Delta Hydrodynamics and Water Salinity with Future Conditions

Technical Appendix C

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Description

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Summary

This appendix presents an initial assessment of the salinity implications of four broad strategies for managing Delta water exports: (1) continue pumping exports through the Delta (the current policy), (2) divert water upstream and convey it around the Delta through a peripheral canal, (3) combine the current through-Delta pumping strategy with a peripheral canal (so-called "dual conveyance" or "dual facility"), and (4) end exports altogether. It also explores the salinity implications of two main aspects of change in the Delta over this century: one to three feet of sea level rise and increased island flooding. We used existing models and previous results of others to evaluate some key water quality issues associated with these conditions. The focus is on salinity, the water quality characteristic of primary interest to water users and the one most easily represented in most models.

Change will occur in the Delta, with outcomes depending on what conveyance strategy is chosen, how the system is operated, and how sea level and climate conditions evolve. With sea level rise predicted over the next century, initial model simulations suggest significant increases in salinity in the Delta, eventually pushing Delta salinity beyond reasonable levels for drinking water and irrigation unless large (and costly) increases in Delta outflows or reductions in upstream use and exports are made. Similarly, permanently flooded western islands significantly increase salinity intrusion into the Delta. In contrast, some islands elsewhere in the Delta might be pre-flooded without long-term effects on Delta salinities. Modeling concurrent sea level rise and island flooding could not be done, but these two effects would be at least additive, making Delta salinity conditions difficult indeed for both urban and agricultural users.

Even when operated with minimum downstream flow restrictions on the Sacramento River to prevent entrainment of aquatic life, a peripheral canal, operated in a dual conveyance mode, allows salt to intrude farther up the Sacramento River. However, salinities in the lower San Joaquin River and the central Delta generally decrease as less water is drawn into the Delta from the saltier Suisun Bay area. With an exclusive peripheral canal, salinity in the southern Delta increases substantially, because the region no longer benefits from mixing lower salinity Sacramento River water with saltier San Joaquin River outflows. For the southern Delta, an exclusive peripheral canal is similar to ending exports altogether.

Sea level rise changes the effects of a peripheral canal over time. While peripheral canal operations increase salinities in the Delta portion of the Sacramento River with one and three feet of sea level rise, San Joaquin River and southern Delta salinities are slightly mitigated with a peripheral canal. Regardless, sea level rise facilitates more salt transport to southern Delta pumps, although the exported blend would benefit from mixing with lower salinity Sacramento River water from a peripheral canal.

This simplified approach for modeling alternative scenarios provides a first cut at likely changes with different export management strategies and changed natural conditions. The analysis also points to many areas that require more detailed modeling work to more thoroughly evaluate issues related to sea level rise, island flooding, and the effects of operational changes (notably varying the timing of exports and the operation of upstream reservoirs) both now and in the future.

Acknowledgments

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Introduction

In our earlier report, *Envisioning Futures for the Sacramento – San Joaquin Delta* (Lund et al., 2007), we considered a range of water management alternatives for the Delta. In broad terms, these alternatives included futures with continued through-Delta exports, exports taken upstream on the Sacramento River and conveyed around the Delta through a peripheral canal (PC), and no exports at all. We provided an initial assessment of promising alternatives based on likely overall economic and environmental performance. However, we did not conduct hydrodynamic analysis of the salinity impacts of management actions. In this appendix, we present an initial assessment of the salinity implications of four broad alternatives: continued through-Delta exports, an exclusive peripheral canal, dual conveyance (combining through-Delta and peripheral canal exports), and no exports. We also explore the salinity implications of two main aspects of long-term change in the Delta: sea level rise and increased island flooding. The focus of the assessment is on salinity levels, the water quality characteristic of primary interest to water users and the one most easily represented in most models.

Salinity transport is driven by the hydrodynamic consequences of management decisions and natural changes within the Delta. The complexities of the Delta (many inflows and outflows of varying salinities, a complex network and strong tidal influence) require a numerical model to estimate the effects of changes to the system. Lacking sufficient time to develop new modeling tools, we gathered existing hydrodynamic and salinity knowledge and supplemented it with information that could be quickly developed with existing computer models of the Delta. The results presented here represent a first-cut at modeled effects of sea level rise, are not exhaustive, and only illustrate the general trends of changes, not the exact levels of change to be experienced in the Delta. Furthermore, with existing tools, it was not possible to consider all management decisions and potential natural changes simultaneously. Notably, island flooding is considered separately from sea level rise, even though these two phenomena are likely to coincide, and we are only able to qualitatively assess their joint effects.

This appendix is organized as follows. The next section provides an overview of the computer modeling tools and approach used for the analysis. We then examine a succession of management and physical change scenarios:

1. what Delta salinity would look like with no exports and with "unimpaired flows" (no exports, no upstream diversions and no upstream reservoirs);

2. the consequences of sea level rise with continued through-Delta export diversions;

3. the consequences of island flooding, again with through-Delta export diversions; and

4. the consequences of introducing a peripheral canal, operated as a dual conveyance facility or alone, with and without sea level rise.

A concluding section summarizes highlights of the analysis and points to areas for further work.

1. Modeling Tools

The first step in modeling is to determine the goal of the exercise and the precise questions to be answered, including the detail of the physics required and the results needed. If few details are required, the model used can be very simple. For instance, a model to simulate net Delta outflow (i.e., flows leaving the Delta for the ocean, net of upstream diversions and exports) could be as simple as a mass balance addition and subtraction of flows and losses, abstracting from detailed knowledge of local flows and water elevations in the Delta.

For this study our goal was to provide a general understanding of trends in flows and salinity concentrations within the Delta. This is still a fairly general level of analysis. As efforts to develop Delta management solutions proceed, more detailed simulation of flow and additional water quality parameters will be needed. For instance, to better assess ecological survival of several species, it will be necessary to simulate residence time, particle tracking, temperature, nutrients and even phytoplankton and higher trophic levels. In short, the choice of model and the way a model is used will vary with the variables that need to be modeled, the physical size and complexity of the problem, and the physics required to adequately describe the problem. There are tradeoffs between greater detail and cost, because model computation time and data requirements increase (often significantly) with the complexity of the model.

Several models are available for tidal estuaries like the Delta. Among the models frequently applied to the Delta and its problems are the three-dimensional models TRIM/ UnTRIM [1] (Casulli and Zanolli, 2002) and Si3D (Smith, 1997) [2]; Resource Management Associates (RMA) Inc.'s two-dimensional model RMA Bay-Delta [3]; and the one-dimensional models DSM2 [4] and the Water Analysis Module (WAM) model from RMA (URS, 2007). While flow and water level can often be represented by a one-dimensional model, many other processes require models in two or three dimensions to properly capture the physics or local detail required for the problem.

The WAM and TAM Models

Given the short time available for our study and our desire to examine several alternatives over a broad range of flow conditions, it was necessary to rely primarily on a model which could operate with great computational speed. One such tool is the WAM model noted above. It is a tidally averaged, simplified network, numerical model developed by RMA for modeling work in the Delta Risk Management Strategy (DRMS) study (DRMS, 2007). The WAM includes code to route water and salinity concentrations in the Delta and to manage the various upstream storage operations feeding the Delta.

The physical network of the Delta is simplified in WAM at locations where conveyance in parallel channels can be represented by a single channel or where cross channels carry so little net flow that the channel can be represented by a mathematical exchange. WAM uses

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[1] TRIM – Tidal, residual, intertidal, mudflat; UnTRIM – Unstructured TRIM.

[2] Si3D – Semi-implicit 3-Dimensional

[3] This model was developed from the RMA2 code (King, 1986).

[4] http://modeling.water.ca.gov/delta/models/dsm2/index.html

tidally averaged longitudinal dispersion algorithms developed from more detailed three-dimensional modeling work to properly mix salt through the channel network (Gross et al., 2007). [5] From that work, dispersion values were developed that vary depending on the location within the Delta; in WAM they have been applied and vary over 28 different channel reaches. WAM also simplifies return flows from agricultural users within the Delta by aggregating the 142 different returns represented in DWR's DSM2 model into five locations. WAM incorporates various operations to respond to the hydrodynamic and salinity responses - upstream reservoir management response, Delta water operations, disruption of Delta irrigation, Delta net losses (or net consumptive water use), and water exports. Since our work only relies on the portion of the model that performs hydraulic calculations, with changes in inflows and exports and sea level rise, we refer to it herein as the Tidally Averaged Model (TAM) to acknowledge the difference.

Thanks to the TAM's computational efficiency, it has been possible to simulate and examine daily output data over 20 consecutive water years (1981-2000) for multiple scenarios. [6] A 20-year simulation using TAM requires about 15 minutes of computation time, whereas a 20-year simulation using the more detailed DSM2 (1-dimensional) and RMA (2-dimensional) Bay-Delta models would require about 10 and 480 hours, respectively. Twenty years provides a reasonable period for scenario analysis. The 1981-2000 period we chose includes both one of the wettest periods (1995–2000) and one of the longest droughts of recent history (1987-1992). Interestingly, the period contains eight years classified as "critical" (the driest water year classification) and seven years classified as "wet" (the wettest classification), a characteristic we use to highlight differences in outcomes in different water year types.

We use TAM to explore water management alternatives and to examine the implications of sea level rise. Although TAM simulated initial advection of salt into the Delta due to levee failures on islands, the additional dispersion associated with water continually pulsing in and out of the breach was not captured. This failure occurs because the longitudinal dispersion coefficients developed for in-channel flows in TAM are unsuitable for simulating dispersion of lateral flow through levee breaches and dispersion dynamics inside the flooded island. While appropriate dispersion coefficients probably can be developed to allow TAM to produce proper results, there was insufficient time to pursue this path for this study.

RMA's Flooded Island Study

As an alternative to using TAM for studies with permanently flooded islands, we examined the effects of various flooded islands using the more complete RMA Bay-Delta model, developed for the DRMS study's flooded-island modeling work (DRMS, 2007). This model has been successfully applied for actual Delta island failures, such as the Jones Tract failure in 2004.

Because the RMA Bay-Delta model is many times slower than TAM, it was necessary to rely on simulations already performed for the DRMS effort. The flooded island study covers a

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[5] The dispersion represents the mixing of water due to all physical mechanisms associated with the hydrodynamics.

[6] Water years run from October 1st to September 30th.

much shorter time frame than the model simulations with TAM. Simulations were performed from April 12, 2002 to December 31, 2004 (roughly two and a half water year

Model Accuracy for the Base Case Alternatives

The efficacy of the two models for the Delta has been documented in the work performed for the DRMS study (URS Corporation/Jack R. Benjamin & Associates, Inc., 2007; DRMS, 2007). In addition, simulation results from each were compared with recorded salinity data (http://www.iep.ca.gov/data.html) at seven locations. These and several other Delta locations referred to in this chapter are presented in Figure C.1. Figures C.2 to C.8 present these comparisons. The simulations employ daily inflow data from the Dayflow historical boundary condition system (http://www.iep.water.ca.gov/dayflow/) managed by the Interagency Ecological Program (IEP). They apply the same operational criteria as those actually used in the periods under study. TAM simulations were performed over water years 1981-2000, and the RMA flooded-island model runs cover the shorter period noted above. Both models demonstrate good agreement with the available field data,[7] as presented below.

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[7] No effort was made to cull obvious outliers from the field data. Field data are made available without guarantee and they are not always available for the periods modeled.

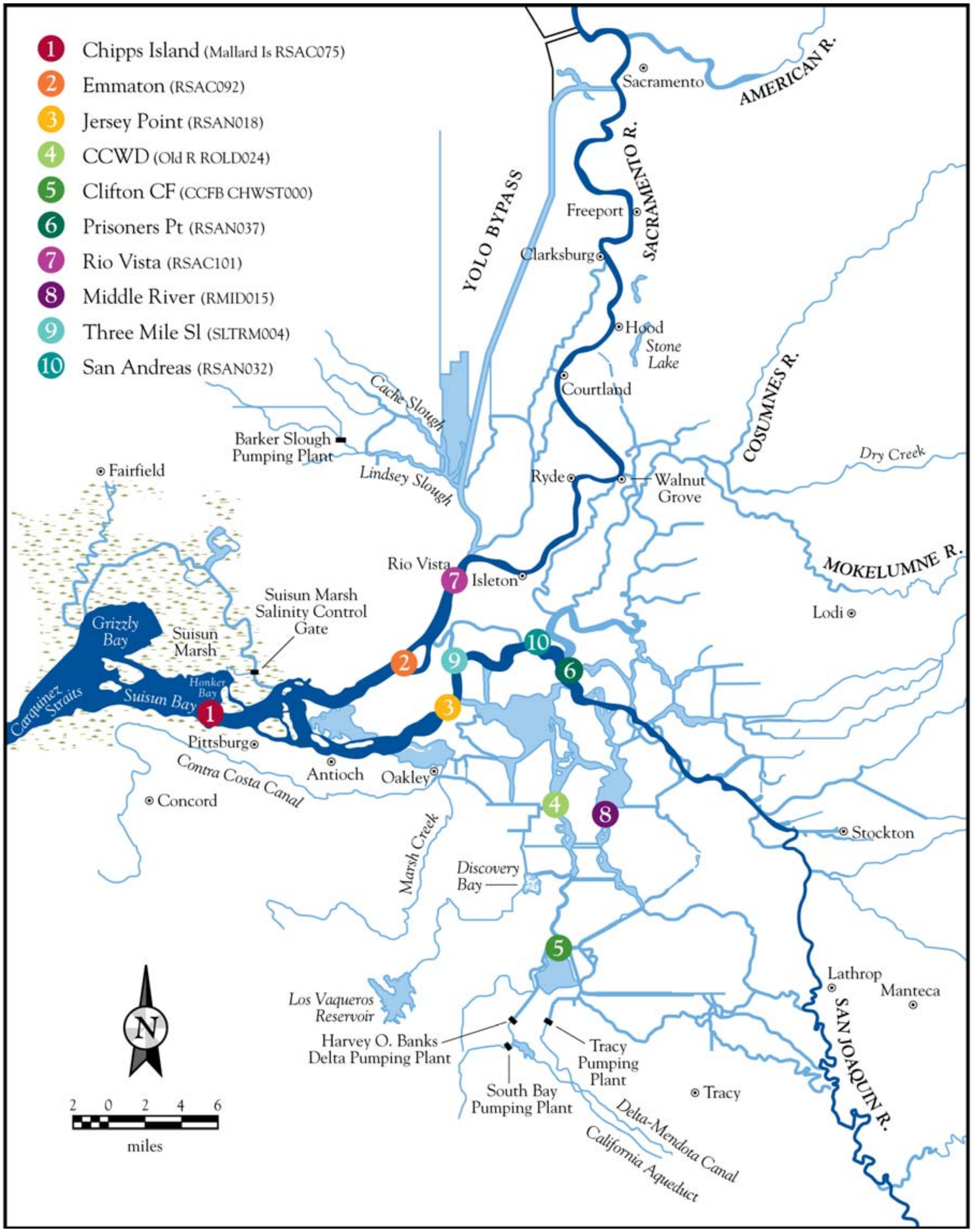

Figure C.1 – Delta locations for water quality comparison

For model testing, results from the simplified fast TAM were compared with those from the complex and slower RMA (2-dimensional model) and with field data for "base case" conditions and reported water operations and conditions. Except where otherwise noted, the scenarios assume the same operational criteria. This includes the same level of daily exports and reservoir releases, the same internal operations of all gates and barriers, and the same agricultural pumping and return flows within the Delta (although, as noted above, agricultural pumping and return flows are aggregated to five locations). For base conditions, TAM and RMA models are generally in good agreement with field salinity data and with each other. Figure C.2 for Old River at Bacon Island data demonstrated the most significant deviation from recorded data. Comparison of TAM with recorded data from the 1995-2005 period produced an 18.6 percent root mean square error but only a 4 percent average error. Differences are likely to result from using Dayflow boundary conditions for flow, fixed electrical conductivity values for the Sacramento River and eastern streams, and errors in the reported data[8] as well as genuine model error.

