## Appendix 5A

# BDCP/California WaterFix FEIR/FEIS Modeling Technical Appendix

# Appendix 5A
# Section A: Modeling Methodology

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# A.1. Introduction

This section summarizes the modeling methodology used for the Bay Delta Conservation Plan/California WaterFix Environmental Impact Report/Environmental Impact Statement (BDCP/CWF EIR/EIS) Existing Conditions, No Action Alternative and other Alternatives. It describes the overall analytical framework and contains descriptions of the key analytical tools and approaches used in the quantitative evaluation of the Alternatives.

BDCP includes several main components that will have significant effects on SWP and CVP operations and the hydrologic response of the system. Most of the Alternatives include construction and operation of new north Delta intakes and associated conveyance, modifications to the Fremont Weir, large scale tidal marsh restoration in the Delta and changes in the operation of the existing south Delta export facilities can significantly influence the hydrologic response of the system.

For the purposes of the modeling, the Alternatives are simulated at three phases in time: Near-Term (NT), representing a point in time 5-10 years into the permit (~2015), Early Long-Term (ELT) representing a point in time 15 years into the permit (~2025), and Late Long-Term (LLT) representing the end of the 50-year permit (~2060).

In the Alternatives including the new north Delta intakes and isolated conveyance facility, the facility is assumed not to be functional until the ELT phase. All the Alternatives, except for Existing Conditions, No Action Alternative, Alternative 2D, Alternative 4A and Alternative 5A, include the tidal marsh restoration. The acreages of the tidal marsh restoration incrementally increase with each phase. NT includes 14,000 acres, ELT includes 25,000 acres and LLT includes 65,000 acres of tidal marsh restoration.

In the evaluation of the No Action Alternative and the other Alternatives at the ELT and LLT phases, sea level rise was assumed to be inherent. ELT assumes 15cm and LLT assumes 45cm sea level rise to exist. The analytical framework and the tools described in this document are developed to evaluate these complex, inter-dependent, large-scale changes to the system. The full modeling assumptions for all the alternatives are provided in Section B.

# A.2. Overview of the Modeling Approach

To support the impact analysis of the Alternatives, modeling of the physical variables (or "physical modeling") such as flows is required to evaluate changes to conditions affecting resources within the Delta as well as effects to upstream and downstream resources. A framework of integrated analyses including hydrologic, operations, hydrodynamics, water quality, and particle tracking analysis are required to provide baseline and comparative information for water supply, surface water, aquatic resources and water quality assessments. This analytical framework is also useful to assess changes in the function of the alternatives under varying assumptions of future, non-project conditions such as climate change, future demands, and changes in Delta morphology.

The Alternatives include complex changes to internal constraints such as Delta conveyance, SWP/CVP water project operations, floodplains and tidal marsh, and Delta channel structure/gates. Both these internal constraints and external constraints such as climate and sea level changes influence the future conditions of reservoir storage, river flow, Delta flows, exports, water quality, and tidal dynamics. Evaluation of these conditions is the primary focus of the physical modeling analyses. The interaction between many of the elements proposed under the Alternatives necessitated modifications to existing analytical tools or application of new analytical tools to account for these dynamic relationships.

Figure A-1 shows the analytical tools applied in these assessments and the relationship between these tools. Each model included in Figure A-1 provides information to the next "downstream" model in order to provide various results to support the impact analyses. Changes to the historical hydrology related to the future climate are applied in the CALSIM II model and combined with the assumed operations for each Alternative. The CALSIM II model simulates the operation of the major SWP and CVP facilities in the Central Valley and generates estimates of river flows, exports, reservoir storage, deliveries, and other parameters. The Delta boundary flows and exports from CALSIM II are then used to drive the DSM2 Delta hydrodynamic and water quality models for estimating tidally-based flows, stage, velocity, and salt transport within the estuary. Particle tracking modeling uses the velocity fields generated under the hydrodynamics to emulate movement of particles throughout the Delta system. River and temperature models for the primary river systems use the CALSIM II reservoir storage, reservoir releases, river flows, and meteorological conditions to estimate reservoir and river temperatures under each scenario. The results from this suite of physical models are used to inform the understanding of effects of each individual scenario considered in the BDCP.

## A.2.1. Analytical Tools

A brief description of the hydrologic, hydrodynamic, water quality, particle transport, reservoir and river temperature modeling tools used in the analytical framework is provided below.

### CALSIM II

The California Department of Water Resources (DWR)/U.S. Bureau of Reclamation (Reclamation) CALSIM II planning model was used to simulate the operation of the CVP and SWP over a range of hydrologic conditions. CALSIM II is a generalized reservoir-river basin simulation model that allows for specification and achievement of user-specified allocation targets, or goals (Draper et al. 2002). CALSIM II represents the best available planning model for the SWP and CVP system operations and has been used in previous system-wide evaluations of SWP and CVP operations (USBR, 1994, 2004, 2008).

Inputs to CALSIM II include water diversion requirements (demands), stream accretions and depletions, rim basin inflows, irrigation efficiencies, return flows, non-recoverable losses, and groundwater operations. Sacramento Valley and tributary rim basin hydrologies are developed using a process designed to adjust the historical sequence of monthly stream flows over an 82-year period (1922 to 2003) to represent a sequence of flows at a future level of development.

Adjustments to historic water supplies are determined by imposing future level land use on historical meteorological and hydrologic conditions. The resulting hydrology represents the water supply available from Central Valley streams to the CVP and SWP at a future level of development.

CALSIM II produces outputs for river flows and diversions, reservoir storage, Delta flows and exports, Delta inflow and outflow, Deliveries to project and non-project users, and controls on project operations. Reclamation's 2008 Operations Criteria and Plan (OCAP) Biological Assessment (BA) Appendix D provides more information about CALSIM II (USBR, 2008a).CALSIM II output provides the basis for multiple other hydrologic, hydrodynamic, and biological models and analyses. CALSIM II results are used to determine water quality, hydrodynamics, and particle tracking in the DSM2 model. The outputs feed into temperature models including the Upper Sacramento River Water Quality Model (USRWQM), the Reclamation Temperature Model, and other habitat and biological models.

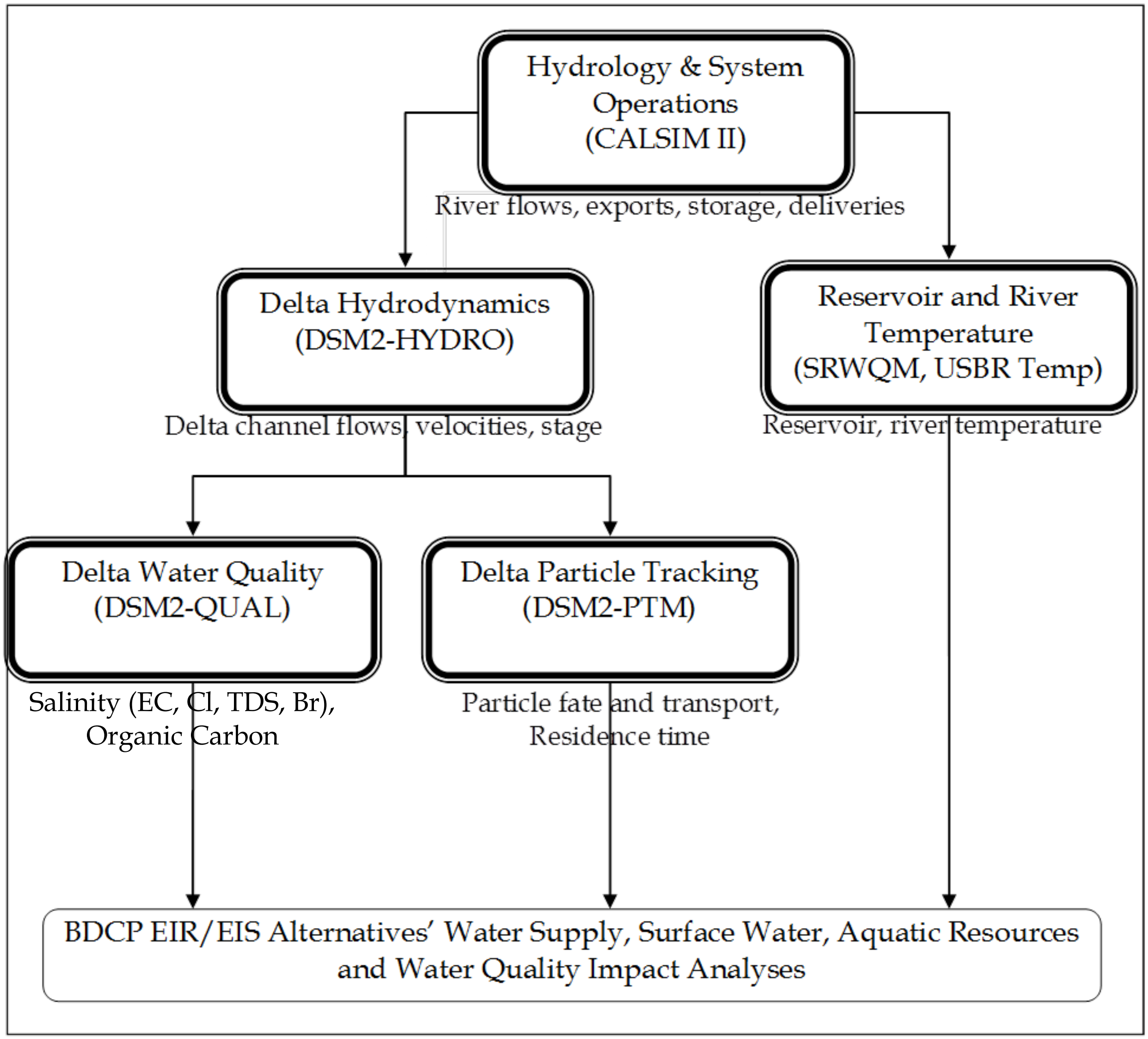


**Figure A-1: Analytical Framework used to Evaluate Impacts of the Alternatives**

### Artificial Neural Network (ANN) for Flow-Salinity Relationships

An Artificial Neural Network (ANN) has been developed (Sandhu et al. 1999, Seneviratne and Wu, 2007) that attempts to faithfully mimic the flow-salinity relationships as modeled in DSM2, but provide a rapid transformation of this information into a form usable by the statewide CALSIM II model. The ANN is implemented in CALSIM II to constrain the operations of the upstream reservoirs and the Delta export pumps in order to satisfy particular salinity requirements. The current ANN predicts salinity at various locations in the Delta using the following parameters as input: Sacramento River inflow, San Joaquin River inflow, Delta Cross

Channel gate position, and total exports and diversions. Sacramento River inflow includes Sacramento River flow, Yolo Bypass flow, and combined flow from the Mokelumne, Cosumnes, and Calaveras rivers (East Side Streams) minus North Bay Aqueduct and Vallejo exports. Total exports and diversions include State Water Project (SWP) Banks Pumping Plant, Central Valley Project (CVP) Tracy Pumping Plant, Contra Costa Water District (CCWD) diversions including diversion to Los Vaqueros Reservoir. The ANN model approximates DSM2 model-generated salinity at the following key locations for the purpose of modeling Delta water quality standards: X2, Sacramento River at Emmaton, San Joaquin River at Jersey Point, Sacramento River at Collinsville, and Old River at Rock Slough. In addition, the ANN is capable of providing salinity estimates for Clifton Court Forebay, CCWD Alternate Intake Project (AIP) and Los Vaqueros diversion locations. A more detailed description of the ANNs and their use in the CALSIM II model is provided in Wilbur and Munévar (2001). In addition, the DWR Modeling Support Branch website (http://modeling.water.ca.gov/) provides ANN documentation.

### Upper Sacramento River Water Quality Model (USRWQM)

The Upper Sacramento River Water Quality Model (USRWQM) was used to simulate the effects of operations on water temperature in the Sacramento River and Shasta and Keswick reservoirs. The USRWQM was developed using the HEC-5Q model to simulate mean daily (using 6-hour meteorology) reservoir and river temperatures at key locations on the Sacramento River. The timestep of the model is daily and provides water temperature each day for the 82 year hydrologic period used in CALSIM II. The model has been used in the previous CVP and SWP system operational performance evaluation (USBR, 2008c). Monthly flows from CALSIM II for an 82 year period (WY 1922-2003) are used as input into the USRWQM after being temporally downsized to daily average flows. Temporal downscaling is performed on the CALSIM II monthly average tributary flows to convert them to daily average flows for HEC5Q input. Monthly average flows are converted to daily tributary inflows based on 1921 through 1994 daily historical record for the following aggregated inflows:

1. Trinity River above Lewiston;

2. Sacramento River above Keswick; and

3. Incremental inflow between Keswick and Bend Bridge (Seven day trailing average for inflows below Butte City).

Each of the total monthly inflows specified by CALSIM II is scaled proportionally to one of these three historical records. Reservoir inflows were proportioned as defined above. Outflows and diversions are smoothed for a better transition at the end of the month without regard for reservoir volume constraints or downstream minimum flows. As flows are redistributed within the month, the minimum flow constraint at Keswick, Red Bluff and Knights Landing may be violated. In such cases, operation modifications are required for daily flow simulation to satisfy minimum flow requirements. A utility program is included in SRWQM to convert the monthly CALSIM II flows and releases into daily operations. More detailed description SRWQM and the temporal downscaling process is included in an RMA calibration report (RMA 2003). For more information on the USRWQM, see Appendix H of the Reclamation's 2008 OCAP BA (USBR, 2008c).

### Reclamation Temperature Model

The Reclamation Temperature Model was used to predict the effects of operations on water temperatures in the Trinity, Feather, American, and Stanislaus river basins and upstream reservoirs. The model is a reservoir and stream temperature model, which simulates monthly reservoir and stream temperatures used for evaluating the effects of CVP/SWP project operations on mean monthly water temperatures in the basin based on hydrologic and climatic input data. It has been applied to past CVP and SWP system operational performance evaluations (USBR, 2008c).

The model uses CALSIM II output to simulate mean monthly vertical temperature profiles and release temperatures for five major reservoirs (Trinity, Whiskeytown, Shasta, Oroville and Folsom), four downstream regulating reservoirs (Lewiston, Keswick, Goodwin and Natoma), and three main river systems (Sacramento, Feather and American), although the model is not be applied to the Sacramento River because the USRWQM was deemed superior as a result of its daily time step. For more information on the Reclamation Temperature Model, see Appendix H of the Reclamation's 2008 OCAP BA (USBR, 2008c).

### DSM2

DSM2 is a one-dimensional hydrodynamic and water quality simulation model used to simulate hydrodynamics, water quality, and particle tracking in the Sacramento-San Joaquin Delta (DWR, 2002). DSM2 represents the best available planning model for Delta tidal hydraulic and salinity modeling. It is appropriate for describing the existing conditions in the Delta, as well as performing simulations for the assessment of incremental environmental impacts caused by future facilities and operations.

The DSM2 model has three separate components: HYDRO, QUAL, and PTM. HYDRO simulates velocities and water surface elevations and provides the flow input for QUAL and PTM. DSM2-HYDRO outputs are used to predict changes in flow rates and depths, and their effects on covered species, as a result of the BDCP and climate change.

The QUAL module simulates fate and transport of conservative and non-conservative water quality constituents, including salts, given a flow field simulated by HYDRO. Outputs are used to estimate changes in salinity, and their effects on covered species, as a result of the BDCP and climate change. Reclamation's 2008 OCAP BA Appendix F provides more information about DSM2 (USBR, 2008b).

DSM2-PTM simulates pseudo 3-D transport of neutrally buoyant particles based on the flow field simulated by HYDRO. It simulates the transport and fate of individual particles traveling throughout the Delta. The model uses velocity, flow, and stage output from the HYDRO module to monitor the location of each individual particle using assumed vertical and lateral velocity profiles and specified random movement to simulate mixing. PTM has multiple applications ranging from visualization of flow patterns to simulation of discrete organisms such as fish eggs and larvae. Additional information on DSM2 can be found on the DWR Modeling Support Branch website at http://modeling.water.ca.gov/.

## A.2.2. Key Components of the Analytical Framework

Major components of the BDCP physical modeling, including Hydrology and Systems Operations Modeling, Reservoir and River Temperature Modeling, Delta Hydrodynamics and

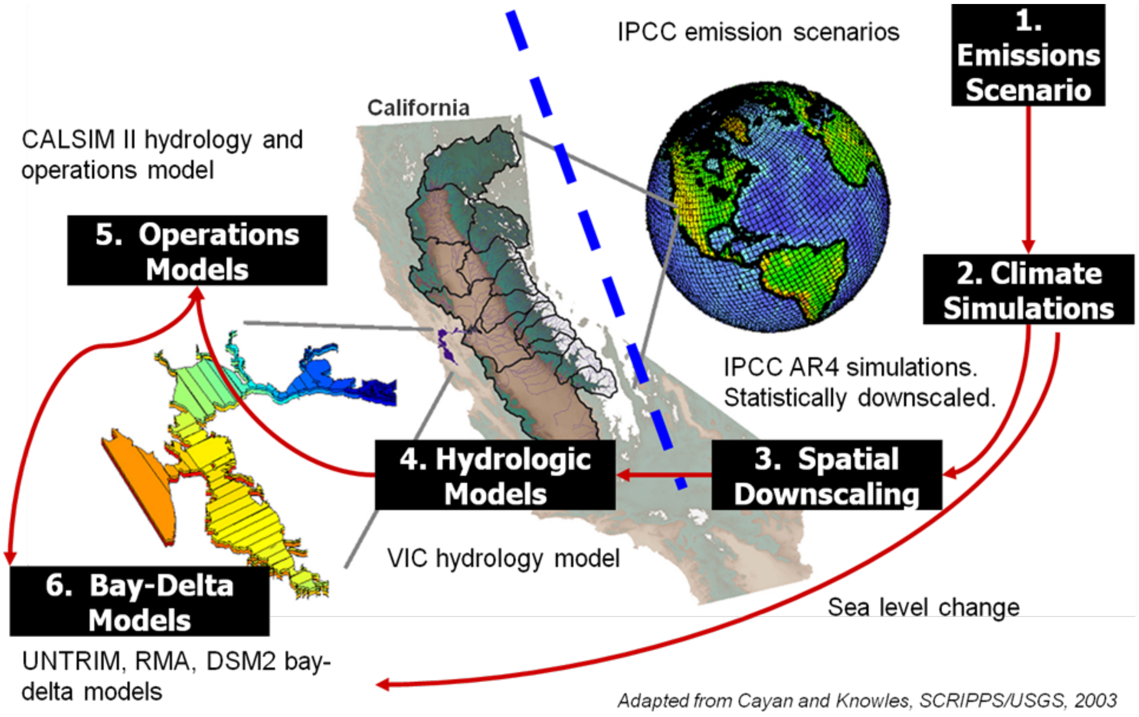
Water Quality Modeling and Delta Particle Transport and Fate Modeling are described in separate sections. Each section describes in detail the key tools used for modeling, data interdependencies and limitations. It also includes description of the process of how the tools are applied in a long-term planning analysis such as evaluating the Alternatives and describe any improvements or modifications performed for application in BDCP modeling.

Section A.3. *Hydrology and Systems Operations Modeling* describes the application of the CALSIM II model to evaluate the effects of hydrology and system operations on river flows, reservoir storage, Delta flows and exports, and water deliveries. Section A.4. *Reservoir and River Temperature Modeling* includes a description of the Sacramento River Water Quality Model for analysis of temperature in the Shasta-Whiskeytown complex and the Sacramento River. Section A.5. *Delta Hydrodynamics and Water Quality* section describes the application of the DSM2 model to implement new elements of the BDCP and resulting effects to tidal stage, velocity, flows, and salinity. Finally, Section A.6. *Delta Particle Transport and Fate Modeling* describes the methodology and application of the DSM2-PTM model for simulating particle transport in the Delta.

### A.2.3. Climate Change and Sea Level Rise

The physical modeling approach applied for the BDCP integrates a suite of analytical tools in a unique manner to characterize changes to the system from “atmosphere to ocean”. Figure A-2 illustrates the general flow of information for incorporating climate and sea level change in the physical modeling analyses. Climate and sea level can be considered the most upstream and most downstream boundary constraints on the system analyzed in the physical modeling for the BDCP. However, these constraints are outside of the influence of the BDCP and are considered external constraints. The effects of these constraints are incorporated into the key models used in the analytical framework.

The selection of the future climate and the sea level rise scenarios is described in Section A.7. *Climate and Sea Level Change Scenarios* section along with the process of science review, incorporation of uncertainty, and analytical methods for selecting appropriate scenarios. For all the selected future climate scenarios, regional hydrologic modeling was performed with the Variable Infiltration Capacity (VIC) hydrology model using temperature and precipitation projections of future climate. In addition to a range of hydrologic process information, the VIC model generates natural streamflows under each assumed climate condition. Section A.8. *Regional Hydrologic Modeling* describes the application of the macro-scale VIC hydrology model that translates the effects of future climate conditions on watershed processes ultimately affecting the timing and volume of runoff.



Adapted from Cayan and Knowles, SCRIPPS/USGS, 2003

**Figure A-2: Characterizing Climate Impacts from Atmosphere to Oceans**

# A.3. Hydrology and System Operations

The hydrology of the Central Valley and operation of the CVP and SWP systems is a critical element toward any assessment of changed conditions in the Delta. Changes to conveyance, flow patterns, demands, regulations, and/or Delta configuration will influence the operation of the SWP and CVP reservoirs and export facilities. The operations of these facilities, in turn, influence Delta flows, water quality, river flows, and reservoir storage. The interaction between hydrology, operations, and regulations is not always intuitive and detailed analysis of this interaction often results in new understanding of system responses. Modeling tools are required to approximate these complex interactions under future conditions.

The Bay Delta Conservation Plan (BDCP) includes several main components that will have significant effects on SWP and CVP operations and the hydrologic response of the system. The proposed construction and operation of new north Delta intakes and associated conveyance, modifications to the Fremont Weir, large scale tidal marsh restoration in the Delta, and changes in the operation of the existing south Delta export facilities can significantly influence the hydrologic response of the system.

This section describes in detail the methodology used to simulate hydrology and system operations for evaluating the effects of the BDCP. It discusses the primary tool (CALSIM II) used in this process and improvements made to the model to better simulate key components of the BDCP.

## A.3.1 CALSIM II

The DWR/USBR CALSIM II planning model was used to simulate the operation of the CVP and SWP over a range of hydrologic conditions. CALSIM II is a generalized reservoir-river basin simulation model that allows for specification and achievement of user-specified allocation targets, or goals (Draper et. al., 2004). The current application to the Central Valley system is called CALSIM II and represents the best available planning model for the SWP and CVP system operations. CALSIM II includes major reservoirs in the Central Valley of the California including Trinity, Lewiston, Whiskeytown, Shasta, Keswick, Folsom, Oroville, San Luis, New Melones and Millerton located along the Sacramento and San Joaquin Rivers and their tributaries. CALSIM II also includes all the major CVP and SWP facilities including Clear Creek Tunnel, Tehama Colusa Canal, Corning Canal, Jones Pumping Plant, Delta Mendota Canal, Mendota Pool, Banks Pumping Plant, California Aqueduct, South Bay Aqueduct, North Bay Aqueduct, Coastal Aqueduct and East Branch Extension. In addition, it also includes some locally managed facilities such as the Glenn Colusa Canal, Contra Costa Canal and the Los Vaqueros Reservoir. Figure A-3 shows the major reservoirs, streams and facilities included in the CALSIM II model.

The CALSIM II simulation model uses single time-step optimization techniques to route water through a network of storage nodes and flow arcs based on a series of user-specified relative priorities for water allocation and storage. Physical capacities and specific regulatory and contractual requirements are input as linear constraints to the system operation using the water resources simulation language (WRESL). The process of routing water through the channels and storing water in reservoirs is performed by a mixed integer linear programming solver. For each time step, the solver maximizes the objective function to determine a solution that delivers or stores water according to the specified priorities and satisfies all system constraints. The sequence of solved linear programming problems represents the simulation of the system over the period of analysis.

**Figure A-3: Major Reservoirs, Streams and Facilities (both CVP and SWP) Included in the CALSIM II Model**

CALSIM II includes an 82-year modified historical hydrology (water years 1922-2003) developed jointly by DWR and USBR. Water diversion requirements (demands), stream accretions and depletions, rim basin inflows, irrigation efficiencies, return flows, non-recoverable losses, and groundwater operations are components that make up the hydrology used in CALSIM II. Sacramento Valley and tributary rim basin hydrologies are developed using a process designed to adjust the historical observed sequence of monthly stream flows to represent a sequence of flows at a future level of development. Adjustments to historic water supplies are determined by imposing future level land use on historical meteorological and hydrologic conditions. The resulting hydrology represents the water supply available from Central Valley streams to the system at a future level of development. Figure A-4 shows the valley floor depletion regions, which represent the spatial resolution at which the hydrologic analysis is performed in the model.

**Figure A-4: CALSIM II Depletion Analysis Regions**

CALSIM II uses rule-based algorithms for determining deliveries to north-of-Delta and south-of-Delta CVP and SWP contractors. This delivery logic uses runoff forecast information, which incorporates uncertainty and standardized rule curves. The rule curves relate storage levels and forecasted water supplies to project delivery capability for the upcoming year. The delivery capability is then translated into SWP and CVP contractor allocations which are satisfied through coordinated reservoir-export operations.

The CALSIM II model utilizes a monthly time-step to route flows throughout the river-reservoir system of the Central Valley. While monthly time steps are reasonable for long-term planning analyses of water operations, two major components of the BDCP conveyance and conservation strategy include operations that are sensitive to flow variability at scales less than monthly: the operation of the modified Fremont Weir and the diversion/bypass rules associated with the proposed north Delta intakes. Initial comparisons of monthly versus daily operations at these facilities indicated that weir spills were likely underestimated and diversion potential was likely overstated using a monthly time step. For these reasons, a monthly to daily flow disaggregation technique was included in the CALSIM II model for the Fremont Weir, Sacramento Weir, and north Delta intakes. The technique applies historical daily patterns, based on the hydrology of the year, to transform the monthly volumes into daily flows. The procedure is described in more detail further in this document. Reclamation's 2008 OCAP BA Appendix D provides more information about CALSIM II (USBR, 2008a).

