \tag{1}$$

where Q is the tidally-averaged flow, S the tidally and cross-section averaged salinity, K the dispersion coefficient, A the cross-sectional area, and x the longitudinal location. The equation was solved and applied in each of 28 sections throughout the existing and extended salt mixing zone. To produce a reasonable 'steady-state' condition the tide was limited to M2 and K1 harmonics and the M2 period was modified to 21 hours so that exactly two M2 cycles occurred for each K1 daily cycle.

The compromise of using a tidally-averaged simulation is that it excludes information on any spring–neap tidal cycle influences and local details of smaller time-scales but long-term information used here remains valid. (Walters et al. 1985; Gross et al. 1999a, 1999b; Warner et al. 2004; Kohne 2010).

WAM is a derivative of the RMA suite of finite element models and it is based on the cross-sectional integration of the Reynolds-Averaged Navier–Stokes (RANS) equations, the latter obtained through turbulence-averaging of the Navier–Stokes equations. The integrated mass and momentum equations are indicated below, together with the transport equation:

$$\frac{\partial (U\,A)}{\partial x} + \frac{\partial (A_s)}{\partial H}\frac{\partial H}{\partial t} - q_s = 0 \tag{2}$$

$$\rho\left(A\frac{\partial U}{\partial t} + A\,U\frac{\partial U}{\partial x} + A\,g\frac{\partial H}{\partial x} + A\,g\frac{\partial a}{\partial x} + \frac{A\,g}{R\,C^2}U\,|U|\right) + \\ A\,g\frac{H}{2}\frac{\partial \rho}{\partial x} - \rho\frac{\partial}{\partial x}\left(E_{xx}\,A\frac{\partial U}{\partial x}\right) - A\,\sigma_x = 0 \tag{3}$$

$$\frac{\partial (C_a\,A)}{\partial t} + \frac{\partial (C_a\,Q)}{\partial x} - \frac{\partial}{\partial x}\left(D_{xx}\,A\frac{\partial C_a}{\partial x}\right) - Sources/Sinks = 0, \tag{4}$$

where U, Q, and A represent the cross-section averaged velocity, the flow discharge and the wetted area, respectively; ρ is the water density; g indicates the acceleration of gravity; H is the water depth; a indicates the position of the bed with respect to a certain datum; C refers to the Chezy resistance coefficient; C_a is the cross-section averaged concentration of any constituent; R expresses the hydraulic radius; E_{xx} is the integrated eddy viscosity of the flow; and D_{xx} is the dispersion coefficient of the constituent, equal to K (Equation 1) for the case of salinity. In turn, x and t represent the spatial and temporal coordinates. The terms included in Equation 3 are, respectively: (i) the unsteady and convective terms; (ii) the pressure gradient term; (iii) the gravity term; (iv) the bottom friction term; (v) the baroclinic term; (vi) the integrated stress term; and (vii) the wind stress term.

Model Validation

Because the purpose of the simplified model is to simulate a wide range of sea level conditions and levee breach events for which there are no observed data, the primary source of calibration and verification is based on measured data that do not represent future conditions.

Several past examinations have demonstrated the calibration and validation of WAM to be useful as a good predictor for its purposes (CDWR 2007b; Fleenor et al. 2008; Behrens et al. 2009; Bombardelli et al. 2010, 2012).

Bombardelli et al. (2012) and Reddy (2012) examined five relatively recent years that covered a rather

Bombardelli et al. (2012) and Reddy (2012) examined five relatively recent years that covered a rather wide range of conditions, including 'dry' to 'wet'[1] years, and low to high export volumes. Years studied were 1998 (wet year, moderate exports); 2003 (above average year on the Sacramento River and below normal on the San Joaquin River, high exports); 2006 (wet year, high exports); 2007 (dry year on Sacramento River and critical on San Joaquin, moderately high exports); and 2008 (critical year, low exports). Comparison of observed and predicted daily-averaged salinity (in μS cm^{-1}) at Chipps Island (western Delta, see Figure 1) for water year 2003 is shown in Figure 3; the predictions were obtained by using the 1-D models WAM and DSM2, and the 2-D model RMA2. Measured data were obtained from the California Data Exchange Center (CDEC, *http://www.cdec.water.ca.gov/*). Clearly, WAM provides a satisfactory prediction of the daily-averaged salinity for that station, throughout the entire water year. In fact, WAM is able to mimic the time occurrence of the relative peaks with reasonable accuracy, and to correctly predict the value of those peaks as well, especially considering the intrinsic difficulties in predicting salinities. WAM seems to provide slightly higher values of salinity than DSM2 and RMA2; however, one needs to take into account that whereas DSM2 works with near-surface values of salinity, RMA2 and WAM use the depth-averaged counterparts. Similar conclusions about the accuracy of predictions can be obtained from Figures 4 to 6, for stations Jersey Point (on the San Joaquin River, Figure 4), Emmaton (on the Sacramento River, Figure 5) and the southern water export pumps (Figure 6). In this last case, WAM offers a prediction close to that of RMA2, and a 1-year simulation is performed in less than 2 minutes, rather than 5 hours for DSM2 and 8 hours for RMA2.

APPLICATION OF WAM

In a big-picture analysis, Lund et al. (2007) investigated and qualified several future management options for the Sacramento–San Joaquin Delta. In later publications, Lund et al. (2010) aggregated the viable options to four major water exports possibilities from the Delta:

1. continue pumping of exports through the Delta;
2. divert water upstream and convey it around the Delta through peripheral conveyance (PC) (canal or tunnel);
3. combine the current through-Delta strategy with a PC ("dual conveyance" or "dual facility"); or
4. end exports altogether.

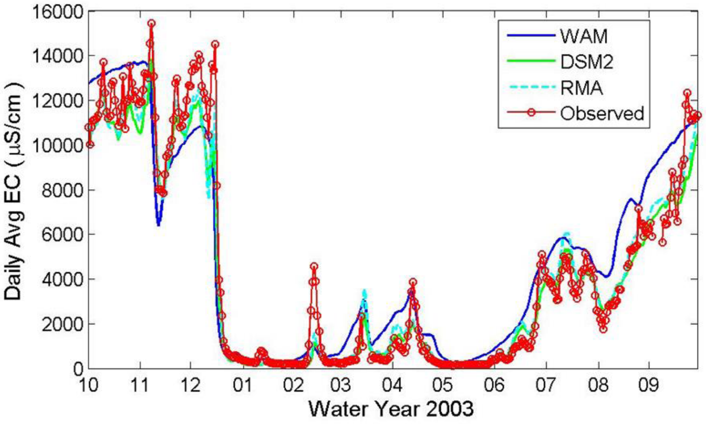

Figure 3 Validation of WAM: comparison of numerical results obtained with WAM, DSM2 and RMA2 with salinity observations for water year 2003 at Chipps Island

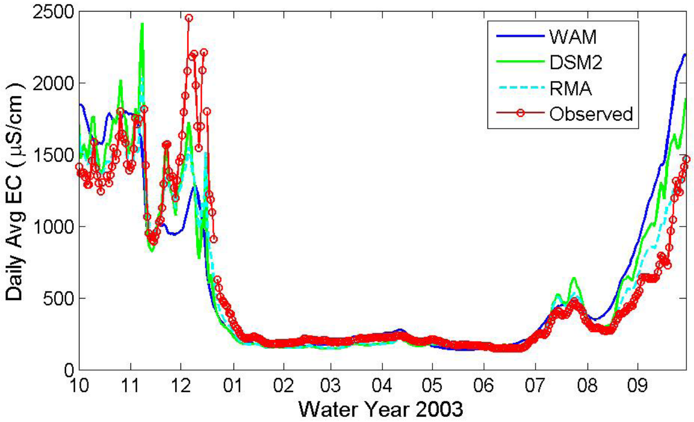

Figure 4 Validation of WAM: comparison of numerical results obtained with WAM, DSM2 and RMA2 with salinity observations for water year 2003 at Jersey Point

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[1] California classifies water years as 'wet,' 'above normal,' 'below normal, 'dry,' and 'critical,' based on factors of current April through July runoff, October through March runoff and the previous year's index. Factors vary for the Sacramento River and San Joaquin River. *http://cdec.water.ca.gov/cgi-progs/iodir/wsi*

We used the hydrodynamic and water quality portions of WAM to examine these long-term options for the Delta; we did not consider upstream reservoir management in this investigation. In our simulations, we used the same WAM model set-up used in the DRMS study, and used WAM to examine these four water export regimes for the Delta over 20 water years, from 1981 through 2000. This modeling effort represents the first log-term examination to estimate effects of sea level rise, and we believe that the results provide important insights about future water quality in the Delta.

