*Integrated Modeling Support*
*Delta Stewardship Council Contract #17400*

# Memo 2. A Survey of Recent Integrated Modeling Applications in the Delta and Central Valley

**January 2020**

***Prepared for:***

Delta Stewardship Council
Ben Geske, P.E., Project Manager

***Project Team:***

Tetra Tech, Inc.
Bachand & Associates
Cramer Fish Sciences
HydroFocus, Inc.
Pax Environmental
University of California at Davis
University of California at Merced

## Acknowledgements

This work was performed under contract (#17400) between the Delta Stewardship Council (DSC) and Tetra Tech Inc. Mr. Ben Geske of the Delta Stewardship Council served as the project manager. The DSC's Integrated Modeling Steering Committee (IMSC), consisting of modeling experts from public agencies and private consulting firms, provided strategic guidance.


## Project Team


**Tetra Tech**: Sujoy Roy, Paul Hutton, Katherine Heidel, Tom Grieb, and Ali Tasdighi

**Bachand & Associates**: Philip Bachand and Yan Liang

**Cramer Fish Sciences**: Travis Hinkelman

**HydroFocus**: Steve Deverel

**Pax Environmental**: Tom Lagerquist

**University of California at Merced**: Josué Medellín-Azuara and Anna Rallings

**University of California at Davis**: Anne Visser and Leslie Panyanouvong

# Contents

## Figures



## Tables

# Executive Summary

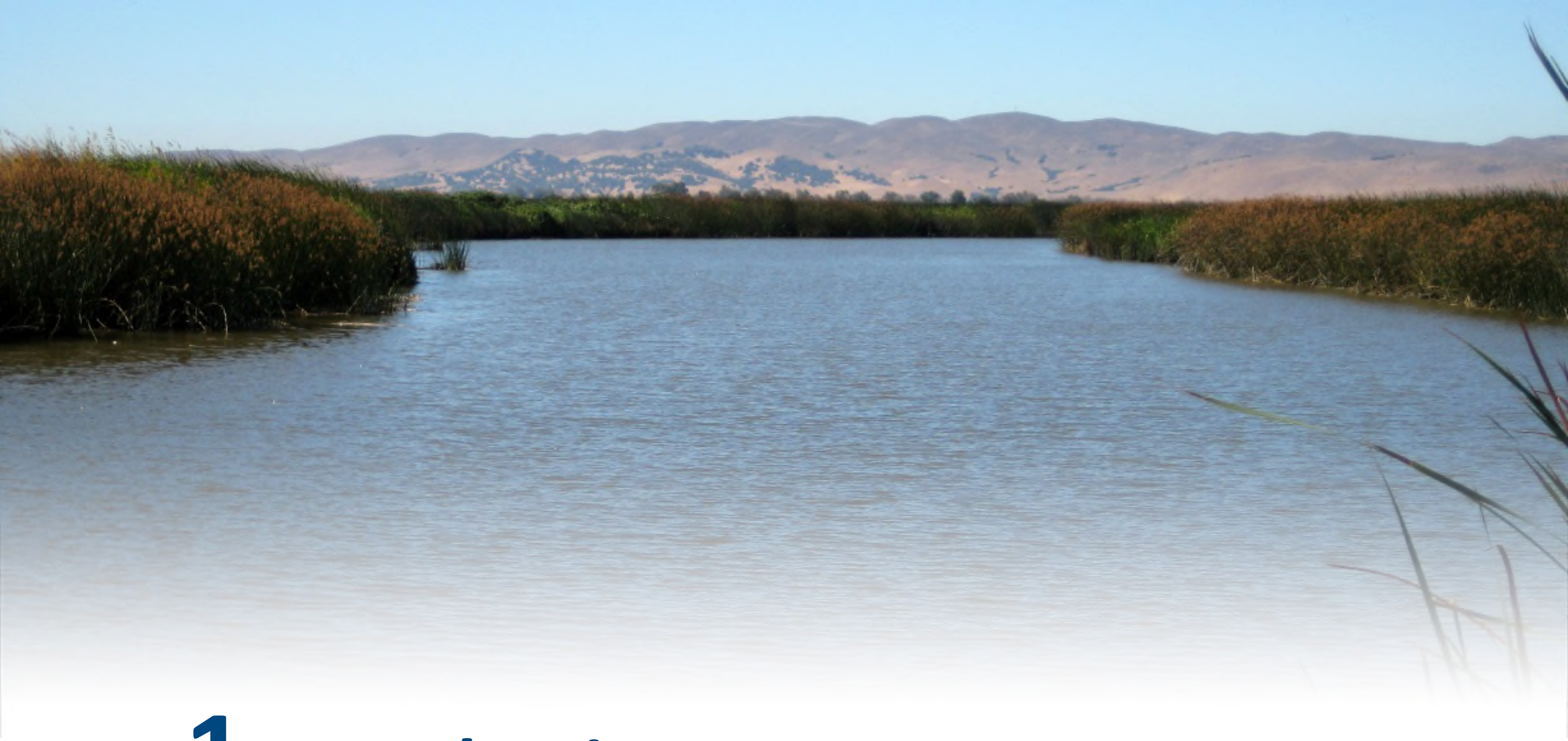
Integrated modeling is defined as an approach where two or more models, typically with different areas of focus, are used together in an analysis. At its most general, the component models in an integrated modeling framework could either focus on the same processes over different geographic areas or could originate in very different disciplines.

This memo presents a survey of how integrated modeling has been implemented, could be or is being implemented, in recent project initiatives in the Delta and Central Valley. This memo presents a survey of fifteen integrated modeling project initiatives in the Delta and Central Valley. This survey was conducted by examining publicly available information on major ongoing or recently completed initiatives and by interviewing key participants in these efforts.

Project initiatives and key participants interviewed as part of this survey are outlined in Table 1. Initiative-specific details are organized by the following common topics:

- Integrated model elements (e.g., hydrodynamics, water quality, economics, ecology)
- Institutional structure of model integration: who managed the process and which organizations participated
- Description of how modeling was or could be used to support decision-making
- Stakeholder involvement in various stages of modeling: development, integration, scenario evaluation
- Description of software and data management processes
- Time and budget resources needed
- Significant challenges in model integration
- Future model integration needs

This memo leads with key findings and lessons learned from the survey. These summary findings are followed by more detailed information for each initiative in the subsequent chapters. This memo serves as the basis for additional steps on defining the challenges and solutions for integrated modeling (Memo 3), on the modeling best practices (Memo 4), and on the synthesis paper on integrated modeling (Memo 5).



# 1 Introduction

Integrated modeling is defined as a modeling approach where two or more models, typically with different areas of focus, are used together in an analysis. At its most general, the component models in an integrated modeling framework could represent the same processes over different geographic areas or represent completely different disciplines. This document presents a survey of how integrated modeling for the Delta and Central Valley has been implemented in the past, is being implemented in the present, or could be implemented in the future. This work is premised on the understanding that integrated models may be a useful approach to evaluate complex environmental problems, whose drivers and impacts may span large geographic areas and cover diverse natural science and social science domains. While integrated modeling may be generally beneficial, it may not be beneficial under all circumstances. In this survey, we attempt to maintain a neutral perspective on the utility of integrated modeling, with the primary goal of discovering how each initiative was or is being performed.

This survey was conducted by i) examining publicly available information on major ongoing or recently completed modeling studies and ii) interviewing key participants in these efforts. In selecting candidate projects for this survey, we sought to identify projects that were large in scope and/or were known to involve a large team of interdisciplinary expertise. This effort was not intended to characterize all ongoing interdisciplinary projects. Project initiatives and key participants interviewed as part of this survey are outlined in Table 1.

The following detailed information was obtained for each modeling initiative from interviews with one or more project participants and from published information:

- Integrated model elements (e.g., hydrodynamics, water quality, economics, ecology)

- Institutional structure of model integration, i.e. who managed the process and which organizations participated
- Description of how modeling was or could be used to support decision-making
- Stakeholder involvement in various stages of modeling: development, integration, scenario evaluation
- Description of software and data management processes
- Time and budget resources needed
- Significant challenges in model integration
- Future model integration needs

In addition to the specific project initiatives described below, we also discussed various cross-cutting themes related to Delta integrated modeling with Drs. Jay Lund (University of California at Davis), John DeGeorge (Resource Management Associates, Davis, California), and Eli Ateljevich (Department of Water Resources, Bay-Delta Modeling Section).

The goal of this survey was to obtain information from a representative and broad sample of integrated modeling efforts and, based on interviews and supporting research, to describe how such work is currently being conducted. The survey is not an exhaustive review of all integrated modeling efforts in California. Furthermore, the survey questions and discussion were primarily oriented toward issues of model integration, and not on specific model outcomes. Chapter 2 provides a summary of findings from the interviews. Subsequent chapters (Chapters 3 through 18) describe each of the project initiatives in further detail. Specific models identified in this work are described in greater detail in Memo 1.

**Table 1**. Project initiatives and key participants interviewed as part of the integrated modeling survey

| Memo Section | Project Initiative | Key Participants Interviewed | Project Description |
|---|---|---|---|
| 3 | California WaterFix | Chandra Chilmakuri (MWD), Maren Greenwood & Rick Wilder (ICF Consultants), Erik Reyes (DWR) | Major proposed infrastructure project to construct tunnels under the Delta |
| 4 | Levee Assessment, Storage, Flood Management and New Infrastructure | Michael Mierzwa & Laura Hollender (DWR) | Planning support for the following programs in the Delta and Central Valley: (1) Central Valley and statewide flood management planning, (2) Delta risk management planning and investment prioritization, (3) flood and ecosystem restoration feasibility investigations, (4) storage project economic justification and operation planning, and (5) Delta conveyance economic justification |
| 5 | Socioeconomic Issues (not a specific project) | Various | Evaluation of challenges and opportunities surrounding integrated modeling as it relates to socioeconomic issues in the Delta |
| 6 | Bay-Delta Water Quality Control Plan Updates | Matt Holland, Subir Saha & Scott Ligare (State Water Resources Control Board) | Update of Delta flow and salinity standards |
| 7 | Water Rights, Consumptive Use & Water Budgets | Tariq Kadir (DWR), William Fleenor (UC Davis) | Consumptive use modeling and measurement for crops and other land use cover in the Delta |
| 8 | Delta Smelt Biological Opinion | Li-Ming He and Matt Nobriga (U.S. Fish and Wildlife Service) | Modeling Delta Smelt behavior and population dynamics to support ongoing Biological Opinion re-consultation |
| 9 | Central Delta Corridor/Future Carbon Markets | Campbell Ingram (Delta Conservancy) | Proposed multi-agency effort to assess options for greater sustainability on publicly owned lands in the western and central Delta. |
| 10 | California EcoRestore | Erik Loboschevsky (DWR) | Multi-agency effort to restore 30,000 acres of habitat in a set of discrete projects across Delta islands |
| 11 | Yolo Bypass Models | Robyn Grimm (Environmental Defense Fund), William Fleenor (UC Davis), Doug Brown (Douglas Environmental), Michael Mierzwa (DWR) | Water and environmental modeling by DWR and other agencies for the Yolo Bypass, a seasonally inundated floodplain used for flood protection, agriculture, fish populations, and migratory waterfowl |
| 12 | Delta Methylmercury Total Maximum Daily Load Modeling | Carol DiGiorgio (DWR) | Evaluation of methylmercury loads and concentrations as a function of water project operations |

| Memo Section | Project Initiative | Key Participants Interviewed | Project Description |
|---|---|---|---|
| 13 | CASCADEII Model Framework | Noah Knowles & Lisa Lucas (US Geological Survey) | U.S. Geological Survey-led model study of climate, hydrology, hydrodynamics, sediment, phytoplankton, bivalves, contaminants, marsh accretion, and fish populations |
| 14 | AFRI Rice Agriculture Modeling | Dennis Baldocchi, William Horwath, Lucas Silva, Steven Deverel, Patricia Oikawa, Amy Merrill, Paul Jacobs, Sandra Bachand, Philip Bachand | Evaluation of growing rice in the Delta to provide alternative income source with added benefits for subsidence mitigation, levee stability, and ecosystem services. Various aspects of land use were monitored and modeled |
| 15 | Modeling for Climate Change Vulnerability Assessment and Adaptation Strategy for the Sacramento-San Joaquin Delta and Suisun Marsh | Kate Anderson (Delta Stewardship Council) | Planning effort to 1) characterize the climate change exposure, sensitivity, and adaptive capacity in the Delta to provides decision relevant information and; 2) create adaptation strategies to support the achievement of the Delta Plan’s coequal goals and to reduce the impacts. |
| 16 | Managed Aquifer Recharge using Floodwater (FloodMAR) | Ajay Goyal, David Arrate, Romain Maendly, Rich Juricich (DWR) | Groundwater recharge using flood flows to increase water security and mitigate downstream flood risks. Modeling used to understand climate-driven surface water allocation and potential for groundwater recharge. |
| 17 | Franks Tract Restoration Feasibility | Eli Ateljevich (DWR) | Hydrodynamic and water quality modeling to evaluate effects of different conceptual restoration designs |
| 18 | Chinook Salmon Life Cycle Model | Vamsi Sridharan and Eric Danner (NOAA) | Mechanistic model evaluation of juvenile Chinook salmon life cycle |

# 2 Key Findings and Lessons Learned

This chapter provides a summary of the cross-cutting findings from our interviews with model practitioners and managers to solicit information on previous and ongoing model integration efforts; findings from these interviews are described in detail in the following chapters. Model integration has been used widely across the Delta and its watershed in many completed studies. The most common applications are where a single factor is being evaluated, such as when water flow is tracked for purposes of water supply and flood control from the upper watershed, through the man-made reservoir systems, into the Central Valley, and through the Delta and Bay. Models that consider water resources and economics (costs of flood protection or agricultural economics) are also in common use. Other emerging applications consider the interaction of water flows with water quality and ecosystem processes. Key findings from our interviews are grouped under the following six headings: drivers, current practices in model integration; successes; challenges; time and budget resources; and future needs to move forward with model integration in the specific initiatives.

## 2.1 Drivers

The most common driver of integrated modeling efforts is a clearly defined regulatory impetus, which in some cases is tied to specific projects. Typical examples of these kind of regulatory-driven projects include restoration projects to meet with endangered species goals and development of new water quality standards. Integrated modeling efforts are also driven by research considerations; in the Delta domain research-driven efforts have typically been led by academic groups or the U.S. Geological Survey. Although there are sufficient examples of both types of drivers, we observed that the best funded, staffed and sustained efforts are those that are tied either to regulatory drivers or to the primary mission of a sponsoring agency.

## 2.2 Current Practices

Current practices in Delta integrated modeling are summarized in the following bullets:

- The most common framework for the integrated use of models is where data from one model is fed into another and where the models are run independently of one another. This framework is especially common of models for upper watershed hydrology and reservoir inflows, reservoir outflows, riverine flows, and estuary hydrodynamics. This methodology is adequate when there are no feedbacks between models and when minimal additional software is needed to pass the outputs from one model to another. Even where the need for data flow is sequential, time and resources are needed to convert the data output into the correct format and units for the downstream model.
- Although non-proprietary models are the workhorse of integrated modeling in the Delta today, there are also prominent proprietary models in use. They are generally considered credible by the stakeholder community. However, proprietary model access by other participants can be limited. Thus, ready access may only be available for pre-run scenarios. For any new general analysis, it may be difficult to accomplish integration without full access to the model.
- Building consensus among stakeholders is an important function of modeling. Models can provide insights into how complex systems work that can be useful for answering stakeholder questions . Model transparency and accessibility and replicability of data and analyses are essential for building trust and consensus among stakeholders.

## 2.3 Successes

Characteristics associated with successful application of integrated models are summarized in the following bullets:

- The most successful integrated modeling efforts are organic, where models are added incrementally and when existing, well-established models are employed. There appear to be few new large-scale integrated modeling efforts, where novel model development is part of the integration effort. Integrated modeling, where separate domain-specific models are developed and tested independently, is beneficial in that it may be easier to manage than a single effort. Specialists in different subject areas may lead the development of their respective models (which can be conducted independently and in parallel), as long as there is a common understanding of inputs and outputs to be shared for integration.
- Model integration has been most successful when the project was conducted within one or two closely related agencies. There are fewer instances in the Delta region of broad-based integration across a wide modeling community.
- For new model frameworks, model testing during calibration and evaluation may also highlight errors in the underlying computer implementation. Sharing this information enhances the credibility and ultimate success of a modeling effort.

## 2.4 Challenges

Challenges associated with successful application of integrated models are summarized in the following bullets:

- In some cases, model use is tied to specific experts, e.g., the expert is the primary developer and the primary entity applying the model. This may occur even in cases where the model is not proprietary. This may be adequate for specialized applications where the expertise to properly apply a model may not be broadly available. However, when such a model is to be used within an integrated framework, lack of public availability presents a serious challenge. If such a model lies downstream of other models, it limits the speed with which integrated runs can be performed. If such a model lies upstream of the other models, it may not be available for the full range of scenarios or within the project timeline. Such models tend to be siloed and are not being adapted as computer technologies (e.g. programming languages, interfaces, etc.) evolve.
- A concern with employing complex models within an integrated framework is that skilled analysts may not be available to run the models even if the underlying models and supporting input files are readily available. Thus, one cannot assume that access to the model alone will lead to credible results. This is a limitation for the general use of specialist models and an associated concern with respect to integration of such models with other models.
- Model availability (including code, input files, and outputs) may be limited for different reasons. For planning studies, model code is often easily available, but inputs and output information can be made available when the studies are complete. For scientific studies, the model code may be under development, and not be released until completion and formal publication, which may often take years in some cases. Finally, some models, such as those used for day-to-day reservoir operations, are not in the public domain and are not expected to be.
- As compared with individual model development and application, most major integration efforts are of longer duration and need committed support over time. This is the case of integration efforts with dependencies between models, where the behavior of one model in an integrated framework affects other models. In such instances, time must be allowed for each model to be set up and calibrated, and also for the models to be made to work together in a reliable manner.
- Automatic calibration of complex numerical code is highly computer intensive and requires dedicated computer resources to accomplish. In some cases, this may require a different computer framework to perform. As a remedy to this challenge, calibration is often performed manually with expert input.

## 2.5 Time and Budget Resources for Integrated Modeling

Most significant integrated modeling efforts are large multi-year projects. While information on project schedule was generally available, information on project cost was not generally available. Cost information was available when an outside entity was contracted to perform a specific task, but this usually does not capture all facets of costs associated with large integrated modeling efforts.