### A.3.2. Artificial Neural Network for Flow-Salinity Relationship

Determination of flow-salinity relationships in the Sacramento-San Joaquin Delta is critical to both project and ecosystem management. Operation of the SWP/CVP facilities and management of Delta flows is often dependent on Delta flow needs for salinity standards. Salinity in the Delta cannot be simulated accurately by the simple mass balance routing and coarse timestep used in CALSIM II. Likewise, the upstream reservoirs and operational constraints cannot be modeled in the DSM2 model. An Artificial Neural Network (ANN) has been developed (Sandhu et al. 1999) that attempts to mimic the flow-salinity relationships as simulated in DSM2, but provide a rapid transformation of this information into a form usable by the CALSIM II operations model. The ANN is implemented in CALSIM II to constrain the operations of the upstream reservoirs and the Delta export pumps in order to satisfy particular salinity requirements. A more detailed description of the use of ANNs in the CALSIM II model is provided in Wilbur and Munévar (2001).

The ANN developed by DWR (Sandhu et al. 1999, Seneviratne and Wu, 2007) attempts to statistically correlate the salinity results from a particular DSM2 model run to the various peripheral flows (Delta inflows, exports and diversions), gate operations and an indicator of tidal energy. The ANN is calibrated or trained on DSM2 results that may represent historical or future conditions using a full circle analysis (Seneviratne and Wu, 2007). For example, a future reconfiguration of the Delta channels to improve conveyance may significantly affect the hydrodynamics of the system. The ANN would be able to represent this new configuration by being retrained on DSM2 model results that included the new configuration.

The current ANN predicts salinity at various locations in the Delta using the following parameters as input: Northern flows, San Joaquin River inflow, Delta Cross Channel gate position, total exports and diversions, Net Delta Consumptive Use, an indicator of the tidal energy and San Joaquin River at Vernalis salinity. Northern flows include Sacramento River flow, Yolo Bypass flow, and combined flow from the Mokelumne, Cosumnes, and Calaveras rivers (East Side Streams) minus North Bay Aqueduct and Vallejo exports. Total exports and diversions include State Water Project (SWP) Banks Pumping Plant, Central Valley Project (CVP) Jones Pumping Plant, and CCWD diversions including diversions to Los Vaqueros Reservoir. A total of 148 days of values of each of these parameters is included in the correlation, representing an estimate of the length of memory of antecedent conditions in the Delta. The ANN model approximates DSM2 model-generated salinity at the following key locations for the purpose of modeling Delta water quality standards: X2, Sacramento River at Emmaton, San Joaquin River at Jersey Point, Sacramento River at Collinsville, and Old River at Rock Slough. In addition, the ANN is capable of providing salinity estimates for Clifton Court Forebay, CCWD Alternate Intake Project (AIP) and Los Vaqueros diversion locations.

The ANN may not fully capture the dynamics of the Delta under conditions other than those for which it was trained. It is possible that the ANN will exhibit errors in flow regimes beyond those for which it was trained. Therefore, a new ANN is needed for any new Delta configuration or under sea level rise conditions which may result in changed flow – salinity relationships in the Delta.

### A.3.3. Application of CALSIM II to Evaluate BDCP Alternatives

Typical long-term planning analyses of the Central Valley system and operations of the CVP and SWP have applied the CALSIM II model for analysis of system responses. CALSIM II simulates future SWP/CVP project operations based on a 82-year monthly hydrology derived from the observed 1922-2003 period. Future land use and demands are projected for the appropriate future period. The system configuration consisting of facilities, operations, and regulations are input to the model and define the limits or preferences on operation. The configuration of the Delta, while not simulated directly in CALSIM II, informs the flow-salinity relationships and several flow-related regressions for interior Delta conditions (i.e. X2 and OMR) included in the model. For each set of hydrologic, facility, operations, regulations, and Delta configuration conditions, the CALSIM II model is simulated. Some refinement of the SWP/CVP operations related to delivery allocations and San Luis target storage levels is generally necessary to have the model reflect suitable north-south reservoir balancing under future conditions. These refinements are generally made by experienced modelers in conjunction with project operators. Water transfers are generally considered "additional" releases that may result in additional exports, additional outflow, or both depending on the purpose, timing, and operations associated with the transfer. However, any water transfer would need to comply with the same conditions as considered for project exports.

The CALSIM II model produces outputs of river flows, exports, water deliveries, reservoir storage, water quality, and several derived variables such as X2, Delta salinity, OMR, and QWEST. The CALSIM II model is most appropriately applied for comparing one alternative to another and drawing comparisons between the results. This is the method in which CALSIM II is applied for the BDCP. For each phase of the Alternatives a companion No Action Alternative simulation has been prepared. The No Action simulation includes the existing infrastructure, existing regulatory restrictions including the recent biological opinions, but may include future demands, climate, and sea level rise depending on the time frame. The Alternative is compared to the No Action Alternative to evaluate areas in which the project changes conditions and the seasonality and magnitude of such changes. The change in hydrologic response or system conditions is important information that informs the effects analysis related to water-dependent resources in Sacramento-San Joaquin watersheds.

There are a number of areas in which the CALSIM II model has been improved or is applied differently for the BDCP analyses. This section briefly describes these key changes.

### Changes to the CALSIM II Model Network

The main feature of the Alternatives that necessitated changes to the CALSIM II model network was the proposed diversion intakes in the north Delta along the Sacramento River. The intakes and associated conveyance allow for SWP and CVP diversions on the Sacramento River between Freeport and Courtland. Some of the Alternatives include up to 5 intakes in this reach of the river with individual diversion capacity up to 3,000 cfs. Since there are relatively small existing diversions and negligible inflows occurring in this reach of the Sacramento River, the CALSIM II aggregates all proposed diversions into a single diversion arc (Figure A-5) near Hood. This diversion arc (D400) conveys water diverted by the SWP and CVP to their respective pumping plants (either Banks PP or Jones PP) in the south Delta. Since dual conveyance – diverting from either or both north and south facilities -- is being considered, the model comingles the water at the pumping plant. Water for each project is tracked separately.

Additional changes were made to the CALSIM II network in the south Delta to allow for better estimation of the Combined Old and Middle River (OMR) flow.

The Delta island consumptive use (DICU) is applied in CALSIM II at five nodes representing regions in the north, west, central, south, and San Joaquin regions of the Delta. A review of the DICU was performed in 2009 to discern if any adjustments would be necessary to best reflect the flow available at the points of diversion. The DICU was disaggregated further, into a total of seven parts, including to split out the DICU upstream and downstream of the proposed north Delta diversion, and portion of the DICU in the south Delta to improve estimates of the OMR flow.

The full schematic for the CALSIM II model is included in Section D.11.

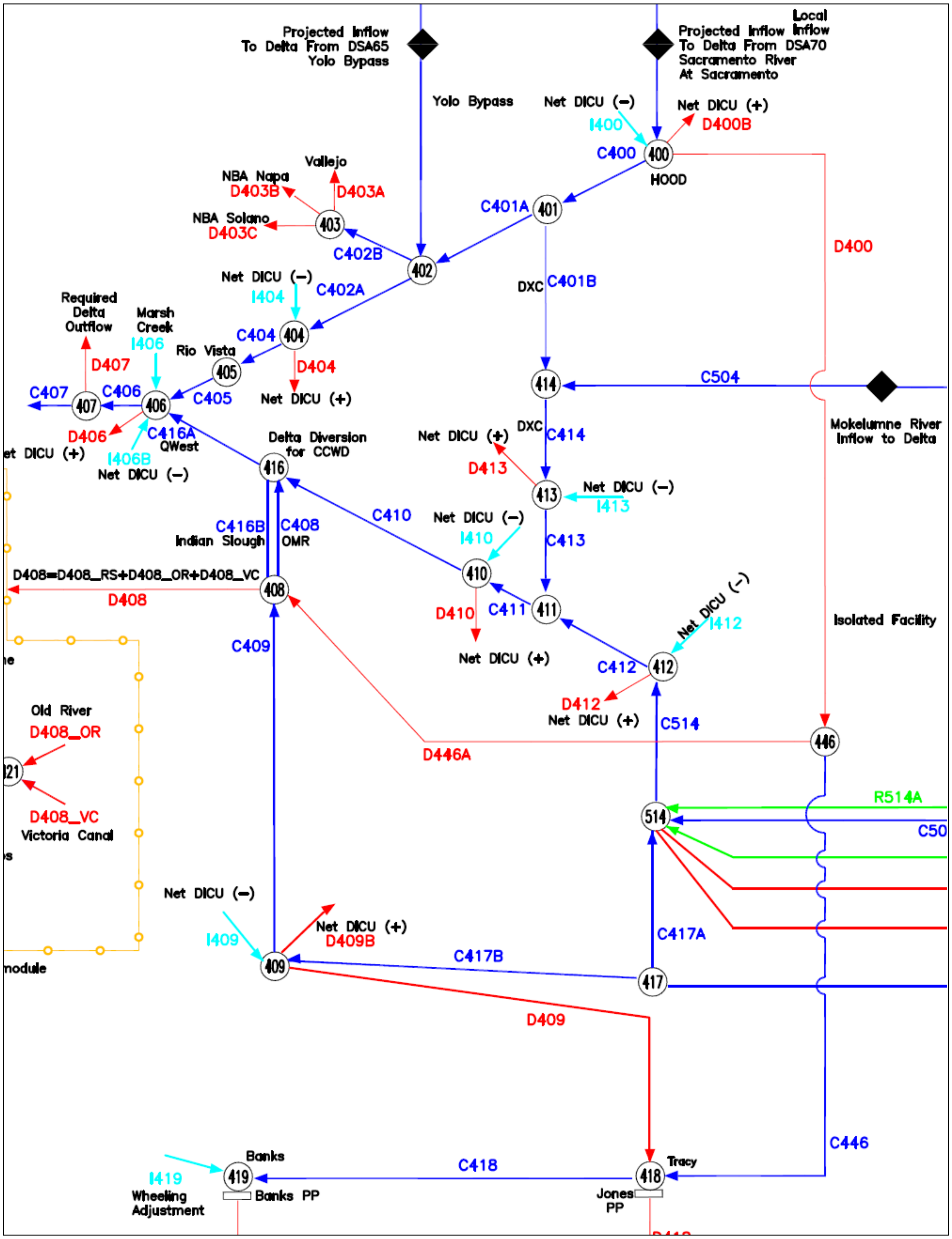


Figure A-5: Updated CALSIM II network for the inclusion of north Delta diversion (D400)

## Incorporation of Sacramento River Daily Variability

As described above, the operation of the modified Fremont Weir and the diversion/bypass rules associated with the proposed north Delta intakes are sensitive to the daily variability of flows. Short duration, highly variable storms are likely to cause Fremont Weir spills. However, if flows are averaged for the month, as is done in a monthly model, it is possible to not identify any spill. Similarly, the operating criteria for the north Delta intakes include variable bypass flows and pulse protection criteria. Storms as described above may permit significant diversion but only for a short period of time. Initial comparisons of monthly versus daily operations at these facilities indicated that weir spills were likely underestimated and diversion potential was likely overstated using a monthly time step.

Figure A-6 shows a comparison of observed monthly averaged Sacramento River flow at Freeport and corresponding daily flow as an example. The figure shows that the daily flow exhibits significant variability around the monthly mean in the winter and spring period while remaining fairly constant in summer and fall months. Figure A-7 shows the daily historical patterns by water year type. It shows that daily variability is significant in the winter-spring while the summer flows are holding fairly constant in the most water year types. The winter-spring daily variability is deemed important to species of concern.

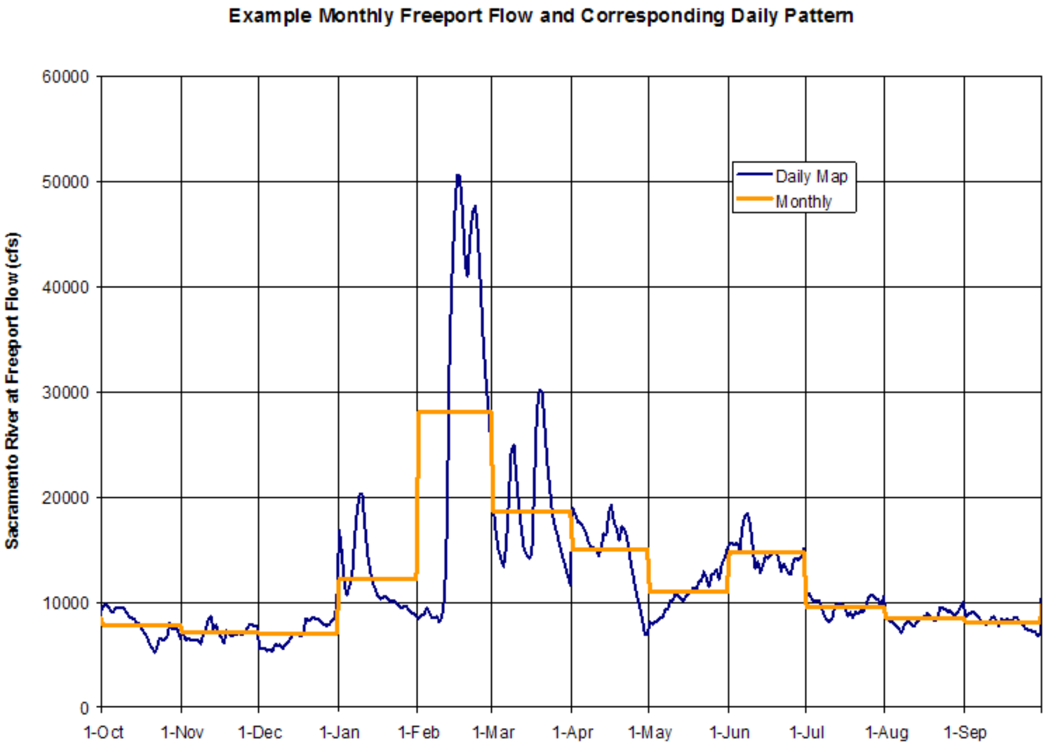


Figure A-6: Example monthly-averaged and daily-averaged flow for Sacramento River at Freeport

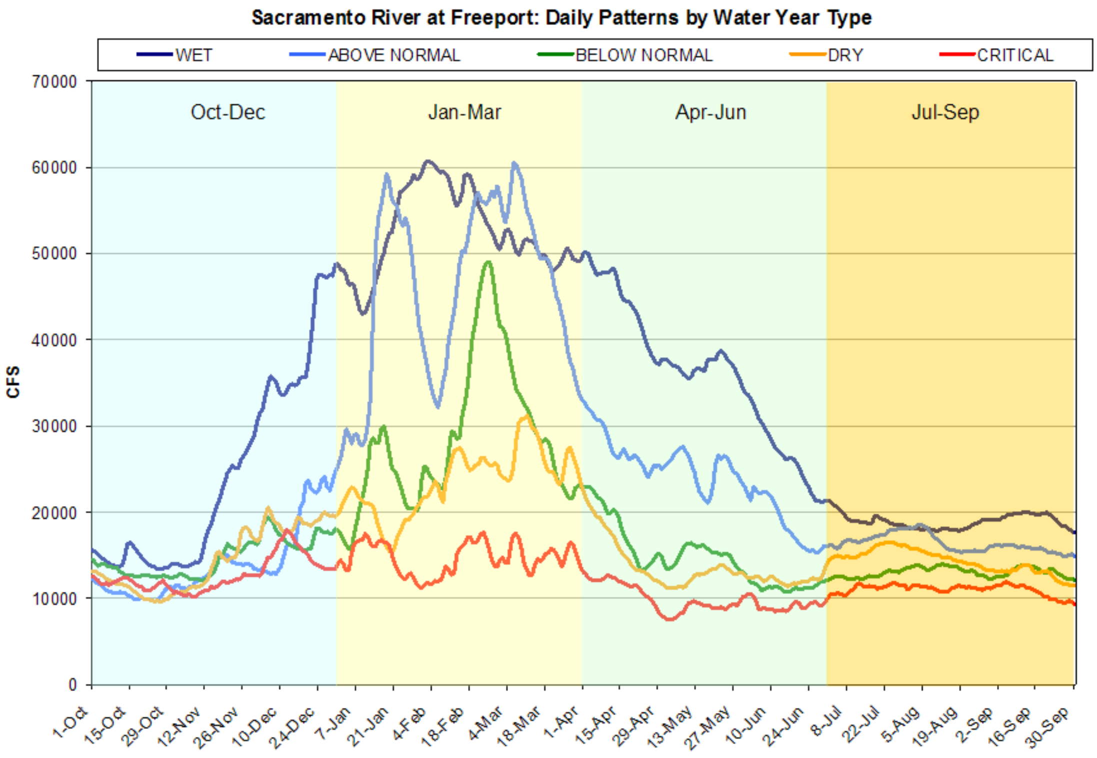


Figure A-7: Mean daily flows by Water Year Type for Sacramento River at Freeport

In an effort to better represent the sub-monthly flow variability, particularly in early winter, a monthly-to-daily flow mapping technique is applied directly in CALSIM II for the Fremont Weir, Sacramento Weir, and the north Delta intakes. The technique applies historical daily patterns, based on the hydrology of the year, to transform the monthly volumes into daily flows. Daily flow patterns are obtained from the observed DAYFLOW period of 1956-2008. In all cases, the monthly volumes are preserved between the daily and monthly flows. It is important to note that this daily mapping approach does not in any way represent the flows resulting from operational responses on a daily time step. It is simply a technique to incorporate representative daily variability into the flows resulting from CALSIM II's monthly operational decisions. It helps in refining the monthly CALSIM II operations by providing a better estimate of the Fremont and Sacramento weir spills which are sensitive to the daily flow patterns and allows in providing the upper bound of the available north Delta diversion in the Alternatives.

## Observed Daily Patterns

CALSIM II hydrology is derived from historical monthly gauged flows for 1922-2003. This is the source data for monthly flow variability. DAYFLOW provides a database of daily historical Delta inflows from WY 1956 to present. This database is aligned with the current Delta infrastructure setting. Despite including the historical operational responses to various regulatory regimes existed over this period, in most winter and spring periods the reservoir operations and releases are governed by the inflows to the reservoirs.

Daily patterns from DAYFLOW used directly for mapping CALSIM II flows for water years 1956 to 2003. For water years 1922 to 1955 with missing daily flows, daily patterns are selected from water years 1956 to 2003 based on similar total annual unimpaired Delta inflow. The daily pattern for the water year with missing daily flows is assumed to be the same as the daily pattern of the identified water year. Correlation among the various hydrologic basins is preserved by selecting same pattern year for all rivers flowing into the Delta, for a given year in the 1922-1955 period. Table A-1 lists the selected pattern years for the water years 1922 to 1955 along with the total unimpaired annual Delta inflow.

Thus, for each month in the 82-year CALSIM II simulation period, the monthly flow is mapped onto a daily pattern for computation of spills over the Fremont Weir and Sacramento Weir and for computing water available for diversions through the north Delta intakes.  A preprocessed timeseries of daily volume fractions, based on Sacramento River at Freeport observed flows, is input into CALSIM II. The monthly volume as determined dynamically from CALSIM II then is multiplied by the fractions to arrive at a daily flow sequence. The calculation of daily spills and daily diversions are thus obtained. In the subsequent cycle (but still the same month), adjustments are made to the daily river flow upstream of the Sacramento Weir and the north Delta intakes to account for differences between the monthly flows assumed in the first cycle and the daily flows calculated in subsequent cycles. For example, if no spill over Fremont was simulated using a monthly flow, but when applying a daily pattern spill does occur, then the River flow at the Sacramento Weir is reduced by this amount. In this fashion, daily balance and monthly balance is preserved while adding more realism to the operation of these facilities.

TABLE A-1
Identified “Pattern” Water Year for the Water Years 1922 to 1955 with Missing Daily Historical Flows

| Water Year | Total Annual Unimpaired Delta Inflow (TAF) | Selected “Pattern” Water Year | Total Annual Unimpaired Delta Inflow (TAF) |
|---|---|---|---|
| 1922 | 32,975 | 1975 | 31,884 |
| 1923 | 23,799 | 2002 | 23,760 |
| 1924 | 8,174 | 1977 | 6,801 |
| 1925 | 26,893 | 1962 | 25,211 |
| 1926 | 18,534 | 1959 | 17,967 |
| 1927 | 38,636 | 1984 | 38,188 |
| 1928 | 26,363 | 1962 | 25,211 |
| 1929 | 12,899 | 1994 | 12,456 |
| 1930 | 20,326 | 1972 | 19,863 |
| 1931 | 8,734 | 1977 | 6,801 |
| 1932 | 24,179 | 2002 | 23,760 |
| 1933 | 14,126 | 1988 | 14,019 |
| 1934 | 12,895 | 1994 | 12,456 |
| 1935 | 28,486 | 2003 | 28,228 |
| 1936 | 30,698 | 2003 | 28,228 |
| 1937 | 25,448 | 1962 | 25,211 |
| 1938 | 56,949 | 1998 | 56,482 |
| 1939 | 12,743 | 1994 | 12,456 |
| 1940 | 37,185 | 1963 | 36,724 |
| 1941 | 46,746 | 1986 | 46,602 |
| 1942 | 42,301 | 1980 | 41,246 |
| 1943 | 36,870 | 1963 | 36,724 |
| 1944 | 17,158 | 1981 | 17,131 |
| 1945 | 26,757 | 1962 | 25,211 |
| 1946 | 28,823 | 2003 | 28,228 |
| 1947 | 16,206 | 2001 | 15,460 |
| 1948 | 23,741 | 1979 | 22,973 |

TABLE A-1
Identified "Pattern" Water Year for the Water Years 1922 to 1955 with Missing Daily Historical Flows

| Water Year | Total Annual Unimpaired Delta Inflow (TAF) | Selected "Pattern" Water Year | Total Annual Unimpaired Delta Inflow (TAF) |
|---|---|---|---|
| 1949 | 19,176 | 1960 | 19,143 |
| 1950 | 23,272 | 1979 | 22,973 |
| 1951 | 39,110 | 1984 | 38,188 |
| 1952 | 49,270 | 1986 | 46,602 |
| 1953 | 30,155 | 2003 | 28,228 |
| 1954 | 26,563 | 1962 | 25,211 |
| 1955 | 17,235 | 1981 | 17,131 |

### Fremont Weir Operations

All the Alternatives include the measure for modifying the current Fremont Weir by notching it to allow for more frequent inundation in the Yolo Bypass. Details of the Fremont Weir and Yolo Bypass Hydraulics are described in Section D.4. The HEC-RAS modeling included in that section provides modified rating curves of the Fremont Weir for use in CALSIM II. CALSIM II simply includes two sets of rating curves, one with the "notch" and one without the notch. Input tables allow specification of when the notch is assumed to be operated. The amount of spill over the Fremont Weir or the notch is computed using the daily patterned Sacramento River flow at Verona and the rating curves included in the model.

### North Delta Diversion Operations

Several of the Alternatives include new intakes (1 to 5 intakes depending on the Alternative) on Sacramento River upstream of Sutter Slough, in the north Delta. Each intake is proposed to have 3,000 cfs maximum pumping capacity. It is also proposed that the intakes will be screened using positive barrier fish screens to eliminate entrainment at the pumps. Water diverted at the five intakes is conveyed to a new forebay in the south Delta via a new isolated conveyance facility capable of conveying up to a maximum flow of 15,000 cfs (the conveyance capacity depends on the Alternative). Detailed assumptions for each Alternative are provided in Section B.

The BDCP proposes bypass (in-river) rules, which govern the amount of water required to remain in the river before any diversion can occur. Bypass rules are designed with the intent to avoid increased upstream tidal transport from downstream channels, to maintain flow supporting the migration of the salmonid and transport of pelagic species to regions of suitable habitat, to preserve shape of the natural hydrograph which may act as cue to important biological functions, to lower potential for increased tidal reversals that may occur because of the reduced net flow in the river and to provide flows to minimize predation effects downstream. The bypass rules include three important components:

- a constant low level pumping of up to 300 cfs at each intake depending on the flow in the Sacramento River,
- an initial pulse protection, and
- a post-pulse operations that permit a percentage of river flow above a certain threshold to be diverted (and transitioning from Level I to Level II to Level III).

It should be noted that these components, as further defined in Tables B-10 through B-17, are represented in CALSIM II to the extent possible. Modeling assumptions may differ from actual operations because of real-time monitoring of fish entry into the Plan Area and other variables. Tables B-10 through B-17 clearly state conditions where biological triggers or off-ramps that cannot be simulated in CALSIM II are assumed.

The bypass rules are simulated in CALSIM II using daily mapped Sacramento River flows as described above to determine the maximum potential diversion that can occur in the north Delta for each day. The simulation identifies which of the three criteria is governing, based on antecedent daily flows and season. An example of the north Delta flows and diversion is illustrated in Figure A-8. As can be seen in this figure, bypass rules begin at Level I in October until the Sacramento River pulse flow develops. During the pulse flow, the constant low level pumping (Level 0) is permitted, but is limited to a certain percentage of river flow. After longer periods of high bypass flows, the bypass flow requirements moves to Level II and eventually Level III which permit greater potential diversion. CALSIM II uses the monthly average of this daily potential diversion as one of the constraints in determining the final monthly north Delta diversion.