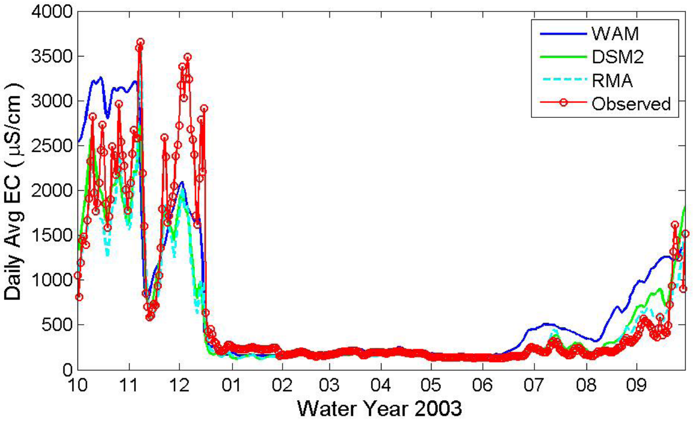

Figure 5 Validation of WAM: comparison of numerical results obtained with WAM, DSM2 and RMA2 with salinity observations for water year 2003 at Emmaton

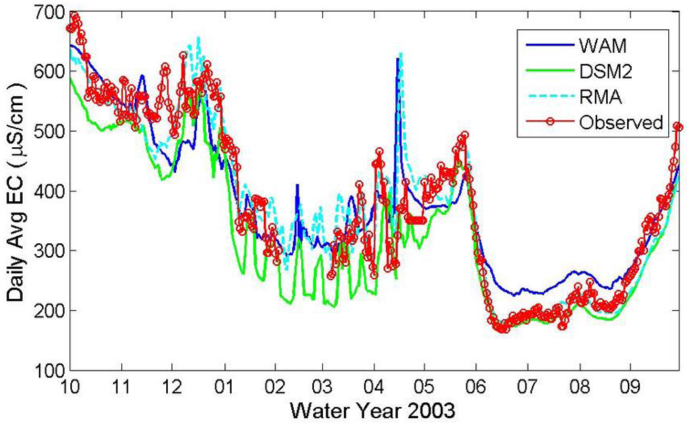

Figure 6 Validation of WAM: comparison of numerical results obtained with WAM, DSM2 and RMA2 with salinity observations for water year 2003 at Southern pump location

Continued Exports Through the Delta

Historical conditions, as defined by DAYFLOW[2] data were used as the Base Case scenario for simulations of water years 1981 through 2000. To examine a range of effects for agricultural, urban, and environmental water uses, we focused output on five locations in the Delta (Figure 1): (1) Chipps Island, used to monitor salinity regulations for fish during the spring; (2) Emmaton, where irrigation water standards are in effect; (3) Jersey Point, an irrigation standard; (4) the Contra Costa Water District (CCWD) pumping plant in the southwestern Delta with more stringent urban standards; and (5) Clifton Court Forebay (Clifton CF) in the southern Delta representing water exports for the SWP and the CVP with year-round urban standards and seasonal irrigation standards.

No Exports and Unimpaired Flows

Two simulations were made that eliminated all exports from the southern Delta. The first had the same inflow conditions as the Base Case but with no exports from the Delta. The second used the ‘Unimpaired’ inflows calculated by CDWR (CDWR 2007a), which represent Delta inflows without upstream operations or diversions. The ‘unimpaired’ flows are not truly ‘natural,’ since available water is routed through current watershed and river systems that do not dampen the flows as would have occurred naturally before the watersheds were modified and the rivers were leveed and channelized.

For the ‘No Water Exports’ scenario, the CVP and SWP exports and North Bay Aqueduct and CCWD diversions were set to zero, so net Delta outflow increased by an equal amount. Internal gates and barriers devised to control internal flows were also eliminated. Results for No Exports and the Base Case appear in Figure 7. Analysis of the figure demonstrates the percentage of days each month when electrical conductivity[3] (EC in µS cm^{-1}) exceeds the spec-

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[2] DAYFLOW is a program developed by the CDWR to estimate average daily flows for the Delta and its tributaries through measurements and calculations *http://www.water.ca.gov/dayflow/*

[3] Technically the values are specific conductance rather than electrical conductivity (EC) since they are corrected to 25°C; however, EC designation is used here because it is embedded into the regulations and community usage.

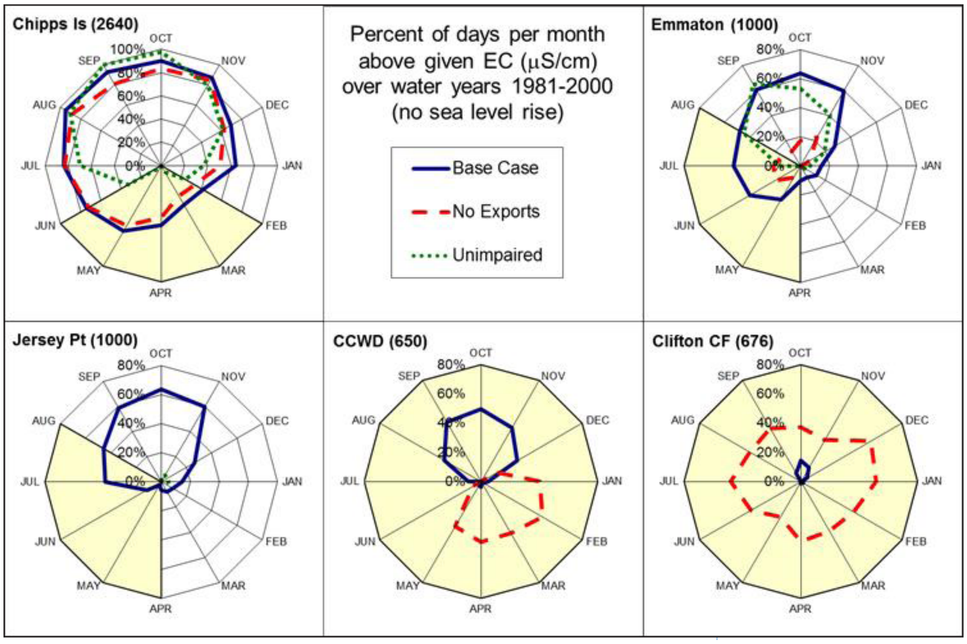

Figure 7 Simulated percentage of days each month exceeding the specified EC (μS cm^{-1}) at locations in the Delta with No Exports and Unimpaired Flows. The figure presents the average monthly values over the simulation period 1981–2000. Shaded areas are periods when compliance with salinity standards is prescribed, although compliance levels vary across water year types (and across months for irrigation standards). In the no-exports scenario, there are no exceedances of the specified EC at Jersey Point. In the Unimpaired Flows scenario, no exceedances occur at CCWD and Clifton CF.

ified limit for each location. Limits at each location were set by the State Water Resources Control Board in decision D-1641, and vary according to location and whether use is agricultural or urban.