## 2.6 Future Considerations

Future considerations in promoting successful application of integrated models are summarized in the following bullets:

- The success and future utility of model integration efforts largely depend upon the overall stakes at risk, the resources dedicated and the primary organization's mission. For instance, integrated modeling efforts like California FloodMAR and the Delta Levee Investment Strategy address the State's water and its security, putting much of California's economy at risk. With large stakes, significant resources are provided to develop the integrated models and to maintain those efforts because these tools become central in the decision-making process. DWR and the DSC led these efforts and these efforts fall squarely within their institutional missions. Thus, one can expect that these tools will evolve and improve over time as has occurred with many individual models being maintained by the State and particularly by DWR. However, other efforts are less likely to have the same success or utility.
- There are no public domain sites that are available today for modelers to share the results of their modeling efforts across the different initiatives discussed above. This includes model code, input files, configuration files, best estimates for key parameters, and representative output files for specific studies. While such information does exist in distributed form, it is housed in different organizations and is not in a form that is easy to search and share across different groups. Importantly, with the growing complexity of models and the sizes of associated files, adequate computer and human resources must be allocated to make this information easily shareable.
- In many institutions that have successfully undertaken integrated modeling efforts, there has been compatibility between the institutions' mission and the tools used (e.g. DWR and USGS).

## 2.7 Summary

Key findings from our interviews with model practitioners and managers provide a good understanding of how integrated modeling is being applied, and the conditions under which integrated modeling is most likely to be successful. Notable challenges to the successful integration of models were identified through this survey. The information provided in this document is the basis for a more detailed presentation of challenges and solutions for integrated modeling in Memo 3, and the basis for the development of an integrated model strategic plan in Memo 5.

# 3 California WaterFix

California WaterFix (or WaterFix) was a major proposed infrastructure project to construct two tunnels under the Delta and develop water intakes near Freeport on the Sacramento River to transport Sacramento River water to the existing intakes in the South Delta for export. The project's estimated capital cost was nearly $17 billion. The project was initially evaluated as part of the Bay Delta Conservation Plan and was renamed as California WaterFix in 2016. The project was intended to address a variety of environmental, seismic, water quality and climate change threats to the current State Water Project (SWP) and Central Valley Project (CVP) infrastructure in the Delta. The WaterFix project was complementary to the California EcoRestore program (described as a separate initiative below) which consists of specific projects to restore estuarine habitat for aquatic species. In 2019, the Department of Water Resources withdrew proposed permits for the WaterFix project and began a renewed environmental review and planning process for a smaller, single tunnel project that will protect a critical source of water supplies for California. In spite of this action, the modeling performed for the Waterfix project is still relevant to evaluate large scale model integration in the Central Valley and Delta.

Given preliminary design concepts for various tunnels, the effects of the WaterFix project on flows, water quality, and biology were examined. Extensive modeling was performed in support of the project's Environmental Impact Report/Environmental Impact Statement (EIR/EIS). The modeling foundation, CalSim II, was used to simulate SWP and CVP operations under future conditions. Using CalSim II output, a variety of integrated models were used to represent hydrodynamics, water quality, and biological responses to WaterFix in the Central Valley and Delta. In particular, the modeling of fisheries responses represents some of the most complex integrated modeling applied for any planning study in the Delta.

### 3.1 Integrated model elements

Integrated modeling for the WaterFix project spanned the following technical disciplines: water project operations, hydrodynamics, water quality (temperature, salinity, sediments, nutrients, and trace contaminants), agricultural economics, ecology, and groundwater.

### 3.2 Institutional structure of model integration

The modeling effort was managed and coordinated by DWR with the support of a large, specialized consultant team. Schedules were driven by the need to complete the EIR/EIS within a defined time frame.

### 3.3 Description of how modeling was used to support decision-making

Integrated modeling was fundamental to the decision-making process. Key decision elements included the following: defining the size of project, defining operating criteria, evaluating water supply benefits, and selecting intake locations, tunnel alignment, and outflow requirements. The modeling effort evaluated changes in key endpoints (such as water quality at key locations and fish population distributions) between baseline conditions and alternative project configurations. The modeling was driven by defined reservoir operating criteria and a standard hydrologic sequence spanning 82 years; the various technical disciples employed different subsets of this hydrologic sequence.

### 3.4 Stakeholder involvement

Interaction with regulatory entities was an important component of the planning process. A notable success of the integrated modeling is that it was successfully used to build consensus among various agencies, resulting in project buy-in from USFWS and NMFS. Working with these stakeholders, an iterative process was used to modify operations criteria to best meet ecological requirements including temperature requirements, bypass flow requirements, and pulse flow protection. WaterFix modeling was not conducted through an open process, and peer-review of the model products outside of the agencies only occurred at specific points during the EIR/EIS review process.

### 3.5 Description of software and data management processes

The following models were used:

- **CalSim II**: Reservoir operations
- **DSM2** (Delta Simulation Model): Delta hydrodynamics and water quality
- **EPTM** (Enhanced Particle Tracking Model): Particle transport with fish behavior to model migration in channels
- **OBAN** (Oncorhynchus Bayesian ANalysis): Model of Central Valley Chinook Salmon
- Artificial Neural Network (ANN) emulators for DSM2: Embedded within the CALSIM model runs

- **HEC-RAS** (Hydrologic Engineering Center-River Analysis System): Modeling of river hydraulics
- **SRWQM** (Sacramento River Water Quality Model): Temperature in Sacramento Valley streams

Key model runs using DWR models (specifically CalSim II and DSM2) are maintained by DWR and were provided to other model teams. Outputs from related models, such as those for water temperature and fisheries impacts, are not stored in a central repository.

## 3.6 Time and budget resources needed

Modeling for WaterFix was performed over more than 10 years and involved a large team of specialists in many different disciplines. The cost for developing the EIR/EIS, of which modeling was a substantial component, was estimated to be $100 million. This was likely the largest integrated modeling effort undertaken for an environmental project in California.

## 3.7 Significant challenges in model integration

Model integration in WaterFix involved the flow of information between independently run models. Iteration between model runs, when done, was implemented manually, with the transfer of input and output files from one team to another. Within this project structure, iteration between any two models being integrated must occur following completion of both runs. If an unacceptable condition is observed in a downstream model, there is no way to make an immediate change to conditions in the upstream model. Such a change must be made after the runs are complete and the models re-run. This constraint adds to the time needed for integrated modeling, but more importantly, real-time feedbacks between models cannot be fully considered. Furthermore, because different teams were running these models, complex model integration (over multiple models) could take several weeks. This was the case with the Winter Run Chinook Salmon Life Cycle Model (LCM, Figure 1). As a consequence, there was insufficient time and resources to comprehensively iterate across the suite of modeling tools used to represent different processes. Below we address challenges associated with each group of models:

### 3.7.1 Operations Modeling through CalSim II

The CALSIM II model was at the core of the integrated modeling effort and provides output at a monthly time step. In contrast, most other downstream models require shorter time steps. To address this, CalSim II output was mapped to a daily time step for use in other models. However, this is not straightforward matter of interpolation from monthly to daily timesteps, because the operations also need be considered at a finer time step. In the WaterFix modeling, North Delta operations were mapped to a daily time step, but the South Delta operations were not. This difference between monthly and daily time step information is most acute during December-June when flows are more variable.

Artificial neural network (ANN) submodels were integrated within CalSim II to provide an emulation of the DSM2 salinity response, i.e., for a given Delta outflow scenario, the ANNs were used to estimate salinity in the western Delta and drive attainment of compliance with current water quality standards. The ANNs added uncertainty to the calculations that was not easily quantified and sometimes provided results that could not be fully explained from the inputs.

The CalSim II modeling uses a conceptual approach termed the “level of development” (or LOD) to fix land use, water diversions, and the regulatory framework over the entire hydrologic sequence. The LOD hydrology is synthetic in that, over any long-term record, the underlying development will also change. The time series in an LOD-based simulation is a statistical representation of the hydrology. Thus, an LOD-based hydrology is inconsistent with a model that is designed to simulate processes that may not be stationary over time (e.g. a fishery population). Also, the LOD approach implemented in CalSim II may not be entirely consistent internally because the hydrology has not been fully detrended to account for historically observed climate change.

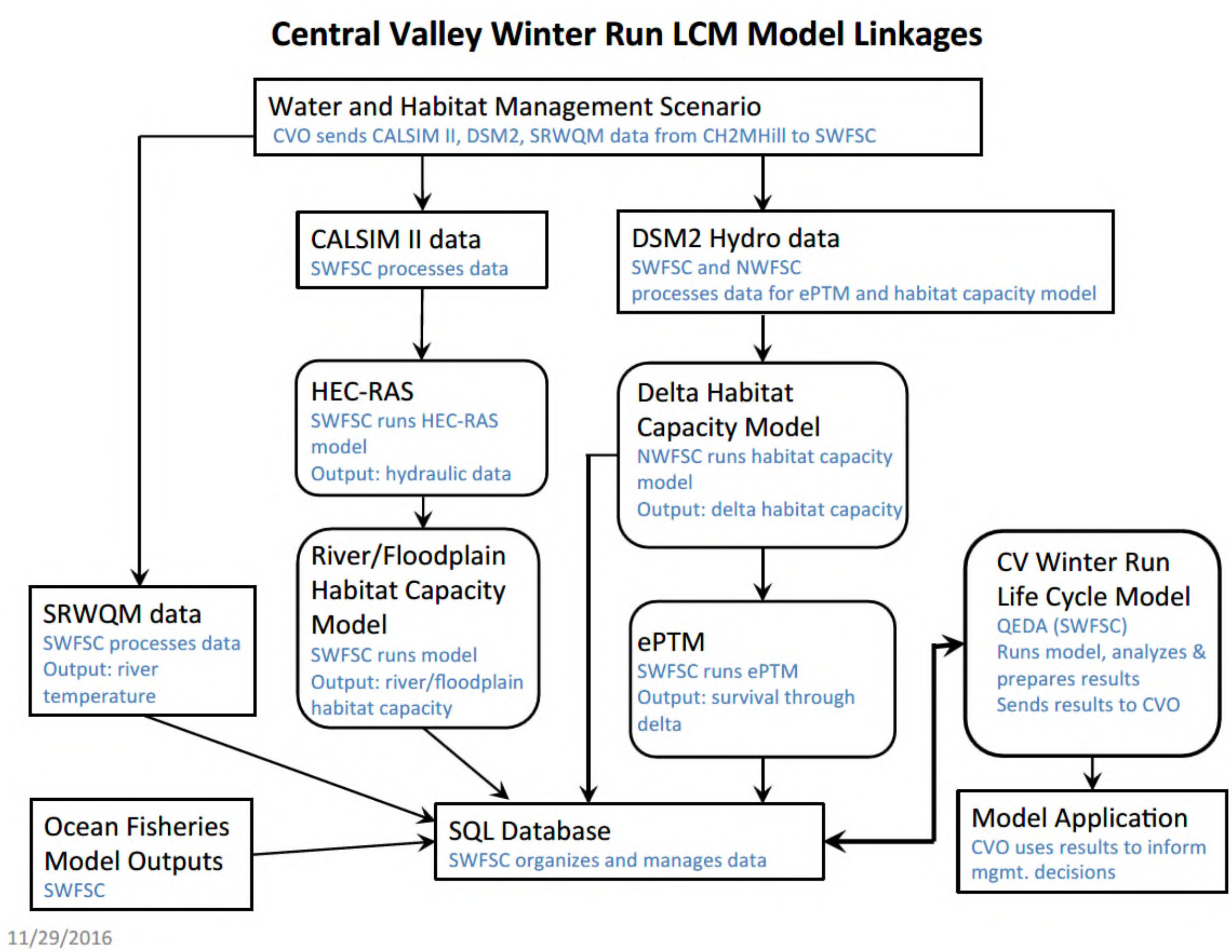



**Figure 1**. Model integration for the Winter Run Chinook Salmon Life Cycle Model (LCM)

Broadly, it is important to understand the appropriate use of a LOD-based CalSim hydrology and limits associated with the conceptual approach. Under scenarios where project operations are expected to change significantly, a CalSim-based approach is needed. However, under scenarios where project operations are not expected to change dramatically from historical conditions, a historical hydrologic sequence may be a more appropriate baseline. Even for projects with WaterFix-scale operational complexity, utilizing historical hydrologic sequences to driver simulations may provide useful insights within an integrated modeling framework.

### 3.7.2 Hydrodynamic & Water Quality Modeling in the Delta

For integrated modeling that was based on the CalSim structure (with a particular combination of inflows and time series information), DSM2 was applied for the WaterFix modeling. This approach was specifically used for long-term planning runs. In other cases, where CalSim outputs are not the driver, other types of models could be applied for analysis. In particular, for certain types of questions, such as changes in geometry in the estuary, more complex multi-dimensional models may be appropriate.

### 3.7.3 Other Models

Adapting the conceptual LOD approach (implicit in the CalSim II and DSM2 planning methodology) to models that are designed to simulate historical conditions presents challenges. Some commonly used biological models (e.g., OBAN and IOS) are statistical models and are not sufficiently parameterized to respond to system changes. Others, such as EPTM are physically based, but need real flows to be used appropriately. The following is an example problem with EPTM – The North Delta diversion assumption in DSM2 was arbitrarily set to maximum pumping beginning at midnight. However, EPTM includes assumptions on how fish move during the day vs. night. This mismatch between assumptions resulted in false impacts.

## 3.8 Future model integration needs

Some of the existing and new models applied in WaterFix were being modified as integration was underway. Some models, particularly those related to ecosystem processes, may still be in development. Ideally, modeling may need to be revisited with the best scientific information now available. Some areas where additional model development is needed include: sediment transport and turbidity, dynamic Delta island processes, ecological processes including primary productivity and harmful algal blooms.

CalSim II, as used in the WaterFix work, assumes that operating rules are static and do not deviate over the entire period of record. This LOD-based conceptual assumption can cause modeling analyses to show false impacts, given that operators can adapt in real time to meet project objectives. Addressing this real-time feedback needs a different perspective on how optimization among different alternatives is performed. While such an effort may be part of a long-term vision, the need for such an effort will likely increase given the types of adaptive and real-time operational constraints that are expected in future.

*3. California WaterFix*

# 4 Levee Assessment, Storage, Flood Management and New Infrastructure

Watershed, reservoir and river hydrologic and hydraulic modeling is a relatively mature topic of model integration and discussed as a common theme. A related suite of models has been used to support the following programs in the Delta and Central Valley: Central Valley and Statewide flood management planning, Delta risk management planning and investment prioritization, flood and ecosystem restoration feasibility investigations, storage project economic justification and operation planning, and Delta conveyance economic justification.

## 4.1 Integrated model elements

Integrated modeling focused on the following domains: climate modeling (both upper watershed inflows and sea level rise in the estuary), watershed and runoff modeling (including probable maximum precipitation/probable maximum flood design), reservoir operations, riverine hydraulics, floodplain mapping (including functional habitat planning), economic loss avoidance – inundation, levee fragility and system performance assessments, pulse flow operational planning, and estuarine hydrodynamics and salinity.

## 4.2 Institutional structure of model integration

This work was led by the Department of Water Resources, included participation of the U.S. Army Corps of Engineers, and was supported by consultants. Some modeling needs were jointly addressed by working with the Department of Fish and Wildlife.

## 4.3 Description of how modeling was used to support decision-making

The suite of integrated models was used to support several related decision-making processes as discussed below:

### 4.3.1 Delta Levee Investments

DWR relies on topographic information and levee performance information to inform funding decisions through the Delta Special Projects program. Updated topographic information has been supported by the program to account for sea level rise. DWR has also prepared levee fragility curves to assess the risk to statewide water supplies associated with current levees through the the Delta Risk Management Strategy (DRMS), though no set design life for current or future levees has been prepared for a natural hydrologic risk approach. DWR has also supported research on seismic impacts on levee fragility (via DRMS and the Delta Knowledge Improvement Program). DWR has funded USACE updates of the Delta stage-frequency curves. The DRMS work also incorporated water quality modeling using the Water Analysis Model (WAM) combined with the fragility work to justify system-scale investments.

### 4.3.2 North Delta Program Investments

Water quality modeling, in combination with flood modeling, has been used to demonstrate the downstream impacts and upstream benefits associated with habitat enhancement of specific restoration projects in the north Delta.

### 4.3.3 Central Valley State Plan of Flood Control Planning / Land-Use Planning

The Central Valley Flood Protection Plan (CVFPP) had an extensive series of studies and linked physical and empirical models that were used to support its $20+ billion investment recommendations. Climate change (upstream/downstream) scenarios were applied to VIC models of Sierra Nevada watersheds to generate runoff that was then routed through the various flood control reservoirs via HEC-ResSim, before entering the Central Valley Floodplain Evaluation and Delineation (CVFED) comprehensive HEC-RAS model. To support the CVFPP-related modeling efforts, an extensive set of different modeling assumptions for different scales / applications of study were developed by DWR in 2011.

Within each protected basin/impact area, a series of different "maximum extent of flooding" floodplain inundation and habitat opportunity models were used to identify the potential consequences/benefits of flooding to inform the need for levee improvement or levee design/possible removal or relocation (i.e. levee setback). These habitat opportunity models looked at the functional habitat needs of various species and the connective of these habitats to other similar habitats to quantify the potential ecosystem benefits. Sediment transport or channel drift modeling was not included in the extensive CVFPP modeling to evaluate the ecosystem benefits of in-channel and connected floodplain vegetation on attenuation of the flood hydrographs. DWR's Flood Managed Aquifer Recharge program (discussed separately) is looking at the additional benefits associated with reducing peak flood events by conveying some of this flood water to detention areas for groundwater recharge. With the CVFPP work, extensive use of physically and empirically based levee fragility curves from the ~$300 million levee evaluation program were used. No work on levee design life nor derogation of levees over time was conducted (funding and time were constraints), but future opportunities for integrated modeling should look at changes of levee performance over time.

The impacts of vegetation on levee fragility were incorporated into the levee evaluation program work via a multi-year California Levee Vegetation Research Program. The significance of this work is to help inform the design of levees such that important riparian habitat can remain on the levees and be managed without increasing the risk of loss due to failure.

DWR also prepared an extensive Urban Levee Design Criteria (ULDC) to assist local agencies design levees to meet a 200-yr Level of Protection. The ULDC work was based on the above-mentioned levee evaluation program and is considered a default objective of many local agencies in determining their optimal Urban Levee of Protection. The modeling implication here is that most system models of the Central Valley assume urban levee performance capable of safely conveying flood flows associated with a 200-yr design water surface profile. However, it is important to note that actual levee designs will have different 200-yr design water surface profiles.

## 4.4 Stakeholder involvement

There is active collaboration across agencies, especially DWR, DFW, and the US Army Corps of Engineers. There is also extensive collaboration with local organizations throughout the watershed.

## 4.5 Description of software and data management processes

The models used are identified below. All models are in public domain except FLO-2D and RMA Bay Delta model.