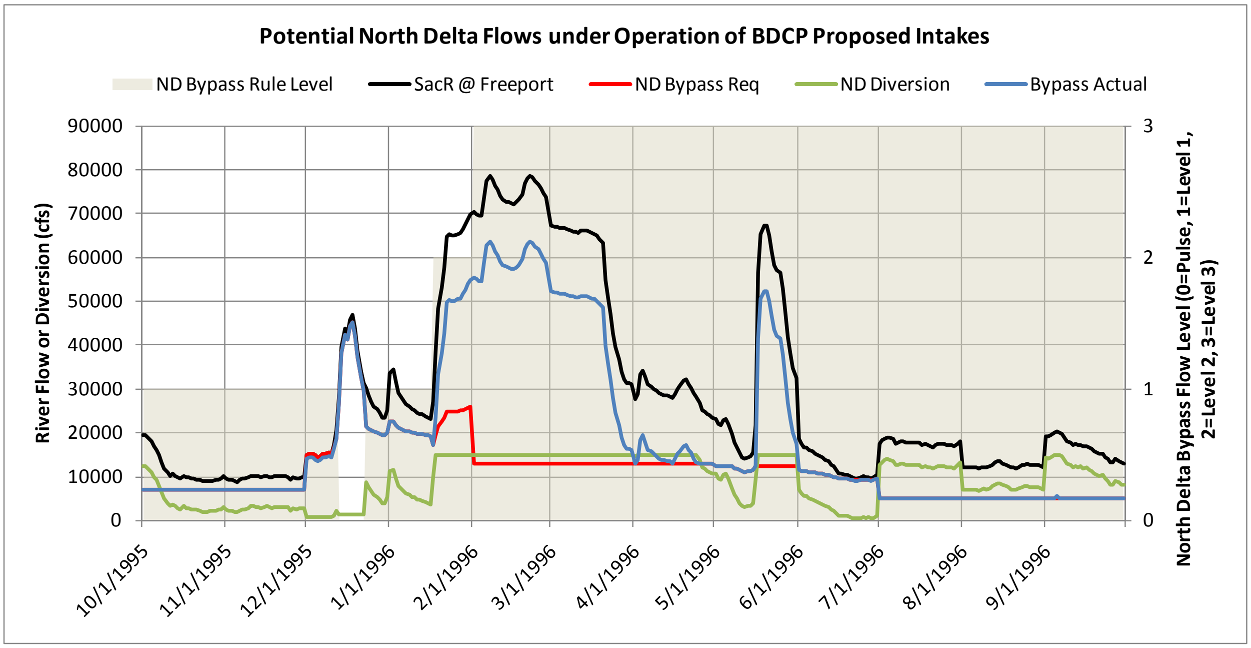


Figure A-8: Example year daily patterns and operation of the north Delta intakes. Note: the grey shading indicates the active bypass rule (0=pulse/low level pumping, 1=level I, 2=level II, and 3=level III).

## ANN Retraining

ANNs are used for simulating flow-salinity relationships in CALSIM II. They are trained on DSM2 outputs and therefore, emulate DSM2 results. ANN requires retraining whenever the flow – salinity relationship in the Delta changes. As mentioned earlier, BDCP analysis assumes different tidal marsh restoration acreages at NT, ELT and LLT phases and 15cm and 45cm sea level rise at ELT and LLT, respectively. Each combination of restoration and sea level condition results in a different flow – salinity relationship in the Delta and therefore require a new ANN.

New ANNs have been developed by DWR for each new proposed combination of tidal marsh and sea level. ANN retraining process is described in Section A.5.3.

### Incorporation of Climate Change

Climate and sea level change are incorporated into the CALSIM II model in two ways. As described in Section A.8., changes in runoff and streamflow are simulated through VIC modeling under representative climate scenarios. These simulated changes in runoff are applied to the CALSIM II inflows as a fractional change from the observed inflow patterns (simulated future runoff divided by historical runoff). These fraction changes are first applied for every month of the 82-year period consistent with the VIC simulated patterns. A second order correction is then applied to ensure that the annual shifts in runoff at each location are consistent with that generated from the VIC modeling. A spreadsheet tool has been prepared to process this information and generate adjusted inflow time series records for CALSIM II. Once the changes in flows have been resolved, water year types and other hydrologic indices that govern water operations or compliance are adjusted to be consistent with the new hydrologic regime.

Sea level rise and restored tidal marsh effects on the flow-salinity response is incorporated in the new ANNs. CALSIM II model simulations require the modeler to select which hydrology should be paired with which sea level/tidal marsh ANN.

The following input parameters are adjusted in CALSIM II to incorporate the effects of climate change:

- Inflow time series records for all major and minor streams in the Central Valley
- Sacramento and San Joaquin Valley water year types
- Runoff forecasts used reservoir operations and allocation decisions
- Delta water temperature as used in triggering biological opinion smelt criteria
- Modified ANNs to reflect the flow-salinity response under sea level change scenarios

The CALSIM II simulations do not consider future climate change adaptation which may manage the SWP and CVP system in a different manner than today to reduce climate impacts. For example, future changes in reservoir flood control reservation to better accommodate a seasonally changing hydrograph may be considered under future programs, but are not considered under the BDCP. Thus, the CALSIM II BDCP results represent the risks to operations, water users, and the environment in the absence of dynamic adaptation for climate change.

## A.3.4. Output Parameters

The Hydrology and System Operations models produce the following key parameters on a monthly time-step:

River flows and diversions

Reservoir storage

Delta flows and exports

Delta inflow and outflow

Deliveries to project and non-project users

Controls on project operations

Some operations have been informed by the daily variability included in the CALSIM II model for the BDCP, and where appropriate, these results are presented. However, it should be noted that CALSIM II remains a monthly model. The daily variability in the CALSIM II model to better represent certain operational aspects, but the monthly results are utilized for water balance. For example, diversions from the north-Delta facilities are informed by the daily variability of Sacramento River flow, whereas diversions from south-Delta intakes are modeled on a monthly time step because daily modeling for Delta would require several assumptions on daily operations that cannot be modeled, and therefore, was not attempted. All diversions are reported on a monthly basis.

Appropriate use of model results is important. Despite detailed model inputs and assumptions, the CALSIM II results may differ from real-time operations under stressed water supply conditions. Such model results occur due to the inability of the model to make real-time policy decisions under extreme circumstances, as the actual (human) operators must do. Therefore, these results should only be considered an indicator of stressed water supply conditions under that Alternative, and should not necessarily be understood to reflect literally what would occur in the future. For example, reductions to senior water rights holders due to dead-pool conditions in the model can be observed in model results under certain circumstances.  These reductions, in real-time operations, would be avoided by making policy decisions on other requirements in prior months. In actual future operations, as has always been the case in the past, the project operators would work in real time to satisfy legal and contractual obligations given then current conditions and hydrologic constraints. Chapter 5, *Water Supply* provides appropriate interpretation and analysis of such model results.

As noted earlier, Reclamation's 2008 OCAP BA Appendix W (USBR 2008e) included a comprehensive sensitivity analysis of CALSIM II results relative to the uncertainty in the inputs. This appendix provides a good summary of the key inputs that are critical for the largest changes in several operational outputs. Understanding the findings from this appendix may help bracket the range of uncertainty in the CALSIM II results.

### A.3.5. Linkages to Other Physical Models

The Hydrology and System Operations models generally require input assumptions relating to hydrology, demands, regulations, and flow-salinity responses. DWR and USBR have prepared hydrologic inputs and demand assumptions for various levels of development (future land use and development assumptions) based on historical hydroclimatic conditions. Regulations and associated operations are translated into operational requirements. The flow-salinity ANN, representing appropriate Delta configuration, is embedded into the system operations model. The river flows and Delta exports from the CALSIM II model are used as input to the Delta Hydrodynamics and Water Quality models and reservoir storage and releases are used as input to the River and Reservoir Temperature models.

# A.4. Reservoir and River Temperature

The CVP and SWP are required to operate the reservoirs and releases such that specific temperature compliance objectives are met downstream in the rivers, to protect habitat for the anadramous fish. Models are necessary to study the impacts of operational changes on the river and reservoir temperatures. Several models are available to study the impacts to the water temperatures on various river systems in the Central Valley. These models in general are capable of simulating mean monthly and mean daily downstream temperatures for long-term operational scenarios taking into consideration the selective withdrawal capabilities at the reservoirs. 2008 OCAP BA Technical Appendix H (USBR, 2008c) provides a good summary of the temperature modeling tools used in this section.

This section briefly describes the tools used to model the reservoir and river temperatures as part of the BDCP physical modeling.

## A.4.1. SRWQM

Sacramento River Water Quality Model (SRWQM) was developed by Reclamation to simulate temperature in the upstream CVP reservoirs and the upper Sacramento River. It was developed using integrated HEC-5 and HEC-5Q models. The HEC-5 component of SRWQM simulates daily flow operations in the upper Sacramento River. The HEC-5Q component of SRWQM simulates mean daily reservoir and river temperatures at Shasta, Trinity, Lewiston, Whiskeytown, Keswick and Black Butte Reservoirs and the Trinity River, Clear Creek, the upper Sacramento River from Shasta to Knights Landing, and Stony Creek based on the flow and meteorological parameters on a 6-hour time step. Figure A-9 shows the model schematic for HEC-5 component of the SRWQM. HEC-5Q is a cross-section based model and has a higher spatial resolution in comparison to the HEC-5 component of SRWQM. The HEC-5Q was customized to simulate the operations of the temperature control device at Shasta Dam.

SRWQM was successfully calibrated based on the observed temperatures in the reservoirs and the upper Sacramento River. More detailed description SRWQM and the calibration performance is included in the calibration report (RMA, 2003).

## A.4.2. Reclamation Temperature Model

Reclamation Temperature Model includes reservoir and stream temperature models, which simulate monthly reservoir and stream temperatures used for evaluating the effects of CVP/SWP project operations on mean monthly water temperatures in the basin. The model simulates temperatures in seven major reservoirs (Trinity, Whiskeytown, Shasta, Oroville, Folsom, New Melones and Tulloch), four downstream regulating reservoirs (Lewiston, Keswick, Goodwin and Natoma), and five main river systems (Trinity, Sacramento, Feather, American and Stanislaus). The river component of the Reclamation Temperature model calculates temperature changes in the regulating reservoirs, below the main reservoirs. With regulating reservoir release temperature as the initial river temperature, the river model computes temperatures at several locations along the rivers. The calculation points for river temperatures generally coincide with tributary inflow locations. The model is one-dimensional in the longitudinal direction and assumes fully mixed river cross sections. The effect of tributary inflow on river temperature is computed by mass balance calculation. The river temperature calculations are based on regulating reservoir release temperatures, river flows, and climatic data.

## A.4.3. Application of Temperature Models to Evaluate BDCP Alternatives

The temperature modeling for planning analysis is driven by the long term operations modeled using CALSIM II. The objective is to find temperature variability in the reservoirs and streams, given CVP/SWP operations, and compare between existing and assumed future scenarios. This section briefly describes the general temperature modeling approach used in a planning analysis and any changes to the approach as part of the BDCP.

### SRWQM

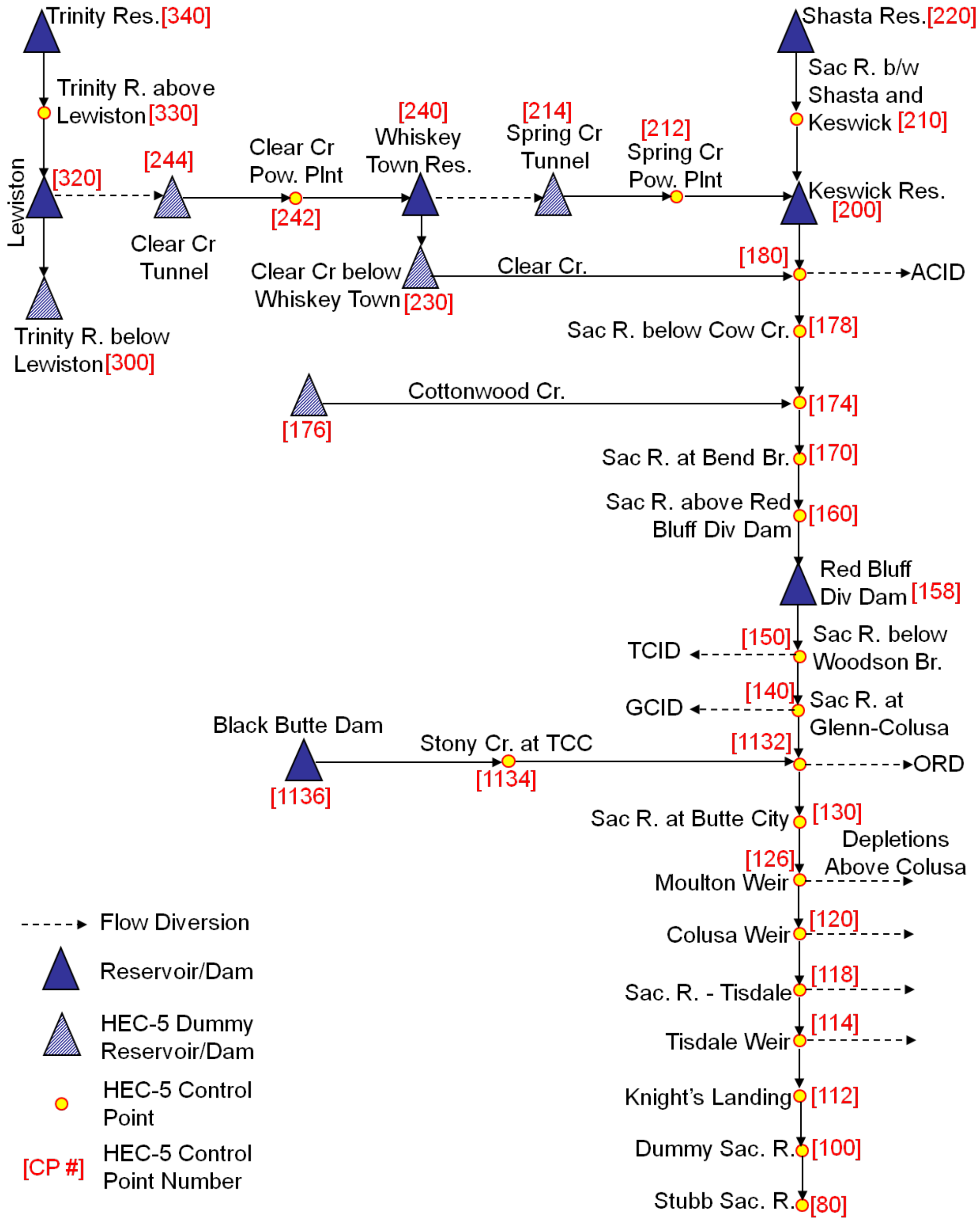
SRWQM is designed for long-term planning simulation of temperature at key locations on the Sacramento River at a mean daily time step that captures diurnal fluctuations and is sensitive to fishery management objectives. The geographical scope of the model ranges from Shasta Dam and Trinity Dam to Knights Landing. Monthly flows, simulated by the CALSIM II model for an 82 year period (WY 1922-2003), are used as input to the SRWQM. Temporal downscaling is performed on the CALSIM II monthly average tributary flows to convert them to daily average flows for SRWQM input. Monthly average flows are converted to daily tributary inflows based on 1921 through 1994 daily historical record for the following aggregated inflows:

- Trinity River above Lewiston.
- Sacramento River above Keswick.
- Incremental inflow between Keswick and Bend Bridge (Seven day trailing average for inflows below Butte City).

Each of the total monthly inflows specified by CALSIM II is scaled proportional to one of these three historical records. Outflows and diversions are smoothed for a better transition at the end of the month without regard for reservoir volume constraints or downstream minimum flows. As flows are redistributed within the month, the minimum flow constraint at Keswick, Red Bluff and Knights Landing may be violated. In such cases, operation modifications are required for daily flow simulation to satisfy minimum flow requirements. A utility program is included in SRWQM to convert the monthly CALSIM II flows and releases into daily operations. More detailed description of SRWQM and the temporal downscaling process is included in calibration report (RMA, 2003). The boundary conditions required for simulating SRWQM planning run are listed in Table A-2.

### Reclamation Temperature Models

The Reclamation temperature model suite is a monthly time-step model. It was applied to estimate temperatures in the Trinity, Feather, American, and Stanislaus River systems. Monthly flows, simulated by the CALSIM II model for an 82 year period (WY 1922-2003), are used as input to the model. Because of the CALSIM II model's complex structure, where applicable, flow arcs were combined at the appropriate temperature nodes to insure compatibility with the temperature model (see Table A-3). Monthly mean historical air temperatures for the 82-year period and other long-term average climatic data for Trinity, Shasta, Whiskeytown, Redding, Red Bluff, Colusa, Marysville, Folsom, Sacramento, New Melones, and Stockton were obtained from National Weather Service records and used to represent climatic conditions for the four river systems.



SRWQM HEC-5 Schematic

Figure A-9: SRWQM HEC-5 Model Schematic

## A.4.4. Incorporating Climate Change Inputs

When simulating alternatives with climate change, some of the inputs to the temperature models are required to be modified. This section states the assumptions and approaches used for modifying meteorological and inflow temperatures in the temperature models.

### SRWQM

SRWQM requires meteorological inputs specified in the form of equilibrium temperatures, exchange rates, shortwave radiation and wind speed. The exchange rates and equilibrium temperatures are computed from hourly observed data at Gerber gauging station. Considering the uncertainties associated with climate change impacts, it was assumed that the equilibrium temperature inputs derived from observed data would be modified by the change in daily average air temperature in the climate change scenarios.

The inflow temperatures in SRWQM are specified as seasonal curve fit values with diurnal variations superimposed as a function of heat exchange parameters. The seasonal temperature values are derived based on the observed flows and temperatures for each inflow. SRWQM superimposes diurnal variations on the seasonal values specified using the heat exchange parameter inputs. The diurnal variations are superimposed by adjusting the equilibrium temperature to reflect the inflow location environment and scaling it based on the heat exchange rate scaling factor and the weighting factor for emphasis on the seasonal values specified (RMA, 1998). In this fashion, any changes in the equilibrium temperature are translated to the inflow temperatures in the SRWQM. Therefore, for the climate change scenarios, the equilibrium temperatures were adjusted for the projected change in temperature, and these influence the inflow temperature, but independent inflow temperature inputs were not changed.

### Reclamation Temperature Models

The Reclamation temperature models require mean monthly meteorological inputs of air and equilibrium temperature, and heat exchange rates. The heat exchange rates and equilibrium temperatures are computed from the mean monthly air temperature data and long-term estimates of solar radiation, relative humidity, wind speed, cloud cover, solar reflectivity and river shading. Considering the uncertainties associated with climate change impacts, it was assumed that the equilibrium temperature and heat exchange rate inputs would be modified by the change in mean monthly air temperature in the climate change scenarios.

Reservoir inflow temperatures were derived from the available record of observed data and averaged by month. The mean monthly inflow temperatures are then repeated for each study year. The inflow temperatures were further modified based on the computed change in mean annual air temperature, by climate-change scenario.

## A.4.5. Output Parameters

SRWQM results in daily averaged temperature results. The Reclamation Temperature Models provide monthly averaged results. In general, the following outputs are generated from the temperature models:

Reservoir temperature thermocline used to compute cold water pool volume in the reservoirs

River temperature at locations along the streams

TABLE A-2
Inputs Required for SRWQM Planning Analysis

| Input Type | Location | Description of the Input |
|---|---|---|
| Initial Storage | Trinity Lake | End-of-day storage to initialize reservoir storage condition at the start of the SRWQM run |
| | Whiskeytown Lake | |
| | Shasta Lake | |
| | Black Butte Reservoir | |
| Reservoir Inflows | Trinity Lake | Daily net inflow to reservoirs computed based on the reservoir inflow and the evaporation |
| | Lewiston Reservoir | |
| | Whiskeytown Lake | |
| | Shasta Lake | |
| | Black Butte Reservoir | |
| Tributary Inflows | Cottonwood Creek | Local unregulated tributary inflows |
| | Thomes Creek | |
| | Colusa Drain | |
| Distributed flows | Bend Bridge | Net inflows, accretions and depletions along the Sacramento River distributed along the River |
| | Lower River | |
| Outflow | Trinity Lake | Daily reservoir release specification |
| | Whiskeytown Lake | |
| | Shasta Lake | |
| | Black Butte Reservoir | |
| Diversions | Clear Creek Tunnel from Lewiston Reservoir | Inter-basin transfer reservoir releases |
| | Spring Creek Tunnel from Whiskeytown Lake | |
| | Anderson Cottonwood Irrigation District Canal | Lumped diversions along various reach of the River specified at point locations |
| | Tehama Colusa Canal | |
| | Glenn Colusa Canal | |
| | Miscellaneous Diversions above | |

TABLE A-2
Inputs Required for SRWQM Planning Analysis

| Input Type | Location | Description of the Input |
|---|---|---|
| | Ord | |
| | West Banks Diversions | |
| | Diversions near Colusa Weir | |
| | Lower River Diversions | |
| Meteorological Inputs including Equilibrium Temperature, Exchange Rate, Shortwave Radiation and Wind Speed | Entire Spatial Domain | Meteorological inputs on 6-hour time step derived primarily from Gerber gauging station. Calibration report provides more details (RMA, 2003). This dataset remains unchanged as long as the climate conditions are the same across the alternatives. |
| Inflow Temperatures | Reservoir and tributary inflows included in the model | Seasonal temperatures based on historical flows and temperatures. These inputs remain unchanged for all alternatives |
| Target Temperatures | Shasta Lake Tail Water | Seasonal temperature targets specified based on the end-of-May Shasta storage conditions |

TABLE A-3
Reclamation Temperature Model Nodes

| River or Creek System | Location |
|---|---|
| Trinity River | Lewiston Dam |
| | Douglas City |
| | North Fork |
| Feather River | Oroville Dam |
| | Fish Barrier Dam |
| | Upstream of Thermalito Afterbay |
| | Thermalito Afterbay Release |
| | Downstream of Thermalito Afterbay |
| | Gridley |
| | Honcut Creek |
| | Yuba River |
| | Bear River |
| | Nicolaus |

TABLE A-3
Reclamation Temperature Model Nodes

| River or Creek System | Location |
|---|---|
| | Nelson Slough |
| | Confluence |
| American River | Folsom Dam |
| | Nimbus Dam |
| | Sunrise Bridge |
| | Cordova Park |
| | Arden Rapids |
| | Watt Avenue Bridge |
| | American River Filtration Plant |
| | H Street |
| | 16th Street |
| | Confluence |
| Stanislaus River | New Melones Dam |
| | Tulloch Dam |
| | Goodwin Dam |
| | Knights Ferry |
| | Orange Blossom |
| | Oakdale |
| | Riverbank |
| | McHenry Bridge |
| | Ripon |
| | Confluence |

## A.4.6. Use of Model Results

Since the temperature models are driven by the operations simulated in CALSIM II on a monthly time step, typically the temperature results are presented on a monthly time step from both SRWQM and the Reclamation Temperature Models. Monthly flows and temperatures are unlikely to address the daily variability in the river temperatures, but reflect changes in the mean. The daily variability, around a changed mean, could be added to the monthly temperature results by scaling the historical daily temperature patterns to reflect the monthly means. However, this approach of incorporating daily variability does not account for the uncertainty associated with the daily flow conditions which are not included in the boundary flows used by the temperature models. Thus, while the models generate daily results they need to be interpreted with the understanding that the monthly changes are the most appropriate use of the modeling results.

## A.4.7. Modeling Limitations

The Reclamation temperature models operate on a monthly time-step. Mean monthly flows and temperatures do not define daily variations that could occur in the rivers due to dynamic flow and climatic conditions. It is important to note that even though SRWQM runs on a daily time step, it adheres to the CALSIM II in terms of the reservoir releases and other operations. Neither SRWQM nor the Reclamation temperature models alter operations to meet a temperature requirement downstream in the River. There is no feedback to CALSIM II to alter the operations, either. Using the daily results from SRWQM to check the compliance includes some uncertainty. Both SRWQM and the Reclamation temperature models perform selective temperature withdrawal based on the tail water temperature target and this may or may not meet the temperature requirement downstream in the River.

## A.4.8. Linkages to Other Physical Models

The Reservoir and River Temperature models require inputs for representative meteorological conditions, reservoir storage, reservoir release rates, tributary flows, and channel morphology. The output from the Reservoir and River Temperature models are sometimes used to evaluate performance of satisfying temperature requirements and refine the simulated project operation in CALSIM II. The temperature outputs are commonly used in the biological assessments of salmonid mortality.

# A.5. Delta Hydrodynamics and Water Quality

Hydrodynamics and water quality modeling is essential to understand the impact of proposed modifications to the morphology of the Delta and the operations of the CVP and SWP. Changes to the configuration of the Delta, restoration of tidal marsh, and project operations will influence the hydrodynamics and water quality conditions in the Delta. The analysis and understanding of the hydrodynamics and water quality changes as a result of these complex changes are critical in understanding the impacts to habitat, species and water users that depend on the Delta.

Large scale tidal marsh restoration and a north Delta diversion are two main components of the BDCP that can significantly alter the hydrodynamics in the Delta, along with the sea level rise which was inherent as part of all the BDCP/CWF Alternatives.

This document describes in detail the methodology used for simulating Delta hydrodynamics and water quality for evaluating the alternatives. It briefly describes the primary tool (DSM2) used in this process and any improvements. Additional detail is included in Section D and appropriate references are provided in here. The portions of the modeling that were performed elsewhere are only described briefly in this document with appropriate references included.

## A.5.1. Overview of Hydrodynamics and Water Quality Modeling Approach

Some of the Alternatives assume changes to the existing Delta morphology through the restoration of large acreages of tidal marshes in the Delta. Also, changes in sea level are assumed in the analysis of the future scenarios. These changes result in modified hydrodynamics and salinity transport in the Sacramento – San Joaquin Delta.

There are several tools available to simulate hydrodynamics and water quality in the Delta. Some tools simulate detailed processes, however are computationally intensive and have long runtimes. Other tools approximate certain processes and have short runtimes, while only compromising slightly on the accuracy of the results. For a planning analysis it is ideal to understand the resulting changes over several years such that it covers a range of hydrologic conditions. So, a tool which can simulate the changed hydrodynamics and water quality in the Delta accurately and that has short runtimes is desired. Delta Simulation Model (DSM2), a one-dimensional hydrodynamics and water quality model serves this purpose.

DSM2 has a limited ability to simulate two-dimensional features such as tidal marshes and three-dimensional processes such as gravitational circulation which is known to increase with sea level rise in the estuaries. Therefore, it is imperative that DSM2 be recalibrated or corroborated based on a dataset that accurately represents the conditions in the Delta under restoration and sea level rise. Since the proposed conditions are hypothetical, the best available approach to estimate the Delta hydrodynamics would be to simulate higher dimensional models which can resolve the two- and three-dimensional processes well. These models would generate the data sets needed to corroborate or recalibrate DSM2 under the proposed conditions so that it can simulate the hydrodynamics and salinity transport with reasonable accuracy.