The ‘No Export’ case presents some interesting contrasts with the Base Case. Without exports, water becomes fresher in the western Delta (Chipps Island, Emmaton, and Jersey Point), but saltier in the southern Delta (Clifton CF). A small reduction in salinity occurs at Chipps Island because of increased net Delta outflow, while greater reductions occur at Emmaton and Jersey Point. Salinity in the southwestern Delta at the CCWD pumps does not change greatly, but there is a seasonal shift, with higher salinity periods moving from fall to winter/spring. The large increase in salinity at the Clifton Court Forebay in the southern Delta is from the greater influence of higher-saline San Joaquin River (SJR) inflows. Without exports, these SJR flows suffer from the following: (a) they are no longer diluted by fresher Sacramento River water drawn southward through the Delta toward the pumps, and (b) barriers directing SJR flow away from the pumps are not in effect in the simulation. In practice, SJR salinity also would change because of reduced irrigation (and agricultural runoff) in the San Joaquin Valley; upstream diversions on the SJR could also increase salinity concentrations downstream.

Unimpaired flow results are also shown in Figure 7. Such ‘naturalized’ flows would have occurred if there were no upstream dams and diversions and no exports. In this simulation, the only diversions included were agricultural pumping and effects in the Delta (DICU), which roughly represent the evapotranspiration that would occur within the Delta under pre-development flow conditions. Since the unimpaired flow inputs are monthly averaged values, the results are somewhat attenuated (lower maximums and higher minimums) relative to the results obtained using daily data while long-term averages would hold. Without upstream and export diversions, simulations show that salinity is reduced dramatically at all locations, except at Emmaton and Chipps in the fall. Again, this simulation does not represent exactly the “natural” Delta before the dredging and diking of the Delta’s marshlands that began in the second half of the 19th century. Instead, this scenario predicts salinity for the current Delta network and landscape under surrogate natural flows.

The results of how south Delta pumping has altered flows in the Old and Middle rivers, which now direct Sacramento River water down through the Delta to the pumps, are shown in Figure 8. On the figure are plots of the cumulative probability of the sum of flows from the Old and Middle rivers (OMR) for the Base Case and those with Unimpaired Flows. While results from Unimpaired Flows for OMR are downstream throughout the period (i.e., flowing toward the ocean), the Base Case has net downstream daily OMR flows less than 15% of the time (Figure 8).

Compared with the bathymetry of today, the intertidal, tule wetlands of the pre-European Delta would have allowed higher outflow rates when water levels rose above the tule vegetation, and would have generated restricted outflow rates at lower water levels, given the much reduced natural channel capacity under low-flow conditions (Baptist et al. 2007), which explains, at least in most part, Figure 8. While this affects timing of outflows, total outflow volumes are only affected by minor changes in evapotranspiration. Even in the 20-year averages shown in Figure 7, the western Delta is fresher in the spring and more saline in the fall. With widespread island failures, the modern Delta would still not revert to the natural Delta of pre-European times, because many islands are now highly subsided with cross channels and deeply dredged shipping channels.

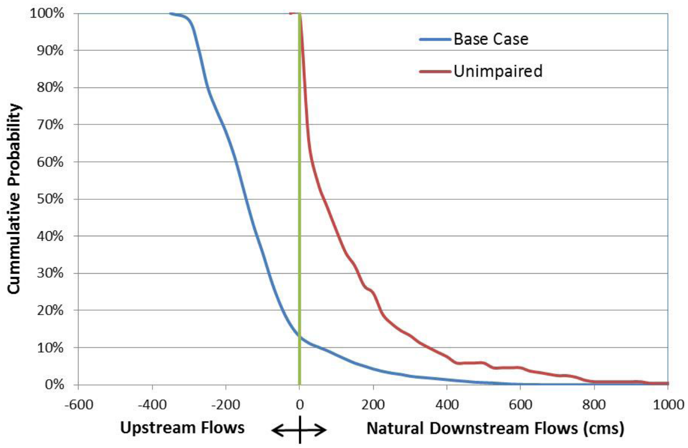

Figure 8 Cumulative probability of the sums of Old and Middle River (OMR) flows for the Base Case and Unimpaired Flow case

Consequences of Sea Level Rise

Sea level rise measured at the San Francisco Golden Gate Bridge has averaged 0.2 cm per year (0.08 in yr^{-1}) over the past century. Most climate models project an increase in the rate of sea level rise during the next century (IPCC 2007). For planning purposes, the Independent Science Board (ISB)[4] has recommended mid-range values for sea level rise of 20.4 to 40.6 cm (8 to 16 in) by 2050 and 71.2 to 99.1 cm (28 to 39 in) by 2100.[5]

As before, this exercise began as a comparison with the 1981 through 2000 Base Case and all islands are assumed to remain intact, and the downstream EC boundary condition (ca. the middle of the northern San Francisco Bay) is assumed to remain a constant 50,000 $\mu S\ cm^{-1}$. To simulate sea level rise, the most downstream boundary condition of the Base Case was raised by an average of 30.48 cm or 91.44 cm (1 or 3 ft), respectively, and the initial water elevation throughout the model domain was increased accordingly.

Water Quality Effects of Sea Level Rise

The simulation results in Figure 9 show an increase in salinity at all five locations compared with the Base Case. With 30.48 cm (1 ft) of sea level rise and no other changes to the Base Case, salinity in the Delta may still be low enough for irrigation during the growing season, but southern Delta salinity increases substantially.[6] On average, Clifton Court Forebay annual average salinity concentration increases by approximately 4% to 26% and for CCWD by approximately 35% to 49%.

Additional salinity intrusion occurs as sea level continues to rise. A sea level rise of 91.44 cm (3 ft) would greatly increase salinity, increasing drinking water treatment costs (Chen et al. 2010) and making

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[4] The ISB is a group that advises the Delta Science Program—the science arm of the Delta Stewardship Council—which was created by California State legislators to achieve the co-equal goals of ecosystem protection and water supply reliability for the Sacramento–San Joaquin Delta.

[5] *http://science.calwater.ca.gov/pdf/isb/meeting_082807/ISB_response_to_ls_sea_level_090707.pdf*

[6] Higher salinity is accompanied by other water quality constituents that increase drinking water treatment cost (Chen et al. 2010).