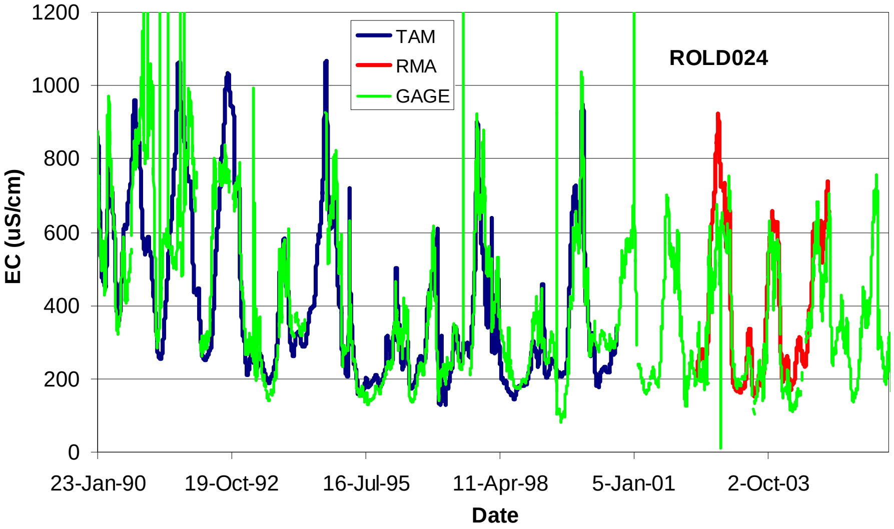

Figure C.2 - Results comparison of TAM and full RMA models with recorded data from IEP on Old River at Byron (ROLD024)

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[8] DWR acknowledges data collection and accuracy issues during period of ROLD024 discussed above.

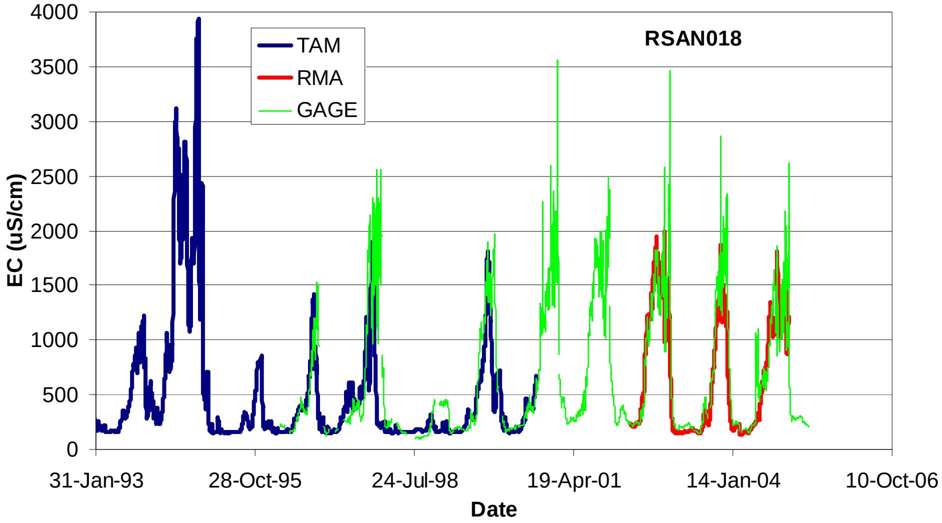

Figure C.3 - Results comparison of TAM and full RMA models with recorded data from IEP for San Joaquin River at Jersey Point (RSAN018)

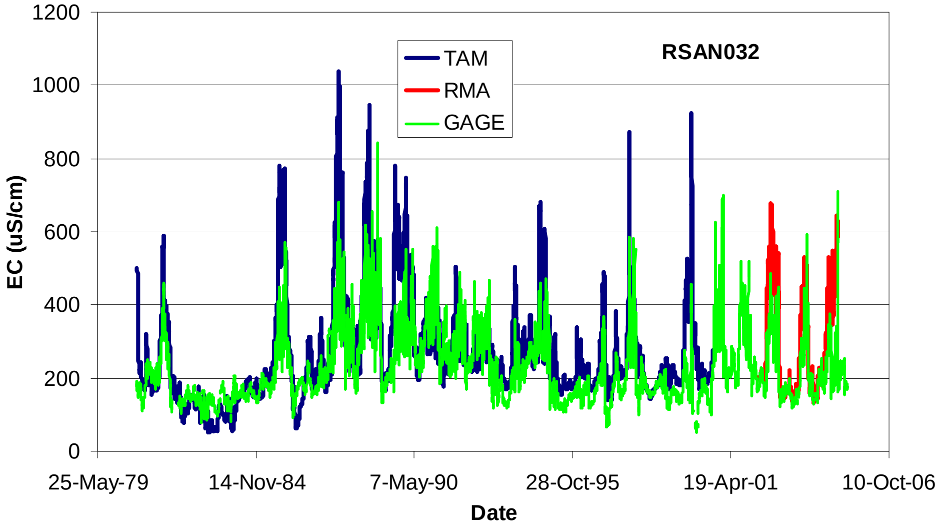

Figure C.4 - Results comparison of TAM and full RMA models with recorded data from IEP for San Joaquin River at San Andreas (RSAN032)

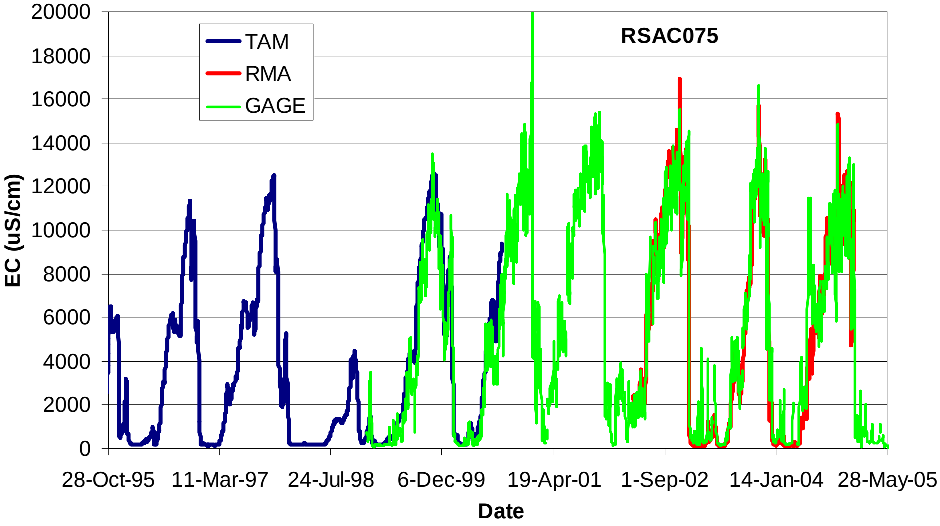

Figure C.5 - Results comparison of TAM and full RMA models with recorded data from IEP for Sacramento River at Chipps Island (RSAC075)

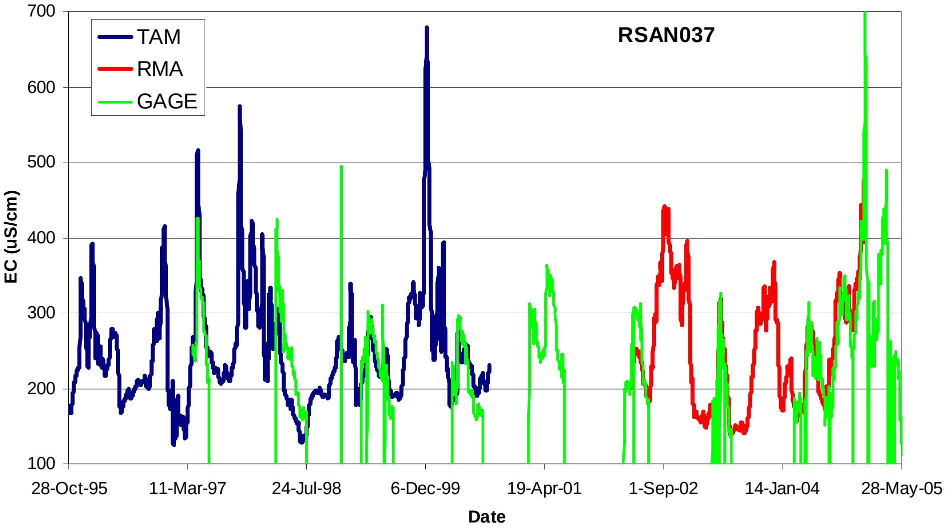

Figure C.6 - Results comparison of TAM and full RMA models with recorded data from IEP for San Joaquin River at Prisoner's Point (RSAN037)

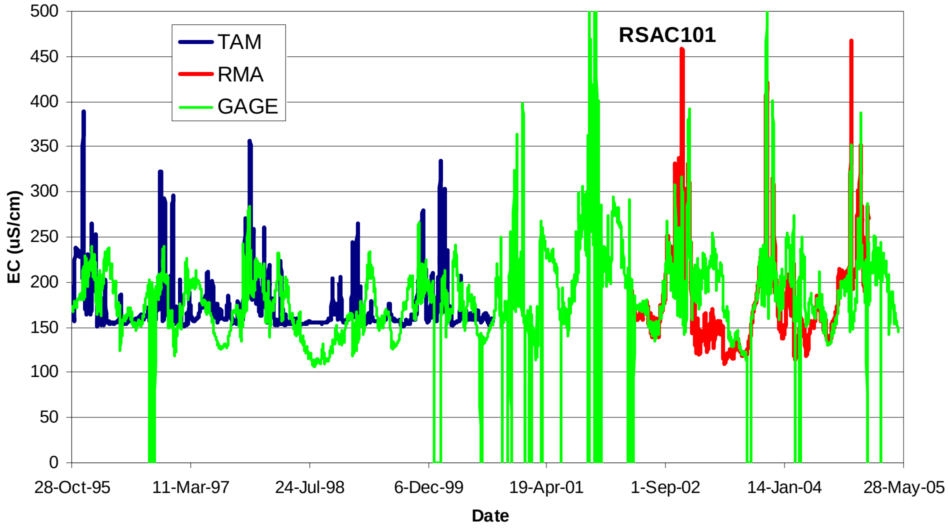

Figure C.7 - Results comparison of TAM and full RMA models with recorded data from IEP for Sacramento River at Rio Vista (RSAC101)

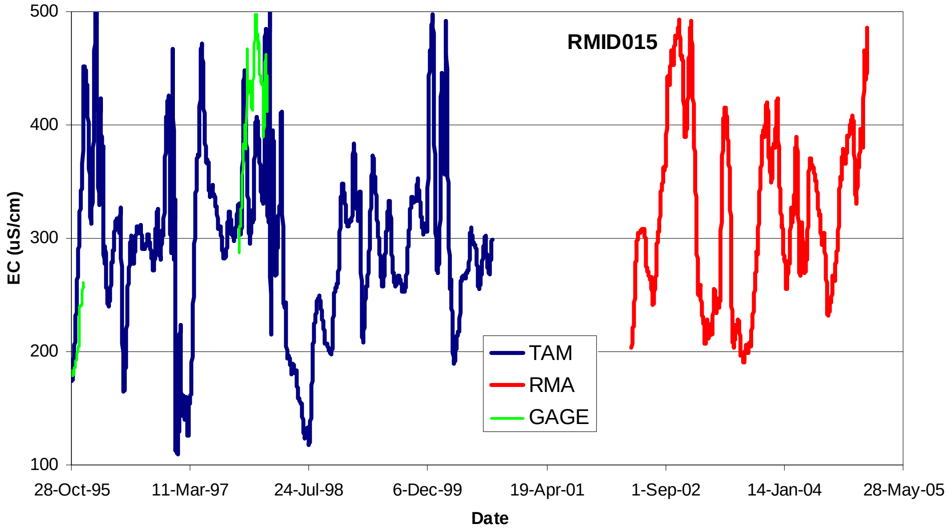

Figure C.8 - Results comparison of TAM and full RMA models with recorded data from IEP for Middle River (RMID015)

This simplified approach for modeling alternative scenarios provides a first cut at likely changes with different export management strategies and changed natural conditions. In the concluding section we highlight the types of additional modeling work that would be useful to explore how these results could change with different operational rules, notably by varying the timing of exports and the operation of upstream reservoirs.

Comparisons of Water Quality across the Delta

Comparisons of salinity between various scenarios and the base case are shown in terms of the percentage of days each month when electrical conductivity (EC in µS/cm) of the water (a surrogate for salinity) exceeds a specified limit. The limits were chosen to represent some of the actual regulatory limits for EC at five locations within the Delta: (1) Chipps Island on the Delta's western edge - a location used to monitor salinity regulations for fish during the springtime (February through June), (2) Emmaton, a north-western location on the Sacramento River where irrigation water standards are in effect from April through August, (3) Jersey Point, a western Delta site on the San Joaquin River (irrigation standards in effect from April through August), (4) the Contra Costa Water District's (CCWD) pumping plant in the southwestern Delta (more stringent urban standards, year-round), and (5) the Clifton Court Forebay (Clifton CF) in the southern Delta, representing exports for the State Water Project (SWP) and the Central Valley Project (CVP) (year-round urban standards and seasonal irrigation standards). [9]

Chipps Island EC is referenced to a value of 2640 µS/cm, the X2 compliance value applied there from February to June, to protect fish.[10] A value of 1000 µS/cm is applied at Emmaton and Jersey Point. At these western Delta locations, compliance values are set for agricultural uses, ranging from 450-2780 µS/cm depending on time of year and water year. (Salinity standards at agricultural locations are generally lowest from April to early-mid summer, and less stringent in dry years). Values referenced at CCWD (650 µS/cm) and Clifton Court Forebay (676 µS/cm) are similar to the EC values needed to comply with drinking water levels for chloride. These sites are also useful proxies for agricultural conditions in the southern Delta.

Although the comparisons indicate shifts in the ability to use water for designated beneficial uses, the analysis does not directly demonstrate regulatory compliance (or lack thereof), since the EC limits used here are fixed over the entire year, whereas for most regulatory standards the limits vary seasonally and by water year type. Also, some of the regulations were not in effect during the entire period of the simulations (in particular, the environmental regulations at Chipps Island did not come into effect until 1999).

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[9] The current EC standards for the Delta are contained in D-1641, adopted in 1999. For an overview, see State Water Resources Control Board, 2000, Tables 1, 2 and 4 (reproduced in Addendum C1)

[10] This standard controls the location of the 2% salinity level and was adopted at the end of the period under analysis, which explains why it is often not met in the base case.

2. No Exports and Unimpaired Flows

One alternative considered in our earlier report (Lund et al., 2007), but found too expensive to pursue, was to abandon the Delta and end exports altogether. What are the likely consequences of ending exports for salinity in the Delta? Given that most diversions from the Delta occur upstream,[11] it is also of interest to assess the implications of "unimpaired" Delta flows, i.e. flows when there are no exports, no upstream diversions and no storage. Application of the TAM allows a quick initial examination of such conditions. The comparisons are with the base case, which includes all diversions as they actually occurred from 1981 to 2000.