- **HEC-HMS** (Hydrologic Engineering Center-Hydrologic Modeling System): Hydrologic modeling in river systems
- **VIC** (Variable Infiltration Capacity Model): For upper watershed runoff processes
- **HEC-RAS** (Hydrologic Engineering Center River Analysis System): River hydraulics
- **UNET:** River hydraulics
- **FLO-2D**: Two-dimensional flood flow
- **HEC-FDA** (Hydrologic Engineering Center Flood Damage Reduction Analysis): Flood risk assessment
- **RMA Bay Delta Model**: Delta hydrodynamics and salinity

- **HEC-ResSim** (Hydrologic Engineering Center Reservoir System Simulation): For modeling reservoir operations
- **CalSim II**: Reservoir operations for Sacramento-San Joaquin River system
- **DSM2** (Delta Simulation Model 2): Delta hydrodynamics and water quality

The following data sets were used:

- Climate projection data from CMIP3/CMIP5
- Updated LiDAR and Bathymetric surveys of the Central Valley and Delta
- Bulletin 17-B statistical regressions
- DWR NULE Geotechnical Overview Report & Geotechnical Assessment Report and ULE Geotechnical Evaluation Report fragility
- ULDC and USACE EM 1110-2-1913 standards
- 2010 Census data, property values and occupancies and estimated structural content databases

Additional tools were created to assist in pre- and post-processing outputs from these models and for transferring data between models; the methodology is described in the CVFPP technical appendices. DWR's Division of Flood Management created a library of models for future use. An overview of flood risk analysis tools used for the 2017 CVFPP Update is presented in Figure 2.

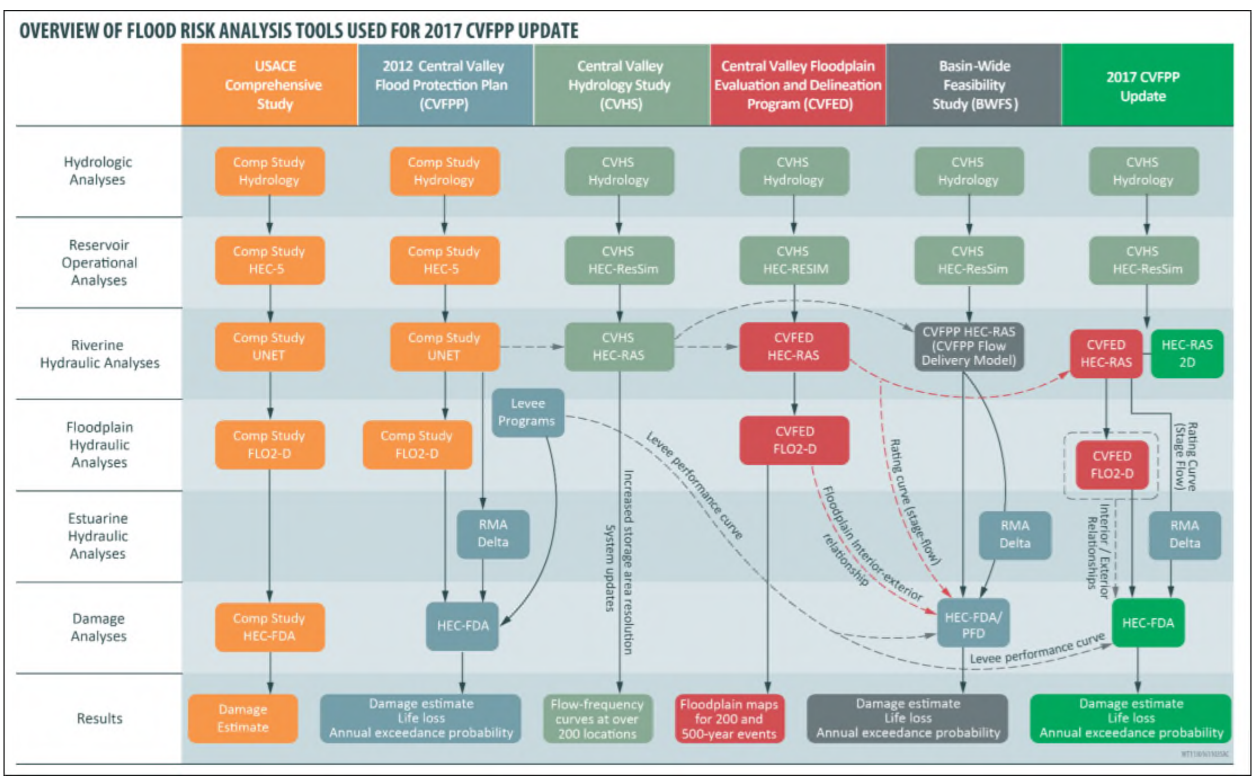



**Figure 2**. Overview of flood risk analysis tools used for 2017 CVFPP Update (DWR, 2017)

## 4.6 Time and budget resources needed

This project is a multi-year continuing process and a central element of DWR's mission. Costs cannot be easily quantified, except for specific elements. Further, modeling costs are not easily separable from data collection costs over the large spatial area of the Central Valley.

## 4.7 Significant challenges in model integration

- Regulatory constraints for future conditions are speculative, making future conditions studies difficult. There should be numerous future conditions studies and a greater reliance on sensitivity studies.
- Where proprietary models are used, and the underlying assumptions are not transparent, it can be difficult to evaluate results.
- Levee fragility is assumed to be static. True natural risk management requires an assessment of a cost-effective level of protection and specified a design life. In the case of loss avoidance studies, levees and other protection systems should degrade with time. In terms of risk management, it should be noted that bathymetry and vegetation will also change over time.
- Levee fragility assessment is extremely expensive and is not likely the first order driver for loss avoidance or risk investment-based assessments. Hydrology (stage/flow-frequency) and asset exposure (complete with inundation modeling) are likely the critical drivers in risk-based decision-support.
- Channel geometry and flow fields: 3-D models are gaining in popularity, but the data used to calibrate these models is limited. Greater care should be taken to describe the specific conditions models are calibrated to address.
- Best practices for designing studies do not exist; thus, clarity on terminology such as calibration, verification, validation, scenarios, conditions, iterations, etc. is lacking. There is a significant need for California to have recommended definitions for use in model/study applications.

## 4.8 Future model integration needs

- Stage/flow-frequency information will need to be updated from time to time; this includes updates of the CVHS/CVFED work. The updates will need to account for longer hydrologic records and physical changes (natural and human) to the system.
- The Delta tidal prism will need to be updated; future expected tidal prisms can be set as a sort of standard to use. This is particularly important for evaluating the benefit of future ecosystem enhancement activities. Climate change both upstream and downstream (i.e., sea-level rise) will change the overall hydrodynamics and levee performance in the Delta. When making investments for habitat restoration or water supply, changes in the hydrodynamics will change what land use and operational decisions / frameworks might be. Other changes include regional physical changes. For example, flooding of Prospect

Island changed the tidal prism, and cumulative restoration projects that rely on tidal mixing could eventually do the same.

- Habitat enhancement and restoration design work have been incorporated into levee improvement designs, but no physical modeling has been used to assess changes in flood risk associated with these ecosystem features. Ecosystem services such as vegetation cover on levee slopes could have the additional benefit of improved levee performance in cases of wave driven scour on levees.
- Carbon sequestration pilot projects have not been well integrated into other sea level rise estimation activities or into fragility-based risk assessments. This is another area of future opportunity, but due to the non-urbanized nature of these projects, economic loss avoidance studies will likely not yield any significant findings. Tying levee reliability into future Delta-wide water quality is the major missing link.
- There is a need to establish multiple baselines: economic, hydraulic, ecosystem, etc. and to clearly list assumptions within these baselines based on the typical types of studies they may be used in evaluating. The result will be a host of baseline documents, but this may be challenging to communicate.

# 5 Socioeconomic Issues

Efforts to develop integrated models to evaluate socioeconomic issues in the Delta region have faced significant challenges and are less developed that applications in other domains. While there has been interest in integrated modeling efforts, this interest has remained largely aspirational. While specific efforts have been proposed, particularly as it relates to inform adaptive management of Delta restoration efforts, these proposed efforts have not yet been implemented. Given these realities, this chapter discusses the challenges and opportunities surrounding integrated modeling as it relates to socioeconomic issues in the Delta from a broad perspective rather than in the context of specific integrated modeling efforts.

## 5.1 Integrated model elements

Although integration has been considered conceptually, no formal efforts at integration across other domains have been made.

## 5.2 Institutional structure of model integration

Work in this area, led by the Delta Protection Commission, has focused on restoration efforts; efforts are also being undertaken by the Department of Water Resources. Much of the focus of these individual agencies has been on identifying regional and local models of development that can be used as best practices.

## 5.3 Description of how modeling was used to support decision-making

Practitioners and decision makers active in this policy arena indicate that visualizations provided by GIS-based models (used as a communication tool for policymakers) are likely to be the most powerful forms of information to support decision making. There is a need for significant stakeholder input to advance such an effort.

While there have been many studies which have sought to present modeling to inform policy decisions in the Delta region, study documentation does not specifically mention how these models influence policy per se.

## 5.4 Stakeholder involvement

Much of these efforts remain undertaken by individual agencies, with little multi-agency collaboration. The Delta Protection Commission and DWR are most active in this area. The Delta Protection Commission has also sought to promote extensive collaboration with local organizations and community members throughout the Delta Region through Participatory Planning Models; these conceptual-based qualitative models are being developed in support of Delta Heritage Project efforts to preserve, restore, and enhance the Delta as an evolving place.

## 5.5 Description of software and data management processes

N/A

## 5.6 Time and budget resources needed

N/A

## 5.7 Significant challenges in model integration

- Socioeconomic models use historical data which often do not provide an accurate account of current conditions and must be interpreted within the context of these limitations.
- Model integration is complex in relation to socioeconomic issues given the variety of regional constraints on economic and social development. For example, the Delta is a floodplain which makes it difficult to promote development.
- Planning measures are slow and take time. Agencies have noted little success in ensuring the wants and needs of the local communities and stakeholders.
- A hierarchical system of checks and balances is needed; this system could be accomplished through a committee of experts and scientists and private public partnerships to streamline multiple individual efforts on the ground.
- The region lacks timely data to support socioeconomic modeling efforts on a continuous basis.
- Ecosystem and agricultural values are hard to quantify due to gaps in data in relation to data collection.

## 5.8 Future model integration needs

- Data used for building integrated modeling will need to be collected on a consistent basis to help provide timely analysis of current trends.

- There is a need to facilitate better communication between state agencies engaged in socioeconomic modeling and local community stakeholders and residents. Scientific information and findings from modeling efforts should be communicated in ways that are accessible to regional decision makers and stakeholders.
- Community stakeholder participation is needed to support socioeconomic modeling efforts. However, community participation remains low and is quite limited throughout the region.

*5. Socioeconomic Issues*

# 6 Bay-Delta Water Quality Control Plan Updates

The State Water Resources Control Board (Water Board) leads the development of the Bay-Delta Water Quality Control Plan (Plan) which establishes water quality standards and flow requirements through the Delta to support municipal, agricultural, and fish and wildlife beneficial uses in the water body. The last major modification to the Plan occurred in 1995, and the last updates were adopted in 2006.

The Water Board is now focused on an update to the Plan to address declines in native aquatic species in the Delta and San Francisco Bay. The Plan is being updated through two separate processes or amendments. The first amendment (Phase 1) is focused on San Joaquin River flows and southern Delta salinity. The second amendment (Phase 2) is focused on the Sacramento River and its tributaries, Delta eastside tributaries (including the Calaveras, Cosumnes, and Mokelumne rivers), Delta outflows, and interior Delta flows.

## 6.1 Integrated model elements

Modeling in support of the Plan amendments include consideration of hydrology and reservoir operations, hydrodynamics, water quality (primarily salinity and temperature), and economics (to evaluate the impacts of changes in water quality standards. The following models have been used:

- **Water Supply Effects (WSE) Model**: Spreadsheet operations model for the lower San Joaquin River; used for Phase 1. This model was based on the CalSim II framework.

- **SacWAM** (Sacramento Water Allocation Model): This model is based on the WEAP (Water Evaluation and Planning System) framework; used for Phase 2.
- **DSM2** (Delta Simulation Model): Delta hydrodynamics and water quality
- **SWAP** (Statewide Agricultural Production Model): Agricultural economics
- **IMPLAN** (IMpact Analysis for PLANning): Community impact analysis, such as revenues and employment, for given change in regulation
- **SALSIM**: Life cycle model for fall-run Chinook in the San Joaquin River Basin
- **Statistical relationships**: Flow vs. abundance for key species – from literature but updated with new data

The Water Board chose to develop alternatives to the CalSim model for reservoir operations analysis because it i) does not allow users to set monthly downstream flow targets as a fraction of the unimpaired flows and ii) does not support rapid and simple evaluation of operational alternatives. The Water Board further determined that CalSim is a difficult to use and the model's results are not easily understood across the wide user community. The Water Board also chose to forgo use of available individual species life cycle models because of the models' rapidly developing states of science and difficulty in hiring knowledgeable consultants to run models. Temperature analyses were considered as part of the Plan amendments; however, the Water Board was unable to independently run scenarios and unable to hire qualified consultants to run the models.

## 6.2 Institutional structure of model integration

Integrated modeling was performed in-house with consulting support. The Water Board has embarked on a long-term strategic plan to enhance in-house modeling capabilities in support of its needs related to water rights administration. Currently the Water Board employs about 20 staff involved in some form of modeling activity.

## 6.3 Description of how modeling was used to support decision-making

Integrated modeling results, including flow and water quality under baseline and alternative scenarios, were used by the Water Board to develop proposed updates to water quality standards. Modeling results supported a variety of physical and biological assessments including: flood control, sediment transport, aquatic and terrestrial species, and recreation. Modeling results also supported economic analyses on the projected costs of different Plan alternatives.

## 6.4 Stakeholder involvement

While integrated modeling for the Plan amendments was generally not conducted as an open process, the Water Board has solicited feedback in several forums. For example, stakeholder workshops were held on modeling issues and meetings are ongoing regarding modeling assumptions and big-picture questions. The SacWAM model was peer-reviewed through the Delta Science Program. Finally, modeling results (as incorporated in draft environmental documents) were made available for extensive public review.

## 6.5 Description of software and data management processes

Many of the models used to support the Plan amendments are in the public domain. For Phase 1, the Water Board developed the WSE model to evaluate effects of proposed Plan amendments on reservoir operations, water supply diversions, and river flow for each of the eastside tributaries. Many of the models and output files used for Phase 1 are available from the Plan web site,[1] including the WSE model, groundwater model, and the agricultural economics model output. Other model files are available on request.

## 6.6 Time and budget resources needed

Modeling analyses in support of Phase 1 and Phase 2 environmental documents have occurred over a period of approximately 6 years.

## 6.7 Significant challenges in model integration

The Water Board had access to pre-run models for its Plan evaluation; however, in many cases it was unable to independently modify scenarios and run these models. This constraint was not a limit on model integration per se, but it limits the types of evaluations that can be performed. As a regulatory agency, some consultants are not available to work for the Water Board, as they may be restricted from working for the Water Board if they have supported another party in a given process. This constraint presents a particular challenge to project implementation when the pool of available consultants is small.

Another consideration is that some of the modeling requires workflows between scientists (e.g., for representing fish response) and engineers (e.g., for representing hydrology and hydrodynamics), with different toolsets, and data standards, and may need additional effort to overcome.

## 6.8 Future model integration needs

- There is a need for simpler models that are more easily understood and applied. Complex models--especially where the user base is small and requires specialized expertise, and where the science is evolving--limit application of an integrated multi-user framework. For regulatory decision making, simpler models may be more effective.
- There is a general need to evaluate and communicate model forecasting skill, given uncertainties in the modeling process.
- There is a need for retrospective analyses to compare model predictions with actual outcomes.

[1] https://www.waterboards.ca.gov/waterrights/water_issues/programs/bay_delta/bay_delta_plan/water_quality_control_planning/2018_sed/

*6. Bay-Delta Water Quality Control Plan Updates*

# 7 Water Rights, Consumptive Use & Water Budgets

Consumptive use modeling and measurement for crops and other land use cover in the Delta has taken various approaches and several iterations of models have been developed. Consumptive use has implications for groundwater pumping and surface water diversions on Delta islands and models have been of interest to the DWR for many years. DWR developed the Integrated Water Flow Model (IWFM) to provide an integrated groundwater-surface water demand model and support consumptive use estimates. Other studies (Siegfried et al., 2014) have integrated the IWFM demand calculator (IDC) tool to develop consumptive use estimates for the complexity of island water demands. The modularity of the IWFM components, such as the IDC, have made it a flexible model for integration (Ercan et al., 2016).

DWR's CalSIMETAW has been the authoritative model for crop and land-use consumption use data in California. Although not specifically developed with integrative components, outputs of these models have been used in follow-on modeling efforts such as the California Water Plan WEAP model (Rayej et al., 2011). Projects such as the Water Plan have highlighted the value of these public models. DWR's Delta Evapotranspiration of Applied Water (DETAW) model is based on CalSIMETAW.

## 7.1 Integrated model elements

The primary domain of these models is surface and groundwater allocations. The core of IWFM has focused development of 3D groundwater modeling (Ercan et al., 2016), augmenting agricultural and urban water demands, water supply in terms of pumping and stream diversions to meet these demands, and the effect of pumping and diversions on the surface and subsurface water resources (Dogrul et al., 2016). The Delta Island

Consumptive Use (DICU) model (now replaced by DETAW) developed monthly island water uses based on water supply, channel diversions, seepage, and return, integrating IWFM-IDC to improve water demand estimates for island water use on two islands (Siegfried et al. 2014).

## 7.2 Institutional structure of model integration

The IWFM and DICU models were developed and maintained by DWR, although IWFM has received greater investment of funds and resources in the two decades to develop significant adaptability to integration with other models (e.g. CalSim). IWFM evolved from DWR's Groundwater and Surface Water Model (IGSM) of the 1990s, which integrated within the code several simulated physical processes such as ground water flow, runoff, root zone accounting. The DICU model has been utilized by regional groups outside DWR, such as the State Water Resources Control Board and The Nature Conservancy, to understand estimates produced by water demand models and suggest improvements (Siegfried et al., 2014).

## 7.3 Description of how modeling was used to support decision-making

The flexibility of IWFM has facilitated integration into several key projects in the past 20 years. The Central Valley Project Improvement Act (CVPIA) utilized several models (e.g. CVPM, PROSIM, CVGSM) which integrated with IWFM to meet the needs of the CVPIA Programmatic Environmental Impact Statement. IWFM was also integrated with C2VSim and SWAP to analyze drought impacts, and evaluate WaterFix and other water management alternatives.