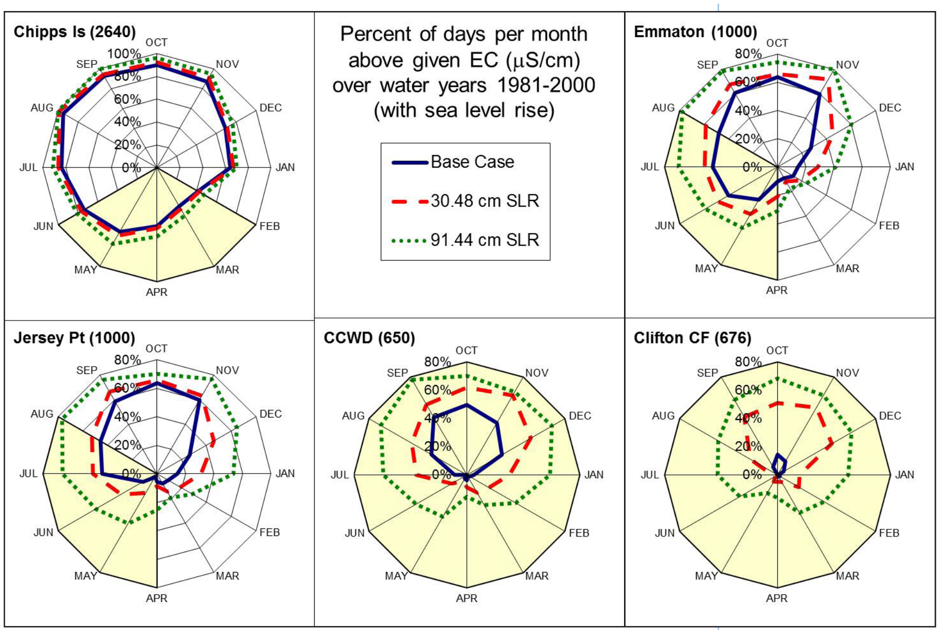

Figure 9 Simulated percentage of days each month exceeding the specified EC ($\mu S\ cm^{-1}$) at locations in the Delta with sea level rise. The figure shows the average monthly values over the simulation period 1981–2000, with 1981–2000 levels of upstream reservoir operations and Delta exports. Shaded areas are periods when compliance with salinity standards is prescribed, although compliance levels vary across water year types (and across months for irrigation standards).

Delta water less suitable for agricultural irrigation (Medellín–Azuara et al. 2008).

In Figure 10, the 7 critical years and the 8 wet years[7] are isolated from the 20-year averages in Figure 9 for Emmaton and Jersey Point. In very dry years, the salinity problems are particularly acute, even with 30.48 cm (1 ft) of sea level rise.

Under current Delta regulations, CVP and SWP export operations are required to maintain Delta salinity standards for Delta uses under most conditions. To provide a rough estimate of the additional flows that would be required to keep Delta salinity at current levels, the additional net Delta outflow needed to maintain the Base Case average salinity at Chipps Island was estimated for 30.48 cm (1 ft) of sea level rise. In these simulations, while holding all other variables constant, Sacramento River flows were increased, as might be accomplished in practice by making additional reservoir releases and reducing upstream diversions (Lund et al. 2008, 2010).[8]

For 30.48 cm (1 ft) of sea level rise, an annual average of 13,450 m^3 (475,000 acre-feet, af) of additional water, provided as additional Sacramento River flows, was required to maintain 1981–2000 salinity conditions at the western edge of the Delta. This volume implies a reduction of more than 10% of average export levels in the 1981–2000 period. The estimate would be on the low end of future needs under sea level rise because earlier years of the 1981–2000 period were not operated under current water quality requirements and all islands were assumed to remain intact. With continued sea level rise, the volume of outflows required to maintain current water quality standards would also continue to rise.

Even without Delta exports or upstream diversions, sea level rise would inevitably increase salinity within the Delta. The probability distribution of the location of X2[9] from the Golden Gate Bridge for Unimpaired Flows with current, 30.48 and 91.44 cm (1 and 3 ft) of sea level rise and the Base Case (historical) are presented in Figure 11. The excursion of salinity moves inland by approximately 5 km per each 30.48 cm (1 ft) of sea level rise. Notably, not all

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[7] 'Critical' and 'Wet' are the two extremes of the five water-year types defined in the 1885 State Water Resource Control Board Water Quality Control Plan.

[8] Increases in net outflows also could occur by reducing export volumes, but in this exercise exports are held constant.

[9] X2 is a Delta outflow objective defining location of 2 PSU salinity at 1-ft from the bottom of the channel under the 1995 Water Quality Control Plan

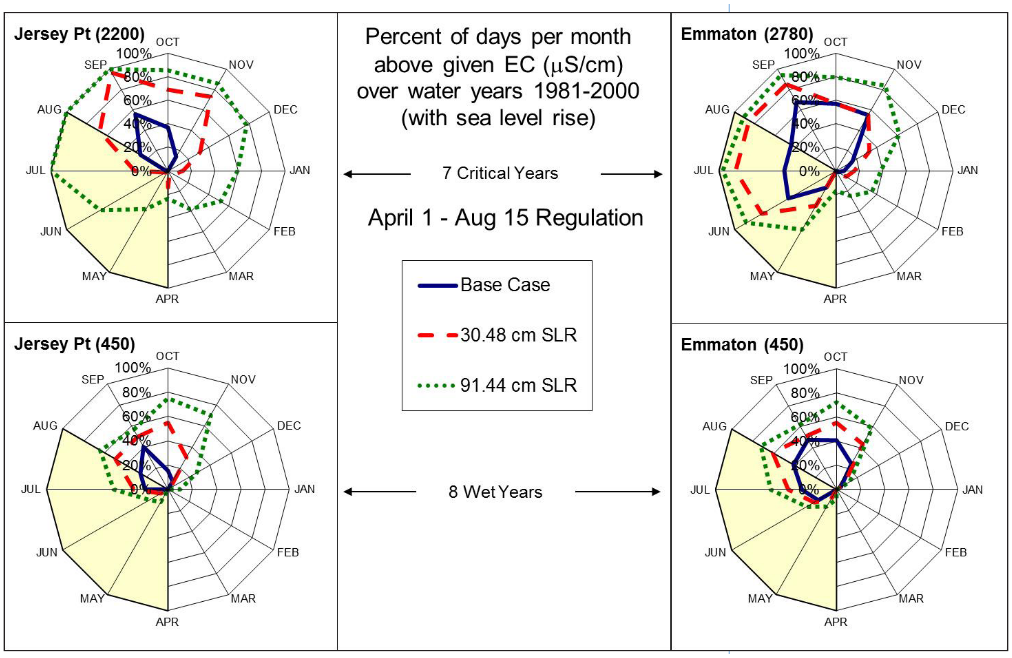

Figure 10 Comparison of wet and critical water years with simulated percentage of days each month exceeding the specified EC (µS cm^{-1}) at locations in the Delta with sea level rise. The figure shows the average monthly values over the simulation period 1981–2000 in critical or wet years with current sea level and one and three feet of sea level rise. Shaded areas are periods when compliance is prescribed to meet irrigation standards, although compliance levels vary across months and water year types.

of the Base Case (historical) data for 1981 through 2000 were operated under the D-1641 salinity regulations. However, the Base Case produces greater salinity intrusion for most of the year, although the upstream extent of the intrusion was not farther into the Delta. The managed inflows of the Base Case produce higher fall outflows than exist in the more natural Unimpaired Flow cases.