Water Quality with No Exports

For the no exports scenario, the exports of the CVP, the State SWP, the CCWD, and the North Bay Aqueduct were set to zero and net Delta outflow increased by an equal amount. Results of the no exports and the base case are shown in Figure C.9. The figure compares the percentage of days each month when EC exceeds a specified limit.

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[11] On average, upstream diversions have accounted for nearly two-thirds of all diversions from the Delta in recent years. See Lund et al. (2007), Table 6.1.

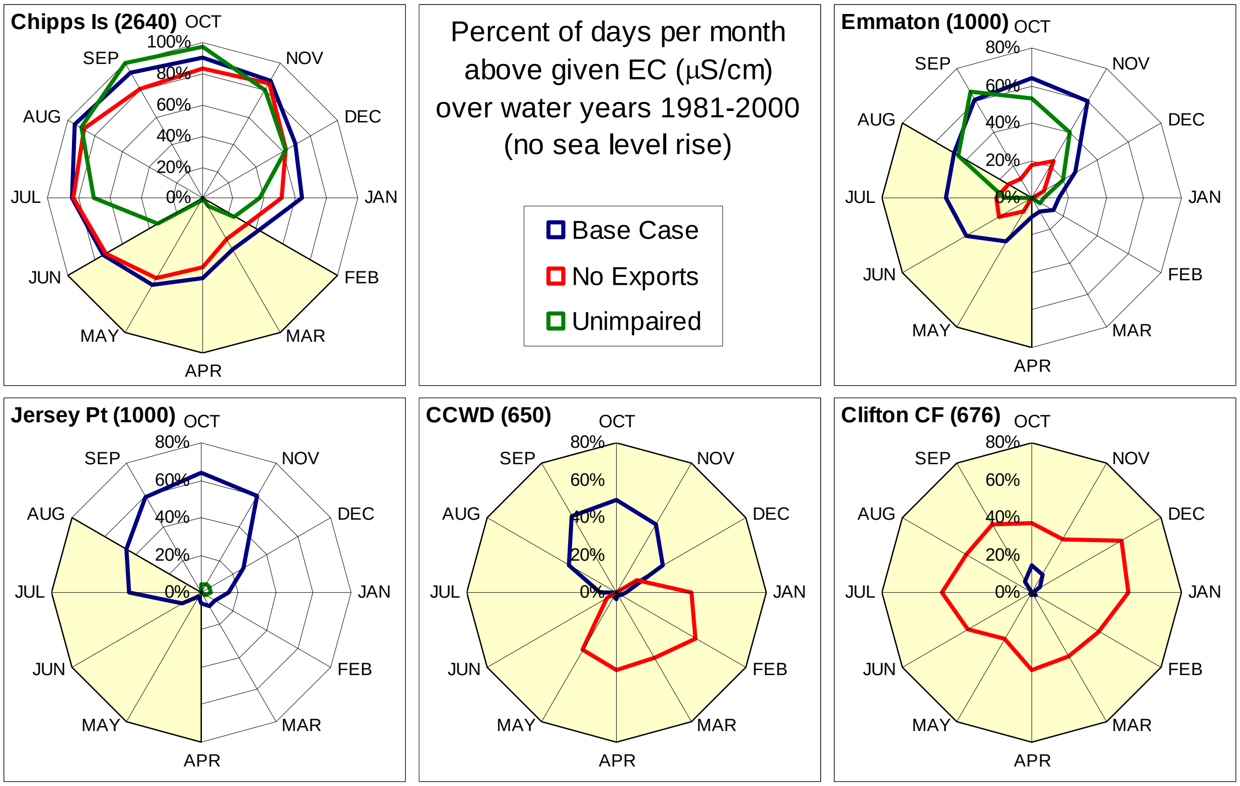

Figure C.9 - Simulated percentage of days each month exceeding the specified EC (µS/cm) at locations in the Delta with no exports and unimpaired flows

NOTES: 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, there are no exceedances at CCWD and Clifton CF.

The no export scenario presents some interesting contrasts with the base case. Without exports, water becomes fresher in the western Delta, but salinity increases in the southern Delta. A small reduction in salinity occurs at Chipps Island, caused by increased net Delta outflow, while greater changes are visible at Emmaton and Jersey Point. Salinity in the southwestern Delta at the CCWD pumps does not change greatly in magnitude, 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 salinity San Joaquin River inflows, which were applied the same as the base case for this simulation. Without exports, these flows are no longer being diluted by the fresher Sacramento River water that is normally drawn through the Delta to the pumps. In practice, San Joaquin River salinities would change as a result of reduced irrigation (and agricultural runoff) in the San Joaquin Valley; changes in upstream diversions on that river could also alter salinity at downstream locations.

Water Quality with Unimpaired Flows

Figure C.9 also shows the results of a simulated scenario with unimpaired flows. Such naturalized flows would have occurred if there were no upstream dams and diversions and no exports. In this simulation, the only diversions allowed were agricultural pumping and returns in the Delta, which roughly represent the evapotranspiration that would occur within the Delta under pre-development flow conditions. Because unimpaired flow was estimated using monthly averaged inflow and salinity data, the results are somewhat muted relative to results that would have been obtained using daily data.

Without upstream or export diversions, there is a dramatic reduction in salinity at all locations, except at Emmaton and Chipps in the fall. However, this simulation does not represent the "natural" Delta that existed before the dredging and diking of the Delta's marshlands in the second half of the 19th century. Instead, the scenario presents salinity for the current Delta network and landscape under natural flows.

To further examine the differences in Delta salinity variability between the recent historical conditions (the base case) and unimpaired flows, Figure C.10 plots the location of X2 – a common demarcation between fresh and salt water in the Delta. The X2 location plotted here is the estimated location of a vertically averaged EC of 2640 µS/cm from model results. For unimpaired flows, there is a high degree of overlap between the 1981-2000 distribution of the X2 location and distribution over a much longer period (1921-2005) – suggesting that the 1981-2000 period is representative of longer term flows. Compared with recent historical operations (the 1981-2000 base case), the location of X2 with unimpaired flows is more uniformly distributed across Sacramento River locations. Recent historical operations have approximately the same overall range (although ranging a little more inland), but the location is more frequently in the inland side of the range. This analysis confirms that recent water operations have maintained Delta salinity in less variable conditions than would have occurred with unimpaired flows.

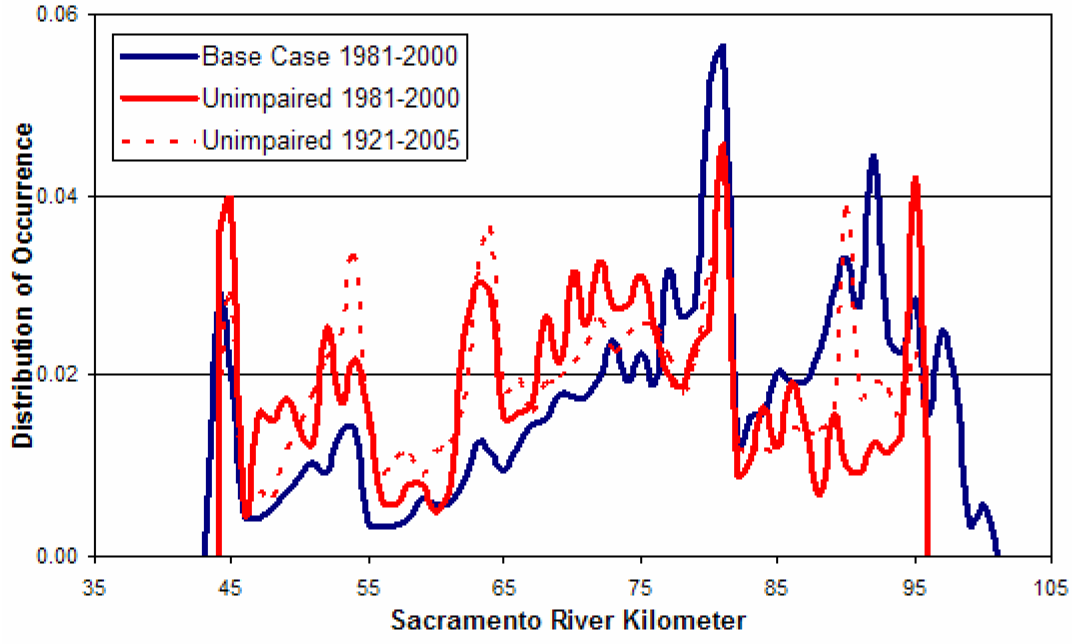

Figure C.10 – Probability distribution of the location of X2 along the Sacramento River

NOTE: The solid and dashed red lines show the distribution of locations of X2 with unimpaired flows for a 20-year and 85-year period, respectively. The blue line shows the distribution of the X2 location in the 20-year base case.

Compared with today's conditions, the inter-tidal, tule wetlands of the pre-European Delta would have allowed higher flow rates when water levels rose above the tule vegetation and restricted outflows at lower water levels, given the much lower natural channel capacity that existed under low-flow conditions (Baptist et al., 2007). Even in the 20-year averages shown in Figure C.9 the western Delta is fresher in the spring and more saline in the fall; it would likely be even more saline in the fall if we had used daily input values. With the restricted low flow regimes of the pre-European Delta, this seasonal salinity would likely have been higher still. Even with catastrophic island failures, the modern Delta would not revert to the natural Delta of pre-European times, because the islands are now highly subsided and cross channels and deeply dredged shipping channels now exist

3. Consequences of Sea Level Rise

Sea level at the location of the Golden Gate Bridge has been increasing by 0.08 inches per year 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 CALFED Independent Science Board (ISB) has recommended that the Delta Vision effort use mid-range values for sea level rise of 8-16 inches by 2050 and 28-39 inches by 2100.[12] Only very recently have examinations begun of the consequences of sea level rise for Delta salinity distributions.

Modeling Issues

There are two salinity consequences of sea level rise. The first is for the ocean to transport its higher salinity (higher density) water farther into the Delta, a process sometimes referred to as "barotropic" flow, resulting directly from the higher water surface elevations. The second, less clear, consequence comes from increasing density-driven, or "baroclinic" flow. Baroclinic flow increases with sea level rise because the deeper water depths result in more strongly stratified water. Deeper water has less vertical mixing because the resistance of the bottom exerts less influence (Hansen and Rattray, 1965). Parts of the Bay are already deepening due to net erosion (Cappiella et al., 2005; Wright and Schoellhamer 2004; Krone 1979). Most one- and two-dimensional models, including the TAM used for this study, employ vertically averaged variables and do not explicitly depict baroclinic influences. Although the tidally averaged dispersion coefficients developed for TAM are drawn from a more sophisticated three-dimensional model that does include baroclinic terms (Gross et al., 2007), TAM results may not properly depict density-driven influences for all flow rates. Without actual sea level rise there is no way to verify the three-dimensional model results.

As above, we began this exercise as a comparison with the 1981-2000 base case. For this exercise, all islands are assumed to remain intact, and the downstream EC boundary condition (about the middle of the northern San Francisco Bay) is assumed to remain a constant 50,000 μS/cm. To simulate sea level rise, the most downstream boundary condition of the base case was raised by an average of one or three feet, respectively, and the initial water elevation throughout the model domain was increased comparably.

Water Quality Effects of Sea Level Rise

The simulation results, shown in Figure C.11, project an increase in salinity at all five locations compared with the base case. With one foot 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 levels in the southern Delta significantly increase salinity and costs of drinking water treatment.[13] On average, Clifton Court Forebay annual average salinity concentration increases by approximately 4 to 26 percent, and CCWD by approximately 35 to 49 percent.

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

[13] Higher salinities are accompanied by other water quality constituents that increase drinking water treatment costs. See Chapter 6 of the main report and Appendix H.

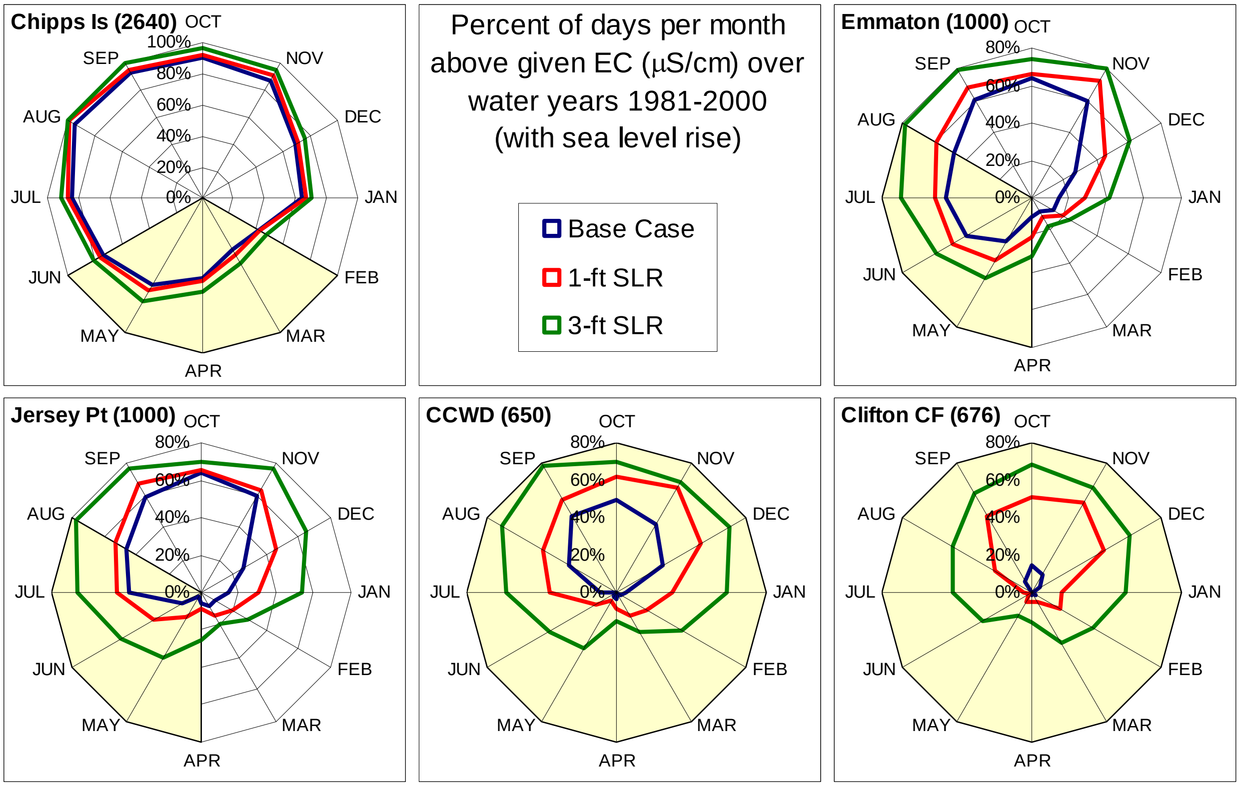

Figure C.11 – Simulated percentage of days each month exceeding the specified EC (µS/cm) at locations in the Delta with sea level rise

Notes: 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).

Additional salinity intrusion occurs as the sea continues to rise. With a three-foot sea level rise, salinity would greatly increase the cost of drinking water treatment and Delta water may be unsuitable for agricultural irrigation. In very dry years, the salinity problems are particularly acute, even with one foot of sea level rise (Figure C.12).