## 7.4 Stakeholder involvement

IGSM (the predecessor of IWFM) was developed in partnership with and financed by the Bureau of Reclamation, State Water Resources Control Board, DWR, and Contra Costa Water District. Following DWR's development of IWFM and IDC, the user groups for these models have been critical sources of stakeholder input and feedback and have been engaged through the models' deployment in many multi-lateral projects.

## 7.5 Description of software and data management processes

Over several iterations, the IWFM model has been developed using objected oriented programming. Several compilation features and modules, such as the IDC, have been added to the model to facilitate integration.

## 7.6 Time and budget resources needed

The IWFM model has been developed for over 20 years (as both the IGSM and IWFM) and included to consistent development, support, and input from both the founding multiagency collaboration as well as DWR.

## 7.7 Significant challenges in model integration

Consumptive use models are spatial and require combinations of detailed grid, boundary conditions, Delta island characteristics/land use, and known locations for diversion/returns—all of which can change over time. Differences in base data for these models, particularly in model grids and in diversions/returns, have resulted in differences among models unrelated to the basic ET calculation in the past. A common dataset would remedy this source of difference across model runs. However, storage of these datasets and software may be a barrier.

Public models such as IWFM and its stand-alone demand calculator (IDC) have thrived due to consistent DWR support; however, continued development and support have struggled with in-house expert turnover and retirement. Maintaining adequate in-house expertise, administrative and financial support, and incentives for expert retention will allow models such as IWFM and IDC to continue to adapt to new modeling domains and software environments.

## 7.8 Future model integration needs

DWR has developed support tools for the IWFM model to support its stand-alone use and integrated use with other models; these tools include mesh builders, soil data builders, and land adjusters. Ongoing development of such support tools is needed for greater IWFM integration flexibility and streamlining. For example, DETAW model was developed as an improvement on the DICU model producing results on a daily time step for a greater number of subareas and improved consistency between DSM2 and CalSim II (Kadir, 2006).

# 8 Water Operations Models for Delta Smelt

Delta smelt (Hypomesus transpacificus) are an endangered native pelagic fish species in the San Francisco Bay Delta (listed since 1993) and have been an active focus of management concern for the past two and a half decades. In December 2008, the U.S. Fish & Wildlife Service (USFWS) issued a biological opinion (BiOp) on the Long-Term Operational Criteria and Plan (OCAP) for coordination of the Central Valley Project and State Water Project. A new BiOp is expected to be released on July 1, 2019.

## 8.1 Integrated model elements

Modeling to represent historical Delta smelt behavior was based on a newly developed individual-based mechanistic model (reported in Rose et al 2013 a,b). The model was developed using biological data from 1995-2005, coupled with physical properties (flow velocities, water levels, salinity, and temperature), and aggregated hourly or daily. This model discretizes the Bay and Delta into 11 boxes of hydraulic similarity. This model was structured to follow the reproduction, growth, mortality, and movement of super-individuals over their entire life cycle and was calibrated using actual Delta smelt catch data. The effects of environmental conditions on Delta smelt were evaluated in specific years with better than or poorer than normal population growth (Rose et al. 2013b); a hypothetical comparison of food limitation versus entrainment effects was conducted (Kimmerer and Rose 2018).

This model is being updated so that it can be used to evaluate the projected response of Delta smelt to future operations or infrastructure. The updated modeling framework will be able to use CalSim for reservoir operations, DSM2 for Delta hydrology and water quality (i.e., salinity and water temperature), and the Rose et al. (2013 a,b) individual-based life cycle model for Delta smelt population dynamics. The number of discrete boxes is slightly modified from the original publication (12 boxes instead of 11). Revised model calibration is being done with 20 years of data from 1995-2015. For integration, it is anticipated that CalSim monthly hydrology will be smoothed to daily values and DSM2 data averaged to daily values.

## 8.2 Institutional structure of model integration

Model integration, including reservoir operations and Delta water quality/hydrodynamic modeling, is being led by the USFWS in Sacramento with support from academic researchers who developed and published the Delta Smelt individual based model. The model will be publicly available.

## 8.3 Description of how modeling was used to support decision-making

The individual-based model is designed to evaluate the effects of near- and long-term management actions on the species population, including new infrastructure, habitat restoration or improvement, and operational changes associated with major new infrastructure in the Delta. In addition, the model is designed to evaluate long-term population trends and sustainability under other drivers such as climate change.

## 8.4 Stakeholder involvement

The models being developed by or with the assistance of USFWS staff will be publicly vetted to provide an opportunity for stakeholder input and understanding of model structures and assumptions. When complete, the models will be made publicly available.

## 8.5 Description of software and data management processes

The individual-based model is being re-coded by its original author and a USFWS hydrologist with direct prior experience working with CalSim and DSM2. The model code is expected to be publicly accessible upon completion and USFWS can provide training if needed. The fisheries models (in their original form) were documented in three peer-reviewed papers (Rose et al., 2013a,b; Kimmerer and Rose 2018). The revised version will be documented in a future publication.

## 8.6 Time and budget resources needed

Support for external researchers has been less than $300,000. Costs associated with agency staff are not specifically delineated here.

## 8.7 Significant challenges in model integration

As discussed above, the calibration period for the updated individual-based model spans 1995-2015. Over this historical period, the necessary mechanistic data are available or can be adequately modeled. For scenario planning, flow regimes are typically characterized by CalSim and are thus provided on a monthly time step. However, flow data at a daily (or finer) scale are needed for compatibility with fishery mechanisms.

Statistical approaches have been developed for interpolating monthly flows to daily flows. Another challenge that is being addressed by the modeling team is to generate a compatible long-term zooplankton data series.

## 8.8 Future model integration needs

Future model development is needed in many areas to support simulation of Delta Smelt behavior:

- Use of models other than CalSim to produce flow time series is being contemplated, including the Sacramento River HEC-RAS model and DAYFLOW.
- More detailed physical system representation may be desirable, such as multi-dimensional hydrodynamics models instead of DSM2.
- A new generation of individual-based models is also under consideration in the research community. With available resources, a web interface can be developed for broader access.

# 9 Delta Public Lands Strategy/Future Carbon Markets

The Delta Public Lands Strategy is a high-level assessment of opportunities and constraints for conservation, agricultural sustainability, flood management, recreation and other Delta priorities let by the Delta Conservancy. The strategy also includes implementation approaches for continuing the successful coordination, engagement, and planning on about 50,000 acres in the western and central Delta. The key drivers for strategy development are to stop subsidence, enhance economic viability, demonstrate improved management, and support multiple benefits.

## 9.1 Integrated model elements

Modeling has not yet occurred on this project. It is proposed that state-of-the-art analysis and decision support tools with system experts would develop possible land- and water-management strategies to provide to inform adaptive management of Delta restoration on public lands and beyond.

There is a need to use integrated models to develop specific strategies for each key driver. Models will be used to explore potential impacts on adjacent landowners such as levee and seepage impacts, trespassing, water quality, water supply and agricultural productivity. It is envisioned that model integration will also serve as a tool for addressing stakeholder questions and concerns and for building consensus.

## 9.2 Institutional structure of model integration

The Delta Restoration Network (DRN) was created with the understanding that restoration efforts will require coordination across many stakeholders to be successful.

This was intended as a new organization, with funding support from Proposition 1 grants. A consensus of shared concerns among leaders of the Delta stakeholder and management community indicated the need to bring people together to resolve issues around ecosystem restoration and its linkages to the Delta community, agriculture and flood protection (14 agencies and some Delta community members participated). This framework focused on restoration alternatives and cumulative impacts analysis within a landscape-scale vision.

## 9.3 Description of how modeling was used to support decision-making

N/A

## 9.4 Stakeholder involvement

N/A

## 9.5 Description of software and data management processes

N/A

## 9.6 Time and budget resources needed

N/A

## 9.7 Significant challenges in model integration

Integrated modeling for the Delta Public Lands Strategy would need to include models that simulate subsidence and subsidence reversal, economics, ecosystem processes, levee impacts, and seepage, greenhouse gas emissions and emissions reductions and water quality. Heretofore, this kind of integration has not occurred on Delta islands. While models generally exist that can simulate the necessary processes, the needed interdisciplinary integration will be a substantial technical, logistical and leadership challenge.

## 9.8 Future model integration needs

The primary model integration need is the development of a framework that will facilitate integration of the different models and modelers.

# 10 California EcoRestore

California EcoRestore is a multi-agency effort to restore 30,000 acres of habitat in a set of discrete projects across Delta islands. The effort spans three primary types of projects: managed wetlands, tidal wetlands, and fish passage. Modeling has some common themes across the different project types and thus can be discussed collectively. Modeling is used to understand the impacts of individual projects on Delta salinity, change in water stage in Delta channels, the nature of habitat created on the islands, and the broader effects on fisheries.

## 10.1 Integrated model elements

The primary modeling elements include hydrodynamics in Delta channels under different operational scenarios, water exchange between channels and wetlands, and levels of inundation in the newly created habitat. Modeling is also performed to understand the effects on fisheries.

## 10.2 Institutional structure of model integration

Much of the modeling is led by the Department of Water Resources and performed by consultants.

## 10.3 Description of how modeling was used to support decision-making

The goal of the modeling is to estimate the quantity and quality of habitat created on individual projects. Given conceptual site designs, modeled metrics include the extent of inundation and residence time, which can affect the habitat and food production for different aquatic species. Following the selection of an initial site-specific design, a more regional assessment is performed of salinity intrusion and potential flooding in the Delta. Adverse regional impacts may require a project design be revisited to mitigate these impacts. In this situation, the modeling is an iterative process to try to optimize site conditions for habitat value and minimizing regional impacts. This basic process is repeated for individual projects. The same modeling framework has transferred to other agencies, i.e., CDFW, and they can use the same general approach and numerical models.

Additional modeling is done on fisheries impacts, using models such as the NMFS Salmon Life-Cycle Models, to inform the overall restoration design. However, these models are not integrated into the iterative design process in the same manner as the hydrodynamic and wetland models. Some of the fishery models are more conceptual in nature, compared to the quantitative models related to flows and salinity.

## 10.4 Stakeholder involvement

Stakeholders are extensively involved in the EcoRestore modeling process. Stakeholders are involved in evaluating model results and reviewing tradeoffs between habitat created and estimated flood and water quality impacts.

## 10.5 Description of software and data management processes

Two primary models (both proprietary) were used for the decision-making process. The RMA Delta model was used to represent Delta hydrodynamics and CBEC hydrologic model was used to represent flow exchange, inundation, and residence times on the islands. Model input information is exchanged between the respective consultants, and relevant model data files are inventoried by them. There is no public repository for the models and data. The model studies are not in the public domain.

## 10.6 Time and budget resources needed

Integrated modeling (in conjunction with site design) for an individual project is an iterative process and can span months to years, depending on the site.

## 10.7 Significant challenges in model integration

- There is a need for clear meta-data on the model outputs to minimize confusion when information is transferred from one model to another.
- A more general concern relates to interpreting the significance of changes that are being calculated through the models. For example, a project scenario may indicate particular magnitudes of salinity and water level changes for a given hydrology. For this information to provide meaningful decision support, guidance on whether this modeled result is meaningful or is merely within model uncertainty. Clear guidelines in this area do not appear to be present.

## 10.8 Future model integration needs

Current work has not considered employing biogeochemical models to understand the effects of restoration on carbon and nutrient transport. There may be feedbacks between flow exchange and biogeochemistry on islands, and such analysis may be considered in the future.

# 11 Yolo Bypass Models

Water and environmental modeling by the Department of Water Resources, and other agencies has taken place in the Yolo Bypass (Bypass), given its key importance to the Sacramento River Basin and the Delta regions. The 57,000-acre Bypass area is a seasonally inundated floodplain intended for flood protection, but also benefits the local economy through agriculture and other development, fish populations, and migratory waterfowl (Howitt *et al.,* 2013). Flooding events are controlled using inlets and weirs connecting the Sacramento River to the floodplain, particularly the Fremont Weir on the north end of the Bypass. The configuration of weirs and levees in the region has an impact on the magnitude, duration, and benefits of flooding events and as such, much modeling attention has been focused on the impact of those configurations (USBR, 2017). In 2017, DWR and USBR released an extensive Environmental Impact Statement /Environmental Impact Report (EIS/EIR) of changes proposed in the Yolo Bypass Salmonid Habitat Restoration and Fish Passage (YBSHRFP) Project. Concurrently, the Central Valley Flood Protection Plan regional feasibility study has led to several projects integrating flood modeling in the Yolo Bypass region (DWR, 2017) – see Chapter 4.

## 11.1 Integrated model elements

The primary domains of modeling in the Yolo Bypass have focused on 1D/2D hydrodynamics; however, additional models integrating economics and agricultural production (Howitt *et al.,* 2013), fish and bird habitat (Suddeth-Grimm & Lund, 2016), and migratory waterfowl (Ducks Unlimited, 2017) have also informed the process. Much of the follow-on modeling at the Yolo Bypass have rested on the results of hydrodynamic modeling (USBR, 2017).

## 11.2 Institutional structure of model integration

DWR and USBR have jointly directed much of the work conducted at the Yolo Bypass for the YBSHRFP, while a larger Yolo Bypass and Cache Slough Partnership was developed for CVFPP projects. Decision on modeling resources, participants, and integration have been under their guidance of these bodies. In the case of the YBSHRFP, technical teams with corresponding advisory teams were assembled to tackle hydrodynamic modeling (USBR, 2017). The team was composed of CBEC and HDR consultants and focused primarily on the use of TUFLOW modeling to estimate impacts of Bypass configuration alternatives. Other studies were commissioned by regional agencies as self-contained studies, often relying on outputs from other studies.

## 11.3 Description of how modeling was used to support decision-making

Studies commissioned by DWR and USBR or through the Delta Science Program often fed into planning and implementation plans for the Yolo Bypass. In the case of the 2017 YBSHRFP, scenario outputs were evaluated through the CEQA process (USBR, 2017). The pre-determined scenarios have provided the decision-makers streamlined results from each study and modeling domain.

## 11.4 Stakeholder involvement

The study solicited public comment during project scoping and during the development of the Draft EIS. Public comments were documented and released in a Public Scoping Report in 2013 and through the draft public comment process. Other multi-objective studies (Suddeth Grimm & Lund, 2016) also integrated input from landowners, particularly in scenario development and evaluation of impacts.

## 11.5 Description of software and data management processes

All the project-related studies required multiple years of evaluation and refinement, collecting primary data and redistributing developed datasets from the various technical teams. Datasets from the CALFED Bay-Delta Program, the Bay Delta Conservation Plan, and California EcoRestore (e.g. the CVFED HEC-RAS geometry developed by DWR in 2014 (USBR, 2017)) were utilized for the project. As part of YBSHRFP, the project relied on the resources provided by CBEC and HDR to develop the primary hydrodynamic model outputs (USBR, 2017). These model outputs were then distributed to other downstream models (Ducks Unlimited, 2017).

## 11.6 Time and budget resources needed

Most recent studies of the Yolo Bypass started in 2013 and stemmed from the Reasonable and Prudent Alternative (RPA) action I.6.1 and I.7, as described in the 2009 National Marine Fisheries Service Biological Opinion (NMFS BO) and the 2012 Yolo Bypass Salmonid Habitat Restoration and Fish Passage Implementation Plan (USBR & DWR, 2012). The Bypass has been of interest for many regional organizations, including the Delta Stewardship Council. However, the most recent USBR/DWR efforts have only recently been released with CEQA recommendations for public comment.

## 11.7 Significant challenges in model integration

Components of Yolo Bypass modeling were developed over different periods of time and entail a variety of project scopes. These models represent different objectives, assumptions, and methods of abstraction. Although model outputs have informed follow-on analyses, disagreements between models have not always been resolved. During the YBSHRFP process, CalSim II and HEC-RAS models were used in various forms to inform the TUFLOW dataset, acknowledging some of the inherent problematic elements of each of the two models. Modeling in the Yolo Bypass would benefit from greater guidance by agencies commissioning studies as well as a streamlined dataset for model development and calibration with model coordination early in the planning process.

The use of TUFLOW during the project also represented a deeper issue with the use of proprietary models. Although strides have been made over the past two decades to find unified, open source models for the Delta region, proprietary software and models have often been used to provide core hydrodynamic modeling. Regardless of their improvements to the model methods, their lack of transparency has been a source of difficulty to modelers seeking to integrate model outputs. Additionally, communicating results from proprietary models has posed challenges in stakeholder engagement. A lack of stakeholder “buy-in” has resulted in costly legal challenges to decisions perceived as complex and opaque. An increased understanding of the role of model results in decision making would enable more effective stakeholder engagement.

Stakeholder engagement was also inhibited by the spatial ambiguity of some Yolo Bypass modeling efforts. A fine spatial granularity of economic and land use data would enable landowners to participate more fully in assessments of agricultural economics such as Suddeth-Grimm and Lund (2016). Farming practices have impacts on both habitat as well as economic outcomes of production; thus, greater involvement by these stakeholders (supported by finer spatial resolution in modeling) would allow for more effective integration of agricultural operations into Yolo Bypass restoration projects.

## 11.8 Future model integration needs

Although the Yolo Bypass has been an area of significant modeling work, several key areas would greatly benefit future efforts. A common data repository and agreed upon standards of modeling for the Bypass would prevent duplication of efforts and fill data gaps in models. Tracking the results of modeling efforts more transparently would allow for more rapid model improvement. The transition from proprietary models to public models would also aid this process. Streamlining model assumptions would also enable a smoother workflow between regional, state, and federally developed models.

More easily integrating groundwater models have also been cited as a data gap for the Yolo Bypass (USBR, 2017). Current surface water models such as CalSim II have difficulty interfacing with groundwater models, and often these surface-groundwater relationships can play an important role in floodplain processes.

# 12 Delta Methylmercury Modeling for TMDL Implementation

Water quality in the Delta, which is known to be impaired for methylmercury (MeHg), is regulated by a total maximum daily load (TMDL) developed by the Central Valley Regional Board and adopted in 2010. A TMDL can require load reductions or other actions to help achieve water quality targets. A subset of the regulated Delta entities, collectively known as the open water workgroup and led by the Department of Water Resources, are required to evaluate whether operational changes or other strategies could be implemented to reduce MeHg loads from open waters of the Delta and the flooded Yolo Bypass. Open water allocations apply to the MeHg load that fluxes to the water column from sediments in open water habitats within channels and floodplains in the Delta and Yolo Bypass.