Figure A-10 shows a schematic of how the hydrodynamics and water quality modeling is formulated for BDCP. UnTRIM Bay-Delta Model (MacWilliams et al., 2009), a three-dimensional hydrodynamics and water quality model was used to simulate the sea level rise effects on hydrodynamics and salinity transport under the historical operations in the Delta.

UnTrim modeling is described in Section D.7. RMA Bay-Delta Model (RMA, 2005), a two-dimensional hydrodynamics and water quality model was used to simulate tidal marsh restoration effects with and without sea level rise on hydrodynamics and salinity transport under the historic operations. RMA modeling is described in Section D.6. The results from the UnTRIM model were used to corroborate RMA and DSM2 models so that they simulate the effect of sea level rise accurately. The results from the RMA model were used to corroborate DSM2 so that it can simulate the effect of tidal marsh restoration with and without sea level rise accurately. The corroboration process and the results are presented in Section D.8.

The corroborated DSM2 was used to simulate hydrodynamics and water quality in the Delta by integrating the tidal marsh restoration and sea level rise effects over a 16-year period (WY 1976 – 1991), using the hydrological inputs and exports determined by CALSIM II under the projected operations. It was also used to retrain ANNs that can emulate modified flow-salinity relationship.

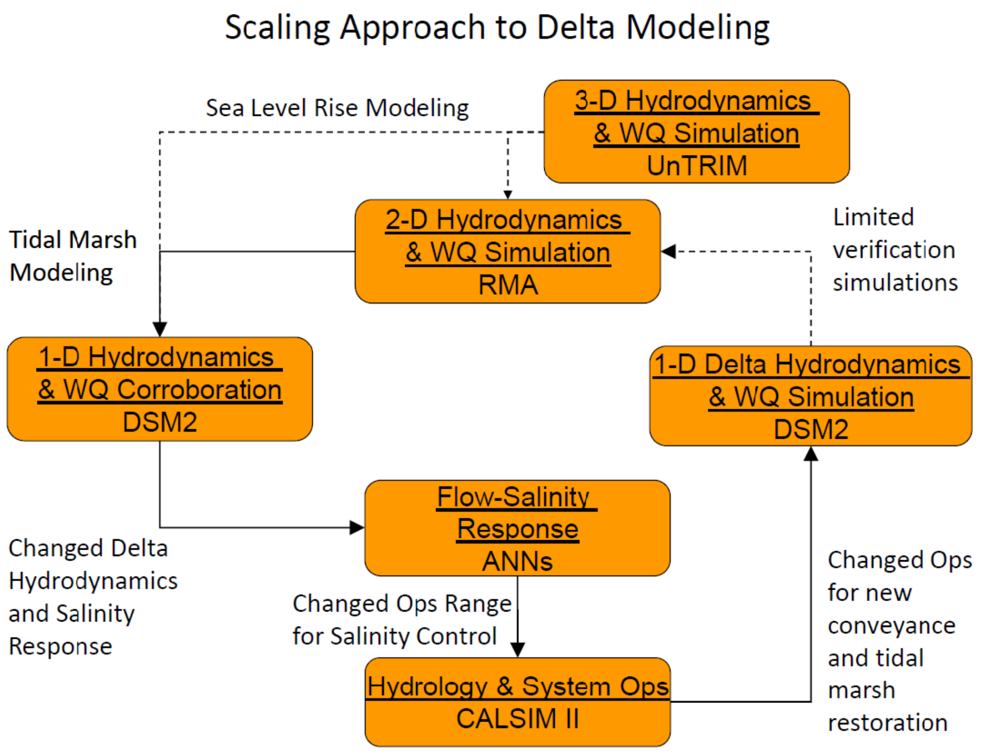


Figure A-10: Hydrodynamics and Water Quality Modeling Approach used in the BDCP

## A.5.2. Delta Simulation Model (DSM2)

DSM2 is a one-dimensional hydrodynamics, water quality and particle tracking simulation model used to simulate hydrodynamics, water quality, and particle tracking in the Sacramento-San Joaquin Delta (Anderson and Mierzwa, 2002). DSM2 represents the best available planning model for Delta tidal hydraulics and salinity modeling. It is appropriate for describing the existing conditions in the Delta, as well as performing simulations for the assessment of incremental environmental impacts caused by future facilities and operations. The DSM2 model has three separate components: HYDRO, QUAL, and PTM. HYDRO simulates one-dimensional hydrodynamics including flows, velocities, depth, and water surface elevations. HYDRO provides the flow input for QUAL and PTM. QUAL simulates one-dimensional fate and transport of conservative and non-conservative water quality constituents given a flow field simulated by HYDRO. PTM simulates pseudo 3-D transport of neutrally buoyant particles based on the flow field simulated by HYDRO.

DSM2 v8.0.4 was used in modeling of the BDCP Existing Conditions, No Action Alternative and the other Alternatives. The v8 of the DSM2 includes several enhancements compared to the v6 such as improved data management, increased speed and robustness, ability to simulate gates with multiple structures and the ability to specify Operating Rules in the HYDRO module. The Operating Rules form a powerful tool which triggers changes in gate operations or source/sink flow boundaries while model is running, based on the current value of a state variable (flow, stage or velocity), pre-specified timeseries or the simulation timestep.

DSM2 hydrodynamics and salinity (EC) were initially calibrated in 1997(DWR, 1997). In 2000, a group of agencies, water users, and stakeholders recalibrated and validated DSM2 in an open process resulting in a model that could replicate the observed data more closely than the 1997 version (DSM2PWT, 2001). In 2009, CH2M HILL performed a calibration and validation of DSM2 by including the flooded Liberty Island in the DSM2 grid, which allowed for an improved simulation of tidal hydraulics and EC transport in DSM2 (CH2M HILL, 2009). Technical report documenting this calibration effort is included in Section D.5. The model used for evaluating the BDCP scenarios was based on this latest calibration.

Simulation of Dissolved Organic Carbon (DOC) transport in DSM2 was successfully validated in 2001 by DWR (Pandey, 2001). The temperature and Dissolved Oxygen calibration was initially performed in 2003 by DWR (Rajbhandari, 2003). Recent effort by RMA in 2009 allowed for improved calibration of temperature, DO and the nutrients transport in DSM2.

### DSM2-HYDRO

The HYDRO module is a one-dimensional, implicit, unsteady, open channel flow model that DWR developed from FOURPT, a four-point finite difference model originally developed by the USGS in Reston, Virginia. DWR adapted the model to the Delta by revising the input-output system, including open water elements, and incorporating water project facilities, such as gates, barriers, and the Clifton Court Forebay. HYDRO simulates water surface elevations, velocities and flows in the Delta channels (Nader-Tehrani, 1998). HYDRO provides the flow input necessary for QUAL and PTM modules.

The HYDRO module solves the continuity and momentum equations fully implicitly. These partial differential equations are solved using a finite difference scheme requiring four points of computation. The equations are integrated in time and space, which leads to a solution of stage and flow at the computational points. HYDRO enforces an "equal stage" boundary condition for all the channels connected to a junction. The model can handle both irregular cross-sections derived from the bathymetric surveys and trapezoidal cross-sections. Even though, the model formulation includes a baroclinic term, the density is held constant, generally, in the HYDRO simulations.

HYDRO allows the simulation of hydraulic gates in the channels. A gate may have a number of associated hydraulic structures such as radial gates, flash boards, boat ramps etc., each of which may be operated independently to control flow. Gates can be placed either at the upstream or downstream end of a channel. Once the location of a gate is defined, the boundary condition for the gated channel is modified from "equal stage" to "known flow," with the calculated flow. The gates can be opened or closed in one or both directions by specifying a coefficient of zero or one.

Reservoirs are used to represent open bodies of water that store flow. Reservoirs are treated as vertical walled tanks in DSM2, with a known surface area and bottom elevation and are considered instantly well-mixed. The flow interaction between the open water area and one or more of the connecting channels is determined using the general orifice formula. The flow in and out of the reservoir is controlled using the flow coefficient in the orifice equation, which can be different in each direction. DSM2 does not allow the cross-sectional area of the inlet to vary with the water level.

DSM2v8 includes a new feature called "operating rules" using which the gate operations or the flow boundaries can be modified dynamically when the model is running based on the current value of a state variable (flow, stage or velocity). The change can also be triggered based on a timeseries that's not currently simulated in the model (e.g. daily averaged EC) or based on the current timestep of the simulation (e.g. a change can occur at the end of the day or end of the season). The operating rules include many functions which allow derivation of the quantities to be used as trigger, from the model data or outside timeseries data. Operating rules allow a change or an action to occur when the trigger value changes from false to true.

### DSM2-QUAL

The QUAL module is a one-dimensional water quality transport model that DWR adapted from the Branched Lagrangian Transport Model originally developed by the USGS in Reston, Virginia. DWR added many enhancements to the QUAL module, such as open water areas and gates. A Lagrangian feature in the formulation eliminates the numerical dispersion that is inherently in other segmented formulations, although the tidal dispersion coefficients must still be specified. QUAL simulates fate and transport of conservative and non-conservative water quality constituents given a flow field simulated by HYDRO. It can calculate mass transport processes for conservative and non-conservative constituents including salts, water temperature, nutrients, dissolved oxygen, and trihalomethane formation potential.

The main processes contributing to the fate and transport of the constituents include flow dependent advection and tidal dispersion in the longitudinal direction. Mass balance equations are solved for all quality constituents in each parcel of water using the tidal flows and volumes calculated by the HYDRO module. Additional information and the equations used are specified in the 19th annual progress report by DWR (Rajbhandari, 1998).

The QUAL module is also used to simulate source water finger printing which allows determining the relative contributions of water sources to the volume at any specified location. It is also used to simulate constituent finger printing which determines the relative contributions of conservative constituent sources to the concentration at any specified location. For fingerprinting studies, six main sources are typically tracked: Sacramento River, San Joaquin River, Martinez, eastside streams (Mokelumne, Cosumnes and Calaveras combined), agricultural drains (all combined), and Yolo Bypass. For source water fingerprinting a tracer with constant concentration is assumed for each source tracked, while keeping the concentrations at other inflows as zero. For constituent (e.g., EC) fingerprinting analysis, the concentrations of the desired constituent is specified at each tracked source, while keeping the concentrations at other inflows as zero (Anderson, 2003).

### DSM2 Input Requirements

DSM2 requires input assumptions relating to physical description of the system (e.g. Delta channel, marsh, and island configuration), description of flow control structures such as gates, initial estimates for stage, flow and EC throughout the Delta, and time-varying input for all boundary river flows and exports, tidal boundary conditions, gate operations, and constituent concentrations at each inflow. Figure A-11 illustrates the hydrodynamic and water quality boundary conditions required in DSM2. For long-term planning simulations, output from the CALSIM II model generally provides the necessary input for the river flows and exports.

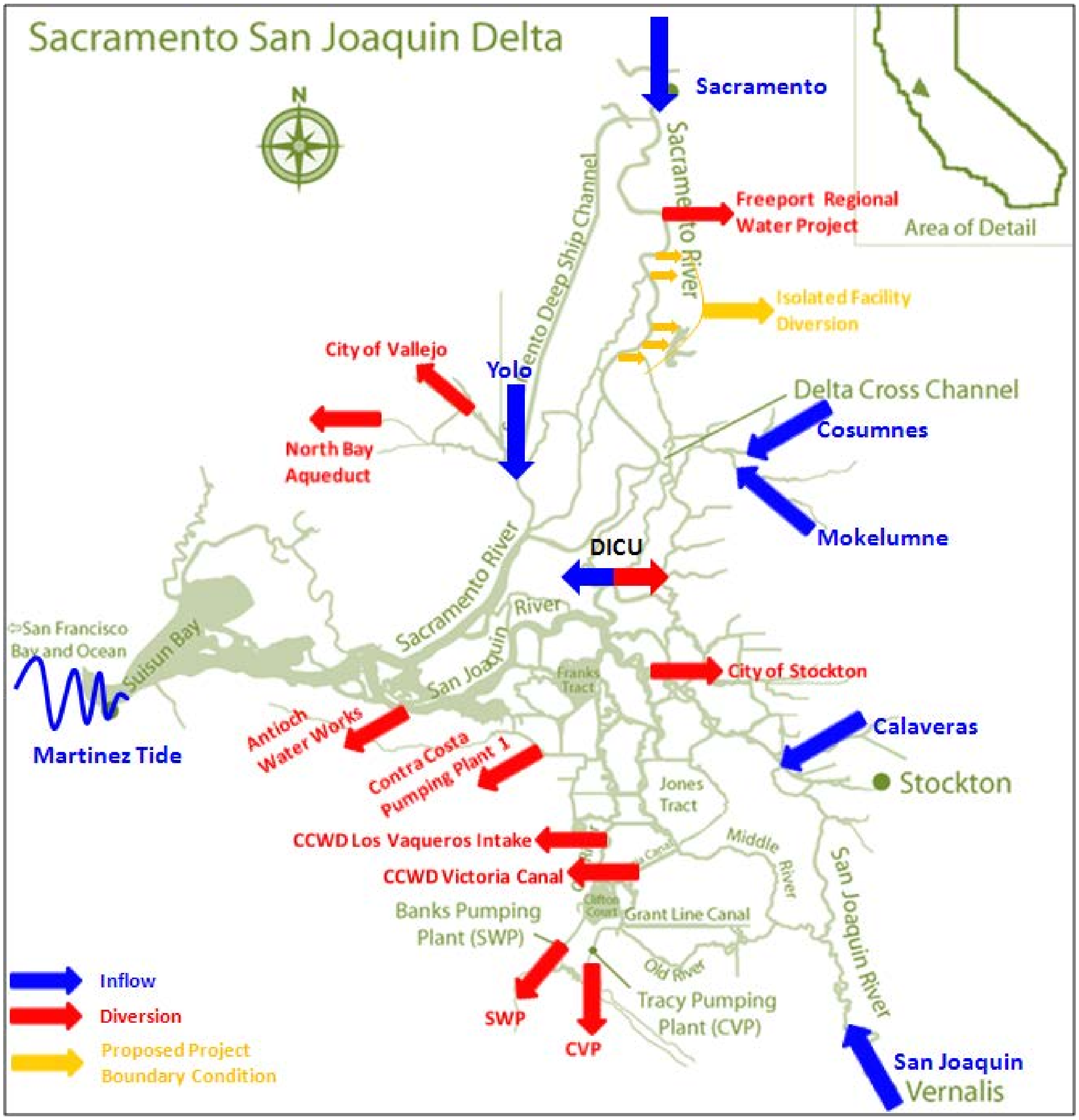


Figure A-11: Hydrodynamic and Water Quality Boundary Conditions in DSM2

For long-term planning simulations, output from the CALSIM II model generally provides the necessary input for the river flows and exports. Assumptions relating to Delta configuration and gate operations are directly input into the hydrodynamic models. Adjusted astronomical tide (Ateljevich, 2001a) normalized for sea level rise (Ateljevich and Yu, 2007) is forced at Martinez boundary. Constituent concentrations are specified at the inflow boundaries, which are either estimated from historical information or CALSIM II results. EC boundary condition at Vernalis location is derived from the CALSIM II results. Martinez EC boundary condition is derived based on the simulated net Delta outflow from CALSIM II and using a modified G-model (Atljevich, 2001b).

The major hydrodynamic boundary conditions are listed in Table A-4 and the locations at which constituent concentrations are specified for the water quality model are listed in Table A-5.

TABLE A-4
DSM2 HYDRO Boundary Conditions

| Boundary Condition | Location/Control Structure | Typical Temporal Resolution |
|---|---|---|
| Tide | Martinez | 15min |
| Delta Inflows | Sacramento River at Freeport | 1day |
| | San Joaquin River at Vernalis | 1day |
| | Eastside Streams (Mokelumne and Cosumnes Rivers) | 1day |
| | Calaveras River | 1day |
| | Yolo Bypass | 1day |
| Delta Exports/Diversions | Banks Pumping Plant (SWP) | 1day |
| | Jones Pumping Plant (CVP) | 1day |
| | Contra Costa Water District Diversions at Rock Slough, Old River at Highway 4 and Victoria Canal | 1day |
| | North Bay Aqueduct | 1day |
| | City of Vallejo | 1day |
| | Antioch Water Works | 1day |
| | Freeport Regional Water Project | 1day |
| | City of Stockton | 1day |
| | Isolated Facility Diversion | 1day |
| Delta Island Consumptive Use | Diversion | 1mon |
| | Seepage | 1mon |

TABLE A-4
DSM2 HYDRO Boundary Conditions

| Boundary Condition | Location/Control Structure | Typical Temporal Resolution |
|---|---|---|
| | Drainage | 1mon |
| Gate Operations | Delta Cross Channel | Irregular Timeseries |
| | South Delta Temporary Barriers | dynamically operated on 15min |
| | Montezuma Salinity Control Gate | dynamically operated on 15min |

TABLE A-5
DSM2 QUAL Boundary Conditions Typically used in a Salinity Simulation

| Boundary Condition | Location/Control Structure | Typical Temporal Resolution |
|---|---|---|
| Ocean Salinity | Martinez | 15min |
| Delta Inflows | Sacramento River at Freeport | Constant |
| | San Joaquin River at Vernalis | 1mon |
| | Eastside Streams (Mokelumne and Cosumnes Rivers) | Constant |
| | Calaveras River | Constant |
| | Yolo Bypass | Constant |
| Delta Island Consumptive Use | Drainage | 1mon (repeated each year) |

Notes: For other water quality constituents, concentrations are required at the same locations

## A.5.3. Application of DSM2 to Evaluate BDCP Alternatives

Several long-term planning analyses used DSM2 to evaluate Delta hydrodynamics and water quality, in the past. In those studies, DSM2 was run for a 16-year[1] period from WY1976 to WY1991, on a 15-min timestep. Typically the inputs needed for DSM2 – inflows, exports, and Delta Cross Channel (DCC) gate operations were provided by the 82-year CALSIM II simulations. The tidal boundary condition at Martinez was provided by an adjusted astronomical tide (Ateljevich and Yu, 2007). Monthly Delta channel depletions (i.e., diversions,

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[1] Model simulation period for DSM2 is further described in *Section D-12. DSM2 16 Year Planning Simulation versus 82Year Planning Simulation*. This section includes a technical memorandum prepared by DWR comparing and contrasting the DSM2 planning simulations performed over the 16 year period versus the 82 year period.

seepage and drainage) were estimated using DWR's Delta Island Consumptive Use (DICU) model (Mahadevan, 1995).

CALSIM II provides monthly inflows and exports in the Delta. Traditionally, the Sacramento and San Joaquin River inflows are disaggregated to a daily time step for use in DSM2 either by applying rational histosplines, or by assuming that the monthly average flow as constant over the whole month. The splines allow a smooth transition between the months. The smoothing reduces sharp transitions at the start of the month, but still results in constant flows for most of the month. Other inflows, exports and diversions were assumed to be constant over the month.

Delta Cross Channel gate operation input in DSM2 is based on CALSIM II output. For each month, DSM2 assumes the DCC gates are open for the "number of the days open" simulated in CALSIM II, from the start of the month.

The operation of the south Delta Temporary Barriers, if included in the model is determined dynamically in using the operating rules feature in DSM2. These operations generally depend on the season, San Joaquin River flow at Vernalis and tidal condition in the south Delta. Similarly, the Montezuma Slough Salinity Control Gate operations are determined using an operating rule that sets the operations based on the season, Martinez salinity and tidal condition in the Montezuma Slough.

For salinity, EC at Martinez is estimated using the G-model on a 15-min timestep, based on the Delta outflow simulated in CALSIM II and the pure astronomical tide at Martinez (Ateljevich, 2001a). The monthly averaged EC for the San Joaquin River at Vernalis estimated in CALSIM II for the 82-year period is used in DSM2. For other river flows, which have low salinity, constant values are assumed. Monthly average values of the EC associated with Delta agricultural drainage and return flows was estimated for three regions in the Delta based on observed data identifying the seasonal trend. These values are repeated for each year of the simulation.

For BDCP, several enhancements were incorporated in the planning analysis approach traditionally used for DSM2. Some of the changes were to address the assumptions for BDCP while the others are improvements which make the DSM2 planning simulations more realistic.

The changes that are based on the BDCP assumptions include modifications to DSM2 to capture the effect of sea level rise, tidal marsh restoration with and without sea level rise, and north Delta diversion intakes. The DSM2 models incorporating above changes were used in developing new ANNs for CALSIM II.

The other enhancement is with regard to the flow boundary conditions used in DSM2. As described above, traditional approach does not represent the variability that would exist in the Delta inflows within a month. Since CALSIM II, from which the boundary flows are derived is a monthly time step model, a new approach was developed to incorporate daily variability in the DSM2 boundary flows using the monthly results from CALSIM II.

The following sections describe in detail various enhancements and changes made to the DSM2 hydrodynamics, salinity and nutrient modeling methods as part of the BDCP analyses.

### Changes to the DSM2 Grid

DSM2 model grid from the 2009 recalibration (CH2M HILL, 2009) was further modified in the north Delta to locate the DSM2 nodes at the proposed north Delta diversion intake locations as agreed on January 29th BDCP Steering Committee meeting. Two new nodes and two new channels are added to the grid and several existing nodes were relocated and channel lengths were modified in the reach upstream of Delta Cross Channel. Figure A-12 shows the grid used in the baseline models for BDCP. The DSM2 grid includes several other changes related to the north Delta diversion intakes and the tidal marsh restoration. DSM2 grids representing various BDCP Alternatives are included in Section D.11.

### Incorporation of Daily Hydrologic Inputs to DSM2

DSM2 is simulated on a 15-minute time step to address the changing tidal dynamics of the Delta system. However, the boundary flows are typically provided from monthly CALSIM II results. In all previous planning-level evaluations, the DSM2 boundary flow inputs were applied on a daily time step but used constant flows equivalent to the monthly average CALSIM II flows except at month transitions.

As shown in Figures A-6 and A-7, Sacramento River flow at Freeport exhibits significant daily variability around the monthly mean in the winter and spring period in the most water year types. The winter-spring daily variability is deemed important to species of concern. In an effort to better represent the sub-monthly flow variability, particularly in early winter, a monthly-to-daily flow mapping technique is applied to the boundary flow inputs to DSM2. The daily mapping approach used in CALSIM II and DSM2 are consistent. The incorporation of daily mapping in CALSIM II is described in the Section A.3.3. A detailed description of the implementation of the daily variability in DSM2 boundary conditions is provided in Section D.9.

It is important to note that this daily mapping approach does not in any way represent the flows that would result from any operational responses on a daily time step. It is simply a technique to incorporate representative daily variability into the flows resulting from CALSIM II's monthly operational decisions.

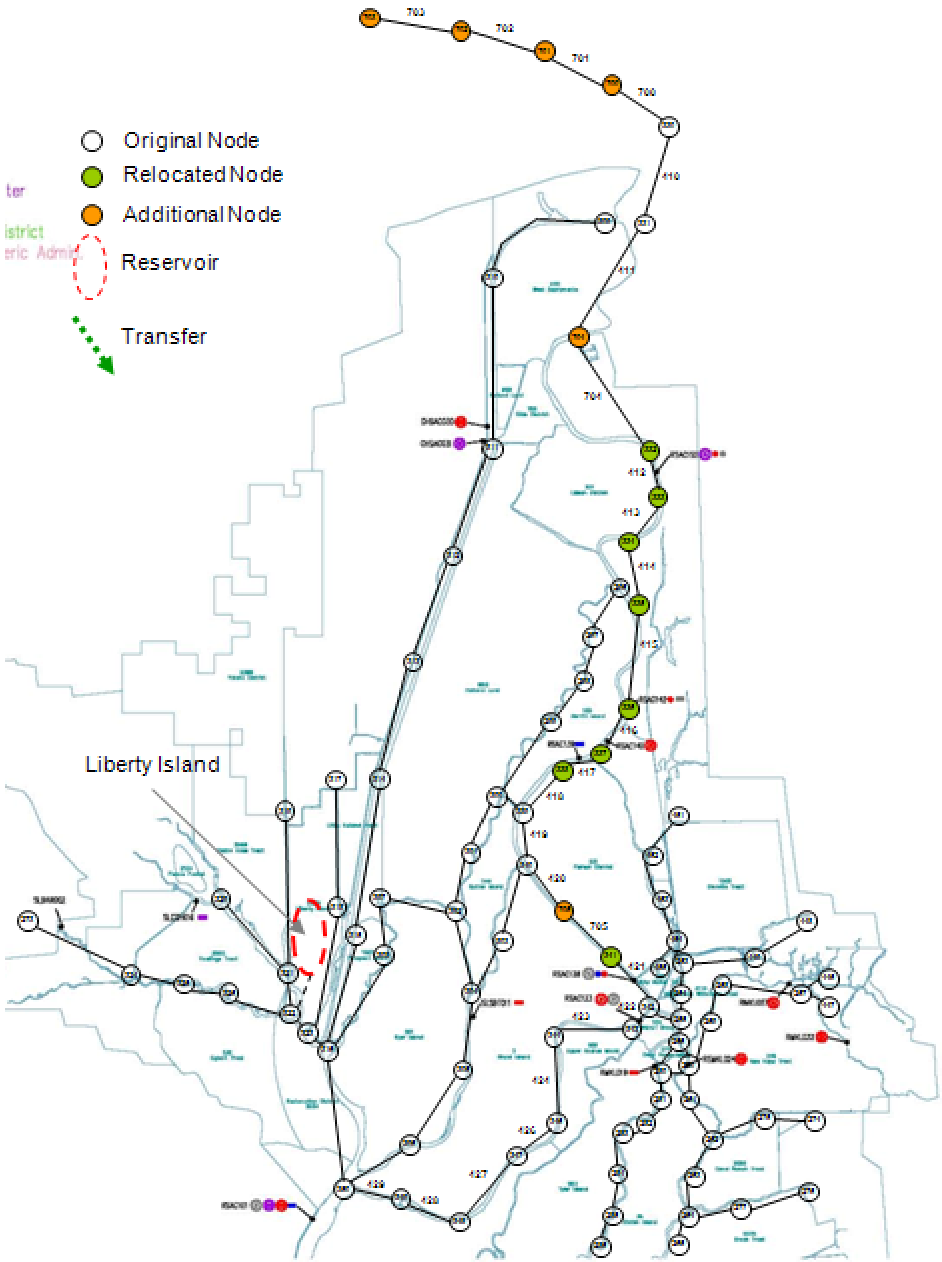


Figure A-12: North Delta DSM2 grid used in the BDCP Modeling (NOTE: Intake locations slightly modified in Chapter 3: Description of Alternatives)

## Incorporating Tidal Marsh Restoration and Sea Level Rise Effects in DSM2 Planning Simulations

The effects of sea level rise were determined from the UNTRIM Bay-Delta model and the effects of tidal marsh restoration were determined from the RMA Bay-Delta model. DSM2 model results were corroborated for the effects of sea level rise and tidal marsh restoration using the UnTRIM and RMA model results. Detailed descriptions of the UnTRIM modeling of the sea level rise scenarios, RMA modeling of the tidal marsh restoration, and DSM2 corroboration are included in the Sections D.7, D.6 and D.8, respectively.