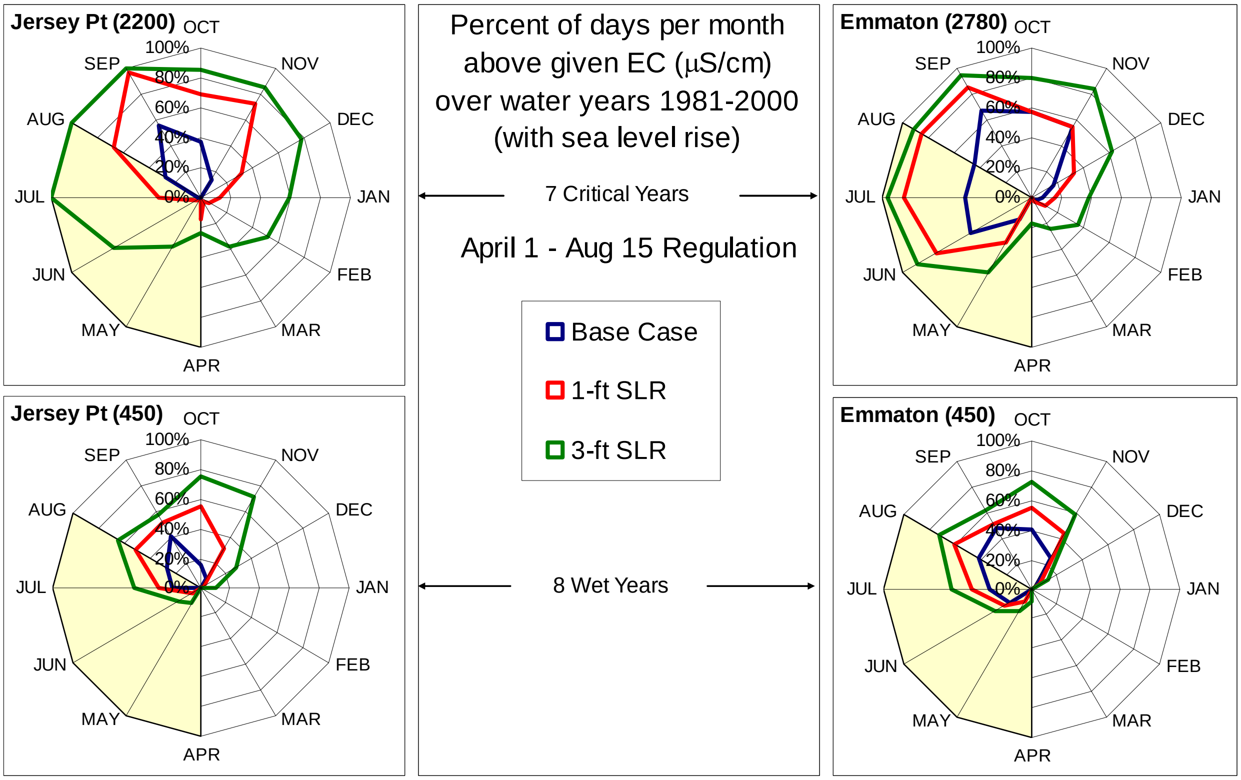

Figure C.12 - Simulated percentage of days each month exceeding the specified EC (µS/cm) at locations in the Delta with sea level rise, critical and wet years

NOTE: 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.

Under current Delta regulations, CVP and SWP export users 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 needed to keep Delta salinity at current levels, we calculated the additional net Delta outflow needed to maintain the base case average salinity at Chipps Island with one foot of sea level rise. In these simulations, while holding all other variables constant, we increased Sacramento River flows, as might be accomplished in practice by making additional reservoir releases and reducing upstream diversions (see Appendix F).[14]

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

With one foot of sea level rise, an annual average of 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 percent of average export levels in the 1981-2000 period (4.9 million acre-feet (maf) per year). 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 X2 requirements. With continued sea level rise, the volume of required outflows would also continue to rise.

4. Consequences of Island Flooding

Over the last 100 years there have been 166 island failures in the Delta. As a consequence of continued sea level rise, periodic flood flows, deteriorating levees and seismic activity, islands will continue to fail; and with seismic activity and floods, many could fail simultaneously. As pointed out in Lund et al. (2007), and Chapter 2 and Appendix B of this report, some flooded islands may not be worth reclaiming based on the economic value of the activities on the islands themselves. It is important to model the water quality consequences of leaving islands permanently flooded following failure, to see whether they have strategic value for maintaining Delta salinity levels.

Past modeling efforts have highlighted the immediate risk of catastrophic island failure to Delta salinity, particularly if the failure occurs when inflows are low, such as in summer or fall. In the case of island levee failures, water rushes into the low-lying Delta islands, pulling salt water further into the Delta, as demonstrated in the 30 and 50 island failure analysis by RMA in 2005 for DRMS (Jack R. Benjamin and Associates, 2005). Here, we pose a different question: what are the long-term consequences, with respect to Delta water quality, of allowing islands that fail to remain permanently flooded? Over the past century, only a handful of Delta islands have been allowed to remain permanently flooded after levee failures.[15]

Island Flooding Scenarios

For this exercise we rely on the simulations performed by Resource Management Associates with the RMA Bay-Delta model for the DRMS effort. The simulations span April 12, 2002 through December 31, 2004. Each scenario was set up with breached levees on the applicable islands. The islands are "pre-flooded" in the sense that, for simulation purposes, they are assumed to be filled with water of salinity equaling that in surrounding channels at the start of the simulation period. This depiction is intended to replicate conditions for an island that has already been flooded for some time; it could also result if the initial flooding occurred during the winter or spring, when significant river flows are available. All simulations had the same inflows, outflows and operations as reported during the simulation period with the only difference being the permanently-flooded islands. Four island flooding scenarios (Figure C.13) were examined that assumed the following islands are permanently flooded:

- Five western islands (Sherman (# 52), Twitchell (# 60), Bradford (# 6), Brannan-Andrus (# 7), and Jersey (# 24)),
- Five eastern islands (Venice (# 66), Mandeville (# 31), McDonald (# 33), Jones (# 25), and Bouldin (# 4)),
- Five southern islands (Palm-Orwood (# 40 and # 41), Bacon (# 1), Woodward (# 70), Jones (# 25), and Victoria (# 67)), and
- Twenty islands (all the preceding islands plus five in the Central Delta: Byron (# 9), Bethel (# 2), Webb (# 68), Holland (# 22), and Quimby (# 44)).

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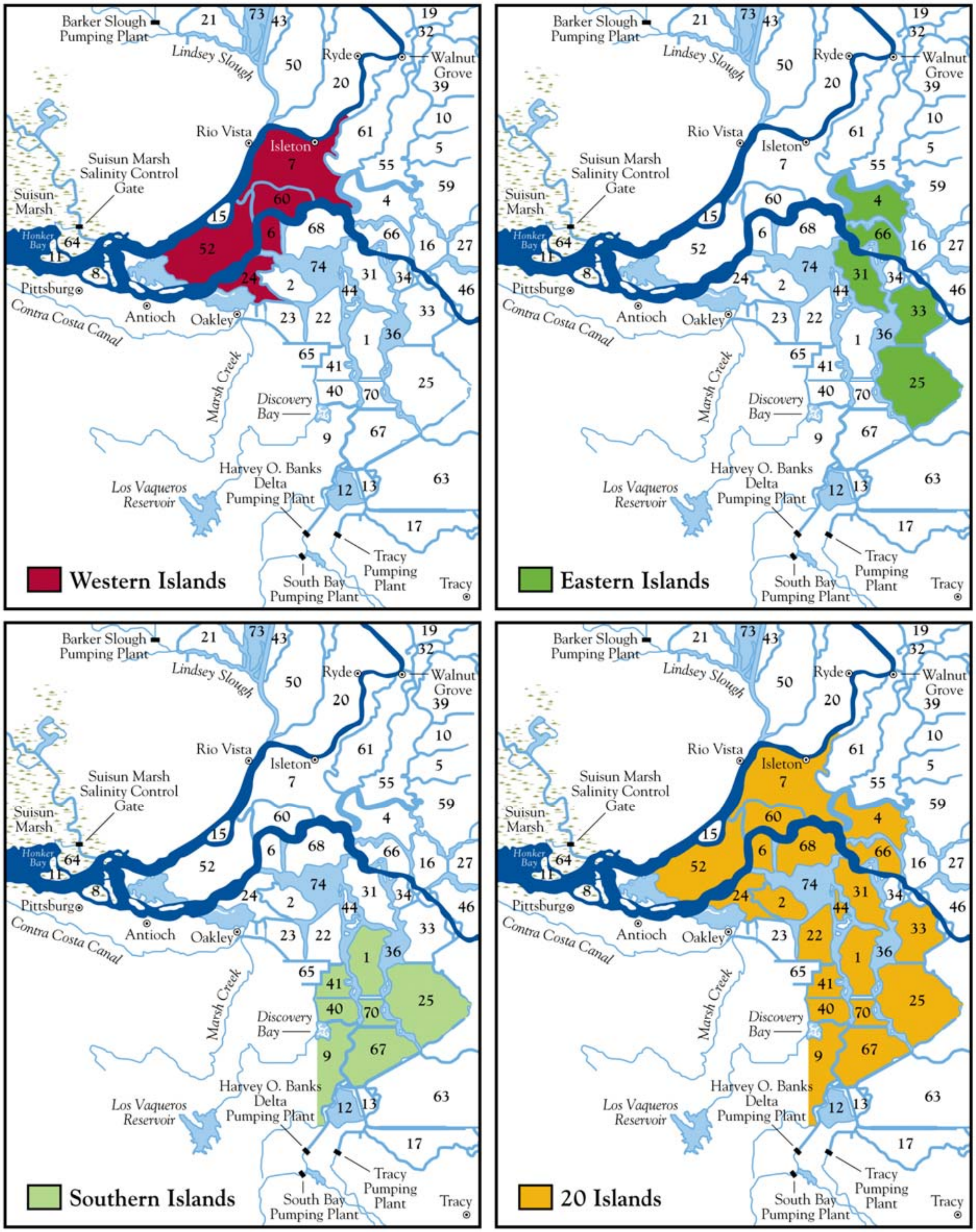
[15] Franks Tract and Mildred Island in the central Delta, and Liberty Island on the lower Yolo Bypass.

Flooded Delta Island Scenarios



🟥 Western Islands

🟩 Eastern Islands

🟩 Southern Islands

🟨 20 Islands

Figure C.13 - Delta island flooding scenarios

Water Quality Implications of Permanent Island Flooding

The island flooding scenarios are compared with the base case in Figure C.14. The results suggest some striking differences in the strategic value of Delta islands for maintaining water quality. The permanent flooding of five western islands increases salinity intrusion to the pumps in the southwest and southern Delta and would significantly affect drinking water treatment costs between August and December. In effect, the long-term consequences of permanent flooding of failed western islands appears to mimic the immediate consequences of levee breaches, pulling higher saline water into the Delta from the Bay. These failures result in little salinity change at Chipps Island and Emmaton, in part since no breaches were included on the Sacramento River side of the islands, changing river flows past Emmaton very little.[16] Only modest changes occur at Jersey Point, because without the "big gulp" of a sudden levee failure, most of the salt water is pulled southward toward the pumps.

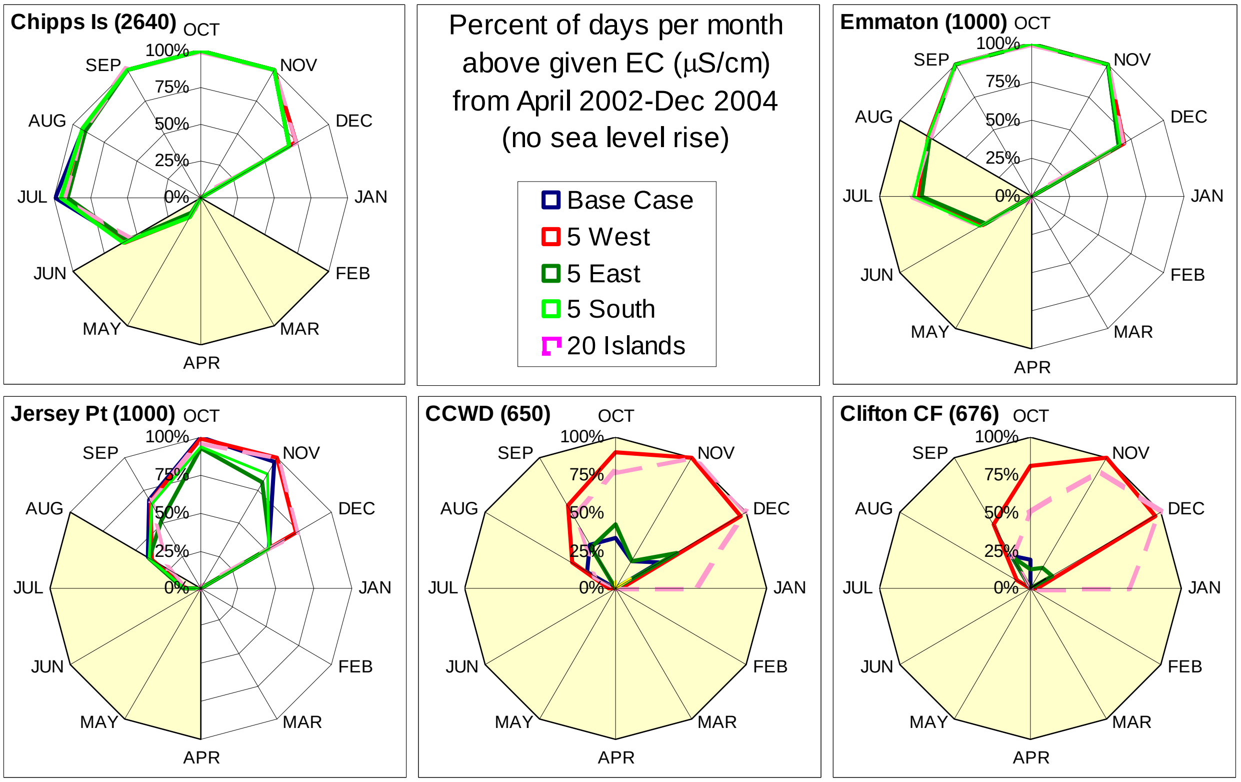


Figure C.14 - Simulated percentage of days each month exceeding the specified EC (µS/cm) at several locations in the Delta with island failures

Notes: Average monthly values over the simulation period April 12, 2002 to December 31, 2004, with that period's reservoir and export operations. 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). At Chipps Island and Emmaton, all five scenarios essentially overlap.

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[16] The location of island breaches affects where water and salts are transported and reinjected into the Delta with each tidal cycle.

In stark contrast, the permanent flooding of eastern or southern islands shows little, if any, long-term salinity effects on the Delta. There are even short periods when the flooded islands improve southern Delta salinity by facilitating flow from the Sacramento River and eastside streams (Calaveras, Mokelumne and Cosumnes) through the Delta toward the southern pumping plants.

The results for the simulation of permanent flooding of twenty islands reinforce these conclusions. The results are very similar to those obtained for the western island scenario, suggesting the unique importance of the western islands for maintaining desirable salinity conditions for through-Delta withdrawals, in the context of continued through-Delta pumping of water exports. As discussed in Appendix B and Chapter 2 of the main report, reliance on stable western islands for continued exports is a particularly risky proposition, given the high probabilities of failure of these islands by mid-century from flood and seismic risks. The estimated failure probabilities range from a low of 34 percent (with an optimistic risk estimate and extensive levee investments) to a high of 95 percent.