Consequences of Peripheral Conveyance of Exports

The potential water quality effects of rerouting some or all export volumes from northern Delta channels through peripheral conveyance (PC) to the southern Delta export pumps has been hotly debated for over 40 years. One justification has been that export users could benefit from lower-salinity water by tapping into fresher Sacramento River flows upstream of the Delta. However, users within the Delta have been concerned that these diversions would increase salinity within the Delta itself. While reducing or eliminating through-Delta pumping could benefit Delta fish populations by returning more natural flow patterns, environmental advocates have expressed concerns

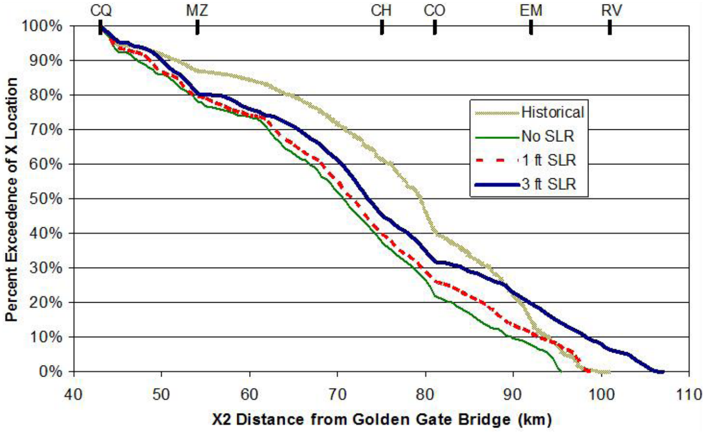

Figure 11 Cumulative probability distributions of daily X2 locations for unimpaired flows (thin green solid line) with 30.48 cm (1 ft) of sea level rise (red dashed line), 91.44 cm (3 ft) of sea level rise (thick solid blue line), and 1981–2000 historical condition (opaque thick brown line), illustrating progressive salinity variability for Unimpaired Flow conditions with sea level rise. X2 is the location of the 2 ppt salinity region of the estuary in km from the Golden Gate Bridge. Thus a lower X2 value indicates that the low salinity zone is farther downstream in the estuary. Paired letters indicate geographical landmarks. CQ, Carquinez Bridge; MZ, Martinez Bridge; CH, Chipps Island; CO, Collinsville; EM, Emmaton; and RV, Rio Vista.

over whether the volume and timing of PC diversions would sufficiently protect fish.

The peripheral canal that went before voters in 1982 was a very large facility—700 cubic meters per second (cms) (25,000 cubic feet per second, cfs) capacity—and was intended to significantly increase water exports from the Sacramento River watershed. Here, we explored a more modest set of alternatives. We used an assumption of stable daily export volumes at levels that occurred during the 1981-2000 simulation period, and PC export capacities that ranged from 57 cms (2,000 cfs) to 425 cms (15,000 cfs) were examined. The system was also simulated as a dual facility with some continued through-Delta exports required by environmental flow constraints imposed on the PC diversions for these alternatives by limiting amounts that can be removed upstream from the Sacramento River (we present an alternative without this environmental constraint as well). The 283 cms (10,000 cfs) minimum flow requirement on the Sacramento River is imposed to prevent flow reversals from tidal influences near potential upstream intake locations. There are potential environmental problems with bi-directional flows at a PC intake (Burau 2007). Many organisms take advantage of tidal flows, moving vertically in the water column to move much farther on the tidal currents than they could otherwise by their own power on the lower net downstream river current. Locating diversion intakes where bi-directional flow occurs could inadvertently draw more of these organisms through PC intakes.

Modeling Dual Conveyance

We examined the effects of operational changes on salinity in the Delta by comparing the current through-Delta export system (the Base Case where all exports flow through the Delta to the pumps) with a dual facility (combining direct withdrawals from the current southern Delta locations with withdrawals from the Sacramento River upstream of the Delta into a PC). For these simulations the through-Delta pumping was reduced by the amount of water diverted upstream from the Sacramento River and conveyed through the upstream diversion. Because the total volume of exports is unchanged, net Delta outflow is also unchanged, although the balance between the Sacramento River and the San Joaquin River flows at the confluence is affected. Four peripheral conveyance capacities were simulated: three—57, 212, 425 cms (2,000, 7,500, 15,000 cfs)—using historical conditions with exports split between the south Delta pumps and the PC as allowed by the upstream environmental flow constraints, and a fourth, which was performed without the flow constraints and restricting the PC export contribution only to leave net downstream flow in the Sacramento River ("PC Only"). The amount extracted from the Sacramento River was never allowed to reduce Sacramento River flow below 283 cms (10,000 cfs), except for the PC Only case, which only takes through-Delta exports when more is needed than the upstream Sacramento River carries (an infrequent case). Since the PC Only scenario requires a maximum capacity of 400 cms (14,050 cfs) to transfer total exports over the 20 water years, it is equivalent to the 425 cms (15,000 cfs) PC without the environmental flow constraint on Sacramento River flows.

Water Quantity and Quality Effects of Peripheral Conveyance

Table 1 shows the volumes of exports withdrawn upstream (PC) and through-Delta for the different alternatives. Although just the PC Only alternative effectively eliminates through-Delta exports, the two largest PC diversions also greatly reduce the need for through-Delta pumping. Clearly, the environmental flow constraint imposed in this work on Sacramento River flow significantly constrains the use of a larger PC diversion. Doubling the PC capacity from 212 to 425 cms (7,500 to 15,000 cfs) increases average exports through the PC by ca. 1.1×10^6 m^3 per day (1,000 af day^{-1}) (Table 1). Using the export demand schedule of the 1981–2000 period, the only scenario in which a PC alone could convey all of the water exports that occurred over the 20 years under examination is the PC Only scenario, which omits this environmental flow constraint.

Although this results-and-operations theory suggests a diminishing return on PC capacity, it should not be interpreted as justifying a hard limit on the ideal size of a PC. The scenarios examined here constrain

Table 1 Average water and salt exports for the Base Case and four peripheral conveyance alternatives

	Water export sources[a]			Salt exported		
		Delta			30.48 cm SLR	
Alternative	**Sac River**	**(10^6 m^3 day^{-1})**	**Total**	**No SLR**	**(10^3 tonnes day^{-1})**	**91.44 cm SLR**
Base case	0.00	16.65	16.65	6.66	8.51	13.57
57 cms PC[b]	3.82	12.83	16.65	5.43	5.92	9.25
212 cms PC[b]	9.75	6.91	16.65	4.56	5.18	7.65
425 cms PC[b]	10.86	5.80	16.65	4.32	4.93	7.16
PC Only	16.65	0.00	16.65	2.59	2.59	2.59

[a] Results are produced using 1981–2000 export levels.

[b] Peripheral conveyance withdrawals are limited by 10,000 cfs environmental flow constraint in Sacramento River for all cases except PC Only. Sacramento River and Delta exports may not sum exactly to total exports because of rounding.

peripheral exports by reproducing the daily timing of exports for the 1981–2000 period. By diverting more water during high flow periods, it would be possible to export considerably higher volumes through a PC while respecting an environmental flow constraint on the Sacramento River. Additional studies need to consider constraints on pumping, PC, upstream consumptive use, reservoir operations, and channel and storage capacity south of the Delta. Considering only pumping and PC capacity constraints, the 1981–2000 yield through a PC with the same 283-cms (10,000-cfs) environmental flow constraint for the Sacramento River was potentially over 55% greater than the actual volume exported (data not shown). While diversions of this magnitude are unlikely for environmental reasons (since sharp reductions in peak Sacramento River flows would have other consequences), the potential illustrates the need to consider operational changes before setting limits on PC export capacity.

There are also environmental reasons for building a larger PC export capacity, without expanding export volumes. A properly managed larger facility would allow more water to be exported on ebb flows, during higher river flows or only during daylight hours, to reduce potential environmental consequences.

Dual Conveyance Water Quality

We calculated the percent of days per month exceeding regulatory EC values from the model results for the Base Case and the dual conveyance system using different PC sizes (Figure 12). Since net Delta outflow remains the same for these alternatives, salinity does not change significantly at Chipps Island. However, salinity increases along the Sacramento River (e.g., Emmaton) as the reduced river flow allows brackish water to move upstream. In normal operations, some Sacramento River water flows past the confluence with the San Joaquin River, mixes with higher-saline water of the bay, and is drawn down to the southern pumps. Here, salinity decreases slightly for locations along the lower San Joaquin River (e.g., Jersey Point), as less salt water is drawn from the west with reduced through-Delta pumping. Just the PC Only case significantly increases salinity at the southwestern and southern Delta pumping locations, for reasons similar to the No Export scenario examined above. With less lower-salinity Sacramento River water being drawn toward the pumps, salinity within the southern Delta is dominated by the higher salinity of San Joaquin River flows.