Because the hydrodynamic and environmental setting is complex and direct field experimentation is not possible, modeling has been envisioned as an approach to evaluate the effects of changes in project operations on MeHg in Delta waters and the Yolo Bypass. The goal is to develop and apply Hg models to predict trends in MeHg production under current or future operational scenarios. This current modeling effort represents a first step in a longer process and creates a framework for future refinements. Sensitivity analysis using the current model is helping to identify some of the more impactful parameters. Additional effort will be required to use this model in a forecasting mode. At the time of this work, no model exists to unify the Delta and the Yolo Bypass domains, separate model are being used with outputs from the Yolo Bypass model providing inputs to the Delta model.

### 12.1 Integrated model elements

The primary model elements represent hydrodynamics, water quality and mercury cycling. Mercury modeling in the Delta is a relatively new topic; thus, this work involves extensive field studies to support quantification of key processes.

### 12.2 Institutional structure of model integration

This work is being led by DWR, with in-house staff developing new code for the DSM2 suspended sediment module and using animation tools to animate both the Delta and Yolo Bypass models. Consultants developed the code for DSM2's bed sediment and mercury modules and adapted the D-MCM model to the Yolo Bypass. Field studies are being conducted by DWR, USGS, and Moss Landing Marine Laboratories.

### 12.3 Description of how modeling was used to support decision-making

The modeling is targeted toward supporting the load allocation process that is part of the MeHg TMDL for the Delta.

### 12.4 Stakeholder involvement

The Open Water Workgroup is composed of staff from DWR, California State Lands Commission, Central Valley Flood Protection Board, U.S. Army Corps of Engineers, and U.S. Bureau of Reclamation. DWR staff leading the technical aspects of the modeling effort and have been engaged with the Central Valley Regional Board and regulated entities through formal mechanisms embedded in the TMDL such as a progress report to the Regional Board.

### 12.5 Description of software and data management processes

Two sets of models are being developed and applied for this project (Figure 3). For the Delta, DWR's hydrodynamic and water quality model, DSM2, is being updated and expanded to include Hg and sediment modules (bed and suspended). As part of this work, DWR is updating the water quality model in DSM2 (QUAL) with a new model for fate and transport of conservative and non-conservative constituents. This new model, the Generalized Transport Model (GTM), will be integrated with the suspended and bed sediment and mercury modules being developed for this project.

The widely used Dynamic Mercury Cycling Model (D-MCM) is being applied for the Yolo Bypass. Hydrodynamics information is being passed to the D-MCM model from a previously developed, two-dimensional TUFLOW model. The TUFLOW model was originally implemented for an unrelated project for fish passage improvements in Yolo Bypass. TUFLOW outputs are also being used in conjunction with erosion microcosm field studies to estimate erosion rates in the Yolo Bypass.

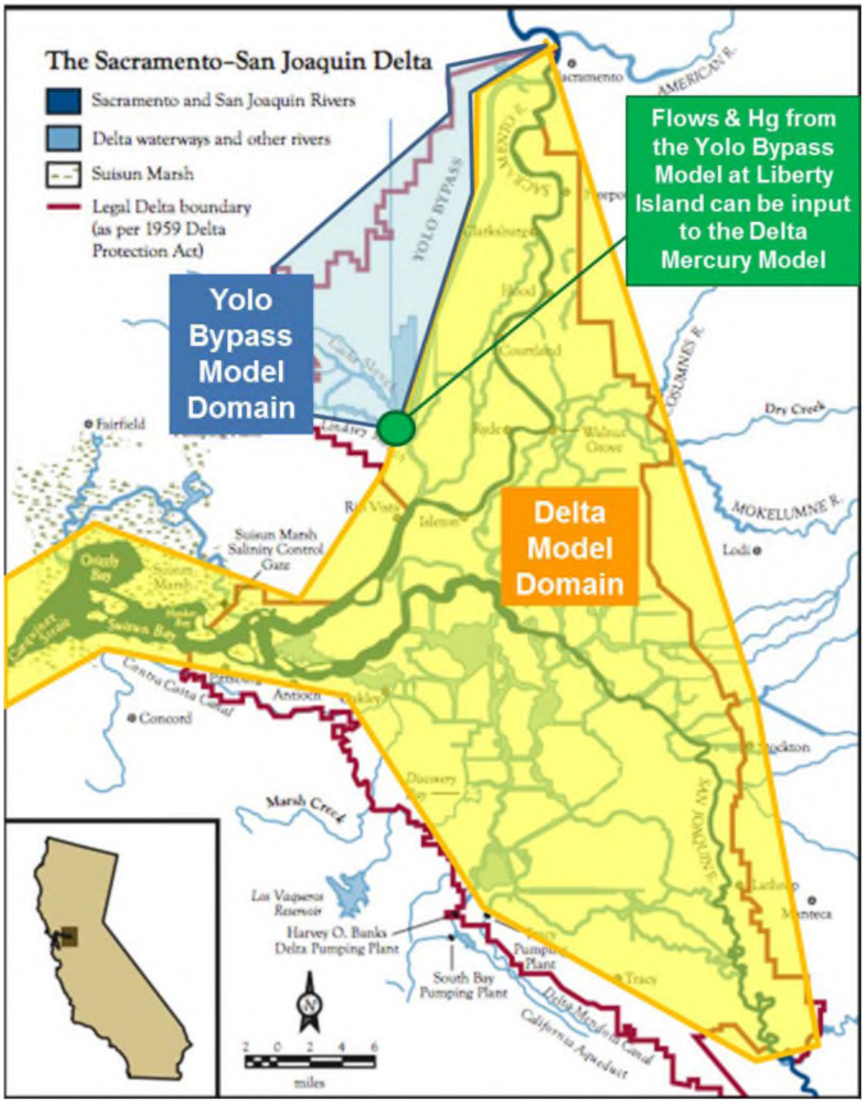



**Figure 3**. Approximate model domains for two methylmercury model frameworks. The modeling domain is the legal Delta and the Yolo Bypass to Fremont weir.

## 12.6 Time and budget resources needed

Significant resources and staff time have been required for developing the new model framework. Not counting laboratory analytical support for data collected for the model, it is estimated that approximately $2.1 million have been expended to date on this modeling effort. The project was initiated in 2014 and is now in its final year.

## 12.7 Significant challenges in model integration

The physical mechanisms are dynamic in the Delta, with feedback between mercury cycling and flow processes. Therefore the models cannot be run independently. The mercury model needs to interact with the flow model at the time-step level. Hence, there has been a need to implement code changes to develop a new Delta mercury module within the Delta hydrodynamics modeling framework.

An alternative modeling approach was used in Yolo Bypass, i.e. an existing hydrodynamic model was used jointly with an existing mercury (D-MCM) model. This approach has the benefit of not creating a new code (as in the Delta), but the model runs are limited by what has already been prepared using the existing TUFLOW model (a 12-year hydrologic time series is available). The TUFLOW model is proprietary, and additional runs are not readily available.

It would be desirable to use one modeling approach instead of two for the integrated Delta and Yolo Bypass domains. At the time of project initiation, SCHISM (DWR's 3-dimensional Delta hydrodynamics model) was not fully developed. Adding a mercury module to SCHISM would allow for a single model over the full geographic extent and would obviate the need to develop additional TUFLOW hydrologic time series for use by the Yolo Bypass D-MCM model. The current models also do not include the impacts of wetlands or bioaccumulation; more resources would be required to incorporate these factors into the base models.

Finally, mercury is an expensive analyte to detect, and there is relatively limited observed data in space and time to characterize transformations. This is a challenge for model development and calibration. Because there is so little data available in the Yolo Bypass, a decision was made to use all the available data to calibrate the model. There may be enough data in the Delta to use some years for calibration and other years for validation. However, a robust calibration and validation for both models can only be made if more data is collected. The Delta RMP begin collecting relevant data in 2016.

## 12.8 Future model integration needs

Because of the uncertainty associated with mercury measurement and modeling, there is a need to perform an adequate sensitivity and uncertainty analysis of the new linked models. This is needed to robustly assess whether changes in project operations have a significant effect on open water MeHg loads and concentrations. Manual calibration has been performed and the modules are now being calibrated using the PEST (Model-Independent Parameter Estimation and Uncertainty Analysis) model.

# 13 CASCADEII Modeling Framework

CASCADE (Computational Assessments of Scenarios of Change for the Delta Ecosystem) is a long-term modeling project led by the USGS to link inter-related models. In the first phase of CASCADE, the focus was on the impacts of climate change scenarios on water quality, flows, water levels, and habitat in the Bay-Delta (2006-2009) and surrounding watershed. In the second phase (2011-present), more extensive linkage has been implemented, focusing climate change drivers across the Bay-Delta watershed, hydrology across the system, hydrodynamics in the estuary, turbidity, sediment transport, phytoplankton, bivalves, contaminants, marsh accretion, and fish (Figure 4). Some aspects of the CASCADE II research are ongoing.

## 13.1 Integrated model elements

A 3-D hydrodynamic model for the San Francisco Bay-Delta based on the new Deltares D-Flow FM (flexible mesh) code is at the core of the integrated modeling framework. D-Flow FM is one component of the Delft3D FM modeling suite. Delft3D-FM is a non-proprietary modeling suite and model set-up files are available for download. Updated versions of the set-up files will be made available as the associated publications are released. DELWAQ is the Deltares water quality/ecology model which is used to model suspended sediment, phytoplankton, and selenium. HABITAT is the Deltares model in which fish and clam habitat are evaluated. WARMER is a separate model which is used to run scenarios for marsh.

A major part of the USGS effort is to test the code, working jointly with Deltares as bugs are identified and resolved. Years of effort have been devoted to the development of key inputs (e.g. bathymetry and grid refinement) and to calibration and validation.

Calibration and validation have been conducted for stage, flow, salinity, and temperature. As improvements and refinements are continually incorporated, performance metrics are re-evaluated.

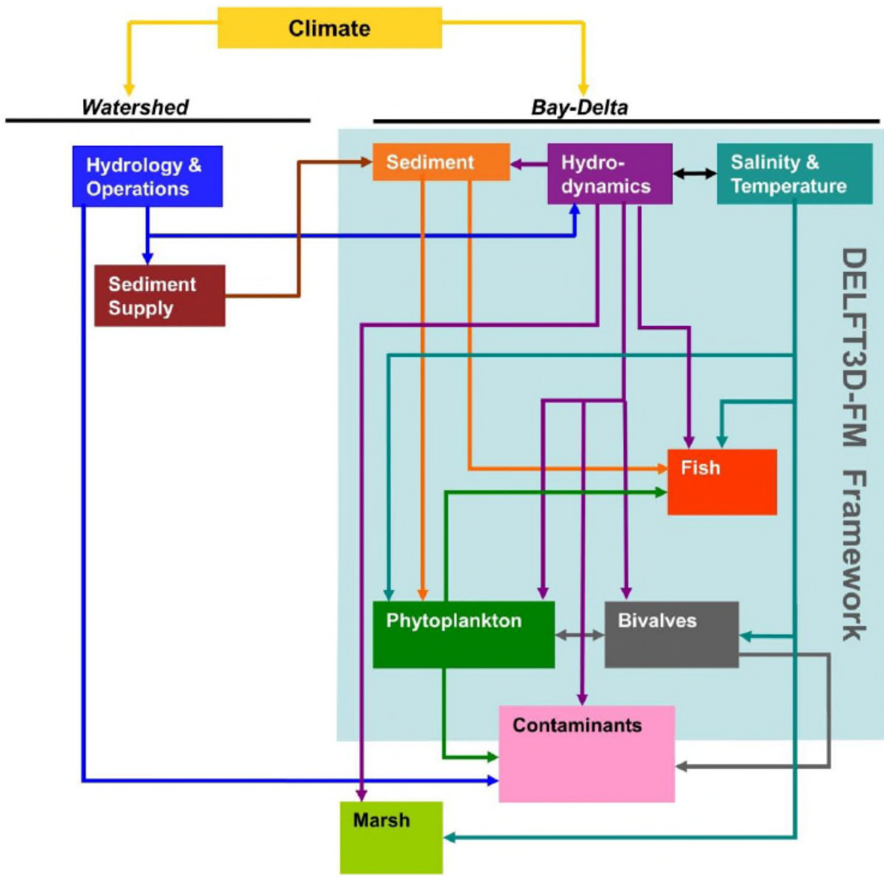



**Figure 4**. Schematic of CASCADE 2 modeling interactions

## 13.2 Institutional structure of model integration

USGS, through its management of model integration, worked with a team of scientists within USGS as well as academic and non-academic collaborators worldwide. Deltares, as a provider of the model source code (through a commitment to release the code in the public domain), was a key participant in the study.

## 13.3 Description of how modeling was used to support decision-making

This project was envisioned as a scientific study supporting the larger mission of the co-equal goals for water supply and ecosystem benefit for the Delta Stewardship Council. Results from both phases of the CASCADE work, documented in a final report, peer-reviewed publications, and conference presentations, improve general scientific understanding of the ecosystem, spanning the Sierras to the coastal waters off San Francisco Bay. The model framework, with its public availability going forward, is expected to provide a basis for future studies that may be more focused on applied decision-making.

## 13.4 Stakeholder involvement

This was a science-driven project with the participation of a large, global multi-disciplinary team. Extensive stakeholder outreach was accomplished through published results, conferences and meetings. All work products are planned to be in the public domain.

## 13.5 Description of software and data management processes.

The scale of the 3-D model required large, dedicated computer resources (computing power as well as storage capacity for model results) that were greater than originally expected. A dedicated computer cluster is used for running the model. Model runs for one water year (with some spin up time) require approximately 3-10 days, with longer run times for wet years.

## 13.6 Time and budget resources needed

The CASCADE project (both phases) has been a major scientific effort spanning more than a decade with the continued participation of principal investigators. CASCaDE2 funding for fiscal years 2012-2017 was provided by the Delta Stewardship Council, the USGS, and San Francisco Estuary Institute (totaling over $7 million over 5 years). Funding has been provided by USGS since fiscal year 2017.

## 13.7 Significant challenges in model integration

Most model linkages in CASCaDE2 depend on the D-Flow FM implementation for representing hydrodynamics in the Bay-Delta. The D-Flow FM source code was in beta form at the inception of the project, and it required several years for completion, calibration, and validation. There are other model dependencies as well. For example, the hydrodynamic model feeds into the estuarine sediment/turbidity model, which in turn is used by ecosystem models. These dependencies have delayed the final implementation of some of the downstream models.

## 13.8 Future model integration needs

The CASCaDE team has received requests from the Delta Independent Science Board and Delta Science program to collaborate and share the modeling frameworks being developed. Working with the CASCaDE team and scientists in other organizations, Deltares has taken the initiative in establishing a "San Francisco Bay-Delta Community Model" website (http://www.d3d-baydelta.org/, Figure 5), providing access to the underlying code and set-up files for the broader modeling community. The D-Flow FM model source code is freely available for download (see http://www.d3d-baydelta.org/index.php/main/ossinstructions). Separately, the model configuration files, representing model inputs such as bathymetry, boundary condition files, and various model parameters, will be provided by USGS. Model inputs and outputs are also being made available online at the California Coastal Atlas (https://californiacoastalatlas.net/).Going forward, it is anticipated that this framework (code and configuration information) can be used for many new applications, focusing on the specific domain areas already studied and also exploring a broader range of scenarios and processes. As a newly emerging use, the modeling framework is now being implemented by CASCaDE collaborators at SFEI to model the effects of nutrients in the Bay and Delta. The Bay and Delta receive a large nutrient loading from the wastewater treatment plant sources in their watershed, and the modeling will provide a nuanced understanding of impacts on the ecosystem in the Bay-Delta. The results of this work are expected to influence future nutrient management in Bay-Delta. The CASCaDE modeling framework is also being implemented in a USGS-led project exploring the effects of 3D hydrodynamics on the distributions of methyl mercury in the Bay-Delta. Another future goal of the CASCaDE team is to adapt their SF Bay-Delta modeling suite for use in assessing the effects and effectiveness of ecosystem restoration.

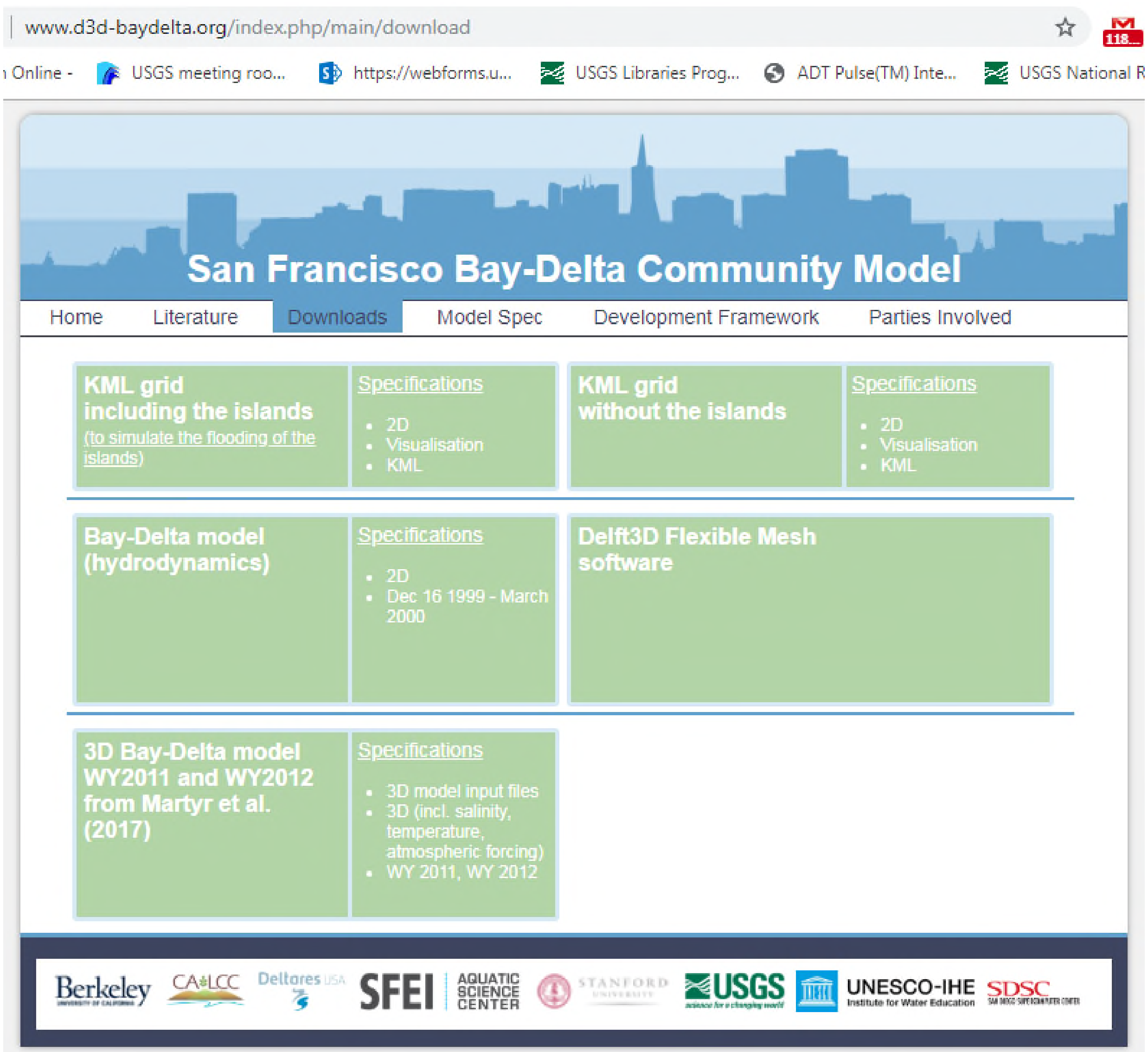



**Figure 5**. Website for San Francisco Bay-Delta Community Model

# 14 AFRI Rice Agriculture Modeling

Historical and present-day agricultural practices in the Delta have led to subsidence, water quality and levee stability problems. The AFRI rice project was implemented to inform on and optimize rice as an alternative crop for Delta growers to stop or reverse past agricultural impacts. Different aspects for implementing rice were considered: greenhouse gas (GHG) emissions, carbon sequestration, land subsidence, levee stability, water quality, mercury speciation and economics. Ecological benefits were not considered as part of this effort.