Using the corroboration described above described, seven (7) separate DSM2 grid configurations and model setups were prepared for use in the planning simulations for the Alternatives. Each configuration corresponds to one combination of sea level rise and restoration scenario.

Using the results from the RMA current conditions and tidal marsh models, three sets of regression relationships were developed to estimate the stage and EC at Martinez location for the 14,000ac (NT), 25,000ac (ELT) and 65,000ac (LLT) restoration scenarios based on the baseline stage and EC at Martinez. Similarly, using the results from the UnTRIM models, two sets of correlations were developed to compute the resulting stage and EC at Martinez location for the 15cm (ELT) and 45cm (LLT) sea level rise scenarios.

Based on the RMA integrated tidal marsh and sea level rise scenarios, two sets of correlations were developed for estimating Martinez stage and EC resulting for the 25,000ac restoration under 15cm sea level rise (ELT) and for the 65,000ac restoration under 45cm sea level rise (LLT) scenarios.

Table A-6 shows the Martinez stage and EC correlations for these seven (7) scenarios described above. It also shows the lag in minutes between the baseline stage or EC and the resulting stage or EC under the scenario with sea level rise and/or restoration. The regressed baseline stage or EC timeseries needs to be shifted by the lag time noted in the Table A-6.

Accurate effects of the tidal marsh restoration and sea level rise are incorporated in DSM2 simulations for the Alternatives in two ways. First, by incorporating consistent grid configuration and model setup identified in corroboration process into the DSM2 model for the selected Alternative, based on the tidal marsh restoration acreage and sea level rise assumptions selected for the Alternative. Second, by modifying the downstream stage and EC boundary conditions at Martinez in the DSM2 model inputs using the regression relationships identified in the corroboration process for the selected restoration and sea level rise assumptions.

As noted earlier, adjusted astronomical tide at Martinez is used as the downstream stage boundary in the DSM2 planning simulation representing current Delta configuration without any sea level rise or tidal marsh restoration. This stage timeseries is modified using one of the stage correlation equations identified in Table A-6 for use in a planning simulation with either restoration or sea level rise or both.

The EC boundary condition in a DSM2 planning simulation is estimated using the G-model based on the monthly net Delta outflow simulated in CALSIM II and the pure astronomical tide (Ateljevich, 2001b). Even though the rim flows and exports are patterned on a daily step in DSM2, the operational decisions are still on a monthly timestep. This means that the net Delta outflow may or may not meets the standards on a daily timestep. Therefore, to estimate the EC boundary condition at Martinez, monthly net Delta outflow simulated in CALSIM II is used. For a planning simulation with either restoration or sea level rise or both, EC timeseries from the G-model is regressed using one of the EC correlations listed in Table A-6 to account for the anticipated changes at Martinez.

TABLE A-6
Correlations to Transform Baseline Martinez Stage and EC for use in DSM2 BDCP Planning Runs with Tidal Marsh Restoration, Sea Level Rise or both Restoration and Sea Level Rise

| **Scenario** | **Martinez Stage (ft NGVD 29)** | | **Martinez EC (µS/cm)** | |
|---|---|---|---|---|
| | **Correlation** | **Lag (min)** | **Correlation** | **Lag (min)** |
| NT (14,000ac) | Y = 0.966 * X + 0.04 | -3 | Y = 1.001 * X + 191.5 | 8 |
| ELT (25,000ac) | Y = 0.964 * X + 0.04 | -4 | Y = 0.999 * X + 114.7 | 10 |
| LLT (65,000ac) | Y = 0.943 * X + 0.06 | -3 | Y = 0.996 * X + 68.2 | 13 |
| 15cm SLR | Y = 1.0033*X + .47 | -1 | Y = 0.9954* X + 556.3 | 0 |
| 45cm SLR | Y = 1.0113*X + 1.4 | -2 | Y = 0.98* X + 1778.9 | -2 |
| ELT (25,000ac &15cm SLR) | Y = 0.968 * X + 0.5 | -5 | Y = 0.999 * X + 357.78 | 9 |
| LLT (65,000ac & 45cm SLR) | Y = 0.958 * X + 1.49 | -9 | Y = 1.002 * X + 1046.3 | 11 |

Notes: X = Baseline Martinez stage or EC and Y = Scenario Martinez stage or EC

## ANN Retraining

ANNs are used for flow-salinity relationships in CALSIM II. They are trained on DSM2 outputs and therefore, emulate DSM2 results. ANN requires retraining whenever the flow – salinity relationship in the Delta changes. BDCP analysis assumes different restoration acreages at NT, ELT and LLT phases. In addition it includes 15cm and 45cm sea level rise at ELT and LLT, respectively. Each combination of restoration and sea level condition results in a different flow – salinity relationship in the Delta and therefore require a new ANN. Table A-7 lists the ANNs developed and used as part of the BDCP analysis.

DWR Bay-Delta Modeling staff has retrained the ANNs for each scenario. ANN retraining process involved following steps:

- Corroboration of the DSM2 model for each scenario as described above
- Range of example long-term CALSIM II scenarios to provide range of boundary conditions for DSM2 models
- Using the grid configuration and the correlations from the corroboration process several 16-year planning runs are simulated based on the boundary conditions from the identified CALSIM II scenarios to create a training dataset for each new ANN
- ANNs are trained using the Delta flows and DCC operations from CALSIM II, EC results from DSM2and the Martinez tide

- The training dataset is divided into two parts. One is used for training the ANN and the other to validate
- Once the ANN is ready a full circle analysis is performed to assess the performance of the ANN

Detailed description of the ANN training procedure and the full circle analysis is provided in DWR's 2007 annual report (Seneviratne and Wu, 2007).

TABLE A-7
List of ANNs Developed and Used in the BDCP Modeling

| ANN | Description | Reference DSM2 Model |
|---|---|---|
| BST_noSLR_111709 | Represents current Delta configuration with no sea level rise | 2009 DSM2 Recalibration |
| BDCP_ROA0ac_SLR15cm_16Mar2010 | Represents current Delta configuration with 15cm sea level rise | DSM2 model corroborated with UnTRIM results for 15cm sea level rise case |
| BDCP_ROA0ac_SLR45cm_18Mar2010 | Represents current Delta configuration with 45cm sea level rise | DSM2 model corroborated with UnTRIM results for 45cm sea level rise case |
| BDCP_ROA14Kac_SLR0cm_22Dec2009 | Represents 14000ac tidal marsh restoration assumed, with no sea level rise | DSM2 model corroborated with RMA results for 14,000ac restoration proposed for NT phase |
| BDCP_ROA25Kac_SLR0cm_29Dec2009 | Represents 25000ac tidal marsh restoration assumed, with no sea level rise | DSM2 model corroborated with RMA results for 25,000ac restoration proposed for ELT phase |
| BDCP_ROA65Kac_SLR0cm_30Mar2010 | Represents 65000ac tidal marsh restoration assumed, with no sea level rise | DSM2 model corroborated with RMA results for 65,000ac restoration proposed for LLT phase |
| BDCP_ROA25Kac_SLR15cm_14Apr2010 | Represents 25000ac tidal marsh restoration assumed, with 15cm sea level rise | DSM2 model corroborated with RMA results for 25,000ac restoration proposed for ELT phase under 15cm sea level rise |
| BDCP_ROA65Kac_SLR45cm_30Mar2010 | Represents 65000ac tidal marsh restoration assumed, with 45cm sea level rise | DSM2 model corroborated with RMA results for 65,000ac restoration proposed for LLT phase under 45cm sea level rise |

## North Delta Diversion Operations

As described in Section A.3.3, several Alternatives include new intakes on Sacramento River upstream of Sutter Slough, in the north Delta. The diversions at the intakes are governed by the bypass rules. The bypass rules are simulated in CALSIM II using daily mapped Sacramento River flow, which provides the maximum potential diversion that can occur in the north Delta for each day. CALSIM II uses the monthly average of this daily potential diversion as one of the constraints in determining the final monthly north Delta diversion. For use in DSM2, the monthly diversion output for the north Delta intakes is mapped onto the daily pattern of the potential diversion estimated in CALSIM II.

In DSM2 diversion at each intake is determined on a 15 min timestep, subject to sweeping velocity criteria so that the fish migrating past the fish screens do not impinge on them. For BDCP, Delta Smelt criterion of 0.4fps, required by DFG (DFG, 2009) is used in determining whether or not water can be diverted at an intake. The intake operations are also subjected to ramping rates that are required to shut off or start the pumps. The current design allows ramping up or down the pumps between 0 and 3,000cfs in less than an hour. These criteria cannot be simulated in CALSIM II. They are dynamically simulated using the operating rules feature in DSM2.

The north Delta diversion operating rule in the DSM2 allows diverting up to the amount specified by CALSIM II each day while subjecting each intake to the sweeping velocity and the ramping criteria. The intakes are operated as long as the daily diversion volume specified by CALSIM II is not met. Once the specified volume is diverted for the day, the pumps are shut off until next day.

The volume corresponding to first 100cfs per intake (for five intakes 500 cfs) of the daily north Delta diversion specified by CALSIM II is diverted equally at all the intakes included for the Alternative. The remaining volume for the day will be diverted such that operation of the upstream intakes is prioritized over the downstream intakes. Intake diversions are ramped over an hour to allow smooth transitions when they are turned on and off.

In the current modeling of the Alternatives, the diversion flow at an intake for each time step is estimated assuming that the remaining diversion volume in a day would have to be diverted in one time step at the upstream-most intake first and immediate downstream one next and so on until the daily specified total is diverted. However, the estimated amount of diversion at each intake is only diverted when the velocity measured just downstream of the DSM2 diversion node is greater than or equal to 0.4fps. If in any time step this criteria is violated then the diversion occurs in a future time step when the velocity is above 0.4fps or may occur at a different intake. The sweeping velocity criterion is measured at 1000ft downstream from the diversion node in DSM2 to minimize potential instabilities in the model. Even though DSM2 produces a cross-sectional averaged velocity, it is not corrected for the velocity profile across the cross-section as the actual screen location is still uncertain.

New channels, transfers and a reservoir are added to the DSM2 grid to simulate up to five (5) north Delta diversion intakes as shown in the Figure A-13. Five channels, 601 – 605, divert water off the Sacramento River and transfer to channel 607 and 608, from where the total diverted water is transferred to a new reservoir (IF_FOREBAY). Figure A-14 shows an example timeseries of sweeping velocities and the diversions at each intake. The plot shows how the intakes are ramped up and down when the velocity falls below 0.4 ft/s.

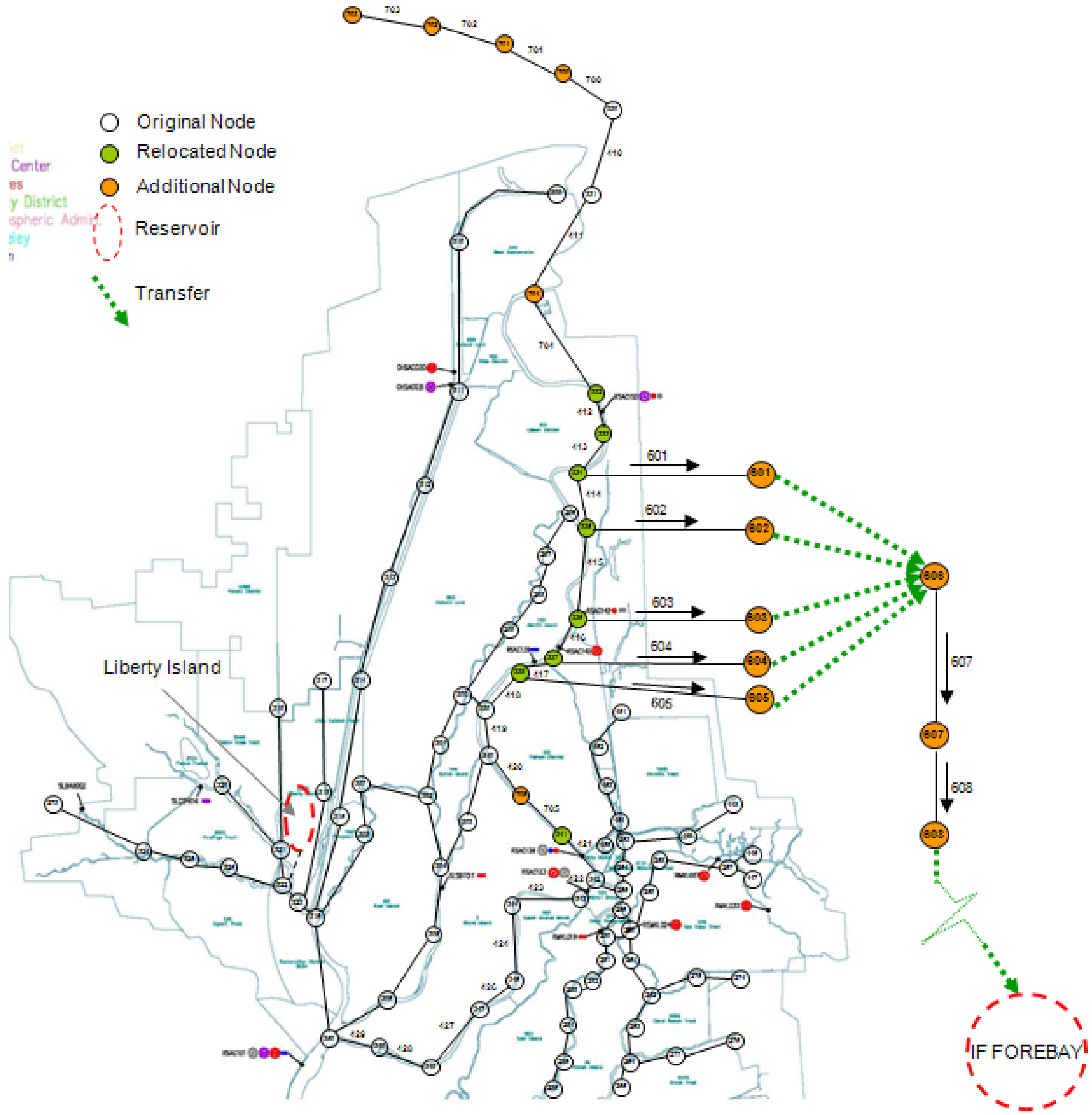


Figure A-13: North Delta DSM2 Grid Modifications for Simulating North Delta Diversions

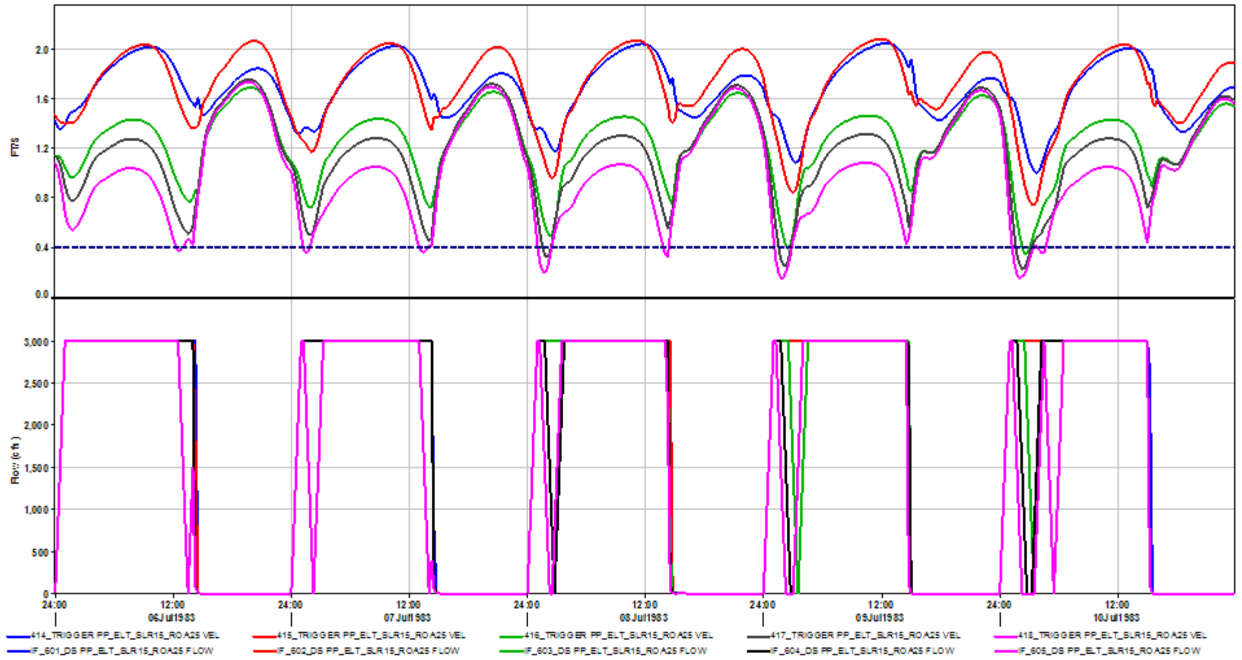


Figure A-14: An Example of Sweeping Velocity and the Diversion at the Five Intakes Simulated in DSM2

## A.5.4. Output Parameters

DSM2 HYDRO provides the following outputs on a 15-minute time step:

Tidal flow

Tidal stage

Tidal velocity

Following variables can be derived from the above outputs:

Net flows

Mean sea level, mean higher high water, mean lower low water and tidal range

Water depth

Tidal reversals

Flow splits, etc.

DSM2 QUAL provides the following outputs on a 15-minute time step:

Salinity (EC)

DOC

Source water and constituent fingerprinting

Following variables can be derived from the above QUAL outputs:

Bromide, chloride, and total dissolved solids

Selenium and mercury

In a planning analysis, the flow boundary conditions that drive DSM2 are obtained from the monthly CALSIM II model. The agricultural diversions, return flows and corresponding salinities used in DSM2 are on a monthly time step. The implementation of Delta Cross Channel gate operations in DSM2 assumes that the gates are open from the beginning of a month, irrespective of the water quality needs in the south Delta.

The input assumptions stated above should be considered when DSM2 EC results are used to evaluate performance of a baseline or an alternative against the standards. Even though CALSIM II releases sufficient flow to meet the standards on a monthly average basis, the resulting EC from DSM2 may be over the standard for part of a month and under the standard for part of the month, depending on the spring/neap tide and other factors (e.g. simplification of operations). It is recommended that the results are presented on a monthly basis. Frequency of compliance with a criterion should be computed based on monthly average results. Averaging on a sub-monthly (14-day or more) scale may be appropriate as long as the limitations with respect to the compliance of the baseline model are described in detail and the alternative results are presented as an incremental change from the baseline model. A detailed discussion is required in this case.

In general, it is appropriate to present DSM2 QUAL results including EC, DOC, volumetric fingerprinting and constituent fingerprinting on a monthly time step. When comparing results from two scenarios, computing differences based on these mean monthly statistics would be appropriate.

## A.5.5. Modeling Limitations

DSM2 is a 1D model with inherent limitations in simulating hydrodynamic and transport processes in a complex estuarine environment such as the Sacramento – San Joaquin Delta. DSM2 assumes that velocity in a channel can be adequately represented by a single average velocity over the channel cross-section, meaning that variations both across the width of the channel and through the water column are negligible. DSM2 does not have the ability to model short-circuiting of flow through a reach, where a majority of the flow in a cross-section is confined to a small portion of the cross-section. DSM2 does not conserve momentum at the channel junctions and does not model the secondary currents in a channel. DSM2 also does not explicitly account for dispersion due to flow accelerating through channel bends. It cannot model the vertical salinity stratification in the channels.

It has inherent limitations in simulating the hydrodynamics related to the open water areas. Since a reservoir surface area is constant in DSM2, it impacts the stage in the reservoir and thereby impacting the flow exchange with the adjoining channel. Due to the inability to change the cross-sectional area of the reservoir inlets with changing water surface elevation, the final entrance and exit coefficients were fine tuned to match a median flow range. This causes errors in the flow exchange at breaches during the extreme spring and neap tides. Using an arbitrary bottom elevation value for the reservoirs representing the proposed marsh areas to get around the wetting-drying limitation of DSM2 may increase the dilution of salinity in the reservoirs. Accurate representation of RMA’s tidal marsh areas, bottom elevations, location of breaches, breach widths, cross-sections, and boundary conditions in DSM2 is critical to the agreement of corroboration results.

For open water bodies DSM2 assumes uniform and instantaneous mixing over entire open water area. Thus it does not account for the any salinity gradients that may exist within the open water bodies. Significant uncertainty exists in flow and EC input data related to in-Delta agriculture, which leads to uncertainty in the simulated EC values. Caution needs to be exercised when using EC outputs on a sub-monthly scale. Water quality results inside the water bodies representing the tidal marsh areas were not validated specifically and because of the bottom elevation assumptions, preferably do not use it for analysis.

# A.6. Delta Particle Tracking Modeling

Particle tracking models (PTM) are excellent tools to visualize and summarize the impacts of modified hydrodynamics in the Delta. These tools can simulate the movement of passive particles or particles with behavior representing either larval or adult fish through the Delta. The PTM tools can provide important information relating hydrodynamic results to the analysis needs of biologists that are essential in assessing the impacts to the habitat in the Delta.

## A.6.1. DSM2-PTM

DSM2-PTM simulates pseudo 3-D transport of neutrally buoyant particles based on the flow field simulated by HYDRO. The PTM module simulates the transport and fate of individual particles traveling throughout the Delta. The model uses geometry files, velocity, flow, and stage output from the HYDRO module to monitor the location of each individual particle using assumed vertical and lateral velocity profiles and specified random movement to simulate mixing. The location of a particle in a channel is determined as the distance from the downstream end of the channel segment (x), the distance from the centerline of the channel (y), and the distance above the channel bottom (z).PTM has multiple applications ranging from visualization of flow patterns to simulation of discrete organisms such as fish eggs and larvae.

The longitudinal distance traveled by a particle is determined from a combination of the lateral and vertical velocity profiles in each channel. The transverse velocity profile simulates the effects of channel shear that occurs along the sides of a channel. The result is varying velocities across the width of the channel. The average cross-sectional velocity is multiplied by a factor based on the particle’s transverse location in the channel. The model uses a fourth order polynomial to represent the velocity profile. The vertical velocity profile shows that particles located near the bottom of the channel move more slowly than particles located near the surface. The model uses the Von Karman logarithmic profile to create the velocity profile. Particles also move because of random mixing. The mixing rates (i.e., distances) are a function of the water depth and the velocity in the channel. High velocities and deeper water result in greater mixing.

At a junction the path of a particle is determined randomly based on the proportion of flow. The proportion of flow determines the probability of movement into each reach. A random number based on this determined probability then determines where the particle will go. A particle that moves into an open water area, such as a reservoir, no longer retains its position information. A DSM2 open water area is considered a fully mixed reactor. The path out of the open water area is a decision based on the volume in the open water area, the time step, and the flow out of the area. At the beginning of a time step the volume of the open water area the volume of water leaving at each opening of the open water area is determined. From that the probability of the particle leaving the open water area is calculated. Particles entering exports or agricultural diversions are considered "lost" from the system. Their final destination is recorded. Once particles pass the Martinez boundary, they have no opportunity to return to the Delta. (Smith, 1998, Wilbur, 2001, Miller, 2002)

## A.6.2. DSM2-PTM Metrics

The particle transport and fate metrics resulting from DSM2 PTM are outlined below.

1. Fate Mapping – an indicator of entrainment. It is the percent of particles that go past various exit points in the system at the end of a given number of days after insertion.
2. Delta-wide Residence Time – an indicator of transport of larval fish and plankton. It is the time taken for 75% of the particles inserted to leave the system via all the exit points.

### A.6.3. PTM Period Selection

PTM simulation periods for the residence time and fate computations were selected based on the simulated Delta inflows and the exports from the No Action Alternative CALSIM II results. A two-pronged approach was used to identify the particle insertion periods such that the selected periods cover the entire range of hydrology and also represent full range of export operations that occurred in the 82-year simulation period. Representative periods with various combinations of total inflow and exports were identified over the whole range of simulated values.

Briefly, the process included sorting all the months in the 82-year period into 25 hydrology bins based on the percent ranks of monthly Sacramento and San Joaquin inflows as shown in Figure A-15. The 984 months were then sorted based on the monthly total Delta inflow and the monthly exports as shown in Figure A-16. Several months falling on the 0.1, 0.2, 0.3, 0.4, 0.5 and 0.6 EI ratio isopleths were manually identified such that they cover all the hydrology bins. Figures A-17 and A-18 show the selected periods plotted on the hydrology binning plot and the EI ratio plot, respectively. Both the plots show that the selected periods cover the full range of hydrology and export operations. Figure A-19 shows number of selected periods in each month. The selected periods were reviewed to ensure representation of all the seasons. The selection was biased to include more periods in the Dec – Jun period. The variability captured in the selected periods, in terms of the hydrology and the operations, is mostly sustained for both the early long-term and late long-term conditions.

### A.6.4. PTM Simulations

PTM simulations are performed to derive the metrics described above. PTM model can track flux at twenty locations in one simulation. The particles are inserted at the 39 locations shown in Figure A-20. These locations are listed in Table A-8. The locations were identified based on the 20mm Delta Smelt Survey Stations. They also include special interest stations such as Mokelumne River and Cache Complex.