For export users, the water quality implications of these changes depend on the blended water that results from south Delta and upstream salinity conditions. As evident in Table 1, salt exports—a measure of salinity in the export mix—decrease significantly with the ability to take some exports from the lower salinity Sacramento River through a PC. The environmental flow constraint on the Sacramento River along with some—albeit reduced—through-Delta exports protect agricultural users in the southern

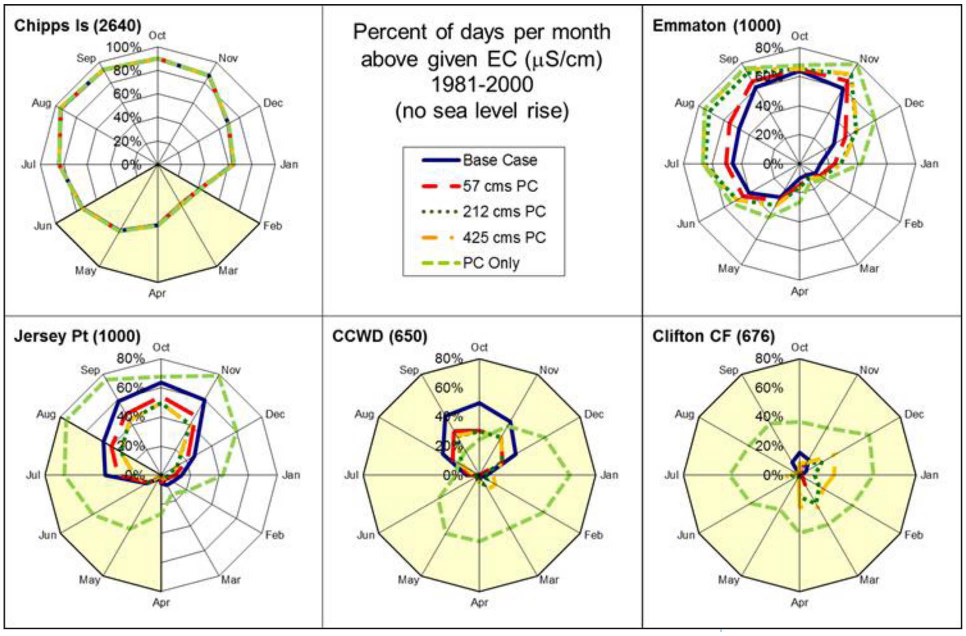

Figure 12 Average percentage of days in each month exceeding the specified EC (μS cm^{-1}) at locations in the Delta for different operational scenarios, at current sea level. Dark blue line indicates results of current Base Case pumping; other colors show results with the following amounts of peripheral canal capacity and a 283 cms (10,000 cfs) minimum flow on the Sacramento River: 57 cms (2,000 cfs) (red, large dash), 212 cms (7,500 cfs) (dark green dots), 425 cms (15,000 cfs) (gold, dash dot). Light green hatched line is results of the PC Only (425 cms (15,000 cfs) with no limit on removal of water from Sacramento River). All scenarios overlap at Chipps since net Delta outflow does not change. Shaded areas are periods when compliance with salinity standards is prescribed, although compliance levels vary across water year types (and across months for irrigation standards).

Delta as well as urban users at the CCWD pumps. However, some additional flow releases would likely be required to attain agricultural salinity standards at Delta locations along the Sacramento River.

Effects of Water Year Variability

The salinity patterns averaged over 2 decades in Figure 12 mask the differences that occur from runoff variability across years. The 7 critical years and the 8 wet years[10] are isolated in Figure 13 from the 20-year averages of Figure 12 for Emmaton and Jersey Point, providing a comparison of the inter-annual variability of salinity for different PC alternatives. The 425-cms (15,000-cfs) PC is not shown since its results are similar to those of the 212-cms (7,500-cfs) PC. The western Delta has substantial variation in water quality between wet and critical years. In critical years, agricultural irrigation in the western Delta would be difficult, even with full through-Delta pumping. Figure 14 shows similar data for the two export pumping locations in the southern Delta. There is less overall variation at these sites, except in the case of the PC Only, which has dramatically more salinity in the critical years at the southern Delta sites.

Sea Level Rise with Peripheral Conveyance

We also simulated each PC alternative with 30.48 and 91.44 cm (1 and 3 ft) of sea level rise, following the same procedure as above. The water quality implications are summarized in Figures 15 and 16. With 30.48 cm (1 ft) of sea level rise, the 57 cms (2,000 cfs) PC does not further increase salinity at any of the locations shown. Both the 212-cms (7,500-cfs) and 425-cms (15,000-cfs) PC facilities increase salinity at Emmaton with 30.48 cm (1 ft) of sea level rise, but suggest slight decreases at Jersey Point and the CCWD pumps, because reduced through-Delta pumping no longer draws as much higher-saline water in from eastern Suisun Bay. A slight seasonal shift in salinity exceedance appears at Clifton Court Forebay but the number of days of exceedance is approximately the same. Since the salinity of export water would still improve because of its blending with lower-saline Sacramento River water, the main water quality concern would be for users within the Delta.

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[10] ‘Critical’ and ‘wet’ are the two extremes of the 5 water year types defined by the 1985 State Water Resource Control Board Water Quality Control Plan.

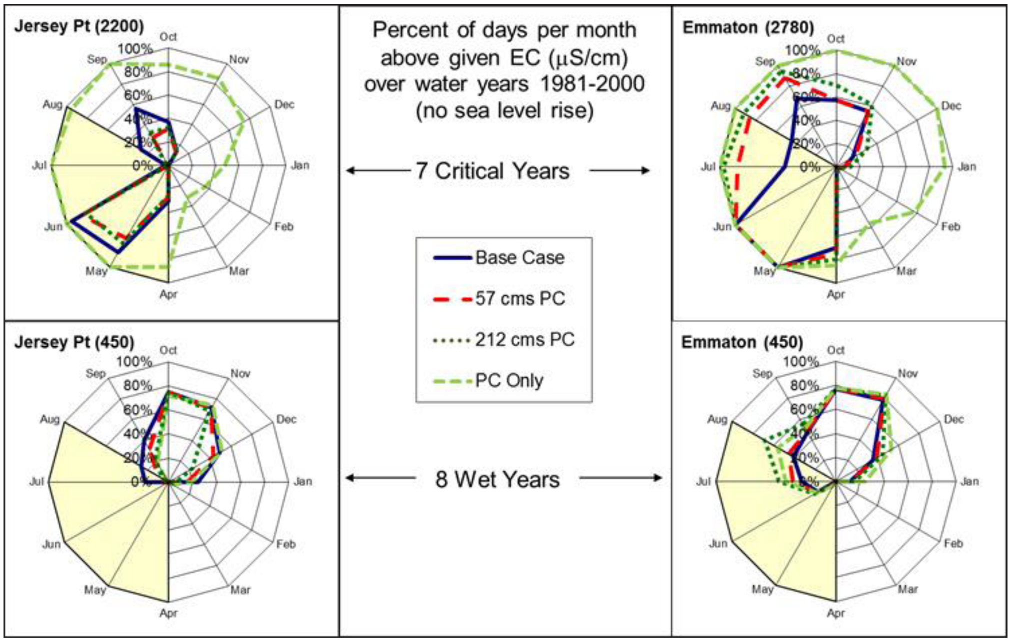

Figure 13 Comparison of wet and critical water years with simulated average percentage of days in each month exceeding the specified EC (μS cm^{-1}) at Emmaton and Jersey Point. Dark blue line indicates results of current Base Case pumping; other colors show results with the following amounts of peripheral canal capacity and a 283 cms (10,000 cfs) minimum flow on the Sacramento River: 57 cms (2,000 cfs) (red, large dash), 212 cms (7,500 cfs) (dark green dots). Light green hatched line is results of the PC Only (425 cms (15,000 cfs) with no limit on removal of water from Sacramento River). Shaded areas are periods when compliance with salinity standards is prescribed, although compliance levels vary across water year types (and across months for irrigation standards).