## 14.1 Integrated model elements

Modeled domains included GHG fluxes (methane emission, photosynthesis, evaporation, net carbon exchange), levee stability, carbon sequestration, land subsidence, groundwater hydrodynamics, water quality and economics.

## 14.2 Institutional structure of model integration

Several institutions were involved in this project: University of California-Davis, University of California-Berkeley, Bachand & Associates, HydroFocus, Siegel Environmental and Stillwater Science. University of California-Davis and Bachand & Associates were project leads.

## 14.3 Description of how modeling was used to support decision-making

The various models used and developed during this project can aid decision making for water security, restoration, land-use planning and economic viability in the Delta.

Questions that can be addressed concern economics, GHG emissions, subsidence mitigation, levee stability and water quality effects of implementing rice on subsided Delta islands.

The Delta is a crucial water source for California and water security and quality are issues that the Delta currently face. Much of the security of Delta waters is reliant on existing levee structures. Using the SUBCALC and Levee Stability models, the effects of rice and wetland implementation on subsidence and levee integrity can be used to aid water security decision making. Additionally, water quality consideration from seepage, drain flow and DOC loads for rice implementation can be informed using the Groundwater-Flow Solute Transport model.

Restoration of the Delta is important for the health of this ecosystem and the services provided therein. Restoration efforts in the Delta are diverse and include tidal habitat restoration, protection of aquatic species and land subsidence reversal. Information from the SUBCALC model can be used to advise on land surface subsidence potential under different land uses. Water quality information from the Groundwater-Flow Solute Transport model can be used to inform how rice implementation may change water quality and affect DOC loads exported from islands. Currently, the PERPMT and SUBCALC models have been used for development of a carbon methodology to inform on the restoration of California costal and deltaic wetlands through GHG reduction and quantification methods (Deverel et al., 2017a).

Models developed from this project can be used for land-use planning purposes in the Delta, specifically to compare rice and wetlands to current agricultural practices of drained crops. Decisions of this sort can be supported by the GHG models (SUBCALC, CANVEG, PEPRMT, DNDC, DAYCENT), subsidence and levee models (SUBCALC, Levee Stability model), water quality model (Groundwater-Flow Solute Transport model), and the economic optimization model DAP. Dependent on which aspects of land-use planning the decision maker would like to optimize, a single model or a combination of these models can be selected. To date, the SUBCALC model has been used to inform on land management practices based on GHG emissions and subsidence by the Air Resources Board.

Economic viability is an important factor in determining the continuance or implementation of existing or new practices. Because the Delta is utilized for so many purposes, there are many components that go into its overall economic value. To understand how the disciplines considered here contribute to the economic value of the Delta; levee stability and ecosystem services (GHG mitigation, water quality considerations and recreational services) were integrated into an Economic Simulation model. This model can be used to determine the monetary value of rice and wetlands in the Delta, inform on how changing practices affect these values and can be used to decide the economic feasibility for rice and wetland implementation.

## 14.4 Stakeholder involvement

Stakeholder involvement during this project was solicited though a series of outreach events and surveys. Outreach events, facilitated by UC Cooperative Extension, were used to inform the Delta farming community about nutrient management and agricultural practices for growing rice. Input from surveys informed on the current-state of knowledge, challenges and costs for growing rice in the Delta. Stakeholder collaboration from DWR was also used to make decisions on land use to reduce subsidence and GHG emissions, resulting in some Delta islands converted into wetlands.

## 14.5 Description of software and data management processes

During this project, both existing models and newly developed models were used. Provided below is i) a list and summary of these models and ii) discussion of some of the model integration processes and their data transfer methods.

Key models developed/modified/used in this project included:

- **DAP** (Delta Agricultural Production, this is a regional production and economic optimization model that was augmented to include GHG, water quality and recreational valuations)
- Economic Simulation model (this is a simulation model that accounts for the economics of levee breaches, GHG emissions, water quality changes and recreational services)
- Groundwater-Flow Solute Transport model (water quality model that simulates transport hydrodynamics in peat soils, used to inform on seepage, drain flow and DOC loads from rice management)
- Levee Stability model (geotechnical model that simulates levee stability and seepage failures based on subsidence, levee height and sea level)
- **SUBCALC** model (land subsidence model that simulate losses from microbial, oxidation and physical processes)

Additional models developed/modified/used included:

- **CANVEG** model (GHG flux model that simulates exchanges between biosphere and atmosphere)
- **DAYCENT** model (biogeochemical model of carbon and nitrogen emissions based on soil, vegetation, climate and management)
- **DNDC** model (simulates carbon and nitrogen gas fluxes between atmosphere, soil and vegetation)
- **PEPRMT** (biogeochemical model that simulates carbon dioxide and methane exchange in wetlands and rice)

There were several model integrations within this project, both within and between disciplines. In all cases, models were run individually and data transfer between models occurred manually by the modelers. There were no iterative processes between models; instead, results from the previous model were used as “scenarios” for the next model.

Integration within similar disciples included the use of land surface height outputs from the SUBCALC model as input into the Levee Stability model to assess how land subsidence could potentially affect levee stability. Interdisciplinary integration included modeling GHG emission for baseline and five additional land-use scenarios on Staten Island using SUBCALC and DNDC; these scenarios were then inputted into DAP where they were used to optimize profit from the island by further allocating other crop practices (Deverel et al., 2017b).

Integration of the various disciplines (GHG, water quality and levee stability) into economic mediums were performed in DAP and in the Economic Simulation models. In the DAP model, consideration was not given to levee stability and the potential for breaching. The cost of levee breaches was accounted for in the Economic Simulation model.

The DAP model was modified from its original form by disaggregating the 53 Delta islands and calibrated for 2007 crop acreage, additions were made to include GHG, water quality and recreational valuations. Integration was performed by incorporating scientific models related to estimating the greenhouse gas emissions, water quality benefits from reductions in phosphorus and nitrogen, and wildlife habitat values from rice and wetlands. These scientific results were transformed into economic values through various means to be used in DAP. Economic valuation was done by using prices from a GHGs offset program, avoided cost from water treatment facilities, and existing studies estimating recreational values of wildlife habitat. Code was developed specifically for the project, augmenting existing code in DAP. Data transfer from previous models were done manually and DAP model output data was in Excel format.

In the Economic Simulation model, the economic costs for levee breaches and flood damages were accounted for using a probabilistic approach for a 50-year period. This was done because prediction of the exact number of future levee failure events was not possible. To transform ecosystem services into monetary values, carbon prices for GHG emissions, water treatment costs for water quality changes and reported recreational values for the Sacramento National Wildlife wetlands were used. Economic feasibility was evaluated using estimated subsidies for rice and wetland implementation along with increases in total ecosystem value and prevention of levee breaching over the 50-year period modeled.

## 14.6 Time and budget resources needed

This completed project lasted seven years with total funding of $5 million plus additional funds from other projects.

## 14.7 Significant challenges in model integration

During model integration, several challenges were encountered that delayed or prevented successful integration. Nontechnical challenges included timing, coordination and organizational structures. Technical challenges arose mainly from difference in spatial scaling.

Model integration was challenged by time and coordination issues. The goal of the project was to evaluate various factors related to rice growing and to integrate those factors into an economic model. Completion of the various factor evaluations/modeling did not leave enough time for the eventual integration into an economic model. Additionally, the perceived project role of many participants was to study or evaluate a particular factor and did not include the final integration step. This lack of a shared final goal made final integration more difficult. The different organizational structures involved in this project had differing goals that were used as a success measure. In each organization, these goals were prioritized which affected the ability to address the project goals and limited collaboration. Lack of a shared common goal could have resulted from insufficient buy-in from partners at the start of the project when this key component needed to be established.

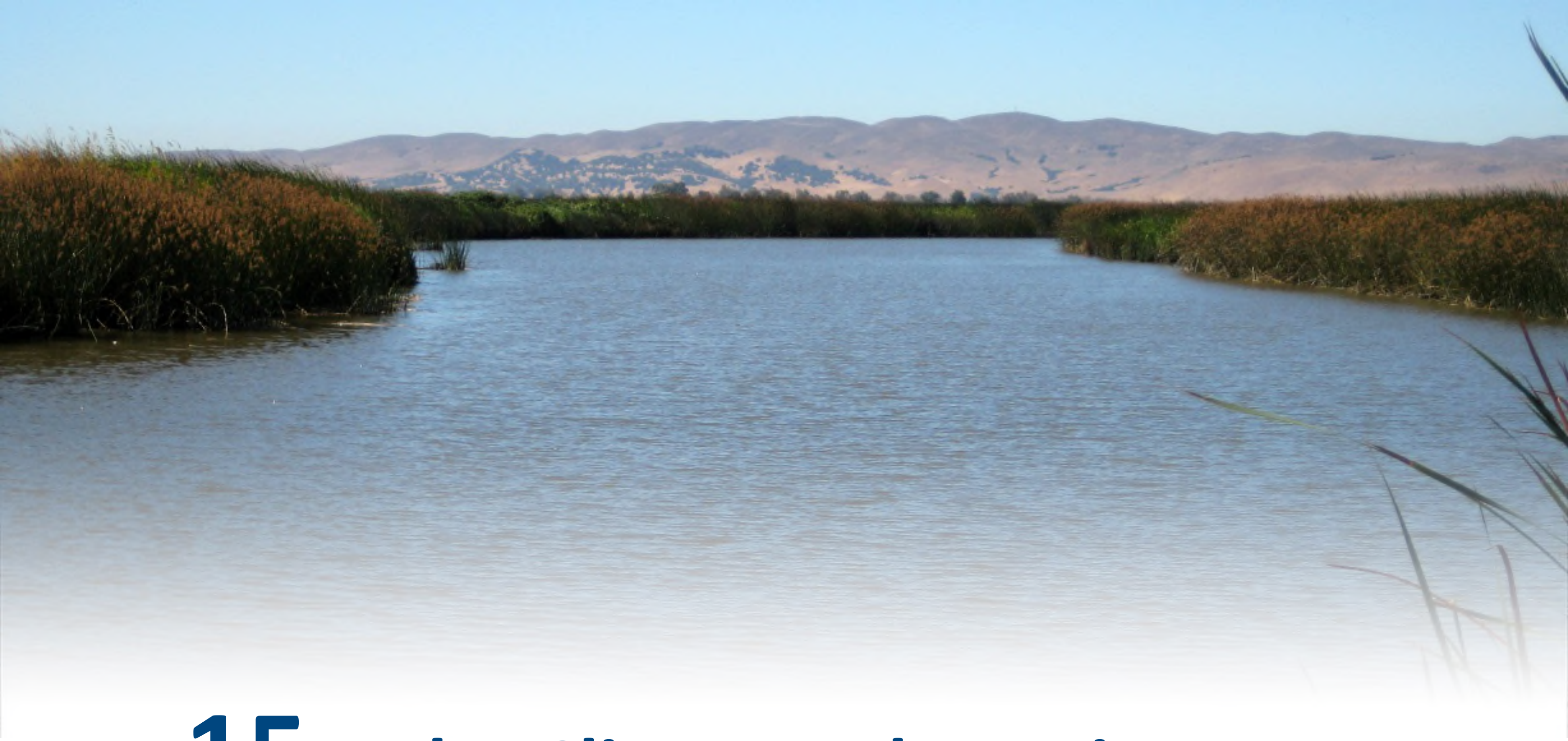
Technical challenges for integration were related to the scaling differences between available data and modeling results and the data needs of subsequent models. Economic models need to have regional data to provide meaningful results. Most scientific studies are very site specific and not readily transferable to an entire region. For example, GHG emissions in the Delta vary depending on the type of land-use and soil. For this project GHG reductions were differentiated throughout the Delta based on land-use and soil types; because this data was available, participants were confident in the regionally scaled GHG emission estimates. In contrast, there was more uncertainty about how well rice would grow in different areas of the Delta due to lack of reliable island-scale weather data in the Delta, where weather can vary significantly. Attempts to integrate within the same discipline encounter a different issue with scaling. When integration was attempted between smaller spatial scale and lower temporal frequency GHG gas chamber flux data with the larger spatial scale and higher temporal frequency eddy covariance chamber data, it was found there was no established method to integrate them. The larger spatial and higher frequency data had much more variability between years that could not be explained using the collected smaller scale data. The SUBCALC model was eventually used to calculate ecosystem effects for the economic model but the two types of measurements were never reconciled.

## 14.8 Future model integration needs

For further integration, better calibrated and validated models are needed that are credible and relevant to the Delta. For this, more data (including a larger suit of variables and land management) is needed. Variables such as temperature and wind can affect yield and need to be considered in the context of rice profitability. More information on the effects of water level and water quality on GHG emissions needs to be obtained. A more comprehensive set of wetting and drying practices need to be considered and its effects on rice yields and GHG emissions. A method of model assessment may need to be implemented to ensure the validity of selected models for the Delta. Also, integrated models need to be compatible spatially, as does the integrated data. If future integration is to be pursued, development of scientific methods similar in scale between different disciplines need to be considered or methods to integrate between scales need to be developed. This project was a research driven project and lacked key factors that would lead to future centralized integration efforts including:

- No central agency houses the effort;
- No reliable funding for future development;
- Value driven from integration of specific components outweighing the value from an integrated model across all disciplines.

We expect findings from this study will continue to inform on Delta efforts specific to water management, greenhouse gas emissions, subsidence and water quality through providing specific tools developed from this project, published and peer reviewed findings, and data. Much of the value from this project will be transferred to planners and practitioners through the expertise and network of the participants in this project.



# 15 Delta Climate Adaptation Modeling

This is an ongoing project led by the Delta Stewardship Council.  This Project will help to implement Executive Order B-30-15, signed by Governor Brown in April 2015, which addresses the need for climate adaptation by directing State agencies to factor climate change into planning and investment decisions. It will build upon State-led adaptation planning efforts within the estuary, adding geographic coverage to current efforts underway by the Delta Stewardship Council and San Francisco Bay Conservation and Development Commission (BCDC) Adapting to Rising Tides program in eastern Contra Costa County. The Project will use lessons learned from initial science synthesis work and analyses conducted as part of the Council's amendment to Chapter 4 (Protect, Restore and Enhance the Delta Ecosystem) of the Delta Plan. The Project is organized into three phases; establishing the framework for project objectives, climate change vulnerability assessment and adaptation strategy.  The project is in its initial phases.

## 15.1 Integrated model elements

Integrated modeling includes five key elements:

- Hydrodynamic modeling using the UnTRIM model (MacWilliams et al., 2007)
- Economic modeling using the Delta Agricultural Production Model
- Watershed modeling (DSM2)
- Climate modeling (Cal-Adapt).

## 15.2 Institutional structure of model integration

Overall project management lies within the Delta Stewardship Council. Participating modeling agencies include Resource Management Associates, USGS, DWR, and the University of California.

## 15.3 Description of how modeling was used to support decision-making

Modeling will be used to assess the effects of sea level rise and model adaptation strategies. Integrated modeling will be used to answer the question: How will climate change affect the State's ability to meet co-equal goals? The intention is for integrated modeling to provide input for State investments now and in future.

## 15.4 Stakeholder involvement

Plans for stakeholder involvement during model development and functioning include ongoing input from the Technical Advisory Committee and local stakeholders throughout the conduct of the project.

## 15.5 Description of software and data management processes

Data flows between models are in the form of input/output files. Individual model teams are responsible for operating the key models identified above in conjunction with other models as needed.

## 15.6 Time and budget resources needed

This work is an ongoing project begun in 2016, with completion expected in 2020.

## 15.7 Significant challenges in model integration

Key modeling and data analysis objectives for the project include transparency, accessibility and replicability. Primary challenges to the project in general and these objectives in particular include i) IT restrictions with State government limit software that can be used on government computers and how much integration can occur and ii) dependence on outside modeling expertise.

## 15.8 Future model integration needs

The primary future needs include i) greater transparency for models is needed to facilitate model integration and ii) institutional support for integrating modeling.

# 16 Managed Aquifer Recharge using Floodwater (FloodMAR)

The California Department of Water Resources (DWR) is exploring FloodMAR, the concept and practice of using flood water from rainfall and snowmelt for groundwater recharge on various landscapes. Groundwater storage is envisioned to provide water security during periods of drought and to prepare for climate change and associated warmer average temperatures that will hasten snow melt. Additional benefits of flood flow diversion include mitigating downstream flood risks. As a first step, this project investigates the potential for groundwater recharge using modeling and model integration in two sub-basins of California: Merced and Tuolumne. This pilot modeling effort is referred to as the FloodMAR Integrated Modeling Effort. A total of twelve sub-basins in California are being considered for future investigation using the knowledge gained and methodologies developed under this pilot modeling effort.