Cumulative Effects of Island Flooding and Sea Level Rise

Although time available prevented us from modeling the combined influences of sea level rise and island failure, the authors, along with others involved in modeling the Delta agree that the effects would at least be additive, if not worse. By mid-century, with expected changes in sea level rise and western island failures, large parts of the Delta will likely have become brackish, unusable for either drinking water or agriculture without costly desalination or very large increases in Delta outflows. It remains uncertain whether flooded eastern and southern island could also have greater effects on salinity intrusion with sea level rise.

5. Consequences of Peripheral Canal Exports

The potential water quality effects of rerouting some or all export volumes from Delta channels to a peripheral canal has been hotly debated for over 30 years. One justification for a canal has been that export users could benefit from lower salinity water by tapping into 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. Although reducing or eliminating through-Delta pumping could benefit Delta fish populations, environmental advocates also have expressed concerns over whether the volume and timing of peripheral canal diversions would sufficiently protect fish.

The peripheral canal that went before voters in 1982 was a very large facility (25,000 cubic feet per second (cfs)), and it was intended to significantly increase the capacity of water exports from the Sacramento River watershed. Here, we explore a more modest set of alternatives. We assume stability of daily export volumes at levels that actually occurred during the 1981-2000 simulation period, and we examine canal capacities ranging from 2,000 cfs to 15,000 cfs, operated as a dual facility with some continued through-Delta exports. We impose an environmental constraint on the canal operation for these alternatives, by limiting the amount of water that can be drawn from the Sacramento River. We omit other existing regulatory constraints on export operations, since most would be rendered moot by sea level rise and island failures. We also examine an alternative without this environmental constraint.

Modeling Dual Conveyance

Effects of operational changes on salinity in the Delta were examined with the TAM model by comparing the current 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 peripheral canal). For these simulations through-Delta pumping was reduced by the amount of water diverted upstream from the Sacramento River and conveyed through the canal. Because the total volume of exports is unchanged, net Delta outflow is unaffected. Four peripheral canal capacities were simulated: 2,000, 7,500, 15,000 cfs, and all available and needed (“PC Only”). The potential amount extracted from the Sacramento River was never allowed to reduce Sacramento River flow below 10,000 cfs, except for the PC Only, which would only take exports from the Delta when more exports are needed than the Sacramento River carries. (In this case – which occurs very infrequently - exports rely on through-Delta pumping.) Because the PC Only requires a maximum capacity of 14,050 cfs to transfer total exports over the 20 water years, it is equivalent to the 15,000 cfs PC without the environmental constraint on Sacramento River flows. Except for the partial peripheral conveyance of exports in these scenarios, all other operational conditions (barriers and gates) were held the same as the base case.

The minimum flow requirement on the Sacramento River is introduced to prevent flow reversals due to tidal influences near potential upstream intake locations. There are potential environmental problems with bi-directional flows at a peripheral canal 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 these organisms through peripheral canal intakes.

Water Quantity and Quality Effects of a Peripheral Canal

Export Volumes and Patterns

Table C.1 compares the volumes of exports drawn through the canal and through the Delta for the different alternatives. Although only the PC Only alternative effectively eliminates through-Delta exports, the two largest canals greatly reduce the need for through-Delta pumping. However, the minimum outflow requirements on the Sacramento River significantly constrain the use of a larger canal. Doubling the canal capacity from 7,500 to 15,000 cfs increases average exports through the canal by less than 1,000 af per day (Table C.1). Using the export demand schedule of the 1981-2000 period, the only scenario in which a peripheral canal alone could convey all of the water exports that occurred over the twenty years under examination is the PC Only scenario, which does not face this environmental constraint.

Table C.1 - Average water and salt exports for the base case and four peripheral canal alternatives

	Water Export Sources			Salt Exported		
Alternative	Sac River (af/day)	Delta (af/day)	Total (af/day)	No SLR	1-ft SLR (tons/day)	3-ft SLR
Base Case	0	13,500	13,500	5,400	6,900	11,000
2,000 cfs PC*	3,100	10,400	13,500	4,400	4,800	7,500
7,500 cfs PC*	7,900	5,600	13,500	3,700	4,200	6,200
15,000 cfs PC*	8,800	4,700	13,500	3,500	4,000	5,800
PC Only	13,500	0	13,500	2,100	2,100	2,100

Note: Results are produced using 1981-2000 export levels. * Peripheral canal withdrawals are limited by 10,000 cfs minimum flow requirement in Sacramento River for all cases except PC Only. Sacramento River and Delta exports may not sum exactly to total exports because of rounding.

As Figure C.15 shows, diminishing returns on peripheral canal capacity would be present for lower minimum Sacramento River flow constraints as well. Plots in Figure C.15 represent the amount of water (af/day) carried by a peripheral canal for a range of minimum flows remaining in the Sacramento River (4,000-12,000 cfs). The distance above each PC Export line to the 13,547 af/day represents the through-Delta pumping requirement to export the average daily amounts during 1981-2000.

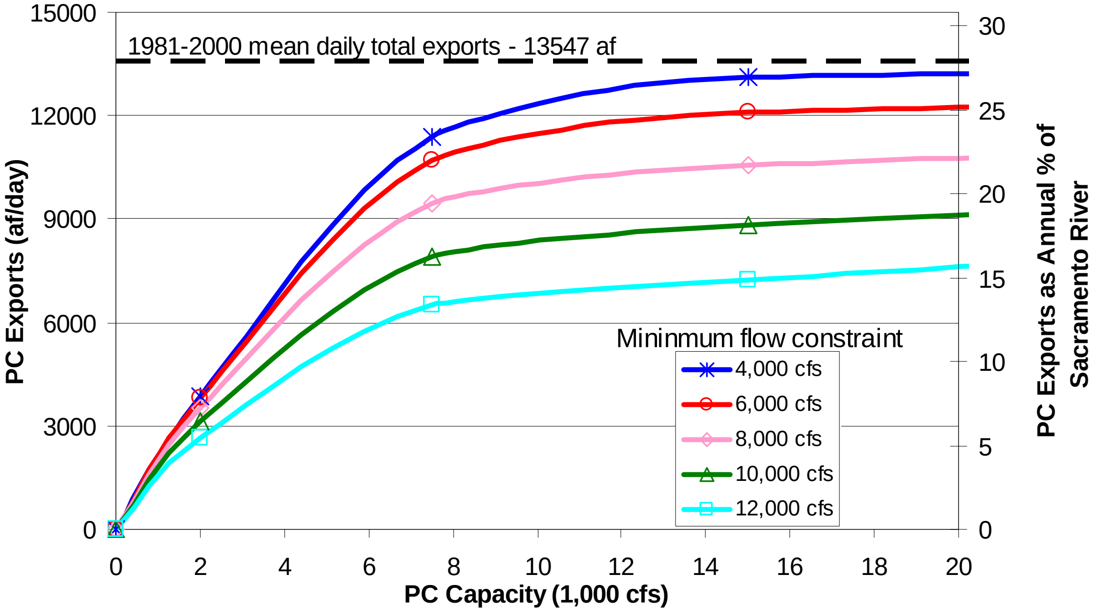

Figure C.15 – Peripheral canal exports for varying peripheral canal capacity and Sacramento River flow constraints for mean daily exports held at 1981-2000 levels

NOTES: The figure shows the share of daily average exports of 13547 af that would be channeled through a peripheral canal for a range of canal capacities (X-axis) and a range of constraints on minimum Sacramento River flow (4,000 to 12,000 cfs minimum), represented by the colored lines.

Although these results and operations theory suggest a diminishing return on peripheral canal capacity, they should not be interpreted as justifying a hard limit on the ideal size of a peripheral canal. For one thing, the scenarios examined here artificially constrain peripheral canal 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 peripheral canal while respecting the minimum outflow requirement on the Sacramento River. Additional studies would need to consider constraints on pumping, canal and storage capacity south of the Delta. Considering only pumping and canal capacity constraints, the 1981-2000 yield through a peripheral canal with the same 10,000 cfs minimum outflow constraint for the Sacramento River was over 55 percent greater than the actual volume exported (7.6 maf/year possible on average versus 4.9 maf/year actual) (Table C.2). While diversions of this magnitude are likely unfeasible for environmental reasons (since sharp reductions in peak Sacramento River flows would have other consequences), the potential 7.6 maf/year delivery illustrates the need to consider operational changes before setting limits on export capacity.

Table C.2 - Potential exports through a peripheral canal of unconstrained capacity while maintaining minimum Sacramento River flow requirement of 10,000 cfs, 1981-2000

Export Volume	Sacramento River Average Flow	Sacramento River Available Flow [a]	Maximum Infrastructure Capacity [b]	Actual Export Volumes	Additional Export Capacity [c]	Potential Additional Exports [d]	Total Possible PC Exports [e]
cfs/day	24,500	16,000	14,900	6,800	8,100	3,600	10,500
af/day	48,600	31,700	29,600	13,500	16,000	7,200	20,700
af/year	17,766,000	11,590,000	10,794,000	4,948,000	5,846,000	2,626,000	7,574,000

NOTES: [a]Amount available after deducting minimum flow requirement (10,000 cfs); [b] Maximum possible exports through the Banks (10,300 cfs) and Tracy (4,600 cfs) pumps; [c] Additional channel capacity ("Maximum Infrastructure Capacity" – "Actual Export Volumes"); [d] Minimum of "Additional Export Capacity" and "Sacramento River Available Flow" (calculated daily); [e] "Actual Export Volumes" + "Potential Additional Exports"

There are also environmental reasons for building a larger capacity peripheral canal to export the same amount of water. Properly managed, a larger facility would enable water to be exported on ebb flows, during higher river flows or only during daylight hours, to reduce the risk of environmental consequences.

Figure C.16 shows monthly patterns of through-Delta exports for the different alternatives. Because all exports flow through the Delta in the base case (shown in dark blue), the through-Delta case represents the total volume of monthly exports for all scenarios. The difference between the area within the dark blue line and the area within the lines representing each peripheral canal is the volume of water carried in that peripheral canal. The PC Only draws water from the Delta only when the Sacramento River flow was less than the minimum constraint and water was still exported from the Delta, so its results are imperceptible on these graphs. In wet years with dual conveyance, the two largest peripheral canals draw very little water from the Delta; in dry years, they draw considerably more, because the 10,000 cfs minimum Sacramento flow requirement limits use of the canal.

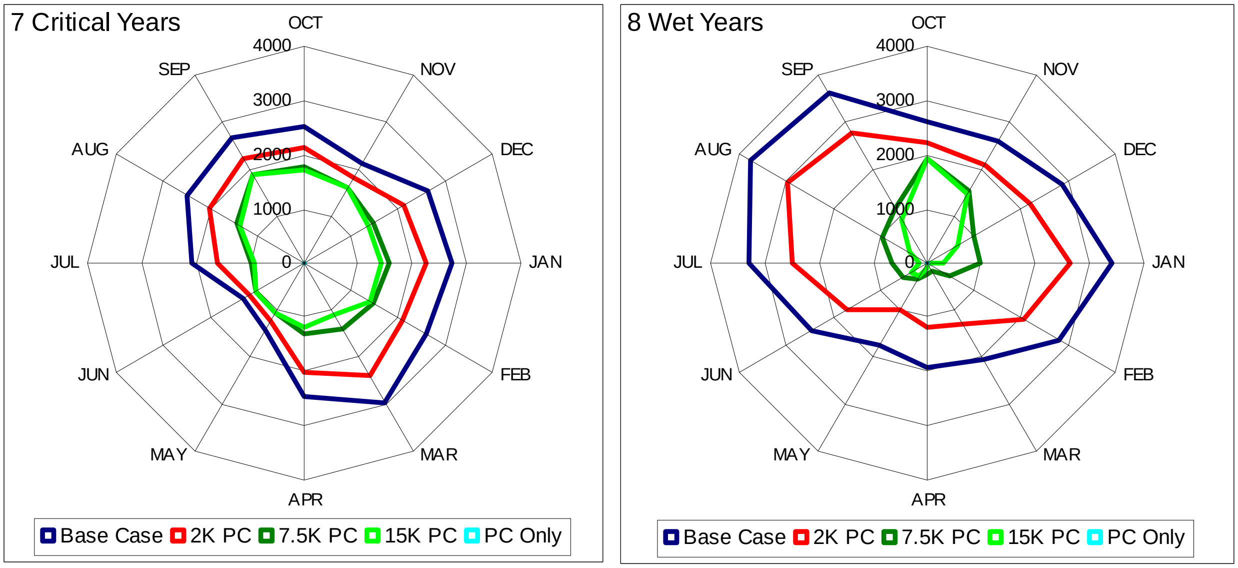

Figure C.16 - Daily averaged through-Delta water exports (cfs) under different operational schemes in critical and wet years at current sea level

Notes: Area inside the dark blue line is total exports from the Delta for the base case with the existing pumping system; area inside other colors show the amount exported from the Delta intake with the following amounts of peripheral canal capacity and a 10,000 cfs minimum flow on the Sacramento River: 2,000 cfs (red), 7,500 cfs (dark green), 15,000 cfs (light green), and 15,000 cfs without a Sacramento River flow constraint (light blue)

Water Quality Implications

Following the approach used to compare salinity for the previous simulations, Figure C.17 presents the percent of days per month exceeding reference EC values for the base case and the dual conveyance system using different canal sizes. Since none of the alternatives changes the net Delta outflow, none produces a significant change in salinities at Chipps Island. However, salinity increases for locations along the Sacramento River (e.g. Emmaton) as the reduced river flow allows brackish water to move upstream. Salinity decreases slightly for locations along the San Joaquin River (e.g. Jersey Point), as less salt water is pulled from the west with reduced through-Delta pumping. Only the PC Only leads to significantly higher salinity at the southwestern and southern Delta pumping locations, for reasons similar to the "no export" scenario examined above. With less clean Sacramento River water being drawn toward the pumps, southern Delta salinity is dominated by the higher salinity San Joaquin River flows.