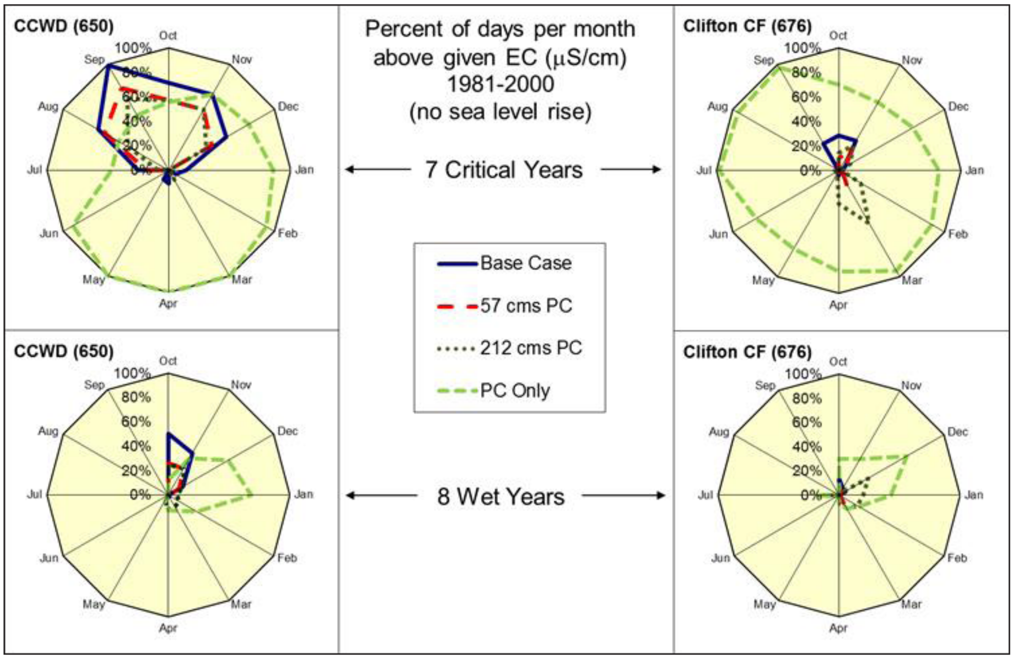

Figure 14 Comparison of wet and critical water years with simulated average percentage of days in each month exceeding the specified EC (μS cm^{-1}) at the CCWD pumping plant and Clifton Court Forebay. Shaded areas are periods when compliance with salinity standards is prescribed, although compliance levels vary across water year types. Drinking water standard is all 12 months.

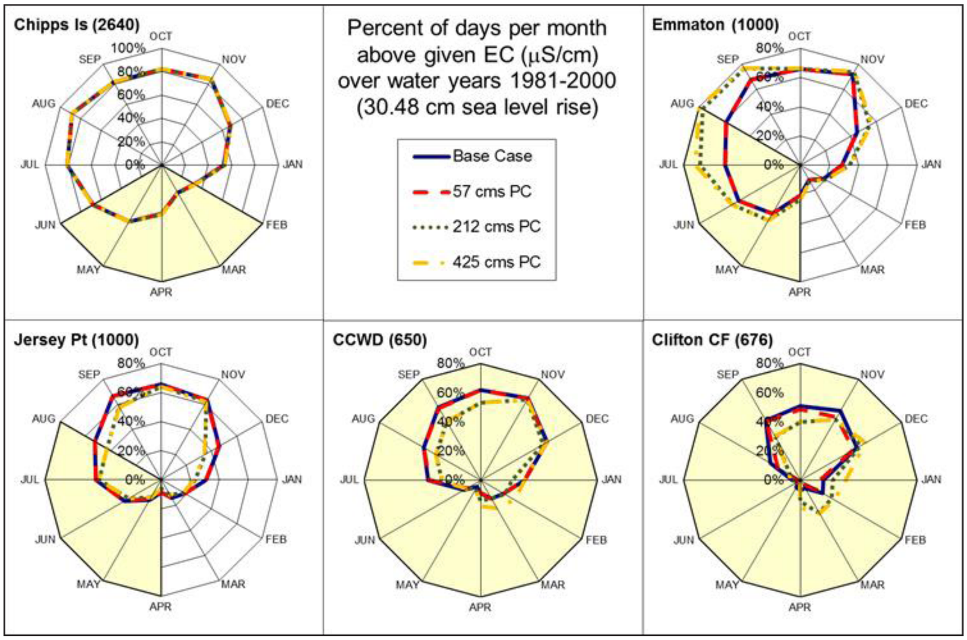

Figure 15 Average percentage of days in each month exceeding the specified EC (μS cm^{-1}) at locations in the Delta for different operational scenarios with 30.48 cm (1 ft) sea level rise. Dark blue line shows the results of current Base Case pumping over 1981-2000; red dashed line: up to 57 cms (2,000 cfs) of peripheral conveyance (PC) exports; dark green dotted line: up to 212 cms (7,500 cfs) of PC exports; light green dash–dot line: up to 425 cms (15,000 cfs) of PC exports. At Chipps Island, all scenarios are roughly identical because net Delta outflow is the same. Base Case and 57 cms PC are about the same, as are 212 cms and 425 cms PC's. Shaded areas are periods when compliance with salinity standards is prescribed, although compliance levels vary across water year types (and across months for irrigation standards).