A total of 39 PTM simulations are performed in a batch mode for each insertion period. For each insertion period, 4000 particles are inserted at the identified locations over a 24.75-hour period, starting on the 1st of the selected month. The fate of the inserted particles is tracked continuously over a 120-day simulation period. The particle flux is tracked at the key exit locations – exports, Delta agricultural intakes, past Chipps Island, to Suisun Marsh and past Martinez and at several internal tracking locations as shown in Figure A-20. Generally, the fate of particles at the end of 30 days, 60 days, 90 days and 120 days after insertion is computed for the fate mapping analysis. For the Delta-wide residence time analysis, the number of days taken for 25%, 50%, 75% of the total inserted particles to be removed via all the exit points in the Delta are computed.

Table A-8: List of Particle Insertion Locations for Residence Time and Fate Computations

| Location | DSM2 Node |
|---|---|
| San Joaquin River at Vernalis | 1 |
| San Joaquin River at Mossdale | 7 |
| San Joaquin River D/S of Rough and Ready Island | 21 |
| San Joaquin River at Buckley Cove | 25 |
| San Joaquin River near Medford Island | 34 |
| San Joaquin River at Potato Slough | 39 |
| San Joaquin River at Twitchell Island | 41 |
| Old River near Victoria Canal | 75 |
| Old River at Railroad Cut | 86 |
| Old River near Quimby Island | 99 |
| Middle River at Victoria Canal | 113 |
| Middle River u/s of Mildred Island | 145 |
| Grant Line Canal | 174 |
| Frank's Tract East | 232 |
| Threemile Slough | 240 |
| Little Potato Slough | 249 |
| Mokelumne River d/s of Cosumnes confluence | 258 |
| South Fork Mokelumne | 261 |
| Mokelumne River d/s of Georgiana confluence | 272 |
| North Fork Mokelumne | 281 |
| Georgiana Slough | 291 |
| Miner Slough | 307 |
| Sacramento Deep Water Ship Channel | 314 |
| Cache Slough at Shag Slough | 321 |
| Cache Slough at Liberty Island | 323 |
| Lindsey slough at Barker Slough | 324 |
| Sacramento River at Sacramento | 330 |
| Sacramento River at Sutter Slough | 339 |
| Sacramento River at Ryde | 344 |
| Sacramento River near Cache Slough confluence | 350 |
| Sacramento River at Rio Vista | 351 |
| Sacramento River d/s of Decker Island | 353 |
| Sacramento River at Sherman Lake | 354 |
| Sacramento River at Port Chicago | 359 |
| Montezuma Slough at Head | 418 |
| Montezuma Slough at Suisun Slough | 428 |
| San Joaquin River d/s of Dutch Slough | 461 |
| Sacramento River at Pittsburg | 465 |
| San Joaquin River near Jersey Point | 469 |

## A.6.5. Output Parameters

The particle tracking models can be used to assist in understanding passive fate and transport, or through consideration of behavior or residence time. In, general the following outputs are generated:

Fate of particles and cut lines or regions

Time of travel breakthrough curves

Residence time

Spatial plots of fate and residence time can be prepared as shown in the Figure A-21 and A-22. Scatter plots of entrainment with a hydrologic variable as shown in Figure A-23 can be helpful in assessing the correlation between hydraulics and entrainment, as well as the spatial extent over which such correlations hold.

### A.6.6. Limitations

PTM results are most often used to understand the potential movement of eggs and larval fish with flow changes. Similarly, the PTM is also used to study the changes in the residence time (residence time being a surrogate of the water quality conditions in the Delta) in the Delta associated with flow changes. However, the PTM only approximates movement of neutrally-buoyant particles based on the hydraulics of flow. They do not include elements of fish behavior such as active swimming or tidal surfing which may be important for certain species and life stages. The version of the PTM model used in this analysis does not have a capability to simulate fish behavior. The PTM model requires input of channel velocity fields from HYDRO model, which leads to the translation of the limitations inherent to HDYRO to the PTM model. The partitioning of the particles at a junction is simplistic and is based on the flow split into different branches at a junction. Information related to higher order hydraulics such as acceleration around the bend and secondary are not simulated in the PTM, despite its use of an approximate 3D velocity field. Use of the PTM results to analyze certain species and life stages with significant active behavior responses should be used with caution. The PTM model used for this analysis is incapable of simulating fish screens and blocking the particles from entering small sump pumps in the Delta channels. While some uncertainty exists in the PTM results, the model is a reasonable tool to compare the movement and fate of particles across various scenarios, if results are interpreted within the context of these limitations.

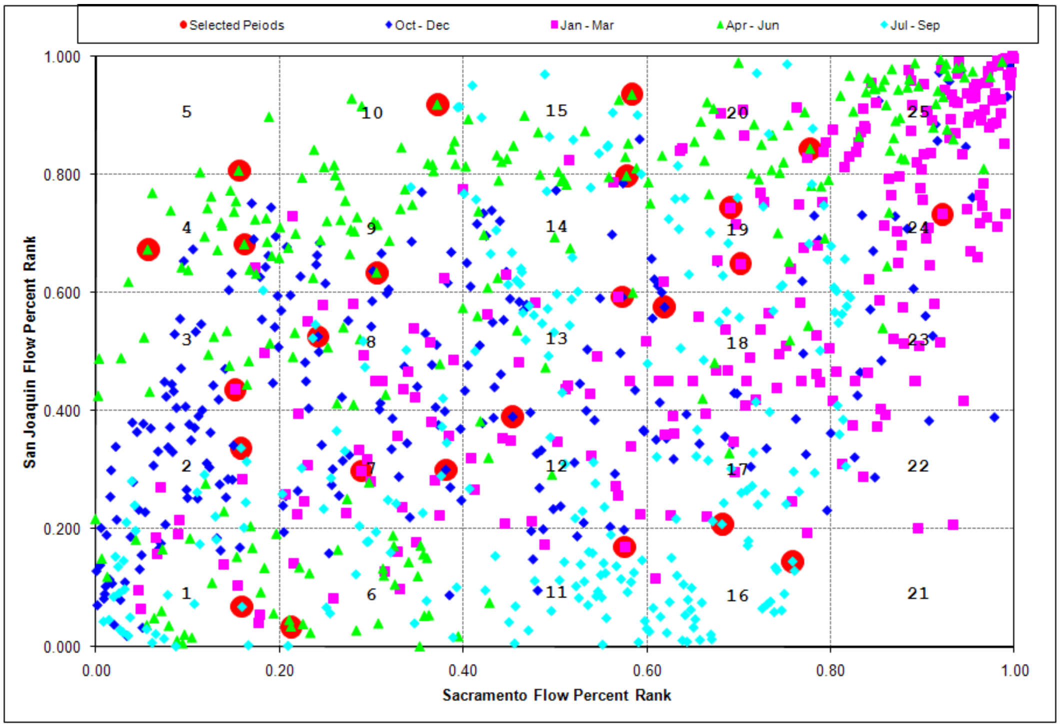


Figure A-15: Sorting of the 984 months (82-years) into 25 hydrology bins based on the percent rank of Sacramento River inflow and San Joaquin River inflow

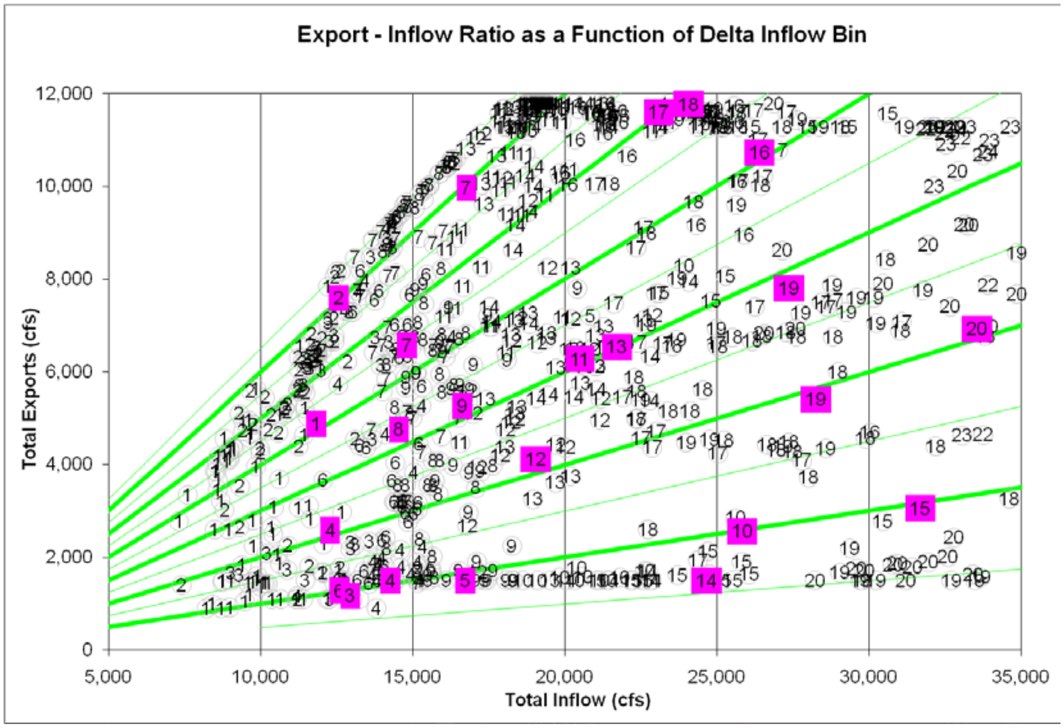


Figure A-16: Identification of months falling on the 0.1, 0.2, 0.3, 0.4, 0.5 and 0.6 EI ratio isopleths while covering the full range of hydrology bins (Numeric labels indicate hydrology bin)

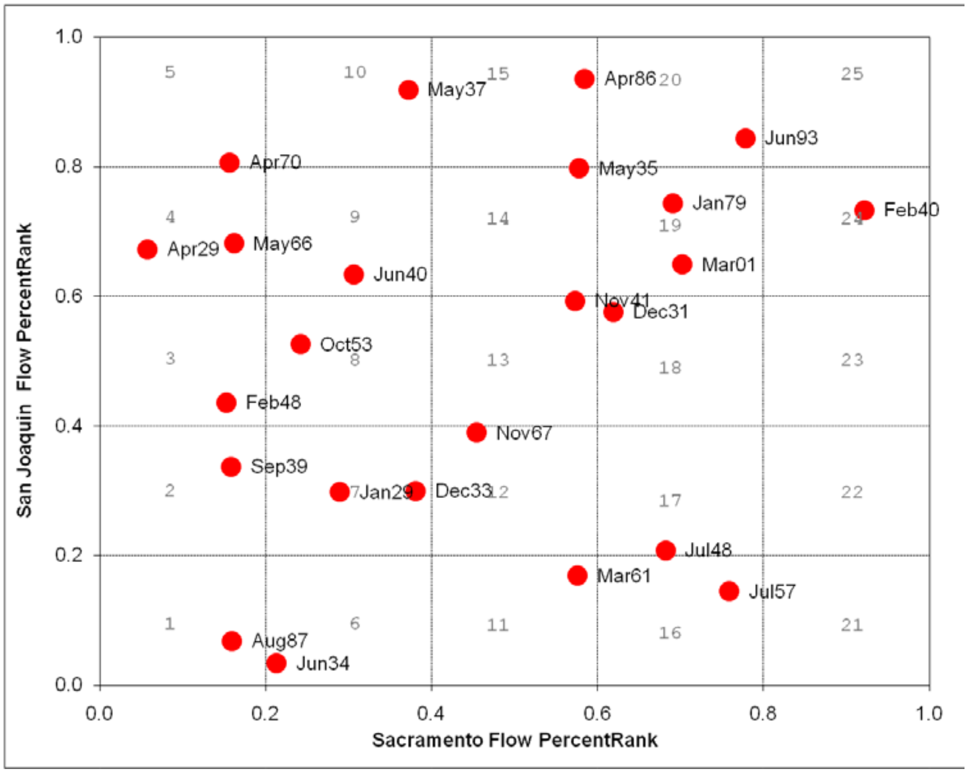


Figure A-17: Selected PTM insertion periods plotted on the Sacramento River and San Joaquin River inflow hydrology bins with month and year identified for each insertion period

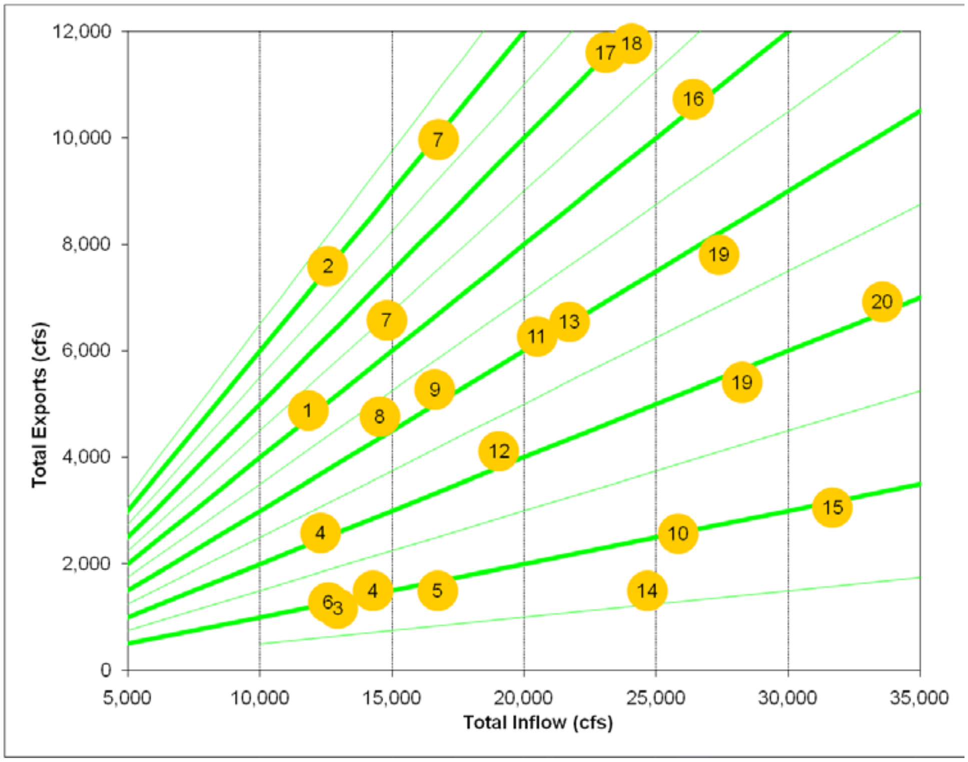


Figure A-18: Selected PTM insertion periods plotted on the EI ratio plot with the hydrology bin for each period identified

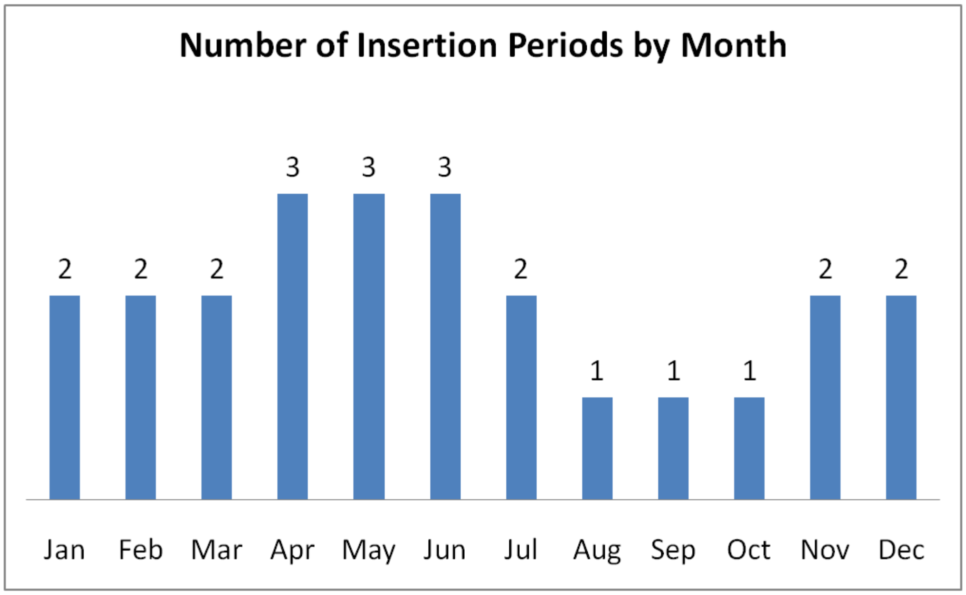


Figure A-19: Number of selected PTM insertion periods in each Month

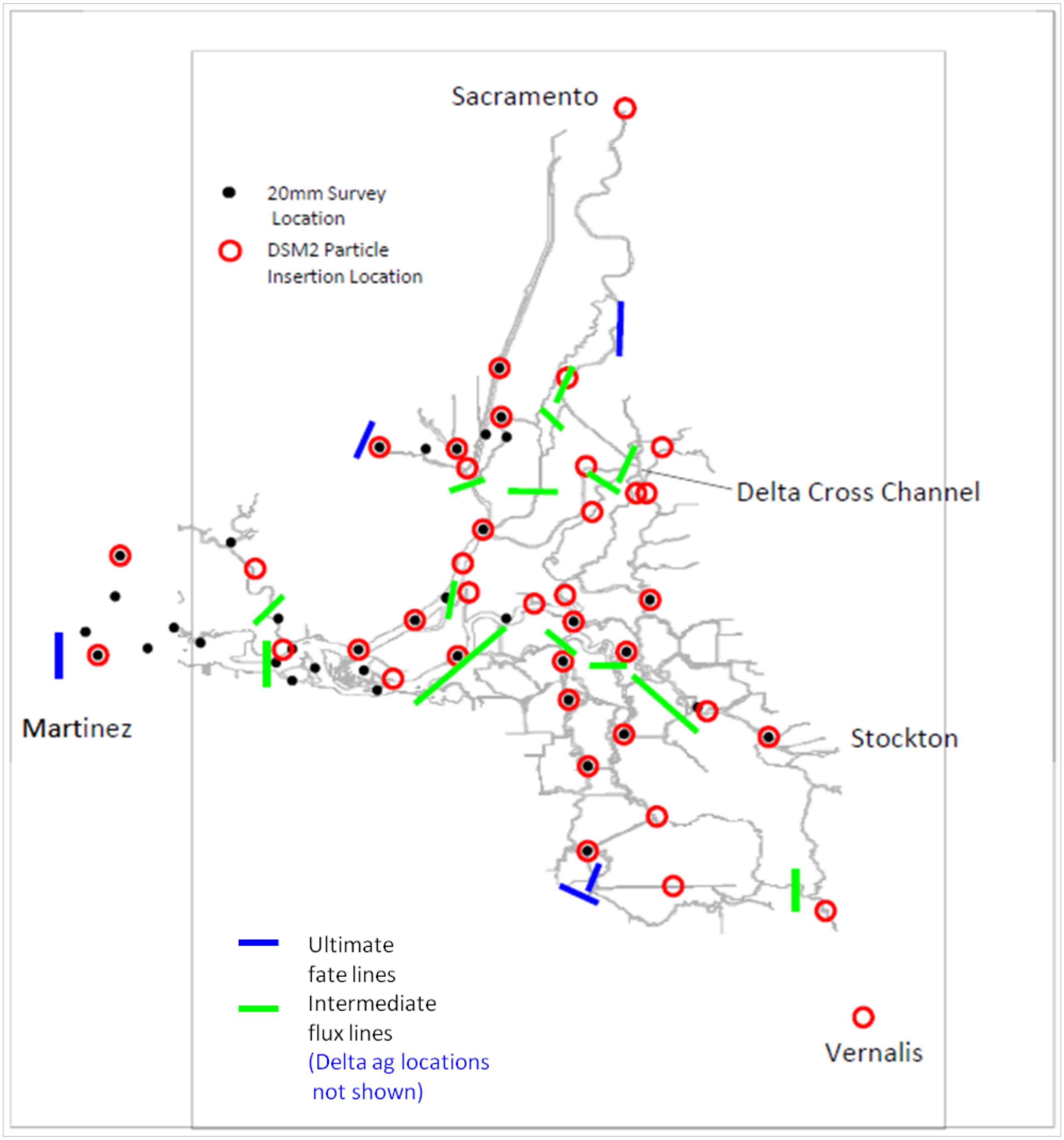


Figure A-20: Particle insertion and tracking locations for residence time and fate computations

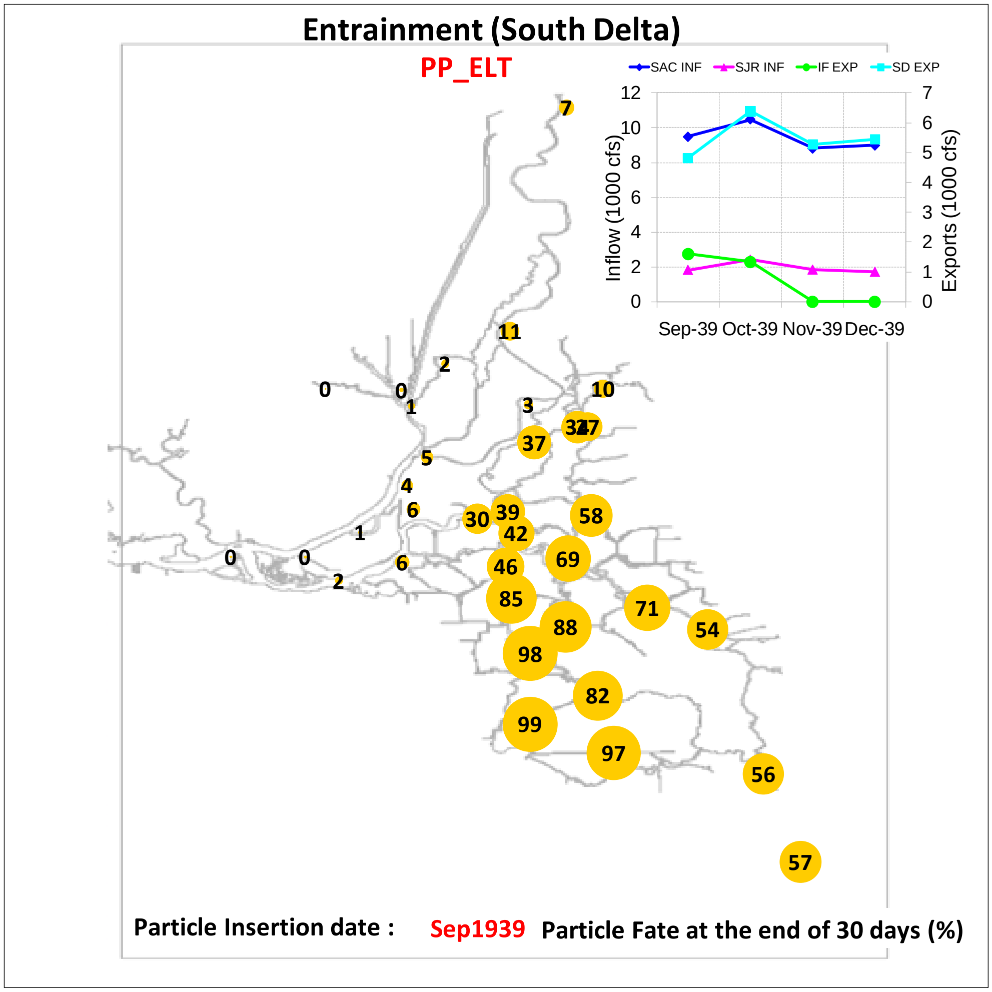


Figure A-21: An example spatial plot showing the percent entrainment for particles released at various locations in the Delta at the end of 30 days after insertion

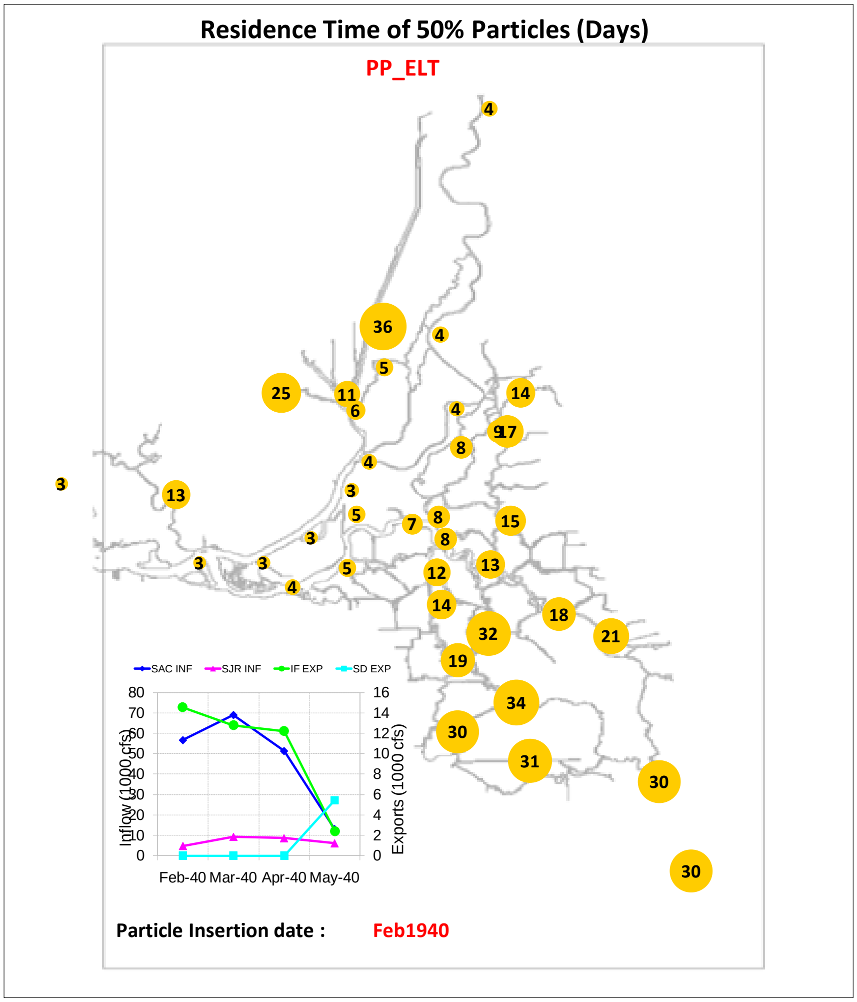


Figure A-22: An example spatial plot showing the residence time for 50 percent particles to exit the Delta