## 16.1 Integrated model elements

Prior to the larger modeling effort, a simplistic spreadsheet model was developed and used to determine roughly the amount of available water for FloodMAR. The simple model showed potential for FloodMAR and this more extensive integrated modeling effort was initiated to obtain more concrete numbers. The following models are used:

- **Sac-SMA** – hydrologic model that simulates watershed runoff from meteorological inputs. Developers: National Weather Service and National Oceanic Atmospheric Administration
- **CalLite** – hydrologic model that simulates hydrology, reservoir operations and water allocations. Developer: DWR

- **HEC-ResSim** – reservoir model that simulates reservoir operations based on operational goals and constraints. Developer: US Army Corps of Engineers, Hydrologic Engineering Center
- **HEC-RAS** – river model that simulates water flow, sediment and solute transport in river systems. Developer: US Army Corps of Engineers, Hydrologic Engineering Center
- **HEC-FIA** – flood model that simulates flood events and associated economic losses and casualties. Developer: US Army Corps of Engineers, Hydrologic Engineering Center
- **IDC Root Zone Model** – irrigation demand model that calculates water demand based on crop, soil, climate and management. Developer: DWR
- **GRAT** – hydrologic and agronomic model that simulates recharge volume and cost based on crop, soil, depth to groundwater, landscape, geology and climate. Developer: Sustainable Conservation
- **FM2Sim** – hydrologic model that simulates crop water demand, precipitation allocation, soil moisture, surface water diversion, and groundwater levels through a linked land surface, groundwater and surface water process. Developer: DWR

## 16.2 Institutional structure of model integration

DWR is the primary institution managing this project.

## 16.3 Description of how modeling was used to support decision-making

In this section we describe model selection, the important questions posed by FloodMAR, the models used to provide answers to those questions, and the three levels of FloodMAR to be considered. Modeling and model integration in this project will inform recharge practices and reservoir management strategies.

Selection of models used in this project were based on key questions:

- How will climate change affect available water for recharge?
- After meeting downstream and irrigation requirements, how much water remains for recharge?
- What are the potential flood damages from climate and reservoir operations?
- Where can we recharge on land?
- How much, what rate and frequency can we recharge?
- Can groundwater levels be stabilized and to what extent?

During model selection, consideration was given to both model capabilities and targeted outcomes under their current configurations and their potential modifications for integration to be more compatible with the FloodMAR Integrated Modeling Effort and the achievement of its goals. The integrated models are used to represent physical processes of the water cycle, water flow and groundwater recharge, starting with meteorological processes (i.e. precipitation); modeling the hydrologic paths of water into rivers, streams and basins collected in reservoirs; and continuing with downstream allocations (Figure 6). To determine how much water will be available for recharge, watershed runoff simulations are made using Sac-SMA based on climate scenarios and weather forecasting. This available water is input into downstream models, CalLite and HEC-ResSim, to inform on reservoir operations and downstream allocations. Information about potential flood events and their associated damages from the upstream climate and reservoir operations are modeled using HEC-RAS and HEC-FIA. To obtain information on the locations and amounts of recharge water achievable, available water from reservoirs are input into the IDC Root Zone Model and GRAT to simulate both potential recharge capacity and determine available land uses for recharge. Results from these previous models combined are input into C2VSim to give final outputs on water demand, water depletion and groundwater levels within the modeled system.

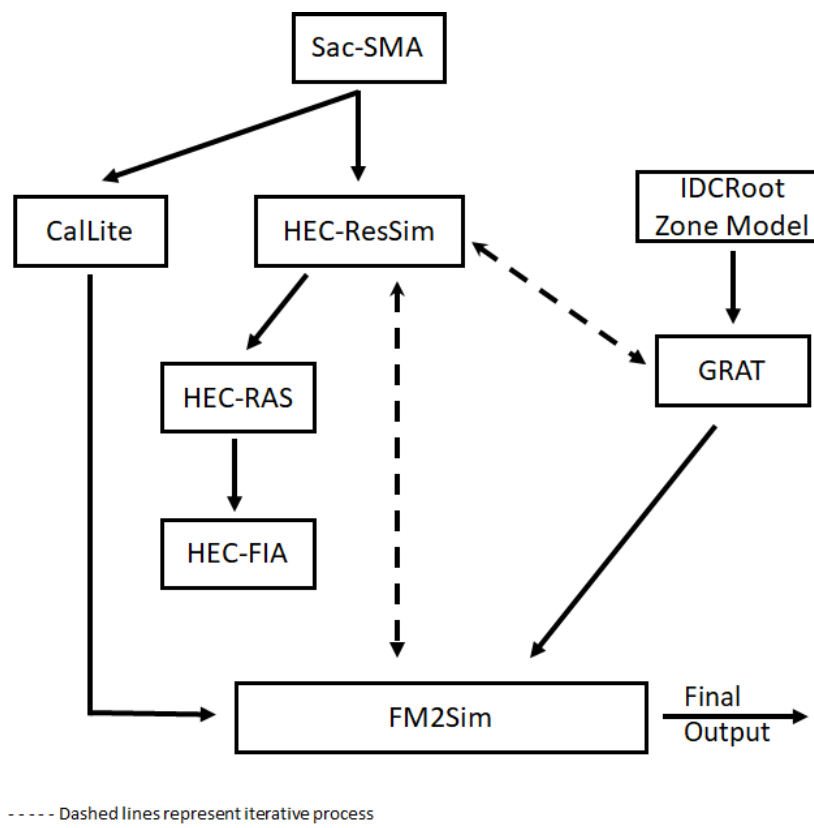



**Figure 6**. Diagram of model integration and data flow for Merced FloodMAR study

Baseline conditions of 500 years are currently being modeled. Once baseline is established, 75 climate change perturbations will follow, representing 0°F to 4°F increase in average temperature and -30% decrease to 30% increase in wetness. Three levels of FloodMAR representing different infrastructure scenarios will be considered:

- Everything-As-Is scenario: In this scenario, only existing infrastructure, conveyance systems and existing operations are considered.

- Reservoir Reoperation: This scenario considers changing how reservoirs are operated so that FloodMAR can be achieved or optimized.
- Additional Infrastructure: This scenario considers adding new infrastructure and conveyance systems to maximize FloodMAR.

The outcome from model results will help develop practical strategies for groundwater recharge that include reservoir operations, diversion methods, downstream allocations and landscape properties based on climate scenarios and weather forecasting.

## 16.4 Stakeholder involvement

GSAs in California need to find ways to comply with SGMA and stabilize groundwater levels. DWR worked with a particular GSA stakeholder and its particular set of problems when developing the modeling scheme. Stakeholder also include partnering developers of the selected models. Stakeholder interest and investment was gained through co-beneficial relationships. Specifically, the efforts put forth here will be returned to model stakeholders in the form of an improved version of the models provided that can support more decision-making needs.

## 16.5 Description of software and data management processes

Many of the models used required modifications, including adding or modifying code to fit project needs. HEC-ResSim was expanded to forecast for an entire year as opposed to two weeks in its original form. Code for water supply, canal demand, diversions, allocations based on storage were also added to HEC-ResSim. FM2Sim was trimmed from the original version of C2VSim; it was geographically clipped for the Merced area and necessary surrounding areas to accommodate edge effects. This trimming was done because incorporating climate change aspects into the full version of C2VSim would have been too labor intensive and not necessary for the effort's regional purposes and goals.

A diagram of the model integration process and model run order is presented in Figure 6. Each model presented in Figure 6 is run as a stand-alone model. The integrated model run starts with meteorological input into the Sac-SMA model, which gives output to reservoir models, CalLite and HEC-ResSim. Flows and diversions modeled using CalLite are input into FM2Sim where it contributes to the final outputs. Flows and diversions modeled using HEC-ResSim are input into HEC-RAS and subsequently RAS output into HEC-FIA to model economic costs and causalities from flood events. Outputs from HEC-ResSim are also input into FM2Sim and GRAT with some iteration between the models to inform the previous model for optimizing water allocations. Crop water demand output from the IDC Root Zone model is used to supplement the GRAT model. Recharge outputs are provided to FM2Sim from GRAT. FM2Sim provides final output to inform water demand, water depletion and groundwater levels based on inputs from CalLite, HEC-ResSim and GRAT.

Currently, data is transferred manually between the models. To aid data transfer processes, scripts are used to aggregate and disaggregate data for use in downstream models that require a different timestep. For quality assurance and quality control, output from each model is checked and resolved for anomalies before proceeding.

## 16.6 Time and budget resources needed

This project has been underway for 1.5 years. The core modeling team in DWR consists of six full-time modelers, with additional help from outside consultants and external model developers.

## 16.7 Significant challenges in model integration

Within any model integration effort, the challenges may vary depending on level of effort, project needs and management. Significant challenges for model integration included both technical and non-technical challenges:

- Gaining trust from stakeholders
- Leadership and communication
- Model screening, selection and modifications to meet project goals
- Focus, resources, value and market

All of the above-mentioned challenges required time and resources for a resolution so the modeling and integration efforts could progress. Each of these is discussed briefly below.

### 16.7.1 Gaining trust from stakeholders

The need to gain trust from stakeholders was identified by DWR as a crucial requirement for successful integrated modeling. Trust from the stakeholders was not inherent during the initial interactions with DWR. Trust had to be cultivated with persistence, effective communication and transparency about the project and its goals. This trust has been critical for the GSA, DWR, partners and stakeholders working collaboratively together to develop an integrated modeling framework with results and outcomes relevant and concrete in value.

### 16.7.2 Leadership and communication

DWR has provided leadership and led communication through this process by providing common visions, common goals and a communication structure. Regular meetings led by DWR are held biweekly to coordinate efforts amongst the different partners and to address technical challenges. This leadership and communication have been critical in advancing the integrated modeling effort forward collaboratively amongst team members. For example, it was noted that integrating models within the similar disciplines required less effort than interdisciplinary integration. Groundwater was the hardest model to integrate because not much interaction between these models and modelers with hydrologic models have occurred previously. Time and effort were needed for the groundwater modelers to understand FloodMAR objectives and then integrate with the other modeling platforms. This was accomplished by creating a good communication system between the interacting modelers.

### 16.7.3 Model screening, selection and modifications to meet project goals

An important task at the front end of the integrated modeling effort was screening possible models to select the most appropriate models. This step focused on starting the technical integration with models compatible with each other and compatible with the project's goals. Once selected, models sometimes required modifications, sometimes due to different designed model goals, and oftentimes to make them temporally compatible or to facilitate data transfer. One typical challenge was working through different timesteps for the different models. Ensuring timestep compatibility can be accomplished in two ways: by modifying the output timestep of the upstream model or by aggregating/disaggregating the output data. There have been challenges for converting monthly outputs for the next model that needs daily or hourly inputs. The first option is labor intensive upfront, but the second option is time-consuming when used in the long term. While not ideal, the second option can work sufficiently for certain needs in the short term. Similar spatial challenges due to spatial incompatibility exist. As discussed earlier, C2VSIM was trimmed down to only address the study area and edge effects such that the model would be more appropriate for assessing regional FloodMAR opportunities.

### 16.7.4 Focus, resources, value and market

The FloodMAR Integrated Modeling Effort focuses solely on regional hydrology in order to assess the potential of FloodMAR in that area to improve water supplies. It is being designed to test different climate drivers over a long period and to consider management opportunities through reservoir re-operation strategies. Significant human resources are available given the importance of creating more sustainable water resources in California under SGMA. DWR expects to utilize this modeling framework to study other sub-basins. Thus, this hydrologically focused effort has significant resources and value across a large market. DWR plans to expand the focus to include other benefits such as fisheries. Relatively reduced funding, less focus of model goals, less clear value or a smaller market might have posed a challenge to successful model integration. These efforts are complicated and each of those factors can effectively dilute and diminish a modeling effort.

## 16.8 Future model integration needs

In the long run, it would be more beneficial to have all input and output of these models reported in the same timestep. Currently, no additional models are considered necessary for FloodMAR modeling. However, there was acknowledgement for the need bring in economic and ecological considerations.

# 17 Franks Tract Restoration Feasibility

Franks Tract and Little Franks Tract are flooded islands in the Central Delta, formed by levee breaches in 1937 and 1982. This area is made up of shallow open water habitat and remnant levees and is managed as part of the Franks Tract State Recreation Area. Franks Tract Restoration is a component of the Delta Smelt Resiliency Strategy adopted in 2016. The goal of the restoration was to restore the historic tidal marsh and create habitat suitable for Delta smelt. Restoration components include decreasing the extent of invasive species (by decreasing their habitat suitability) and supporting food webs to enhance Delta smelt populations. Modeling was performed to evaluate different project alternatives for restoration of Franks Tract that met the objectives of habitat restoration and of the local communities. Franks Tract Restoration is part of a larger interagency effort on the Delta Smelt Strategy, which includes integrated modeling to evaluate the benefits of individual projects on the species (CDFW, 2018). A team of state and federal agencies, water contractors and non-governmental organizations (the Collaborative Science and Adaptive Management Team) developed an assessment framework to evaluate the outcomes of projects (such as Franks Tract) over time.

## 17.1 Integrated model elements

SCHISM, DWR's 3-D hydrodynamics model of the Delta, was the primary model used for this project. Tidal and tidally-averaged flows were considered across the restoration area and salinity (including compliance requirements with existing regulations) was evaluated across the Delta. Particle tracking analysis was used to evaluate the movement of Delta smelt as part of the project analysis.

## 17.2 Institutional structure of model integration

The project was led by the California Department of Fish and Wildlife (CDFW) and modeling was performed by DWR. Project alternatives were developed by CDFW and by a student team at the University of California at Davis. The project alternatives were developed as part of a studio design exercise for landscape architecture students at UC Davis.

## 17.3 Description of how modeling was used to support decision-making

Three-dimensional flow and salinity modeling were performed over the entire Delta (Ateljevich and Nam, 2017) to evaluate local flow fields and salinity for different project alternatives. The area of focus is shown in Figure 7. The modeling was used to explore alternatives to meet desired depth and salinity targets in the restored project. Particle tracking analysis demonstrated that the changes in flows associated with the project would lead to an appreciable drop in entrainment of Delta smelt from sites west of Franks Tract. Because of the large geographic scale of the modeling, factors beyond the local scale were also evaluated, including i) salinity at different compliance stations in the Delta and ii) the interacting effects of other planned restoration projects (see EcoRestore projects for example) on the Franks Tract project. Overall, the modeling was used to evaluate the nature of the habitat to be created and impacts of different alternatives, and thus supported the selection of an alternative for conceptual design.

## 17.4 Stakeholder involvement

Stakeholder participation was key in the project, although not specifically related to the modeling. In addition to CDFW, stakeholders such as State Parks and local communities were involved in selecting the best concepts for moving forward. Experts in landscape architecture at UC Davis supported an effort to engage stakeholders for planning the future of Franks Tract through interviews, workshops, and participatory mapping exercises. The UC Davis research showed that there is extensive fishing and recreational boating uses within the project area; these uses support the local economy of service industries such as marinas, shops, and restaurants. Local stakeholders and the public were offered an opportunity to provide feedback on the restoration concept.

## 17.5 Description of software and data management processes

The modeling was implemented using the SCHISM model for hydrodynamics and water quality, configured for the San Francisco Bay Delta (http://baydeltaoffice.water.ca.gov/modeling/deltamodeling/models/bay_delta_schism/) (Ateljevich and Nam, 2017).

## 17.6 Time and budget resources needed

The configuration of the SCHISM model for the Bay-Delta is a long-term effort, beginning in 2015. The specific modeling described here was a one year study, part of a larger effort at evaluating alternatives for Franks Tract restoration.

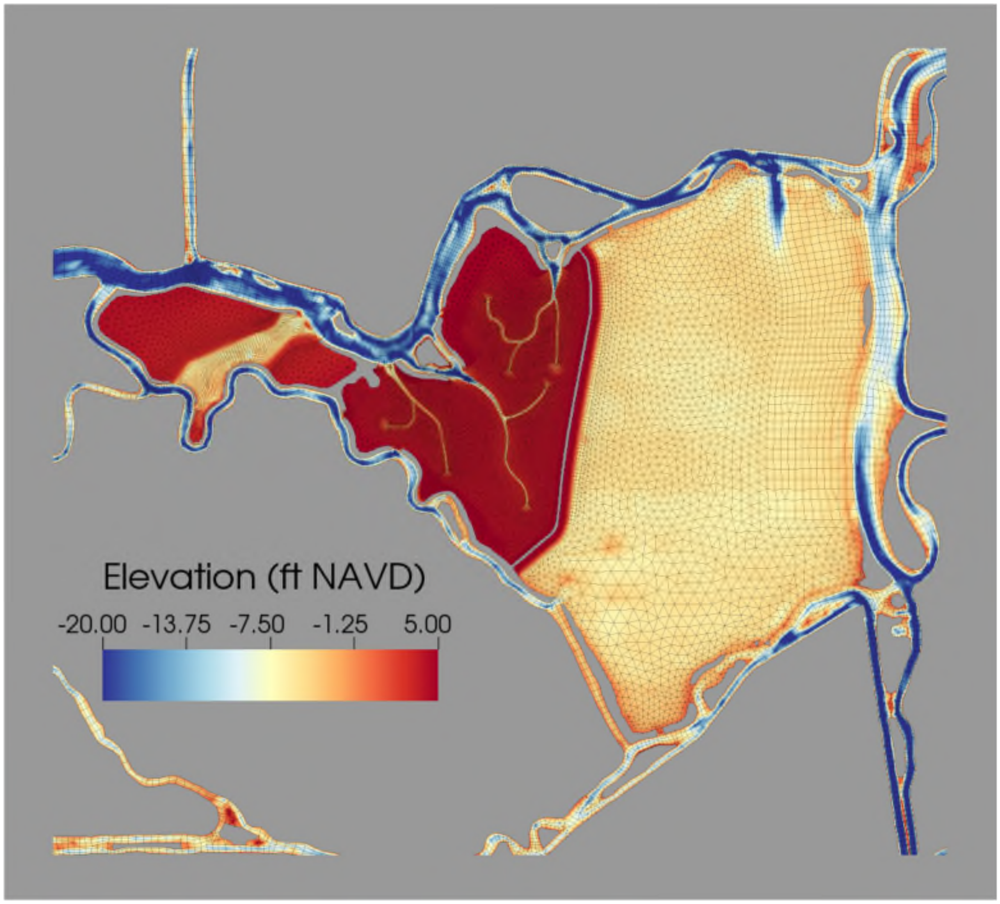



**Figure 7**. Model grid and bathymetry for Franks Tract as implemented in the SCHISM model (Ateljevich and Nam, 2017).

## 17.7 Significant challenges in model integration

The primary modeling challenges related to the complexity and computational requirements associated with the SCHISM model, limiting use to specialists and limiting the ability to integrate with other models.

## 17.8 Future model integration needs

Going forward, it will be important to integrate the SCHISM model hydrodynamics with more representative models of biogeochemistry, nutrient cycling and food-webs to better evaluate the impact of proposed changes to the ecosystem upon which Delta smelt depend. This modeling framework will have general application for restoration projects in the Delta, going beyond Franks Tract to other projects that are within the scope of the EcoRestore program.

*17. Franks Tract Restoration Feasibility*

# 18 Enhanced Particle Tracking Model Component of the Chinook Salmon Life Cycle Model

The Delta Science Panel (DSP) conducted a review in 2011 to provide recommendations on how the National Marine Fisheries Service should incorporate life cycle modeling of Chinook salmon into analyses related to the Operations Criteria and Plan (OCAP), Biological Opinion (BiOp), and Reasonable Prudent Alternatives (RPA) evaluation. Based on a review of existing tools and project needs, the panel recommended the creation of a new salmonid life cycle model for the endangered Winter run Chinook salmon.