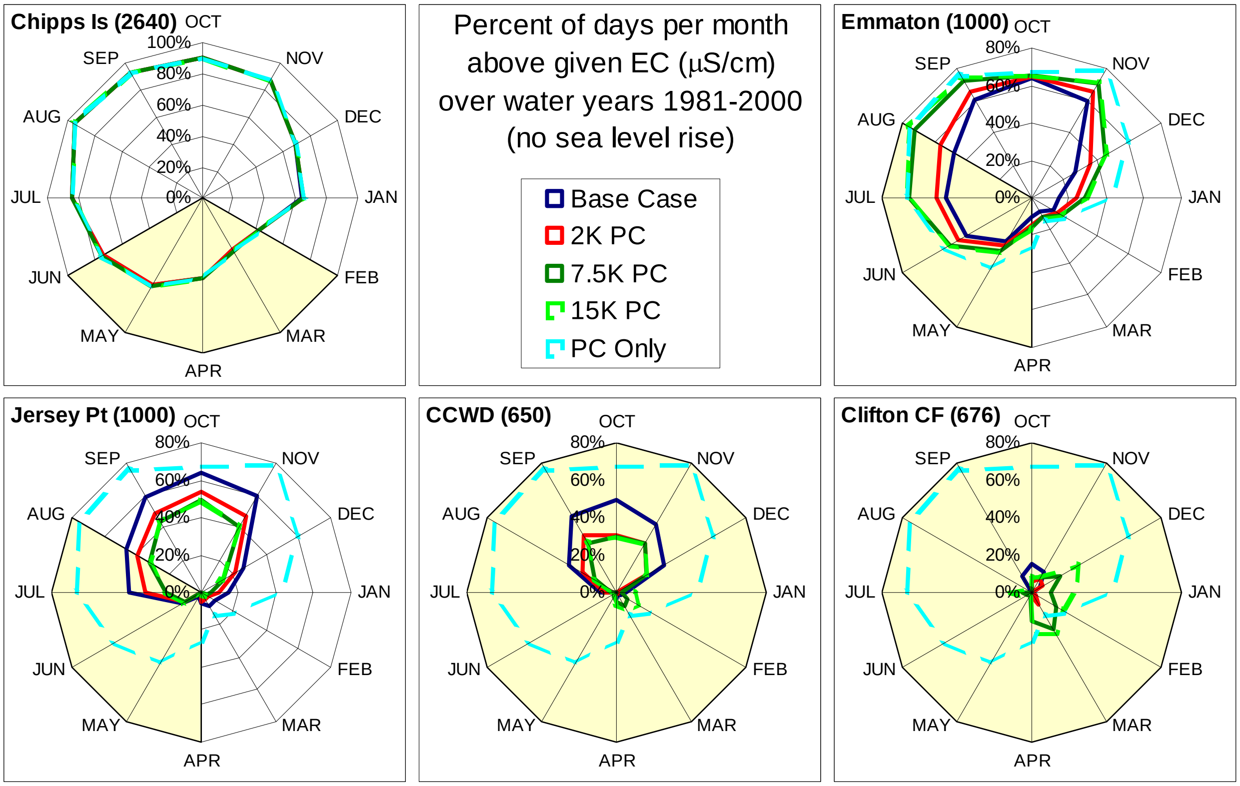

Figure C.17 - Average percentage of days in each month exceeding the specified EC (µS/cm) at locations in the Delta for different operational scenarios, at current sea level

Notes: Dark blue line is results of current base case pumping; other colors show results with the following amounts of peripheral canal capacity and a 10,000 cfs minimum flow on the Sacramento River: 2,000 cfs (red), 7,500 cfs (dark green), 15,000 cfs (light green). Light blue hatched line is results of the PC Only (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).

For export users, the water quality implications of these changes depend on the combination of resulting south Delta and upstream salinity conditions. As Table C.1 shows, salt exports – a summary measure of salinity levels in the export mix – decrease significantly with the ability to take some exports from the lower salinity Sacramento River. The minimum flow requirement on the Sacramento River along with some, albeit reduced, level of continued through-Delta exports protect agricultural users in the southern Delta as well as urban users at the CCWD pumps. However, some additional flow releases would likely be required to maintain agricultural salinity standards at Delta locations along the Sacramento River.

Effects of Runoff Variability

Of course, the average salinity patterns over two decades presented in Figure C.17 mask the differences that occur from runoff variability across years. Figure C.18 isolates the seven critical years and the eight wet years from the averages in Figure C.17 for Emmaton and Jersey Point. This breakdown provides a simple comparison of the inter-annual variability of salinity at different locations for the different peripheral canal alternatives. (The 15,000 cfs PC is not shown since its results are similar to those of the 7,500 cfs PC.) In the western Delta, there is 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 C.19 presents 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 results in dramatically increased salinity in the critical years at the southern Delta sites.

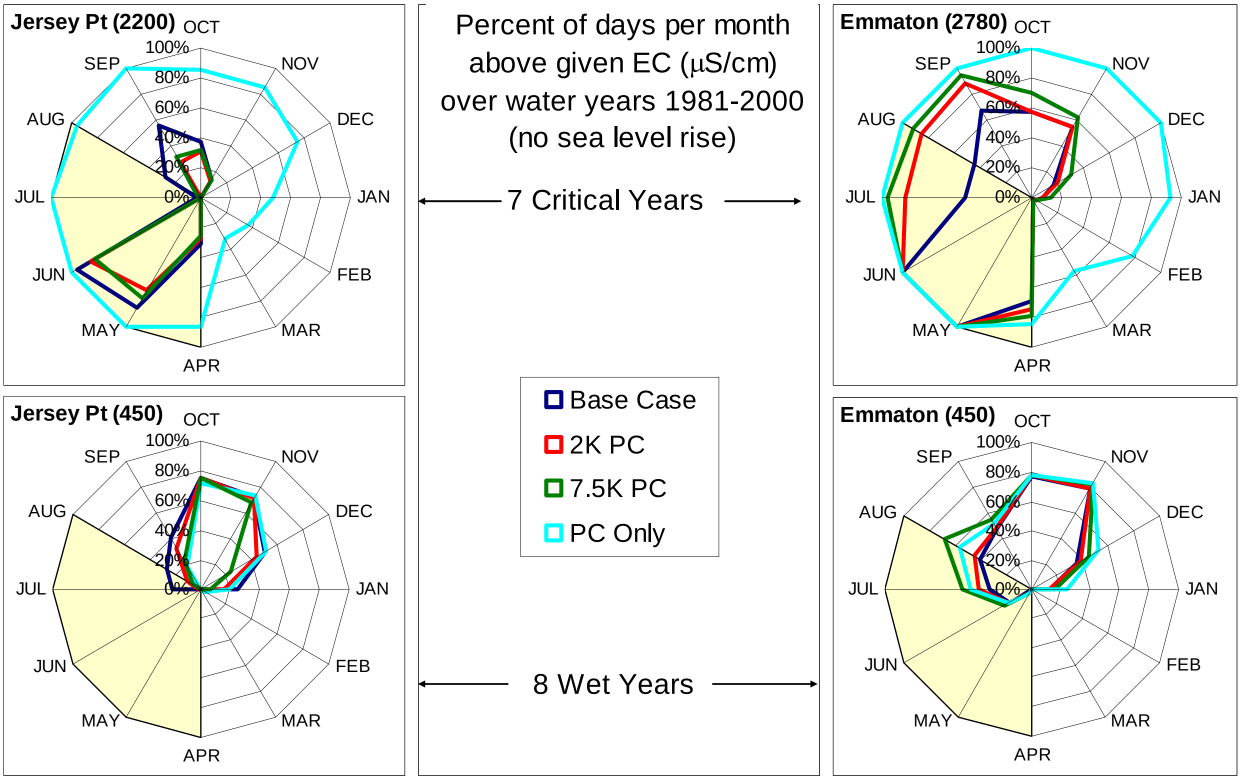

Figure C.18 - Average percentage of days in each month exceeding the specified EC (μS/cm) at Emmaton and Jersey Point for different operational scenarios in critical or wet years

Notes: Dark blue line is results of current base case pumping; other colors are results of exports through a peripheral canal of different capacities: 2,000 cfs (red); 7,500 cfs (dark green); PC Only (light blue). Simulation results for the 15,000 cfs PC are very similar to the 7,500 cfs case. Shaded areas are periods when compliance is prescribed, although compliance levels vary across months and water year types.

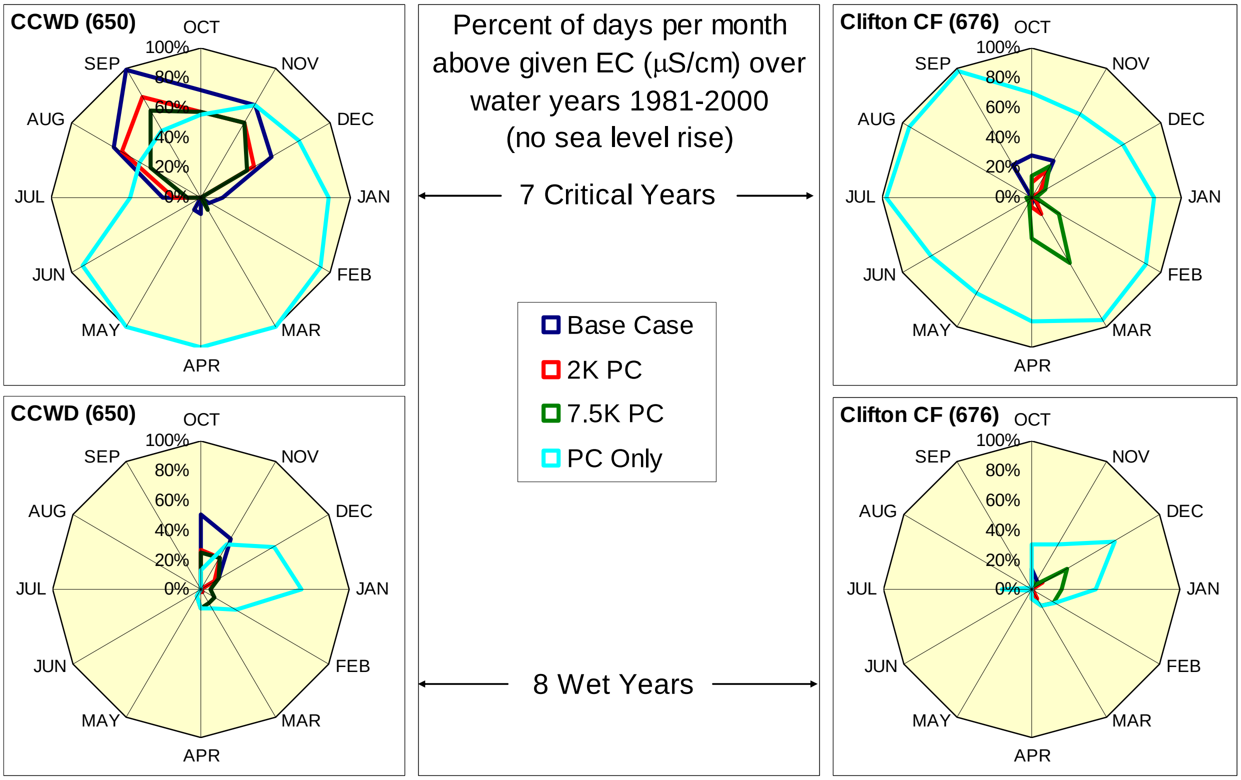

Figure C.19 – Average percentage of days in each month exceeding the specified EC (µS/cm) at the CCWD pumping plant and Clifton Court Forebay for different operational scenarios in critical or wet years

Notes: Shaded areas are periods when compliance with salinity standards is prescribed, although compliance levels vary across water year types.

Sea Level Rise with a Peripheral Canal

Simulations of each peripheral conveyance alternative were also performed with one and three feet of sea level rise, following the same procedure as above. The water quality implications are summarized in Figures C.21 and Figure C.22. With one foot of sea level rise, the 2,000 cfs PC does not further increase salinity at any of the locations shown. Both the 7,500 and 15,000 cfs PC facilities increase salinities at Emmaton with one foot of sea level rise, but suggest slight improvements at Jersey Point and CCWD pumps, as reduced through-Delta pumping no longer pulls as much higher-saline water in from the eastern Suisun Bay. A slight seasonal shift in salinity exceedance appears at Clifton Court Forebay but the number of days of exeedances remains approximately the same. Since the salinity of export water would still improve due to blending with lower saline Sacramento River water, the main water quality concern would be for users within the Delta.

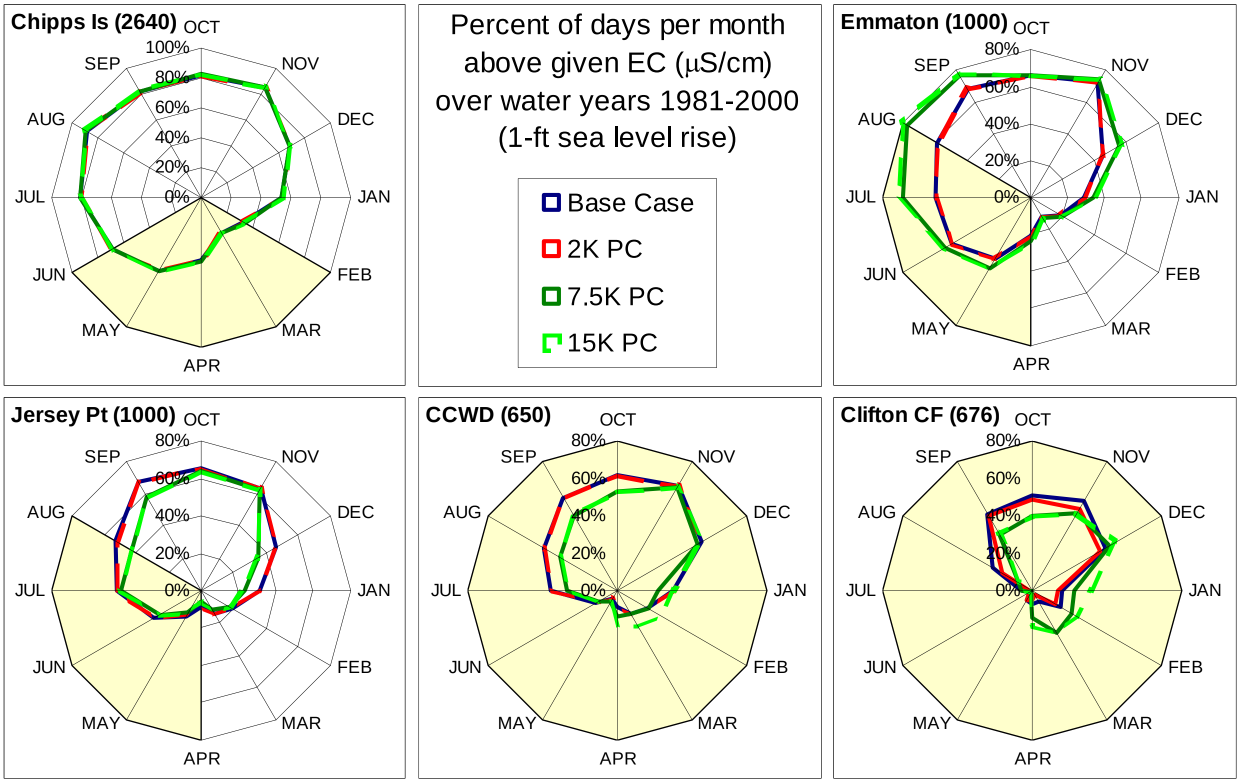

Figure C.21 - Average percentage of days in each month exceeding the specified EC (µS/cm) at locations in the Delta for different operational scenarios with one foot sea level rise

Notes: Dark blue line shows the results of current base case pumping over 1981-2000; red line: up to 2,000 cfs of peripheral canal (PC) exports; dark green: up to 7,500 cfs of PC exports; light green line: up to 15,000 cfs of PC exports. At Chipps Island, all scenarios are roughly identical because net Delta outflow is the same. Base Case and 2,000 cfs PC are about the same, as are 7,500 cfs and 15,000 cfs 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).