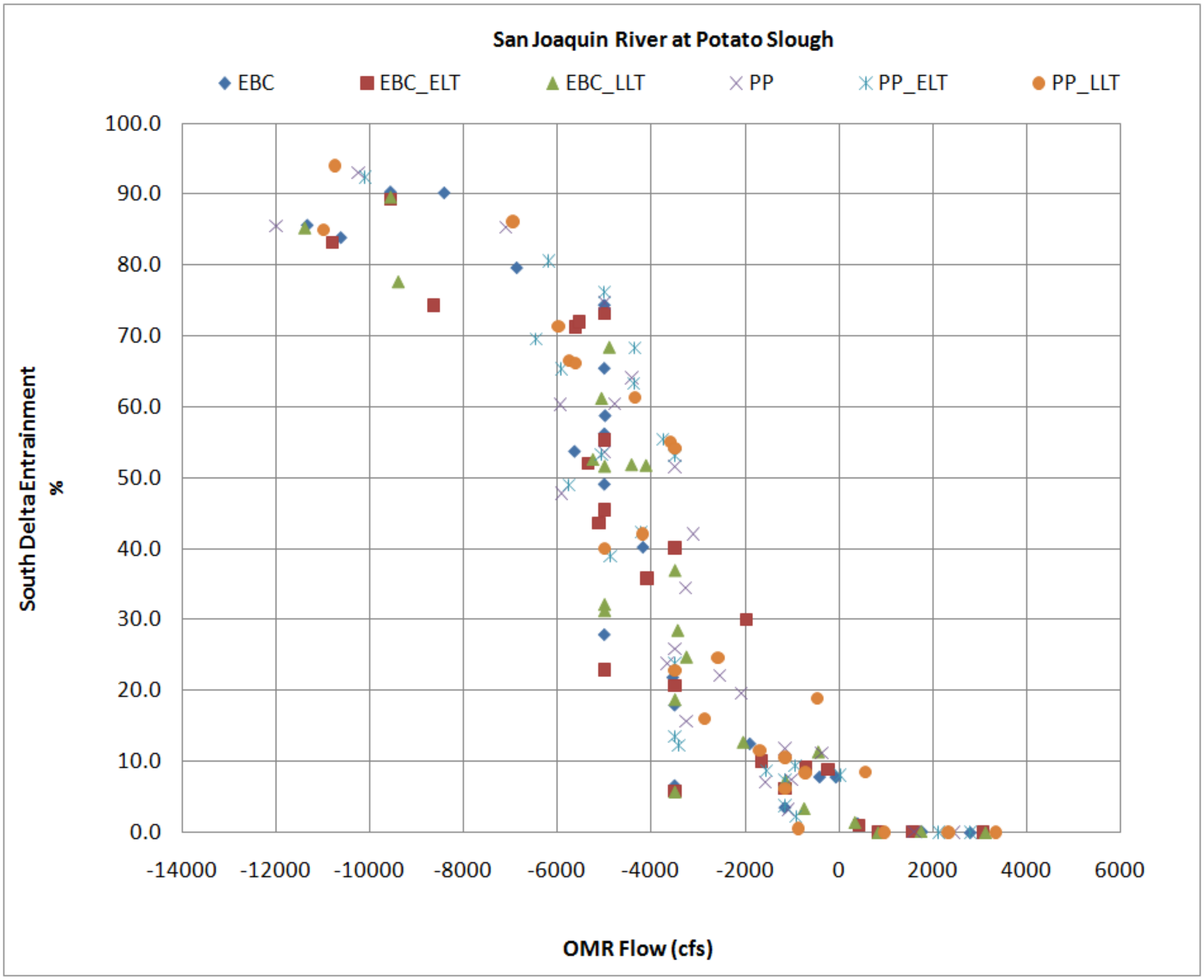


Figure A-23: An example scatter plot showing the percent entrainment of particles at south Delta pumps inserted at San Joaquin River at Potato Slough location and OMR flow, 60 days after the particles were inserted

# A.7. Climate Change and Sea Level Rise Scenarios

## A.7.1. Selection of BDCP Climate Scenarios

A technical subgroup was formed with representatives from DWR, Reclamation, USFWS, and NMFS to review the technical merits of several approaches for incorporating climate change into BDCP analytical processes. The outcome of this coordinated effort is described in Section D.2. The issues of multi-decadal variability in the sampling of any one GCM projection and the superiority of multi-model projections over any one single projection were emphasized by the group members. These and other comments received from the group members led to the recommendation of the following criteria to guide the selection of climate scenarios:

- Select a range of scenarios to reflect the uncertainty with GCM projections and emission scenarios;
- Select scenarios that reduce the "noise" inherent with any particular GCM projection due to multi-decadal variability that often does not preserve relative rank for different locations and time periods;
- Select an approach that incorporates both the mean climate change trend and changes in variability; and
- Select time periods that are consistent with the major phases used in BDCP planning.
- The selected approach for development of climate scenarios for the BDCP incorporates three fundamental elements. First, it relies on sampling of the ensemble of GCM projections rather than one single realization or a handful of individual realizations. Second, it includes scenarios that both represent the range of projections as well as the central tendency of the projections. Third, it applies a method that incorporates both changes to the mean climate as well as to the variability in climate. These elements are described further in the sections below.

## A.7.2. Downscaled Climate Projections

A total of 112 future climate projections used in the IPCC AR4, subsequently bias-corrected and statistically downscaled (BCSD), were obtained from Lawrence Livermore National Laboratory (LLNL) under the World Climate Research Program's (WCRP) Coupled Model Intercomparison Project Phase 3 (CMIP3). This archive of contains climate projections generated from 16 different GCMs developed by national climate centers (Table A-9) and for SRES emission scenarios A2, A1b, and B1. Many of the GCMs were simulated multiple times for the same emission scenario due to differences in starting climate system state, thus the number of available projections is greater than simply the product of GCMs and emission scenarios. These projections have been bias corrected and spatially downscaled to 1/8th degree (~12km) resolution over the contiguous United States through methods described in detail in Wood et al. 2002, Wood et al. 2004, and Maurer 2007.

TABLE A-9
General Circulation Models used in the World Climate Research Program's (WCRP) Coupled Model Intercomparison Project Phase 3 (CMIP3) Database

| Modeling Group, Country | WCRP CMIP3 I.D. |
|---|---|
| Bjerknes Centre for Climate Research | BCCR-BCM2.0 |
| Canadian Centre for Climate Modeling & Analysis | CGCM3.1 (T47) |
| Meteo-France / Centre National de Recherches Meteorologiques, France | CNRM-CM3 |
| CSIRO Atmospheric Research, Australia | CSIRO-Mk3.0 |
| US Dept. of Commerce / NOAA / Geophysical Fluid Dynamics Laboratory, USA | GFDL-CM2.0 |
| US Dept. of Commerce / NOAA / Geophysical Fluid Dynamics Laboratory, USA | GFDL-CM2.1 |
| NASA / Goddard Institute for Space Studies, USA | GISS-ER |
| Institute for Numerical Mathematics, Russia | INM-CM3.0 |
| Institut Pierre Simon Laplace, France | IPSL-CM4 |
| Center for Climate System Research (The University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change (JAMSTEC), Japan | MIROC3.2 (medres) |
| Meteorological Institute of the University of Bonn, Meteorological Research Institute of KMA | ECHO-G |
| Max Planck Institute for Meteorology, Germany | ECHAM5/ MPI-OM |
| Meteorological Research Institute, Japan | MRI-CGCM2.3.2 |
| National Center for Atmospheric Research, USA | CCSM3 |
| National Center for Atmospheric Research, USA | PCM |
| Hadley Centre for Climate Prediction and Research / Met Office, UK | UKMO-HadCM3 |

## A.7.3. Climate Periods

Climate change is commonly measured over a 30-year period. Changes in temperature and precipitation for any particular scenario are compared to a historical period. The historical period of 1971-2000 is selected as the reference climate since it is the currently established climate normal used by NOAA and represents the most recent time period. Corresponding to the long-term timelines of the BDCP analysis, in which climate change is likely to be relevant, future climate periods are identified as approximately 2025 (2011-2040) [early long-term] and 2060 (2046-2075) [late long-term]. The difference in mean annual temperature and precipitation among the two future periods and historic period were identified as the climate change metric.

### A.7.4. Multi-Model Ensemble and Sub-Ensembles

The recommended approach makes use of all 112 downscaled climate projections of future climate change described in the previous section. The group of multi-model, multi-emission scenario projections is termed the ensemble. Individual model-emission scenario projections are termed “members” of the ensemble. It is often useful to characterize climate change projections in terms of the simulated change in annual temperature and precipitation compared to an historical reference period. At any selected 30-yr future climatological period, each projection represents one point of change amongst the others. This is graphically depicted in Figure A-24 for a region in Feather River watershed.

Since the ensemble is made up of many projections, it is useful to identify the median (50th percentile) change of both annual temperature and annual precipitation (dashed blue lines). In doing so, the state of climate change at this point in time can be broken into quadrants representing (1) drier, less warming, (2) drier, more warming, (3) wetter, more warming, and (4) wetter, less warming than the ensemble median. These quadrants are labeled Q1-Q4 in Figure A-24. In addition, a fifth region (Q5) can be described that samples from inner-quartiles (25th to 75th percentile) of the ensemble and represents a central region of climate change. In each of the five regions the sub-ensemble of climate change projections, made up of those contained within the region bounds, is identified. The Q5 scenario is derived from the central tending climate projections and thus favors the consensus of the ensemble.

Through extensive coordination with the State and Federal teams involved in the BDCP, the bounding scenarios Q1-Q4 were refined in April 2010 to reduce the attenuation of climate projection variability that comes about through the use of larger ensembles. A sensitivity analysis was prepared for the bounding scenarios (Q1-Q4) using sub-ensembles made up of different numbers of downscaled climate projections. The sensitivity analysis was prepared using a “nearest neighbor” (k-NN) approach. In this approach, a certain joint projection probability is selected based on the annual temperature change-precipitation change (i.e. 90th percentile of temperature and 90th percentile of precipitation change). From this statistical point, the “k” nearest neighbors (after normalizing temperature and precipitation changes) of projections are selected and climate change statistics are derived. Consistent with the approach applied in OCAP, the 90th and 10th percentile of annual temperature and precipitation change were selected as the bounding points. The sensitivity analysis considered using the 1-NN (single projection), 5-NN (5 projections), and 10-NN (10 projections) sub-ensemble of projections. These were compared to the original quadrant scenarios which commonly are made up of 25-35 projections and are based on the direction of change from 50th percentile statistic.

The very small ensemble sample sizes exhibited month by month changes that were sometimes dramatically different than that produced by adding a few more projections to the ensemble. The 1-NN approach was found to be inferior to all other methods for this reason. The original quadrant method produced a consensus direction of change of the projections, and thus produced seasonal trends that were more realistic, but exhibited a slightly smaller range due to the inclusion of several central tending projections. The 5-NN and 10-NN methods exhibited slightly wider range of variability than the quadrant method which was desirable from the "bounding" approach. In most cases the 5-NN and 10-NN projections were similar, although they differed at some locations in representation of season trend. The 10-NN approach (Figure A-24) was found to be preferable in that it best represented the seasonal trends of larger ensembles, retained much of the "range" of the smaller ensembles, and was guaranteed to include projections from at least two GCM-emission scenario combinations (in the CMIP3 projection archive, up to 5 projections – multiple simulations – could come from one GCM-emission scenario combination). The State and Federal representatives agreed to utilize the following climate scenario selection process for BDCP:

(1) the use of the original quadrant approach for Q5 (projections within the 25th to 75th percentile bounding box) as it provides the best estimate of the consensus of climate projections and
(2) the use of the 10-NN method to developing the Q1-Q4 bounding scenarios.

An automated process has been developed that generates the monthly and annual statistics for every grid cell within the Central Valley domain and identifies the members of the sub-ensemble for consideration in each of the five scenarios.

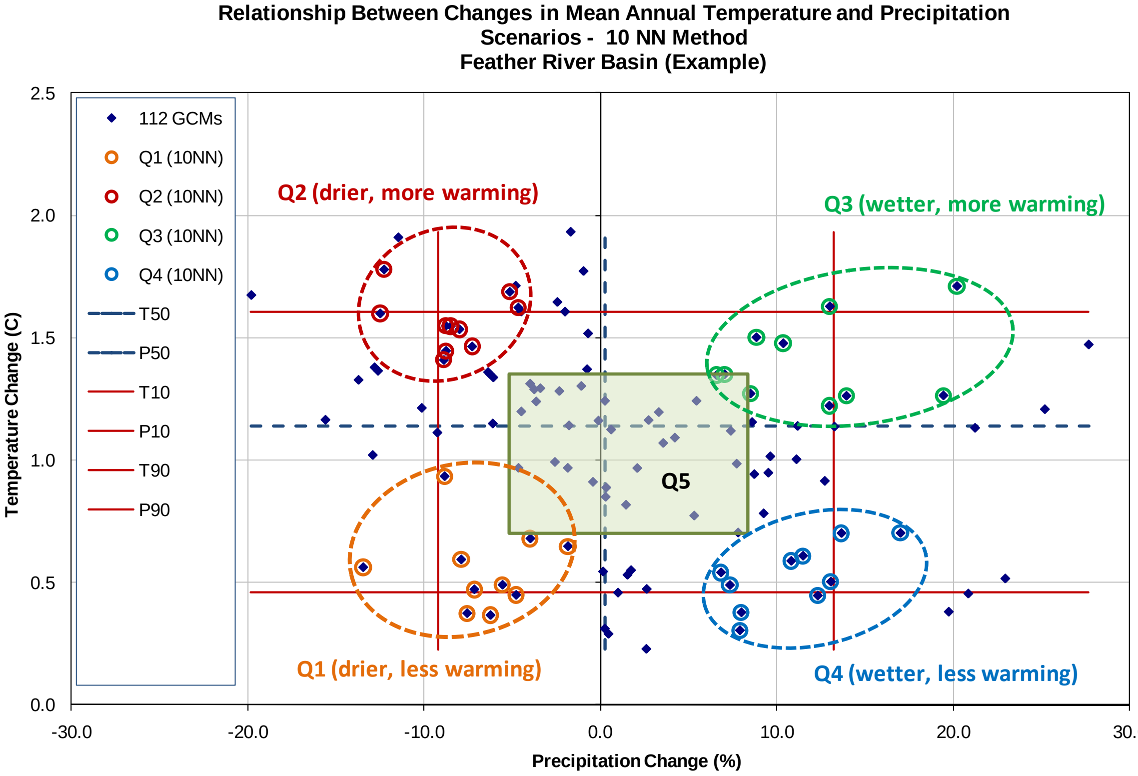


Figure A-24. Example downscaled climate projections and sub-ensembles used for deriving climate scenarios (Q1-Q5), Feather River Basin at 2025. The Q5 scenario is bounded by the 25th and 75th percentile joint temperature-precipitation change. Scenarios Q1-Q4 are selected to reflect the results of the 10 projections nearest each of 10th and 90th joint temperature-precipitation change bounds. Note: the temperature and precipitation changes are normalized before determining the nearest neighbors.

## A.7.5. Incorporating Changes in Mean Climate and Climate Variability

Climate is usually defined as the "average" condition of weather over a period of time. More rigorously, climate can be defined as the "statistical description" in terms of mean and variability of the relevant quantities over a period of time ranging from months to millions of years (IPCC TAR). The standard averaging period defined by the World Meteorological Organization (WMO) is 30 years. The parameters that are most often associated with the description of climate state are temperature, precipitation, and wind speed. Thus, climate change refers to a shift in the statistical properties of climate variables over extended periods of time.

One difficulty that arises in implementing climate change into long-term water resources planning is that the natural variability is often greater than the magnitude of change expected over several decades. In many water resource management areas, it is the extreme events (droughts and floods) that drive the decision-making and long-range planning efforts. Thus, there is a need to combine the climate change signal with the range of natural variability observed in the historical record.

In many current climate change analyses, only the mean state of climate change is analyzed through the use of the "delta" method. In this method, temperature and/or precipitation are adjusted by the mean shift from one future 30-year period to a historical 30-year period. However, climate change is unlikely to manifest itself in a uniform change in values. In fact, the climate projections indicate that the changes are nonlinear and shifts in the probability distributions are likely, not just the mean values. In other analyses, a transient 30-year depiction of climate is used and compared against a similar 30-year historical period. Hydrologic analyses are performed and summarized as the "mean" change between the future and base periods. This latter approach is roughly what has been applied in the OCAP and CAT processes. The difficulty with this approach is that the natural observed variability may be large and not fully present in the 30-year period, resulting in truncated variability. Also, because the sequence of variability is different under each period it is difficult to make comparisons between the resulting hydrologic variables beyond the mean response.

In order to incorporate both the climate change signal and the natural variability in the longer-term observed record, the recommended approach is to create an expanded time series which allows use of the long-term observed records. The approach is similar to that applied by the Climate Impacts Group for development of hydrologic scenarios for water planning in the Pacific Northwest (Wood et al 2002, Salathe et al 2007, Hamlet et al 2009), applied in the Lower Colorado River, Texas studies (CH2M HILL 2008), and recent Reclamation planning (USBR, 2010). The approach uses a technique called "quantile mapping" which maps the statistical properties of climate variables from one data subset with the time series of events from a different subset. In this fashion, the approach allows the use of a shorter period to define the climate state, yet maintains the variability of the longer historic record. The quantile mapping approach involves the following steps:

1. Extract a 30-year slice of downscaled climate projections based on the ensemble subset for the quadrant of interest and  centered on the year of investigation (i.e. 2025 or 2060)
2. For each calendar month (i.e. January) of the future period, determine the statistical properties (cumulative distribution function, CDF) of temperature and precipitation at each grid cell
3. For each calendar month of the historical period (1971-2000 in our case), determine the statistical properties (CDFs) of temperature and precipitation at each grid cell
4. Develop quantile maps between the historic observed CDFs and the future downscaled climate CDFs, such that the entire probability distribution (including means, variance, skew, etc) at the monthly scale is transformed to reflect the climate scenario
5. Using the quantile maps, redevelop a monthly time series of temperature and precipitation over the observed period (1915 -2003) that incorporates the climate shift of the future period
6. Convert monthly time series to a daily time series by scaling monthly values to daily sequence found in the observed record

The result of the quantile mapping approach is a daily time series of temperature and precipitation that has the range of variability observed in the historic record, but also contains the shift in climate properties (both mean and expanded variability) found in the downscaled climate projection. Figure A-25 provides an example of this process a grid cell in the Feather River watershed. As shown in this figure, the precipitation change quantities are not expected to shift uniformly across all percentiles. For example, in this wetting climate scenario, the median (50th percentile) January precipitation is projected to exhibit almost no change from baseline conditions. However, for large precipitation events (i.e. the 90th percentile) January precipitation is projected to increase by almost 2 mm/day (more than 2 inches/month). That is, the climate shift is larger at higher precipitation events and lower at low precipitation events. While this may be different for each climate scenario, future period, spatial location, and month, the need to map the full range of statistic climate shift is important to characterize the projected effects of climate change.

The resulting changes in the climate variables under the selected scenarios are presented in Section D.3.1.

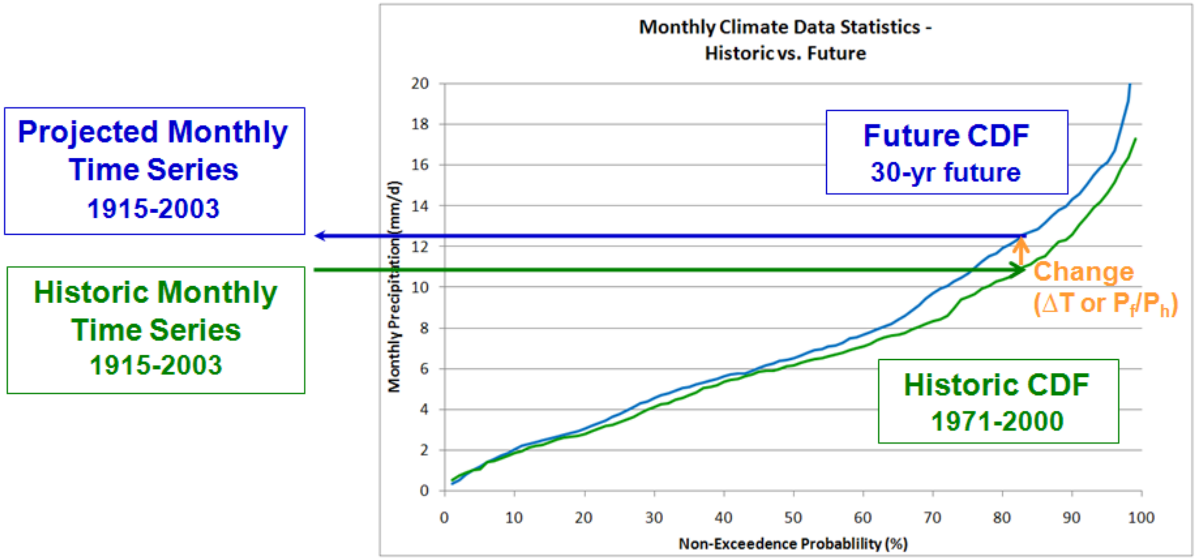


FIGURE A-25:
Historical Monthly Precipitation Statistics for a Grid Cell in Feather River Basin (January - EXAMPLE ONLY)

## A.7.6. Sea Level Rise Scenarios

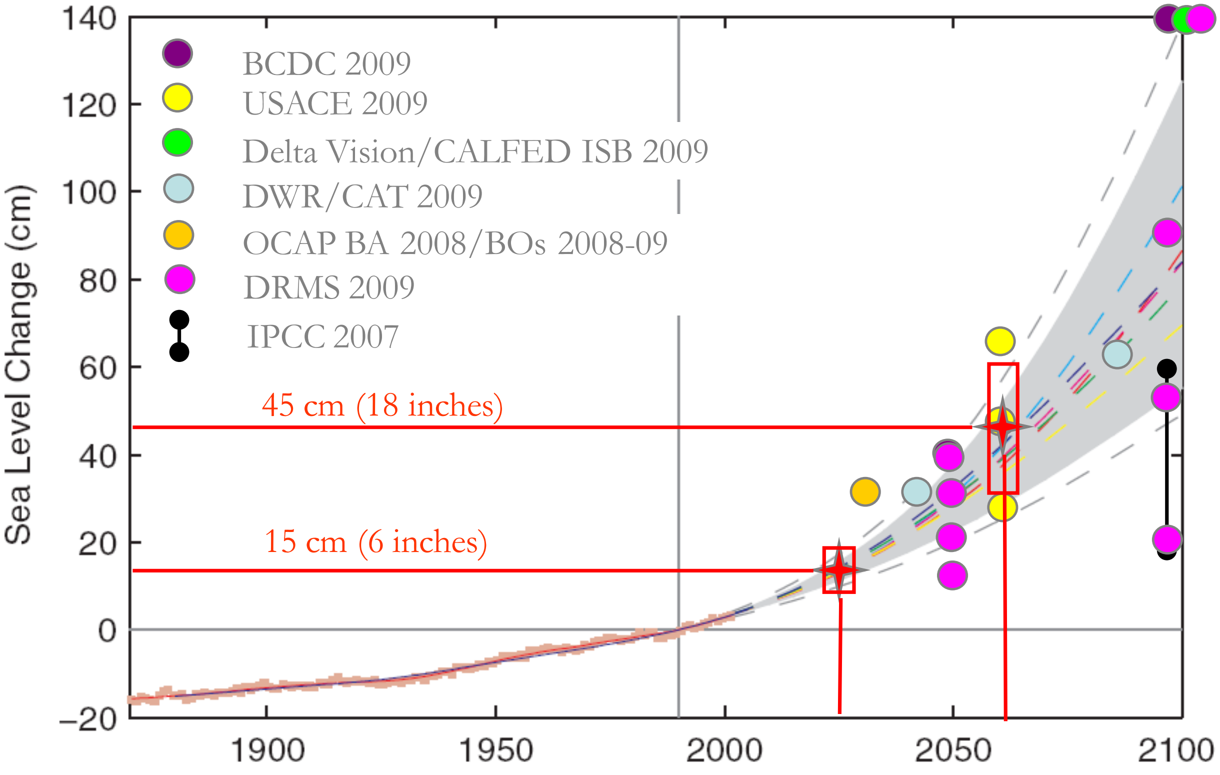
In early 2007, the IPCC released their latest assessment of the scientific assessment for projections of future climate. Included in the IPCC AR4 were revised estimates of global mean sea level rise. The IPCC estimates are based on physical models that attempt to account for thermal expansion of oceans and storage changes associated with melt of land-based ice and snowfields (Healy 2007). Since their release, the IPCC AR4 sea level rise estimates have been widely criticized for their failure to include dynamic instability in the ice sheets of Greenland and Antarctica, and for their under-prediction of recent observed increases in sea level.

Due to the limitations with the current state of physical models for assessing future sea level rise, several scientific groups, including the CALFED Independent Science Board (ISB) (Healy 2007), recommend the use of empirical models for short to medium term planning purposes. Both the CALFED ISB and CAT 2009 assessments have utilized the empirical approach developed by Ramsdorf (2007) that projects future sea level rise rates based on the degree of global warming. This method better reproduces historical sea levels and generally produces larger estimates of sea level rise than those indicated by the IPCC (2007). When evaluating all projections of global air temperature, Ramsdorf projects a mid-range sea level rise of 70 – 100 cm (28 – 40 inches) by the end of the century, and when factoring the full range of uncertainty the projected rise is 50 - 140 cm (20 – 55 inches). The CAT scenarios utilized an identical empirical approach, but limited the sea level rise estimates to the degree of warming range from 12 GCM projections selected for that study.

Using the work conducted by Ramsdorf, the projected sea level rise at the early long-term timeline for the BDCP analysis (2025) is approximately 12 - 18 cm (5 - 7 inches). At the late long-term timeline (2060), the projected sea level rise is approximately 30 – 60 cm (12 – 24 inches).