The Delta, a region of high human-induced stress and mortality for rearing and migrating juvenile salmon, is hydrodynamically complex owing to its estuarine nature. This domain provides many alternative migration routes and habitats to salmon, owing to its significant channelization, varied geomorphologies and ecologies and topological complexity. Thus, a critical component of the life cycle model is the enhanced Particle Tracking Model (ePTM), an agent-based PTM that simulates the routing, migration dynamics and survival of juvenile salmon through the Delta in response to the system hydrology, water operations and hydrodynamics.

The movement of fish in the estuarine environment is a complex, multi-dimensional and multi-scale process. The primary focus of the ePTM modeling has been to integrate hydrodynamics with the biology and ecology of salmon migration. Integration for this project may be seen as the bridging of scales between processes and motion. For example, there are environmental variables such as temperature and salinity that vary over tidal timescales. Fish movement such as predator avoidance and social behavior happen over seconds to minutes. On the other hand, migration through a reach of river happens over a few hours to a few days. A major thrust of this modeling effort is in using the literature and data analysis techniques to bridge these gaps and produce a model of fish migratory movement at the 15-minute to hourly timescale, so that small-scale local effects may be integrated into a gross movement, while concurrently, the response to tidal variations in the environment may also be represented. This integrated model is currently under development and described below.

## 18.1 Integrated model elements

The ePTM includes hydrodynamics, water quality and ecology in a limited sense to model the migration of juvenile Chinook salmon through the Delta. The hydrodynamics and salinity in the Delta are modeled using DSM2. Statistical and Machine Learning (S&ML) models are used to represent rearing and migrating juvenile salmon movements in response to environmental covariates such as flow, salinity, temperature, daylight hours, turbidity, and dissolved oxygen. Information on predator types and densities in the Delta is also used. In addition, CalSim is used to estimate the habitat availability for rearing salmon in the Delta.

Movement patterns obtained from the S&ML models, in conjunction with the best available scientific information from the literature and the expertise of domain experts, are used to build an agent-based behavioral sub-model of juvenile salmon movement and mortality. The ePTM then uses the behavioral sub-model to move migrating fish in response to the modeled hydrodynamics and salinity field. It also estimates the survival of migrating fish using the X-T model of Anderson et al. (2005), a stochastic model that relates mortality to the path length of fish traversing a reach as well as their travel time through the reach. In order to represent the migration and survival of smolt that have reared as fry in the Delta, simulated fish are seeded uniformly at all the nodes in the DSM2 grid and subsequently tracked. Then the habitat capacity estimates are used to modify the effective survival of simulated fish through the Delta. This is in accordance with the hypothesis that the usage of rearing habitat is proportional to the carrying capacity in each geographical region.

## 18.2 Institutional structure of model integration

This project spans several technical domains, including hydrology, water resources management, hydrodynamics, physical oceanography, ecology, and data science. The development team includes staff from NMFS, UCSC, USGS, DWR and private consulting.

## 18.3 Description of how modeling was used to support decision-making

Earlier iterations of the ePTM were used to estimate the survival of Sacramento river- and Yolo Bypass floodplain- rearing smolts and Delta-rearing fry passing through the Delta. The model was also subsequently used to study the changes in the population dynamics of salmon as a result of the actions of the NMFS Biological Opinion for California WaterFix.

The ePTM is a key component of the Winter Run Chinook Salmon Life Cycle Model, a stage-structured ecological model of salmon population dynamics. This model, which represents the entire-salmon life cycle across the different regions of the Central Valley and coastal Pacific Ocean, uses inputs from the disciplines of hydrology and water resources management, salmon biology, and ecology of freshwater, estuarine and oceanic habitats.

The integrated modeling was used to:

- show conclusively that juvenile salmon do not behave like passive particles in the environment, and that the science of their migration biology is complex,
- test alternate hypotheses about juvenile salmon migration dynamics,
- design studies to better understand salmon movement in tidal systems,
- learn the complex and non-linear feedbacks between juvenile salmon migration and the environment and water operations in the Delta,
- understand the intricate relationship between salmon population and the ecosystem across all the entire life cycle of the fish, and
- provide the best available scientific information to water managers and habitat restoration experts who might need them.

## 18.4 Stakeholder involvement

Model development is led by the Southwest Fisheries Science Center (SWFSC). SWFSC provides the domain expertise about hydrodynamic modeling as well as fish behavior submodels. The SWFSC also collects the hydroacoustic data used for model calibration and validation, as well as information on the spatial and temporal distribution of predators in the Delta.

Model calibration and validation is performed by USGS. USGS provides expertise on the Bayesian calibration technique used in model development, as well as the statistical analysis required to process field data collected by SWFSC to service the model development. USGS is also involved in the development of behavior submodels in the ePTM.

The hydrodynamic model, DSM2, and the baseline PTM was provided by DWR. SWFSC and USGS collaborate closely with DWR in developing the ePTM. Currently, DWR hosts its own version of the model (known as the Eco-PTM) which uses elements of both the ePTM as well as the USGS's STARS statistical model. The ePTM differs from the eco-PTM in that the hydrodynamics in the former are more accurate than in the latter, while the junction routing does not involve the STARS model. In addition, the ePTM uses a slightly different formulation of the X-T survival model than the Eco-PTM. The eventual goal is to merge the SWFSC ePTM model with the DWR eco-PTM.

### 18.5 Description of software and data management processes

The DSM2 model serves as the foundation of the integrated model platform. The ePTM is an extension to the Java-based PTM that is included in DSM2. Model calibration and validation is performed in Python, Matlab and R, and several scripts have been developed to pre-, post-process, and visualize the model results. NMFS maintains the model. Because the scientific aspects of the model are still being updated, a public release has not been made. The model also mandates a very steep learning curve. When public access is provided, it will be through a public share web site such as GitHub.

### 18.6 Time and budget resources needed

This project has been an ongoing multi-investigator effort since 2011. The model went through several revisions and re-calibrations over this period. The current version of the model is undergoing biological and hydrodynamic updates to the code and will be recalibrated and deployed in the Fall of 2019. Funding for this work continues to be provided by USBR and CDFW.

In the subsequent iteration of the model, scheduled to be deployed by mid-2020, velocity and turbulent diffusivity fields within key junctions and open-water regions in the Delta will be parameterized from SCHISM 3D hydrodynamic model results. Funding for this work is provided by CDFW.

### 18.7 Significant challenges in model integration

Distinct from previous and on-going efforts to represent salmon migration in the Delta, this project is an attempt to build a fully mechanistic model. This means that first principles will be used to explain as many aspects of salmon behavior and survival as possible through observed data. Phenomenological aspects of the model will be restricted to only those parts of the behavior and survival that cannot be explained mechanistically.

This design goal imposes several challenges. The first challenge relates to the incorporation of data. There is a wealth of information on salmon behavior and movement from laboratory and field studies, as well as tagging studies in the Delta and other estuarine systems. However, since the scopes of these studies were different, the results themselves often significantly varied across studies. In addition, there is a lot of available data that has not been explored fully. These realities mean that whatever scientific model is developed will represent a common minimum synthesis. The primary challenge is to find the optimal and most parsimonious synthesis. The second challenge related to the representation on salmon in models: because salmon are sentient biological entities, understanding and representing their behavior is more challenging than modeling purely physical systems or passive biological entities. The third challenge relates to the complexity of the aquatic system being modeled. The anthropogenic influences on Delta water management mean that this system is more complicated than most, and this also impacts the decision-making aspects of salmon migration through the system. Bridging the challenges in the spatial and temporal scales of salmon movement, migration, and environmental variability is the overall challenge that this modeling needs to address.

## 18.8 Future model integration needs

As the model is one-dimensional, many multi-dimensional hydrodynamic processes such as turbulence, wind driven circulation, tidal pumping, gravitational circulation, detailed junction dynamics, advection along coherent structures cannot be addressed. In addition, fish movements in response to sub-DSM2-channel scale flow and environmental features, social behavior and accurate survival mechanisms cannot be addressed as i) such data is not easily obtainable and ii) the model is intended to represent migration, not small-scale fish movement.

Future modeling needs include route selection data at key system junctions, cross-sectionally resolved flow data, and predator density maps to better represent the junction routing and mortality sub-models.

# 19 References


Anderson, J.J., Gurarie, E. and Zabel, R.W., 2005. Mean free-path length theory of predator–prey interactions: application to juvenile salmon migration. Ecological Modelling, 186(2), pp.196-211.

Ateljevich, E. and K. Nam., 2017. Hydrodynamic Modeling in Support of Franks Tract Restoration Feasibility Study, (Appendix A in CDFW, 2018). Available at: https://nrm.dfg.ca.gov/FileHandler.ashx?DocumentID=155006&inline (accessed June 10, 2019).

Baldocchi, D.D. and Harley, P.C., 1995. Scaling carbon dioxide and water vapour exchange from leaf to canopy in a deciduous forest. II. Model testing and application. Plant, Cell & Environment, 18(10), pp.1157-1173.

California Department of Fish & Wildlife (CDFW), 2018. Franks Tract Futures? Multi-Benefit Restoration Synthesis Report, June. Available at: https://www.wildlife.ca.gov/Conservation/Watersheds/DCF#41062618-franks-tract-restoration-feasiblity (accessed June 10, 2019).

Deverel, S.J. and Leighton, D.A., 2010a. Historic, recent, and future subsidence, Sacramento-San Joaquin Delta, California, USA. San Francisco Estuary and Watershed Science, 8(2). doi:10.15447/sfews.2010v8iss2art1.

Deverel, S.J. and Leighton, D.A., 2010b. Historic, recent, and future subsidence, Sacramento-San Joaquin Delta, California, USA – Appendix B: Subsidence Model. San Francisco Estuary and Watershed Science, 8(2).

Deverel, S., Oikawa, P., Dore, S., Mack, S., Silva, L., 2017a. Restoration of California Deltaic and Coastal wetlands, version 1.0. American Carbon Registry. Available at: https://americancarbonregistry.org/carbon-accounting/standards-methodologies/restoration-of-california-deltaic-and-coastal-wetlands/california-wetland-restoration-methodology-v1.0-April-2017.pdf.

Deverel, S., Jacobs, P., Lucero, C., Dore, S. and Kelsey, T.R., 2017b. Implications for Greenhouse Gas Emission Reductions and Economics of a Changing Agricultural Mosaic in the Sacramento–San Joaquin Delta. San Francisco Estuary and Watershed Science, 15(3). Available at: https://cloudfront.escholarship.org/dist/prd/content/qt99z2z7hb/qt99z2z7hb.pdf?t=plpdj7.

Deverel, S.J., Leighton, D.A., Lucero, C. and Ingrum, T., 2017c. Simulation of subsidence mitigation effects on island drain flow, seepage, and organic carbon loads on subsided islands Sacramento–San Joaquin Delta. San Francisco Estuary and Watershed Science, 15(4).

Dogrul, E.C., Brush, C.F., and Kadir, T.N., 2016 Groundwater Modeling in Support of Water Resources Management and Planning under Complex Climate, Regulatory, and Economic Stresses. Water, 8:592. doi:10.3390/w8120592.

Ducks Unlimited, 2017. Waterfowl Impacts of the Yolo Bypass Salmonid Habitat Restoration and Fish Passage Project – An effects analysis tool. Available at: http://yolobasin.org/wp-content/uploads/2018/01/Waterfowl-Impacts-of-the-Yolo-Bypass-Salmonid-Habitat-Restoration-and-Fish-Passage-Project_2017Oct20.pdf (accessed May 13, 2019).

DWR, 2017. 2017 CVFPP Update – Scenario Technical Analyses Summary Report, February. Available at: https://water.ca.gov/LegacyFiles/cvfmp/docs/CVFPP-2017-TechnicalAnalysesSummary-PubDraft.pdf (accessed May 13, 2019).

DWR, 2018a. FloodMAR White Paper, June. Available at: https://water.ca.gov/-/media/DWR-Website/Web-Pages/Programs/All-Programs/Flood-MAR/DWR_FloodMAR-White-Paper_06_2018_updated.pdf?la=en&hash=350DBD68452230C5CF1706C3E8EB1E3E3E613C25 (accessed March 1, 2019).

DWR, June 2018b. Flood-MAR Research and Data Development Framework Discussion Draft, June. Available at: https://water.ca.gov/-/media/DWR-Website/Web-Pages/Programs/All-Programs/Flood-MAR/20180724_Flood-MAR-Development-Framework_Draft.pdf?la=en&hash=D6FAE74C374C0D9C81F4B08465EA76BE75A22936 (accessed March 1, 2019).

DWR, 2019. Flood-MAR Using Floodwater for Managed Aquifer Recharge Public Workshop, August. Available at: https://water.ca.gov/-/media/DWR-Website/Web-Pages/Programs/All-Programs/Flood-MAR/Flood-MAR-Public-Workshop_August-18-2018.pdf?la=en&hash=38B62B23C1A0ADFB4C85E02D7B7E84107B696923 (accessed March 1, 2019).

Ercan, A., Dogrul, E.C., and Kadir, T.N., 2016. Investigation of the groundwater modelling component of the Integrated Water Flow Model (IWFM), Hydrological Sciences Journal, 61:16, 2834-2848, doi: 10.1080/02626667.2016.1161765.

Fertitta-Roberts, C., Oikawa, P.Y. and Jenerette, G.D., 2019. Evaluating the GHG mitigation-potential of alternate wetting and drying in rice through life cycle assessment. Science of The Total Environment, 653, pp.1343-1353.

Howitt, R., MacEwan, D., Garnache, C., Medellin Azuara, J., Marchand, P. Brown, D., Six, J., and Lee, J., 2013. Agricultural and Economic Impacts of Yolo Bypass Fish Habitat Proposals. Available at: http://baydeltaconservationplan.com/Libraries/Dynamic_Document_Library/YBFEPT_Agricultural_and_Economic_Impacts_of_Yolo_Bypass_Fish_Habitat_Proposals_4-12-13.sflb.ashx

Jacobs, P.J., 2015. Economic Models for Conservation Planning and Policy: Exploring Wetland Conversion and Values in the Sacramento-San Joaquin Delta. Masters Thesis. University of California, Davis. Available at: https://search.proquest.com/openview/8972023a17dc89a3b2bb27a958cded87/1?pq-origsite=gscholar&cbl=18750&diss=y.

Kadir, T.N., 2006. Estimates for Consumptive Water Demands in the Delta using DETAW. In “Methodology for Flow and Salinity Estimates in the Sacramento-San Joaquin Delta and Suisun Marsh”. Department of Water Resources.

Kimmerer, W.J. and Rose, K.A., 2018. Individual-Based Modeling of Delta Smelt Population Dynamics in the Upper San Francisco Estuary III. Effects of Entrainment Mortality and Changes in Prey. Transactions of the American Fisheries Society, 147(1), pp.223-243.

Li, C., Six, J., Horwath, W.R. and Salas, W., 2014. Calibrating, Validating, and Implementing Process Models for California Agriculture Greenhouse Gas Emissions. California Environmental Protection Agency, Air Resources Board, Research Division.

MacWilliams, M.L., Gross, E.S., DeGeorge, J.F., and Rachiele, R.R., 2007. Three-dimensional hydrodynamic modeling of the San Francisco Estuary on an unstructured grid, IAHR, 32nd Congress, Venice Italy, July 1-6, 2007.

Merrill, A., Siegel, S., Morris, B., Ferguson, A., Young, G., Ingram, C., Bachand, P., Shepley, H., Singer, M. and Hume, N., 2010. Greenhouse gas reduction and environmental benefits in the Sacramento-San Joaquin Delta: advancing carbon capture wetland farms and exploring potential for low carbon agriculture. The Nature Conservancy. Available at: http://www.stillwatersci.com/resources/2010merrilletal_deltacarbon.pdf.

Oikawa, P.Y., Jenerette, G.D., Knox, S.H., Sturtevant, C., Verfaillie, J., Dronova, I., Poindexter, C.M., Eichelmann, E. and Baldocchi, D.D., 2017. Evaluation of a hierarchy of models reveals importance of substrate limitation for predicting carbon dioxide and methane exchange in restored wetlands. Journal of Geophysical Research: Biogeosciences, 122(1), pp.145-167.

Rayej, M., Snyder, R.L. Snyder, Orang, M.N. Orang, S. Geng, S. and S. Sarreshteh, S., 2011. "CALSIMETAW and WEAP models for water demand planning", Proc. ICID 21st Int. Congress on Irrigation and Drainage ICID Transactions No.30-A., Available at: https://www.weap21.org/Downloads/ICID_WEAP_SIMETAW.pdf

Rose, K.A., Kimmerer, W.J., Edwards, K.P. and Bennett, W.A., 2013a. Individual-based modeling of delta smelt population dynamics in the upper San Francisco Estuary: I. Model description and baseline results. Transactions of the American Fisheries Society, 142(5), pp.1238-1259.

Rose, K.A., Kimmerer, W.J., Edwards, K.P. and Bennett, W.A., 2013b. Individual-based modeling of Delta Smelt population dynamics in the upper San Francisco Estuary: II. Alternative baselines and good versus bad years. Transactions of the American Fisheries Society, 142(5), pp.1260-1272.

Siegfried, L.J., Fleenor, W.E., and Lund, J.R., 2014. Physically based modeling of Delta Island Consumptive Use: Fabian Tract and Staten Island, California. San Francisco Estuary and Watershed Science, 12(4). Doi: http://dx.doi.org/10.15447/sfews.2014v12iss4art2

Suddeth Grimm, R., & Lund, J.R., 2016. Multi-Purpose Optimization for Reconciliation Ecology on an Engineered Floodplain: Yolo Bypass, California. San Francisco Estuary and Watershed Science, 14(1).

U.S. Bureau of Reclamation, 2017. Yolo Bypass Salmonid Habitat Restoration and Fish Passage Project Draft Environmental Impact Statement/Environmental Impact Report.

University of Massachusetts & DWR, 2017. California Climate Risk: Evaluation of Climate Risks for California Department of Water Resources. Available at: https://water.ca.gov/-/media/DWR-Website/Web-Pages/Programs/All-Programs/Climate-Change-Program/Files/California-Climate-Risk-Evaluation-of-Climate-Risks-for-California-Department-of-Water-Resources.pdf (accessed March 1, 2019).

USBR & DWR, 2012 Yolo Bypass Salmonid Habitat Restoration and Fish Passage Implementation Plan. Available at: https://www.usbr.gov/mp/bdo/docs/bypass-fish-passage-implementation-plan.pdf