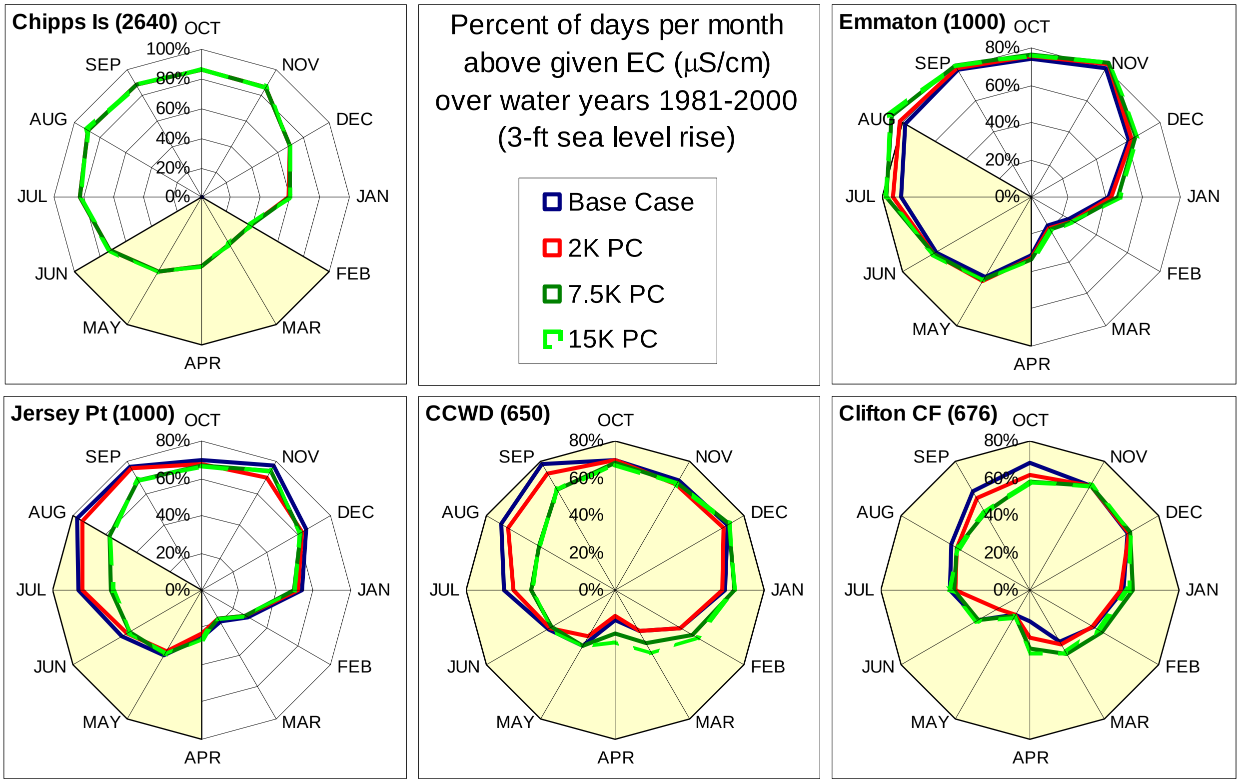

Figure C.22 - Average percentage of days in each month exceeding the specified EC (µS/cm) at locations in the Delta for different operational scenarios with 3 feet of sea level rise

Notes: Dark blue line shows the results of current base case pumping over 1981-2000; red line: up to 2,000 cfs of peripheral canal (PC) exports; dark green: up to 7,500 cfs of PC exports; light green line: up to 15,000 cfs of PC exports. At Chipps Island, all scenarios are roughly identical because net Delta outflow is the same, and there is very little difference among alternatives at Emmaton. Elsewhere, the base case and 2,000 cfs PC are approximately the same, as are the 7,500 cfs and 15,000 cfs 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).

With a three feet increase in sea level, salinities increase further at Emmaton for all alternatives, with little difference between the base case and the various sizes of peripheral canal. However, the results suggest that peripheral canal use would somewhat mitigate higher salinities in the south Delta resulting from sea level rise. Regardless, remaining through-Delta export water would be more saline, although the exported blend would still have lower salinity.

Summing Up: Salinity Consequences of Sea Level Rise and a Peripheral Canal

The scenarios examined above demonstrate the considerable additional costs of sea level rise to export users with the current through-Delta pumping system. A peripheral canal can significantly mitigate these effects by making lower salinity water available. Although a peripheral canal does not eliminate the effects of sea level rise if it is operated as a dual conveyance facility (Table C.1, Figure C.22), even a small canal holds off the effects of sea level rise for many years.

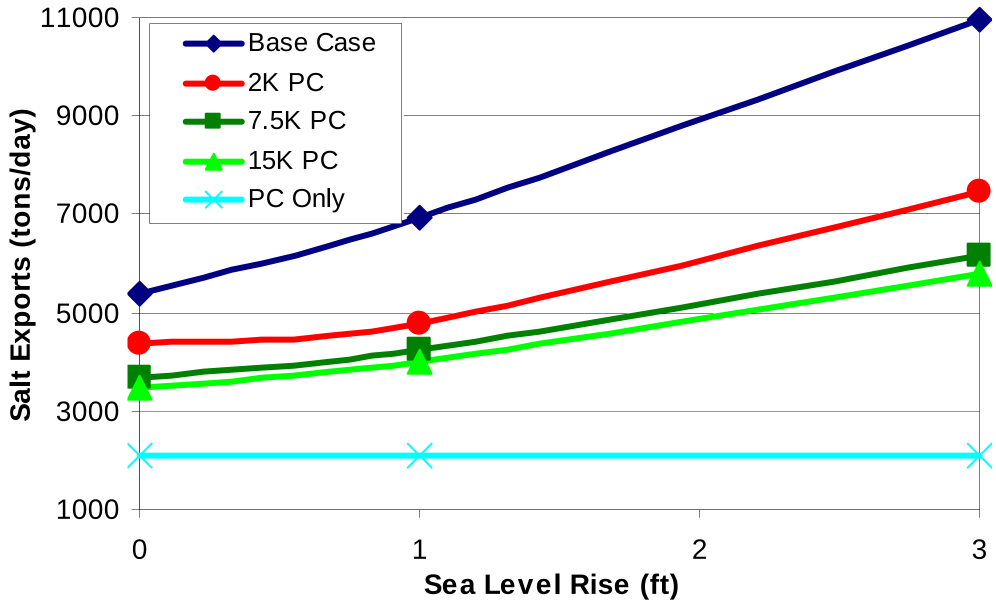

Figure C.22 - Salt exports for varying peripheral canal capacity and sea level rise

NOTES: The calculations assume 13,547 af/day of exports on average, as occurred from 1981-2000.

While export salinity would benefit from peripheral canal operations, in-Delta agricultural pumping would not enjoy the same improvements. Table C.3 shows 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. Figure C.23 presents these data graphically in percentage terms. While current salinity standards at Clifton Court Forebay are constant over the irrigation compliance period (at 1,000 (μS/cm), 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 (See Addendum C1, Table 2). The data represent number of days over the compliance limit, but do not signify specific violations because regulations are for a 14-day average.

The results highlight that some policy tradeoffs between south Delta and export users in the short term will diminish over time. Under current conditions, a peripheral canal operated with environmental flow constraints only worsens salinity for western Delta agriculture on the Sacramento River, and actually improves conditions for western Delta farmers on the San Joaquin River side. With one foot of sea level rise, the natural conditions in the western Delta deteriorate considerably, and by three feet there is little difference among alternatives (except the PC Only, which imposes no minimum flows on the Sacramento River). All alternatives suggest that, with continuing sea level rise, irrigation in western and southern parts of the Delta is unsustainable in places that could not be connected to a peripheral canal.

Table C.3 - Annual number of days during irrigation season (April 1 – August 15) over EC limits, 1981-2000

	Through-Delta	2,000 cfs PC	7,500 cfs PC	15,000 cfs PC	PC Only
Emmaton					
No SLR	36	48	59	60	69
1-ft SLR	59	58	68	68	N/A
3-ft SLR	75	80	80	80	N/A
Jersey Pt					
No SLR	13	3	1	1	2
1-ft SLR	30	29	10	10	N/A
3-ft SLR	66	60	61	60	N/A
Clifton CF					
No SLR	0	0	2	4	16
1-ft SLR	16	8	11	12	N/A
3-ft SLR	115	84	100	97	N/A

NOTE: N/A signifies data not available (scenarios have not been simulated). For salinity standards at the 3 locations, see Addendum Tables 1 through 3

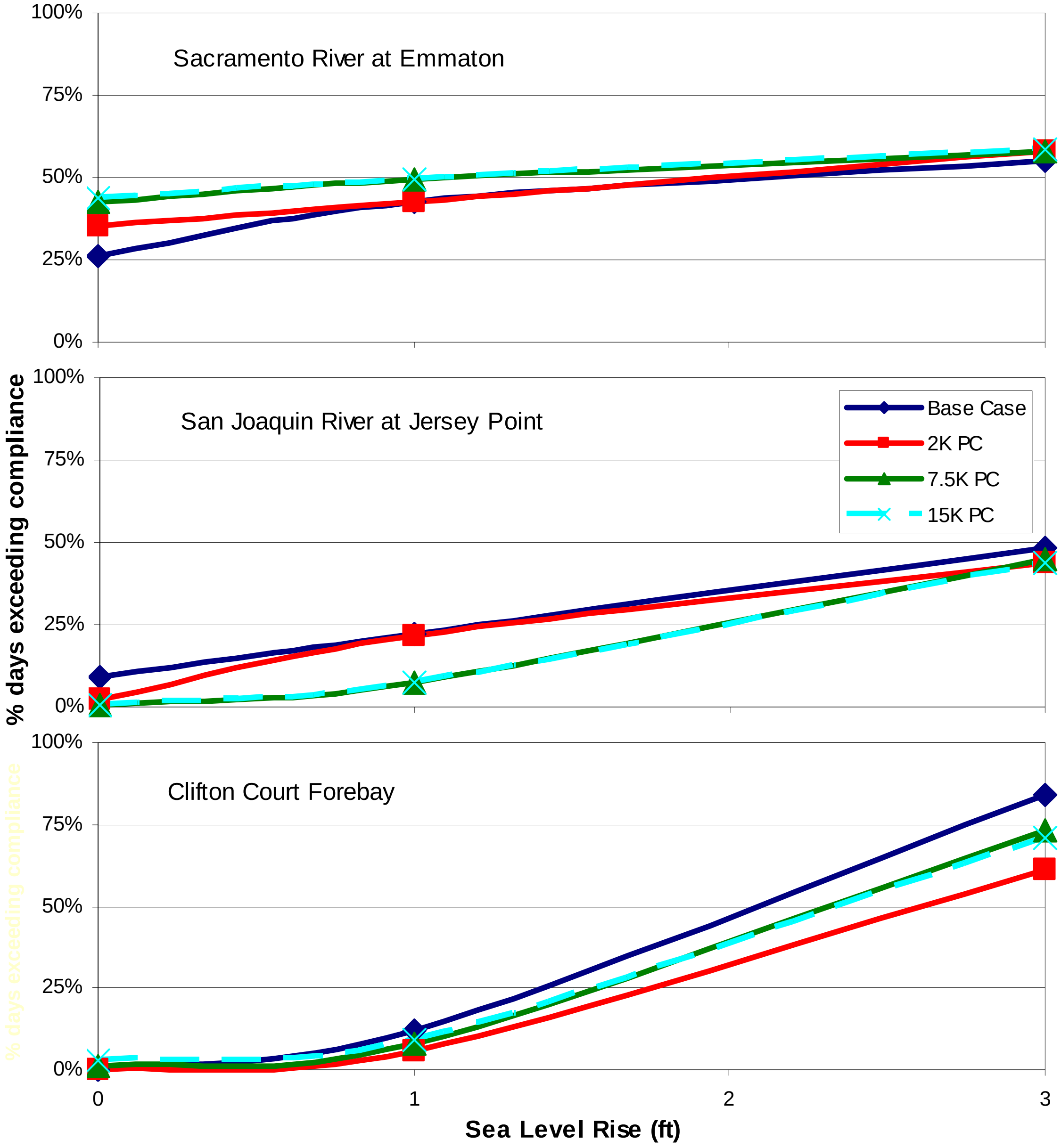

Figure C.23 - Average share of days above irrigational regulation limits during the irrigation season with sea level rise

NOTE: Figure shows share of days exceeding compliance limit for daily average EC during the irrigation season (April 1 through August 15, or 137 days). For irrigation salinity standards see Addendum Table 2.

Conclusions

The goal of this modeling exercise is to evaluate some of the key water quality issues associated with broad export management alternatives and anticipated changes in the Delta as a result of sea level rise.

Key Findings

Initial modeling examinations, using available tools, indicate change will occur in the Delta in the future, with outcomes depending on what conveyance strategy is chosen, how the system is operated, and how sea level and climate conditions evolve. Sea level rise during the next century will significantly affect salinity in the Delta. Eventually, sea level rise will increase salinities beyond reasonable levels for drinking water and irrigation in parts of the Delta unless large increases in Delta inflows or reductions in exports are made.

Permanently flooded western islands significantly increase salinity intrusion into the Delta even if the islands are pre-flooded to avoid a "big gulp" associated with ill-timed levee failures. Islands elsewhere in the Delta might be pre-flooded without long-term effects on Delta salinities provided the western islands remain intact. Modeling concurrent sea level rise and island flooding was not possible in the time available for this work. However, these two effects would at the very least be additive, making Delta salinity conditions difficult indeed for both urban and agricultural users.

Even when operated with minimum flow restrictions on the Sacramento River to prevent entrainment of aquatic life, a peripheral canal, operated in a dual conveyance mode, allows salinity to intrude farther up the Sacramento River. Salinities in the lower San Joaquin River and the western Delta generally decrease as less water is drawn down from the saltier Suisun Bay area. With Sacramento River minimum flow constraints, increasing the capacity of a peripheral canal has diminishing returns without additional storage south of the Delta. With a pure peripheral canal, 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 outflows. Sea level rise changes the effects of a canal over time. Whereas implementation of a peripheral canal increases salinities in Delta portions of the lower Sacramento River with one and three feet of sea level rise, salinities are somewhat mitigated with a peripheral canal on the San Joaquin River and southern Delta. A small amount of sea level rise facilitates the movement of fresh Sacramento River water toward the pumps, although that effect is somewhat muted as sea level rises to three feet above current levels.

Directions for Further Investigations

The initial modeling investigation undertaken here points to many areas that require more detailed modeling work regarding sea level rise, island flooding, and the effects of operational changes both now and in the future:

Sea level rise. The hydrodynamic community now suggests that increasing sea levels will be accompanied by changes in tidal range. There is some lack of agreement on whether tidal range changes will be accentuated or muted in the Delta by the San Francisco Bay. This effort will require new bathymetric information on the margins of the Bay that will be submerged and an understanding of how management of the periphery of the Bay would change with sea level rise to facilitate the new model grids required. In particular, if Bay Area communities erect new levees to protect their infrastructure and other assets from sea level rise, this would have a much different effect than if the Bay is allowed to significantly expand its surface area. Current models assume that the Bay geometry will remain unchanged. Expansion of the Bay's surface as a result of salt marsh restoration or abandonment of shoreline structures could lessen the effects of sea level rise on the Delta. Although a second order effect, the downstream salinity boundary condition should be investigated to estimate changes due to sea level rise.

Island flooding. Although sea level rise will eventually increase salinity in the Delta with or without island failures, additional investigation is needed to assess the minimum number of western islands required to maintain current salinity levels until the effects of sea level rise become overwhelming. Investigations are also warranted to examine the effects of varying the locations and numbers of levee breaches. Investigating more detailed geometries and the effects of spring/neap tidal cycles could also be important, especially for the timing of failures.