In 2011, the United States Army Corps of Engineers (USACE) issued guidance on incorporating sea level change in civil works programs (USACE 2011). The guidance document reviews the existing literature and suggests use of a range of sea level change projections, including the "high probability" of accelerating global sea level rise. The ranges of future sea level rise were based on the empirical procedure recommended by the National Research Council (NRC, 1987) and updated for recent conditions. The three scenarios included in the USACE guidance suggest end of century sea level rise in the range of 50 to 150 centimeters (20 to 59 inches), consistent with the range of projections by Rahmstorf (2007) and Vermeer and Rahmstorf (2009). The USACE Bulletin expires in September 2013.

These sea level rise estimates are also consistent with those outlined in the USACE guidance circular for incorporating sea-level changes in civil works programs (USACE 2009). Due to the considerable uncertainty in these projections and the state of sea level rise science, it is proposed to use the mid-range of the estimates for each BDCP timeline: 15 cm (6 inches) by 2025 and 45 cm (18 inches) by 2060. In addition, sensitivity scenarios will be prepared to consider sea level rise of up to 60 cm by 2060.



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## A.7.7. Changes in Tidal Amplitude

As discussed previously, mean sea level has been increasing across the globe and is exhibited on all U.S. coasts and almost all long-term stations. Tidal amplitude appears to be increasing, particulary in the eastern Pacific but the trend is not consistent for all stations on the West Coast. Tidal amplitude can be significantly affected by physical changes in coasts, harbors, bays, and estuaries. At long-term open-ocean stations along the California coast (La Jolla, Los

Angeles, San Francisco, and Crescent City), which are less influenced by the physical changes, Flick et al. (2003) found a statistically significant increase in tidal amplitude (MHHW - MLLW), except at Crescent City which showed a slight decreasing trend. At San Francisco, the trend in tidal amplitude was found to be around 3-5% increase per century. Jay (2009) recently completed research into changes in tidal constituents, using long-term stations. Results indicated that on average tidal amplitude along the West Coast increased by about 2.2% per century. San Francisco indicated higher increases, while some stations (Alaska/Canada) were relatively constant. Jay hypothesized that global sea level rise may be influencing the location of the amphidrominc points (locations in the ocean where there are no tides) and thus affecting tidal range. However, Jay notes that it remains unclear whether rapid evolution of tidal amplitudes can be described as a symptom of global climate change.

Inland stations such Alameda and Port Chicago showed larger increases in tidal amplitudes than open ocean stations (9% and 26%, respectively). These inland stations have both short records and may be influenced by physical changes in the Bay. The importance of long-term tide records and open-ocean stations is stressed by both Flick et al and Jay for identifying trends in tidal amplitude due to the 18.6-year periodicity and influence of physical changes. Flick et al discounts the use of these inland stations for trends in tidal amplitude. In addition, Flick et al found that other nearby stations exhibited a decreased tidal amplitude trend (Point Reyes at -12% per century and Monterey at -14% per century).

Due to the considerable uncertainty associated with the tidal amplitude increase and the evolving science relating these changes to climate change and mean sea level rise, it is recommended to include a sensitivity analysis of increased tidal amplitude. The recommendation is to evaluate the effect of an amplitude increase of 5% per century, relying on the published observed trends of Flick et al and Jay and assuming that they would continue in the future. We do not propose using the inland stations trends, adhering to guidance from Flick et al. Thus, it is proposed to include one sensitivity simulation with the UNTRIM model, which incorporates an open-ocean tidal boundary, with increased tidal amplitude of 5% per century to contribute to understanding of the relative effect of amplitude increase in comparison to mean sea level increase.

## A.7.8. Analytical Process for Incorporating Climate Change

The analytical process for incorporation of climate change effects in BDCP planning includes the use of several sequenced analytical tools (Figure A-2). The GCM downscaled climate projections (DCP), developed through the process described above, are used to create modified temperature and precipitation inputs for the Variable Infiltration Capacity (VIC) hydrology model. The VIC model simulates hydrologic processes on the 1/8th degree scale to produce watershed runoff (and other hydrologic variables) for the major rivers and streams in the Central Valley. The changes in reservoir inflows and downstream accretions/depletions are translated into modified input time series for the CALSIM II model. The CALSIM II simulates the response of the river-reservoir-conveyance system to the climate change derived hydrologic patterns. The CALSIM II model, in turn, provides monthly flows for all major inflow sources to the Delta, as well as the Delta exports, for input to the DSM2 hydrodynamic model. DSM2 also incorporates the assumptions of sea level rise for an integrated assessment of climate change effects on the estuary.

At each long-term BDCP analysis timeline (Early Long-Term: 2025 and Late Long-Term: 2060), five regional climate change projections are considered for the 30-year climatological period centered on the analysis year (i.e. 2011-2040 to represent 2025 timeline). DSM2 model simulations have been developed for each habitat condition and sea level rise scenario that is coincident with the BDCP timeline. New Artificial Neural Networks (ANNs) have been developed based on the flow-salinity response simulated by the DSM2 model. These sea level rise-habitat ANNs are subsequently included in CALSIM II models. The CALSIM II model has been simulated with each of the five climate change hydrologic conditions in addition to the historical hydrologic conditions for the No Project/No Action Alternative and Alternative 1A, to understand the sensitivity of projected operations to the range of climate change scenarios. For other Alternatives CALSIM II simulations have been developed only for the mid-range climate change scenario (Q5).

# A.8. Regional Hydrologic Modeling

Regional hydrologic modeling is necessary to understand the watershed-scale impacts of historical and projected climate patterns on the processes of rainfall, snowpack development and snowmelt, soil moisture depletion, evapotranspiration, and ultimately changes in streamflow patterns. Future projected climate change, downscaled from global climate models (GCMs), suggests substantial warming throughout California and changes in precipitation. The effect of these changes in critical to future water management. In most prior analyses of the water resources of the Central Valley, the assumptions of hydroclimatic “stationarity”, the concept that variability extends about relatively unchanging mean, have been made. Under the stationarity assumption, the observed streamflow record provides a reasonable estimate of the hydroclimatic variability. However, recent observations and future projections indicate that the climate will not be stationary, thus magnifying the need to understand the direct linkages between climate and watershed processes. Hydrologic models, especially those with strong, directly linkages to climate, enable these processes to be effectively characterized and provide estimates of changes in magnitude and timing of basin runoff with changes in climate conditions.

## A.8.1. Variable Infiltration Capacity (VIC) Model

The VIC model (Liang et al. 1994; Liang et al. 1996; Nijssen et al. 1997) is a spatially distributed hydrologic model that solves the water balance at each model grid cell. The VIC model incorporates spatially distributed parameters describing topography, soils, land use, and vegetation classes. VIC is considered a macro-scale hydrologic model in that it is designed for larger basins with fairly coarse grids. In this manner, it accepts input meteorological data directly from global or national gridded databases or from GCM projections.  To compensate for the coarseness of the discretization, VIC is unique in its incorporation of subgrid variability to describe variations in the land parameters as well as precipitation distribution. Parameterization within VIC is performed primarily through adjustments to parameters describing the rates of infiltration and baseflow as a function of soil properties, as well as the soil layers depths. When simulating in water balance mode, as done for this California application, VIC is driven by daily inputs of precipitation, maximum and minimum temperature, and windspeed. The model internally calculates additional meteorological forcings such short-wave and long-wave radiation, relative humidity, vapor pressure and vapor pressure deficits. Rainfall, snow, infiltration, evapotranspiration, runoff, soil moisture, and baseflow are computed over each grid cell on a daily basis for the entire period of simulation. An offline routing tool then processes the individual cell runoff and baseflow terms and routes the flow to develop streamflow at various locations in the watershed. Figure A-26 shows the hydrologic processes included in the VIC model.

The VIC model has been applied to many major basins in the United States, including large-scale applications to California’s Central Valley (Maurer et. al 2002; Brekke et al 2007; Cayan et al. 2009), Colorado River Basin (Christensen and Lettenmaier, 2009), Columbia River Basin (Hamlet et al 2010), and for several basins in Texas (Maurer et al 2003; CH2M HILL 2008). The VIC model application for California was obtained from Dan Cayan and Tapash Das at Scripps Institute of Oceanography (SIO) and is identical to that used in the recent Climate Action Team (2009) studies. The VIC model was simulated by CH2M HILL and comparisons were performed with SIO to ensure appropriate transfer of data sets. No refinements to the existing calibration was performed for the BDCP application.

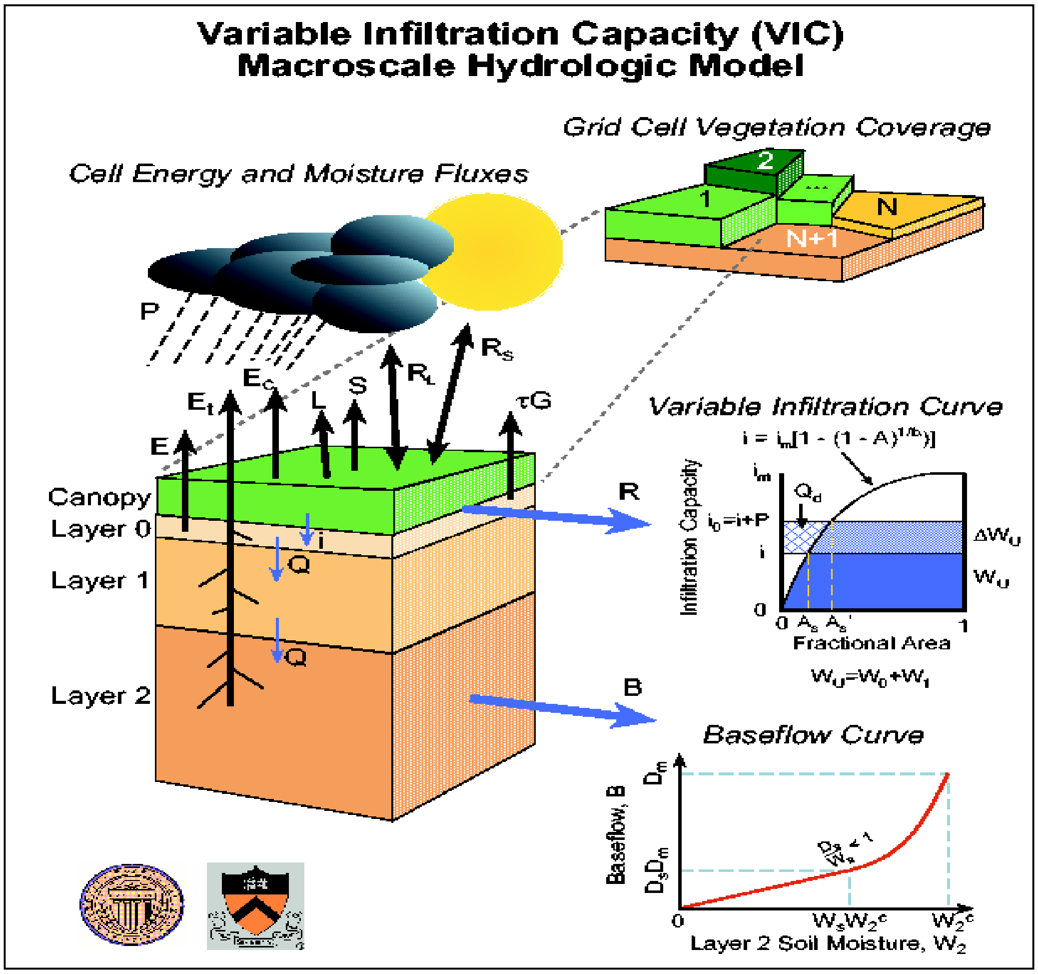

Figure A-26. Hydrologic Processes Included in the VIC Model (Source: University of Washington 2010)

## A.8.2. Application of VIC Model for BDCP Evaluations

The regional hydrologic modeling is applied to support an assessment of changes in runoff associated with future projected changes in climate. These results are intended for use in comparative assessments and serve the primary purpose of adjusting inflow records in the CALSIM II long term operations model to reflect anticipated changes in climate. This section describes the regional hydrologic modeling methods used in the planning analysis for BDCP. The general flow of information is shown graphically in Figure A-2.

The GCM downscaled climate projections (DCP) are used to adjust historical California climate for the effects of climate change for each of the climate scenarios described in Section A.7. The resulting adjusted climate patterns, primarily temperature and precipitation fields are used as inputs to the VIC hydrology model. The VIC model is simulated for the each of the five climate scenarios at each BDCP long-term timeline. The VIC model simulations produce outputs of hydrologic parameters for each grid cell and daily and monthly streamflows at key locations in the Sacramento River and San Joaquin River watersheds. The changes in "natural" flow at these locations between the observed and climate scenarios are then applied to adjust historical inflows to the CALSIM II model.

### Model Domain

The VIC application for California was originally developed by University of Washington (Wood et al, 2000), but has been subsequently refined by Ed Maurer and others (Maurer et al 2002). The model grid consists of approximately 3000 grid cells at a 1/8th degree latitude by longitude spatial resolution. The VIC model domain is shown in Figure A-27 and covers all major drainages in California.

### Observed Meteorology

The VIC application for the BDCP is run in water balance mode with inputs consisting of daily precipitation, minimum temperature, maximum temperature, and windspeed. The model internally calculates additional meteorological forcings such short-wave and long-wave radiation, relative humidity, vapor pressure and vapor pressure deficits. Daily gridded observed meteorology was obtained from the University of Washington (Hamlet and Lettenmaier 2005) for the period of 1915-2003. This data set adjusts for station inhomeniety (station length, movement, temporal trends) and is comparable to a similar observed data set developed by Maurer et al (2002) for the 1950-99 overlapping period. The longer sequence of this observed meteorology data set allow for improved simulation techniques and integration with CALSIM II model with commensurate time coverage. In addition, this observed data set is currently being applied by Cayan et al (2010) for the recent study on Southwest drought and Hamlet et al (2010) in their study of climate change in the Pacific Northwest. To better understand the sensitivity of the VIC modeling to different observed meteorology, comparative simulations using both the Hamlet data set and the Maurer data set were performed. The resulting simulated streamflows were comparable between the two data sets with relatively minor differences in individual months and years.

### Daily Meteorology for Future Climate Scenarios

Scenarios of future climate were developed through methods as described in Section A.7. These ensemble informed scenarios consist of daily time series and monthly distribution statistics of temperature and precipitation for each grid cell for the entire state of California. Historical daily time series of temperature and precipitation are converted to representative future daily series through the process of quantile mapping which applies the change in monthly statistics derived from the climate projection information onto the input time series. The result of this process (described in detail in Section A.7.) is a modified daily time series that spans the same time period as the observed meteorology (1915-2003). Daily precipitation and temperature are adjusted based on the derived monthly changes and scaled according to the daily patterns in the observed meteorology. Wind speed was not adjusted in these analyses as downscaling of this parameter was not available, nor well-translated from global climate models to local scales.

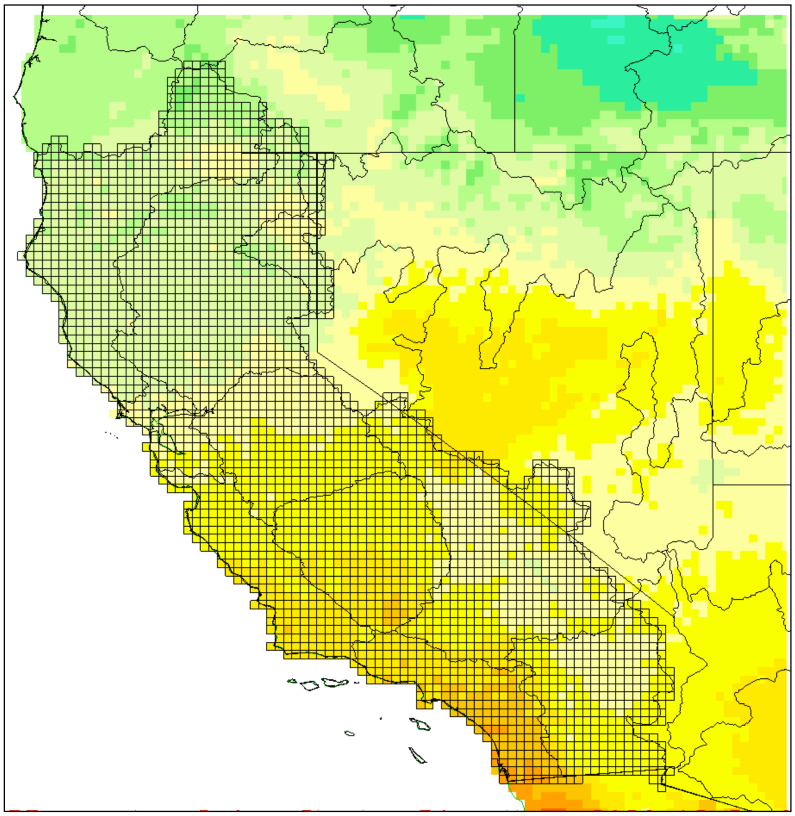

Figure A-27: VIC model domain and grid as applied for the BDCP application.

### Grid Cell Characterization and Water Balance

As described previously, the VIC model was simulated in water balance mode. In this mode, a complete land surface water balance is computed for each grid cell on a daily basis for the entire model domain. Unique to the VIC model is its characterization of sub-grid variability. Sub-grid elevation bands enable more detailed characterization of snow-related processes. Five elevation bands are included for each grid cell. In addition, VIC also includes a sub-daily (1 hour) computation to resolve transients in the snow model. The soil column is represented by three soil zones extending from land surface in order to capture the vertical distribution of soil moisture. The VIC model represents multiple vegetation types as uses NASA's Land Data Assimilation System (LDAS) databases as the primary input data set.

For each grid cell, the VIC model computes the water balance over each grid cell on a daily basis for the entire period of simulation. For the simulations performed for the BDCP, water balance variables such as precipitation, evapotranspiration, runoff, baseflow, soil moisture, and snow water equivalent are included as output. In order to facilitate understanding of these watershed process results, nine locations throughout the in the watershed were selected for more detailed review. These locations are representative points within each of the following hydrologic basins: Upper Sacramento River, Feather River, Yuba River, American River, Stanislaus River, Tuolumne River, Merced River, and Upper San Joaquin River. The flow in these main rivers are included in the Eight River Index which is the broadest measure of total flow contributing to the Delta. A ninth location was selected to represent conditions within the Delta itself.

## Routing of Streamflows

The runoff simulated from each grid cell is routed to various river flow locations using VIC's offline routing tool. The routing tool processes individual cell runoff and baseflow terms and routes the flow based on flow direction and flow accumulation inputs derived from digital elevation models (Figure A-28). For the simulations performed for the BDCP, streamflow was routed to 21 locations that generally align with long-term gauging stations throughout the watershed. For the VIC application for the BDCP, several additional streamflow routing locations were added to ensure that all major watersheds contributing to Delta inflow were considered. The primary additions were the smaller drainages in the upper Sacramento Valley consisting of Cottonwood Creek and Bear River and the Eastside streams consisting of Cosumnes, Mokelumne, and Calaveras Rivers. Table A-10 lists these 21 locations. The flow at these locations also allows for assessment of changes in various hydrologic indices used in water management in the Sacramento-San Joaquin Delta. Flows are output in both daily and monthly time steps. Only the monthly flows were used in subsequent analyses. It is important to note that VIC routed flows are considered "naturalized" in that they do not include effects of diversions, imports, storage, or other human management of the water resource.

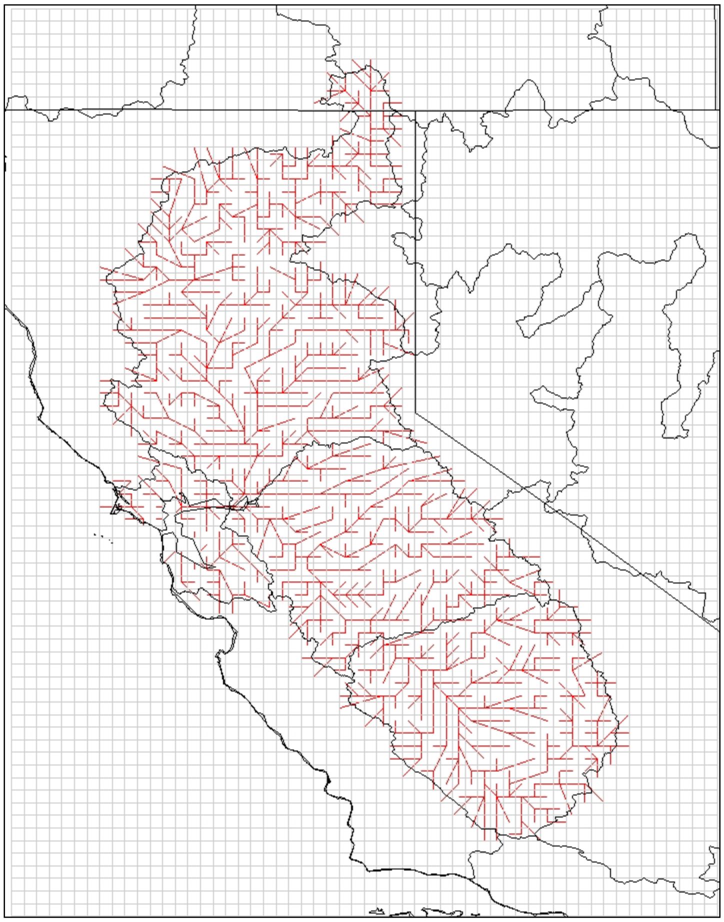

Figure A-28: VIC model routing network as applied for the BDCP application.

Table A-10: Listing of flow routing locations included in the VIC modeling.

| Abbr | Name | Lat | Lon | VIC Lat | VIC Lon |
|---|---|---|---|---|---|
| SMITH | Smith River at Jed Smith SP | 41.7917 | -124.075 | 41.8125 | -124.063 |
| SACDL | Sacramento River at Delta | 40.9397 | -122.416 | 40.9375 | -122.438 |
| TRINI | Trinity River at Trinity Reservoir | 40.801 | -122.762 | 40.8125 | -122.813 |
| SHAST | Sacramento River at Shasta Dam | 40.717 | -122.417 | 40.6875 | -122.438 |
| SAC_B | Sacramento River at Bend Bridge | 40.289 | -122.186 | 40.3125 | -122.188 |
| OROVI | Feather River at Oroville | 39.522 | -121.547 | 39.5625 | -121.438 |
| SMART | Yuba River at Smartville | 39.235 | -121.273 | 39.1875 | -121.313 |
| NF_AM | North Fork American River at North Fork Dam | 39.1883 | -120.758 | 39.1875 | -120.813 |
| FOL_I | American River at Folsom Dam | 38.683 | -121.183 | 38.6875 | -121.188 |
| CONSU | Cosumnes River at Michigan Bar | 38.5 | -121.044 | 38.3125 | -121.313 |
| PRD_C | Mokelumne River at Pardee | 38.313 | -120.719 | 38.3125 | -120.813 |
| N_HOG | Calaveras River at New Hogan | 38.155 | -120.814 | 38.1875 | -120.813 |
| N_MEL | Stanislaus River at New Melones Dam | 37.852 | -120.637 | 37.9375 | -120.563 |
| MERPH | Merced River at Pohono Bridge | 37.7167 | -119.665 | 37.9375 | -119.563 |
| DPR_I | Tuolumne River at New Don Pedro | 37.666 | -120.441 | 37.6875 | -120.438 |
| LK_MC | Merced River at Lake McClure | 37.522 | -120.3 | 37.5625 | -120.313 |
| MILLE | San Joaquin River at Millerton Lake | 36.984 | -119.723 | 36.9375 | -119.688 |
| KINGS | Kings River - Pine Flat Dam | 36.831 | -119.335 | 37.1875 | -119.438 |
| COTTONWOOD | Cottonwood Creek near Cottonwood | 40.387 | -122.239 |  |  |
| CLEARCREEK | Clear Creek near Igo | 40.513 | -122.524 |  |  |
| BEARCREEK | Bear River near Wheatland | 39.000 | -121.407 |  |  |

## A.8.3. Output Parameters

As discussed previously the following key output parameters are produced on a daily and monthly time-step:

Temperature, precipitation, runoff, baseflow, evapotranspiration, soil moisture, and snow water equivalent on grid-cell and watershed basis

Routed streamflow at major flow locations to the Sacramento Valley and San Joaquin Valley

The results from VIC modeling for the selected climate scenarios are presented in Section D.3.2.

## A.8.4. Critical Locations for Analysis

The watershed hydrologic process information can be characterized for each of the approximately 3,000 grid cells, but the nine locations described above provide a reasonable spatial coverage of the changes anticipated in Central Valley. The routed streamflows at all 21 locations identified in Table A-10 are necessary to adjust the inflow timeseries and hydrologic indices in the CALSIM II model. Analysis of flows for watersheds much smaller than what is included here should be treated with caution given the current spatial discretization of the VIC model domain. The streamflows included in this analysis and used to adjust hydrology in the CALSIM II model account for over 95% of the total natural inflow to the Delta.

## A.8.5. Modeling Limitations

The regional hydrologic modeling described using the VIC model is primarily intended to generate changes in inflow magnitude and timing for use in subsequent CALSIM II modeling. While the model contains several sub-grid mechanisms, the coarse grid scale should be noted when considering results and analysis of local scale phenomenon. The VIC model is currently best applied for the regional scale hydrologic analyses. The model is only as good as its inputs. There are several limitations to long-term gridded meteorology related to spatial-temporal interpolation and bias correction that should be considered. In addition, the inputs to the model do not include any transient trends in the vegetation or water management that may affect streamflows; they should only be analyzed from a “naturalized” flow change standpoint. Finally, the VIC model includes three soil zones to capture the vertical movement of soil moisture, but does not explicitly include groundwater. The exclusion of deeper groundwater is not likely a limiting factor in the upper watersheds of the Sacramento and San Joaquin River watersheds that contribute approximately 80-90 percent of the runoff to the Delta, however, in the valley floor groundwater management and surface water regulation is considerable. Water management models such as CALSIM II should be utilized to characterize the heavily “managed” portions of the system.

## A.8.6. Linkages to Other Physical Models

The VIC hydrology model requires input related to historic and future meteorological conditions. Long-term historical gridded datasets have been obtained to characterize past climate. Future estimates of meteorological forcings are derived from downscaled climate projections incorporating the effects of global warming. The changes in routed streamflows between historic and future VIC simulations are used to adjust inflows and hydrologic indices for use in the CALSIM II model.

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