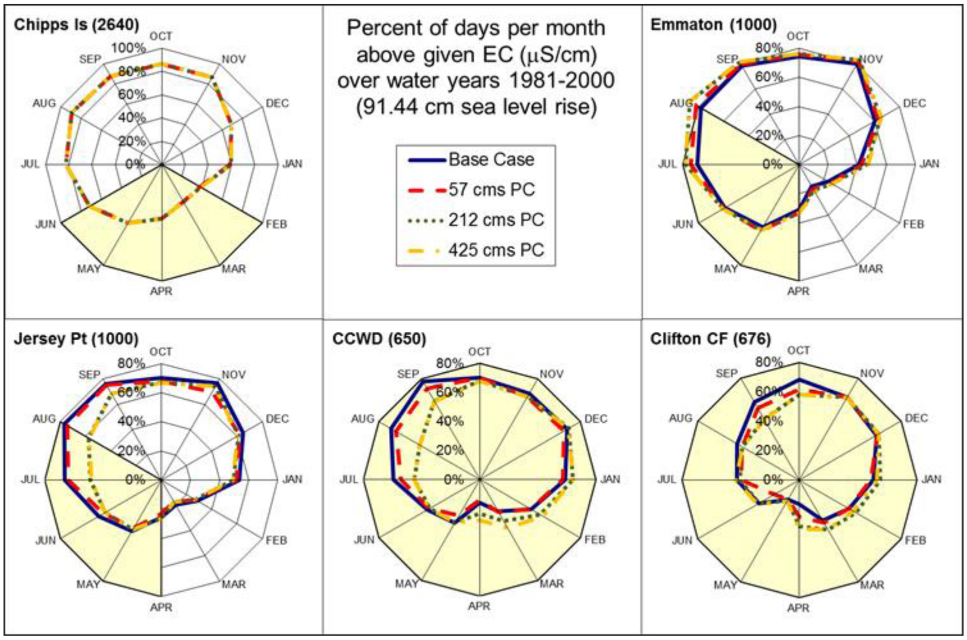

Figure 16 Average percentage of days in each month exceeding the specified EC (μS cm^{-1}) at locations in the Delta for different operational scenarios with 91.44 cm (3 ft) of sea level rise. Dark blue line shows the results of current Base Case pumping over 1981-2000; red dashed line: up to 57 cms (2,000 cfs) of peripheral conveyance (PC) exports; dark green dotted line: up to 212 cms (7,500 cfs) of PC exports; light green dash–dot line: up to 425 cms (15,000 cfs) of PC exports. At Chipps Island, all scenarios are roughly identical because net Delta outflow is the same. Base Case and 57 cms PC are about the same, as are 212 cms and 425 cms PC exports. Shaded areas are periods when compliance with salinity standards is prescribed, although compliance levels vary across water year types (and across months for irrigation standards).

Table 2 Annual number of days during irrigation season (Apr 1 – Aug 15) over electrical conductivity ($\mu S\ cm^{-1}$) limits, 1981–2000

	Through-Delta	57 cms PC	212 cms PC	425 cms PC	PC Only
Emmaton					
No SLR	36	48	59	60	69
30.48 cm SLR	59	58	68	68	N/A[a]
91.44 cm SLR	75	80	80	80	N/A
Jersey Point					
No SLR	13	3	1	1	2
30.48 cm SLR	30	29	10	10	N/A
91.44 cm SLR	115	84	100	97	N/A
Clifton Court Forebay					
No SLR	0	0	2	4	16
30.48 cm SLR	16	8	11	12	N/A
91.44 cm SLR	115	84	100	97	N/A

a N/A signifies data not available (scenarios have not been simulated).

With a 91.44 cm (3 ft) increase in sea level, salinity increases further at Emmaton for all alternatives, with little difference between the Base Case and the various sizes of PC. However, the results suggest that PC use would somewhat mitigate higher-saline water levels in the south Delta from sea level rise (Figure 16). Regardless, remaining through-Delta export water would be more saline, although the exported blend would still have lower salinity than current exports.

The cases examined above demonstrate the additional costs of sea level rise to export users with the current through-Delta pumping system; either through increased salinity or reduced water availability resulting from the increased net Delta outflows needed to prevent salt intrusion. A PC can significantly mitigate these effects by making lower salinity water available. Although a PC does not eliminate the effects of sea level rise when operated as a dual conveyance facility (see Table 1, and Figures 15 and 16), even a small PC holds off the export salinity effects of sea level rise for many years.

While export salinity would benefit from PC operations, in-Delta agricultural pumping would not enjoy the same improvements. Listed in Table 2 is the number of days during the 137-day irrigation season (April 1 through August 15) that the compliance EC levels would be exceeded at Emmaton, Jersey Point and Clifton Court Forebay locations for these same sea level rise and water export alternatives. While current salinity standards at Clifton Court Forebay are constant over the irrigation compliance period (at 1,000 $\mu S\ cm^{-1}$), standards at both Emmaton and Jersey Point vary seasonally and with water-year type. Standards are somewhat less stringent at Jersey Point and Emmaton in drier years.[11] The data represent the number of days over the compliance limit, but do not signify specific violations because regulations specify a 14-day average.

With sea level rise, some policy trade-offs between users in the south Delta and export users diminish over time. Currently, a PC operated with environmental flow constraints only increases salinity for western Delta agriculture on the Sacramento River, but decreases salinity for western Delta farmers on the San Joaquin River side. With 30.48 cm (1 ft) of sea level rise, the conditions in the western Delta deteriorate considerably, and by 91.44 cm (3 ft) there is little difference among alternatives (except the PC Only,

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[11] *http://www.waterboards.ca.gov/waterrights/board_decisions/adopted_orders/decisions/d1600_d1649/wrd1641.pdf*

which imposes no environmental flow constraint on the Sacramento River). All alternatives suggest that with continuing sea level rise, irrigation in the western and southern parts of the Delta, if they did not flood, is unsustainable in places that could not be connected to an upstream diversion (PC).

MODELING LIMITATIONS

No hydrodynamic and water-quality model can exactly replicate historical results. Each model is an approximate solution of an approximate representation of reality. While the use of dispersion coefficients based on 3-D modeling makes WAM useful in sea level rise and island flooding events, the tidally averaged representation of WAM can never resolve daily variations or even spring and neap cycle changes. The aggregation of channels makes the model impractical for detailed examination of those channels which are combined. The substitution of some cross-connecting channels with regressions could lend them less accurate for changes in flow outside of the regression development. However, the intended use is to screen the multiple input variables and the numerous operational choices to determine which combinations should be examined more closely with more highly detailed models.

CONCLUSIONS

We performed numerical simulations over a 20-year period using a 1-D model, WAM, to examine the effects of sea level rise and operational changes on diverse Delta futures. Dispersion coefficients based on 3-D model results were used to improve the salt transport efficacy of the model. We used WAM to evaluate some key water quality issues associated with broad export-management alternatives and anticipated changes in the Sacramento–San Joaquin Delta.

Hydrodynamic and water-quality modeling results are needed to inform planning and policy decisions for the new Delta as sea level continues to rise and more islands become permanently flooded (Lund et al. 2008, 2010). Significant advances to allow better representation of sea level rise and permanently flooded islands together are still needed. It is imperative to develop solid tools to support this kind of decision-making process. In the meantime, the work presented here is the beginning of a larger project at UC Davis aimed at developing those solid tools. In spite of the simplifications of Delta representation inherent to the tools employed, we believe that several quantitative insights gained with the simulations presented in this paper are robust. The simulations provided the following three highlights: (1) Salinity changes will occur in the Delta with outcomes depending on export conveyance strategy, how the system is operated, and how sea level and climate evolve. Sea level rise during the next century will significantly affect salinity in the Delta. Eventually, sea level rise will increase salinity beyond reasonable levels for drinking water and irrigation in parts of the Delta without large increases in Delta inflows or reductions in exports. (2) Even when operated with environmental flow constraints on the Sacramento River to prevent entrainment of aquatic life, a PC, operated in dual-conveyance mode, allows salinity to intrude farther up the Sacramento River, without modification of upstream controls. Salinity in the lower San Joaquin River and the western Delta generally decreases as less water is drawn down from the saltier Suisun Bay area. As PC capacity increases, there is a diminishing return on total exports through the PC. Some improvement on PC exports could be achieved with additional storage south of the Delta allowing the peaks of Sacramento River to be exported. With exclusive PC use, salinity in the southern Delta increases substantially, because the region no longer benefits from the mixing of lower salinity Sacramento River water with more-saline San Joaquin River inflows. (3) Sea level rise changes the effects of PC over time. Whereas peripheral diversions increase salinity in the Delta portions of the lower Sacramento River with 30.48 and 91.44 cm (1-ft and 3-ft) of sea level rise, salinity is somewhat mitigated on the San Joaquin River and southern Delta.

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