Water operations. Model simulations also are needed to look beyond the static operations assumed in this analysis. Upstream storage releases and reduced upstream diversions should be examined for different Delta export operations, including reoperation of internal control (Delta Cross Channel and various barriers). Examinations of tidal excursions near future peripheral canal intake locations will have to be determined to protect the aquatic species. The hydraulics and water quality outcomes must be known to make better decisions for water exports and Delta ecosystem management.

For instance, there is a need to understand the limits of peripheral canal capacity with more flexible operations of upstream reservoirs and downstream conveyance and storage capacity. Using historical operations, we find that exports through a peripheral canal are limited to roughly 3.2 maf per year on average when minimum flow requirements of 10,000 cfs are maintained on the Sacramento River. While maintaining these flow requirements, considerable additional export capacity may exist if operations are modified, with higher diversions during higher flow periods. Feasible diversion volumes will depend not only on the implications of such changes in salinity within the Delta, but also on environmental consequences of reducing high flows on the Sacramento River below peripheral canal intakes.

Operational changes also should be investigated in more detail to assess the extent of bi-directional flow changes with combined changes in operations, sea level rise and island failures. While our preliminary results could be interpreted by some to think that building a bigger peripheral conveyance capacity does not offer additional benefits or more flexibility, there may be operational benefits from greater capacity with sea level rise. As an example, one solution to the increased risks of bi-directional flow effects from an upstream intake may be to take water only on ebb tides, which would require greater canal capacity.

To undertake these analyses, one-, two- and three-dimensional models are needed to perform the hydraulic examination on varying scales. The TAM tidally averaged model has great promise as a broad qualitative tool and should be revisited to see if refinements will provide more precise quantitative answers.

Additionally, models are needed to evaluate the specific effects of various water system configurations and operations on the Delta ecosystem. Ideally, such models would integrate hydrodynamic and water quality data with the attributes of key Delta species and habitats.

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Addendum C1. Salinity Standards under D-1641

Source: State Water Resources Control Board, 2000.

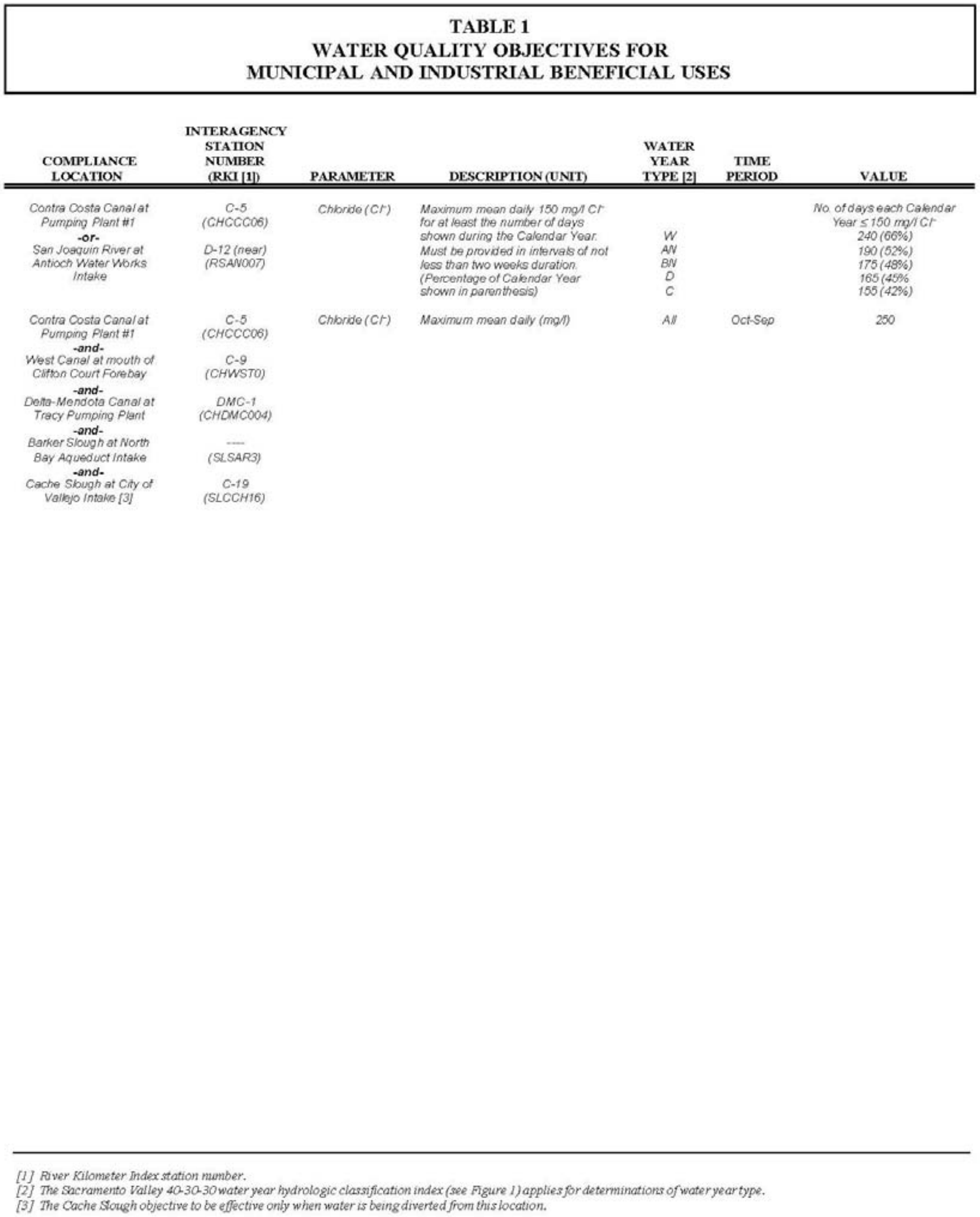

TABLE 1
WATER QUALITY OBJECTIVES FOR
MUNICIPAL AND INDUSTRIAL BENEFICIAL USES

COMPLIANCE LOCATION	INTERAGENCY STATION NUMBER (RKI [1])	PARAMETER	DESCRIPTION (UNIT)	WATER YEAR TYPE [2]	TIME PERIOD	VALUE
Contra Costa Canal at Pumping Plant #1 **-or-** *San Joaquin River at Antioch Water Works Intake*	*C-5 (CHCCC06)* *D-12 (near) (RSAN007)*	*Chloride (Cl^-)*	*Maximum mean daily 150 mg/l Cl^- for at least the number of days shown during the Calendar Year. Must be provided in intervals of not less than two weeks duration. (Percentage of Calendar Year shown in parenthesis)*			*No. of days each Calendar Year ≤ 150 mg/l Cl^-*
				W		*240 (66%)*
				AN		*190 (52%)*
				BN		*175 (48%)*
				D		*165 (45%*
				C		*155 (42%)*
Contra Costa Canal at Pumping Plant #1 **-and-** *West Canal at mouth of Clifton Court Forebay* **-and-** *Delta-Mendota Canal at Tracy Pumping Plant* **-and-** *Barker Slough at North Bay Aqueduct Intake* **-and-** *Cache Slough at City of Vallejo Intake [3]*	*C-5 (CHCCC06)* *C-9 (CHWST0)* *DMC-1 (CHDMC004)* *----- (SLSAR3)* *C-19 (SLCCH16)*	*Chloride (Cl^-)*	*Maximum mean daily (mg/l)*	*All*	*Oct-Sep*	*250*

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[1] *River Kilometer Index station number.*
[2] *The Sacramento Valley 40-30-30 water year hydrologic classification index (see Figure 1) applies for determinations of water year type.*
[3] *The Cache Slough objective to be effective only when water is being diverted from this location.*

TABLE 2
WATER QUALITY OBJECTIVES FOR AGRICULTURAL BENEFICIAL USES

COMPLIANCE LOCATION	INTERAGENCY STATION NUMBER (RKI [1])	PARAMETER	DESCRIPTION (UNIT) [2]	WATER YEAR TYPE [3]	TIME PERIOD	VALUE
WESTERN DELTA						
Sacramento River at Emmaton	*D-22 (RSAC092)*	*Electrical Conductivity (EC)*	*Maximum 14-day running average of mean daily EC (mmhos/cm)*		*0.45 EC April 1 to date shown*	*EC from date shown to Aug 15 [4]*
				W	*Aug 15*	*----*
				AN	*Jul 1*	*0.63*
				BN	*Jun 20*	*1.14*
				D	*Jun 15*	*1.67*
				C	*----*	*2.78*
San Joaquin River at Jersey Point	*D-15\ (RSAN018)*	*Electrical Conductivity (EC)*	*Maximum 14-day running average of mean daily EC (mmhos/cm)*		*0.45 EC April 1 to date shown*	*EC from date shown to Aug 15 [4]*
				W	*Aug 15*	*----*
				AN	*Aug 15*	*----*
				BN	*Jun 20*	*0.74*
				D	*Jun 15*	*1.35*
				C	*----*	*2.20*
INTERIOR DELTA						
South Fork Mokelumne River at Terminous	*C-13 (RSMKL08)*	*Electrical Conductivity (EC)*	*Maximum 14-day running average of mean daily EC (mmhos/cm)*		*0.45 EC April 1 to date shown*	*EC from date shown to Aug 15 [4]*
				W	*Aug 15*	*----*
				AN	*Aug 15*	*----*
				BN	*Aug 15*	*----*
				D	*Aug 15*	*----*
				C	*----*	*0.54*
San Joaquin River at San Andreas Landing	*C-4 (RSAN032)*	*Electrical Con-Ductivity (EC)*	*Maximum 14-day running average of mean daily EC (mmhos/cm)*		*0.45 EC April 1 to date shown*	*EC from date shown to Aug 15 [4]*
				W	*Aug 15*	*----*
				AN	*Aug 15*	*----*
				BN	*Aug 15*	*----*
				D	*Jun 25*	*0.58*
				C	*----*	*0.87*
SOUTHERN DELTA						
San Joaquin River at Airport Way Bridge, Vernalis	*C-10 (RSAN112)*	*Electrical Conductivity (EC)*	*Maximum 30-day running average of mean daily EC (mmhos/cm)*	*All*	*Apr-Aug* *Sep-Mar*	*0.7* *1.0*
-and-						
San Joaquin River at Brandt Bridge site[5]	*C-6 (RSAN073)*					
-and-						
Old River near Middle River [5]	*C-8 (ROLD69)*					
-and-						
Old River at Tracy Road Bridge [5]	*P-12 (ROLD59)*					
EXPORT AREA						
West Canal at mouth of Clifton Court Forebay	*C-9 (CHWST0)*	*Electrical Conductivity (EC)*	*Maximum monthly average of mean daily EC (mmhos/cm)*	*All*	*Oct-Sep*	*1.0*
-and-						
Delta-Mendota Canal at Tracy Pumping Plant	*DMC-1 (CHDMC004)*					

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[1] River Kilometer Index station number.

[2] Determination of compliance with an objective expressed as a running average begins on the last day of the averaging period. The averaging period commences with the first day of the time period for the applicable objective. If the objective is not met on the last day of the averaging period, all days in the averaging period are considered out of compliance.

[3] The Sacramento Valley 40-30-30 water year hydrologic classification index (see Figure 1) applies for determinations of water year type.

[4] When no date is shown, EC limit continues from April 1.

[5] The 0.7 EC objective becomes effective on April 1, 2005. The DWR and the USBR shall meet 1.0 EC at these stations year round until April 1, 2005. The 0.7 EC objective is replaced by the 1.0 EC objective from April through August after April 1, 2005 if permanent barriers are constructed, or equivalent measures are implemented, in the southern Delta and an operations plan that reasonably protects southern Delta agriculture is prepared by the DWR and the USBR and approved by the Executive Director of the SWRCB. The SWRCB will review the salinity objectives for the southern Delta in the next review of the Bay-Delta objectives following construction of the barriers.

Table 4

Number of Days When Maximumu Daily Average Electrical Conductivity of 2.64 mmhos/cm Must Be Maintained at Specified Location (a)

PMI (b)	Chipps Island (Chipps Island Station D10)					PMI (b)	Port Chicago (Port Chicago Station C14) (d)					PMI (b)	Port Chicago (Port Chicago Station C14) (d)				
(TAF)	FEB	MAR	APR	MAY	JUN	(TAF)	FEB	MAR	APR	MAY	JUN	(TAF)	FEB	MAR	APR	MAY	JUN
≤ 500	0	0	0	0	0	**0**	0	0	0	0	0	**5250**	27	29	25	26	6
750	0	0	0	0	0	**250**	1	0	0	0	0	**5500**	27	29	26	28	9
1000	28 [c]	12	2	0	0	**500**	4	1	0	0	0	**5750**	27	29	27	28	13
1250	28	31	6	0	0	**750**	8	2	0	0	0	**6000**	27	29	27	29	16
1500	28	31	13	0	0	**1000**	12	4	0	0	0	**6250**	27	30	27	29	19
1750	28	31	20	0	0	**1250**	15	6	1	0	0	**6500**	27	30	28	30	22
2000	28	31	25	1	0	**1500**	18	9	1	0	0	**6750**	27	30	28	30	24
2250	28	31	27	3	0	**1750**	20	12	2	0	0	**7000**	27	30	28	30	26
2500	28	31	29	11	1	**2000**	21	15	4	0	0	**7250**	27	30	28	30	27
2750	28	31	29	20	2	**2250**	22	17	5	1	0	**7500**	27	30	29	30	28
3000	28	31	30	27	4	**2500**	23	19	8	1	0	**7750**	27	30	29	31	28
3250	28	31	30	29	8	**2750**	24	21	10	2	0	**8000**	27	30	29	31	29
3500	28	31	30	30	13	**3000**	25	23	12	4	0	**8250**	28	30	29	31	29
3750	28	31	30	31	18	**3250**	25	24	14	6	0	**8500**	28	30	29	31	29
4000	28	31	30	31	23	**3500**	25	25	16	9	0	**8750**	28	30	29	31	30
4250	28	31	30	31	25	**3750**	26	26	18	12	0	**9000**	28	30	29	31	30
4500	28	31	30	31	27	**4000**	26	27	20	15	0	**9250**	28	30	29	31	30
4750	28	31	30	31	28	**4250**	26	27	21	18	1	**9500**	28	31	29	31	30
5000	28	31	30	31	29	**4500**	26	28	23	21	2	**9750**	28	31	29	31	30
5250	28	31	30	31	29	**4750**	27	28	24	23	3	**10000**	28	31	30	31	30
≥5500	28	31	30	31	30	**5000**	27	28	25	25	4	**>10000**	28	31	30	31	30

[a] The requirement for number of days the maximum daily average electrical conductivity (EC) of 2.64 mmhos per centimeter (mmhos/cm) must be maintained at Chipps Island and Port Chicago can also be met with maximum 14-day running average EC of 2.64 mmhos/cm, or 3-day running average NDOIs of 11,400 cfs and 29,200 cfs, respectively. If salinity/flow objectives are met for a greater number of days than the

by linear interpolation.

[b] PMI is the best available estimate of the previous month's Eight River Index. (Refer to Footnote 9 for Table 3 for a description of the Eight River Index.)

[c] When the PMI is between 800 TAF and 1000 TAF, the number of days the maximum daily average EC of 2.64 mmhos/cm (or maximum 14-day running average EC of 2.64 mmhos/cm, or 3-day running average NDOI of 11,400 cfs) must be maintained at Chipps Island in February is determined by linear interpolation between 0 and 28 days.

[d] This standard applies only in months when the average EC at Port Chicago during the 14 days immediately prior to the first day of the month is less than or equal to 2.64 mmhos/cm

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