Integrated Modeling in the Delta:

Status, Challenges and a View to the Future

Management Summary

January 2020

Prepared for:
Delta Stewardship Council

Simulation modeling is an increasingly common tool for supporting decision-making processes in the Delta and its contributing watersheds. Modeling, which entails the mathematical representation of physical, chemical, biological, or socioeconomic systems, is performed using a variety of independently developed software tools.[i] Model outputs from different disciplines may need to be integrated to effectively support complex, large-scale, multi-stakeholder decision-making processes. For example, initiatives that propose significant changes to upstream reservoir operations must evaluate linked responses to downstream flows, water quality, ecosystem services, water supply availability, and associated urban and agricultural economics.

Looking to the future, there is a need for model integration to be implemented more efficiently, with greater consistency, and across a wider range of disciplines. Over the past three years, state and federal agencies involved in Delta decision-making processes have expressed a need for greater coordination among model developers to advance the status of integrated modeling. Based on the direction from the Delta Plan Interagency Implementation Committee, the Delta Stewardship Council (DSC) formed an Integrated Modeling Steering Committee (IMSC) to help guide these efforts. The IMSC was given the charge to develop a strategic plan for building a sustainable modeling community and a governance framework over the short- (1-5 years), intermediate- (5-10 years) and long-term (10-30 years). Advancement of model integration is also noted as a key action in the 2019 Delta Science Plan, and recommended by the Delta Independent Science Board, which provides oversight on adaptive management in the Delta.[ii] The project summarized in this document implements these broad directions to further support and develop integrated modeling in the Delta community. In the following pages, the status of integrated

modeling is evaluated, key challenges and solution approaches to advance model integration are identified, the basis for future actions are outlined, and a set of alternative future directions for management action are presented.

Status of Integrated Modeling

We conducted a survey of recent and ongoing integrated modeling applications in the Delta. Publicly available information on sixteen major ongoing or recently completed modeling studies was examined and key participants were interviewed. 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. Our goal 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.

We found that integrated modeling in the Delta was being widely used in the physical, chemical, and biological domains, with growing and emerging opportunities in the economic and social science domains, respectively. In some cases, new integrated models are being developed that encompass knowledge across different technical areas. However, model integration is typically being performed by manually converting output from one model into input for another model. While this approach is functional, it is not very efficient and cannot be used in all situations. In general, we found that integrated modeling is providing utility for evaluating complex, high-stakes initiatives if supported by sufficient resources and if the missions and goals of the participating agencies or organizations are aligned to the modeling needs.

Challenges for Integrated Modeling

Although integrated modeling across different spatial and disciplinary domains can be beneficial in supporting complex decision-making processes, the added complexity of getting two or more models to work together effectively raises practical challenges. These challenges may be grouped into two broad categories: institutional and technological.

Institutional challenges, concerned with the human side of simulation modeling, relate to the overall decision-making setting, expertise and funding needs, and stakeholder engagement. Technological challenges, concerned with the computational, scientific and engineering side of simulation modeling, include issues such as model compatibility, data exchange management, model accessibility, overall complexity of integrated models, propagation of uncertainty across integrated models, and the overall limitations in model testing.

Our assessment of these institutional and technological challenges found that advancement of model integration is not driven solely by experts. Even when the technological challenges of model integration are met through expert collaboration, successful development of integrated models require broader participation in the modeling process (such as model sponsors and other stakeholders) to address institutional challenges.

Institutional and Technological Approaches to Facilitate Integrated Modeling

Following our assessment of institutional and technical challenges, we identified several approaches to facilitate integrated modeling in the Delta. Identified institutional approaches include:

- **Institutional commitment and leadership support** – For any integrated modeling effort to be successful, leadership is needed to provide motivation to participants and sustained funding support is needed to allow novel integrated model frameworks to develop. Such efforts involve some risk in that the resulting tools may not work as intended, may take too much time to develop, or may be too computationally complex to be of practical use. Even when the integration effort is not a top-down driven exercise, leadership is needed to support modelers to go beyond existing modeling practices in creating new integrated applications.
- **Expert community development** – Expert communities can take the form of user groups (many of which are already in existence), a virtual community of practice, or a physical location for interested participants to work together (i.e. a modeling "collaboratory"). Developing interagency expert communities can also be fostered by various regional, state, and national forums that involve technical exchange among modelers, scientists and engineers.
- **Education** – Topics relevant to integrated modeling should be emphasized in the education curriculum of modeling, science and engineering students. Targeted continuing education opportunities should also be provided for staff in participating organizations and for the broader stakeholder community.

Several technological approaches to facilitate model integration were identified:

- **Model documentation** – An obvious and straightforward technological approach, model documentation should address model structure and processes and the data being exchanged between models. Documentation minimizes the opportunities for error in translation across models, a major concern in most model integration efforts.
- **Model user interfaces** – While not essential for model integration *per se*, model user interfaces allow greater accessibility and understanding of data input and output needs and are therefore beneficial for cross-disciplinary interaction.
- **Data exchange standards** – These standards are an essential element for creating frameworks that allow models to share information in various dynamic formats. Several data exchange frameworks are in active development in the environmental domain to promote efficient and transparent inter-model communication.
- **Formal evaluation of uncertainty propagation in linked models** – This technological approach is evolving and is the subject of ongoing research. While this approach can promote more informed use of model results in decision making, it can be highly computationally demanding.

- **Model emulation** – An approach that replaces complex models with simplified approximations, the primary benefit of model emulation is the reduction of computational requirements. In many cases, emulators can be embedded within another model. Several emulation approaches are available, with some currently being used in the Delta.
- **Adopting "big data" approaches** – Related analysis tools are undergoing rapid development, especially in the commercial realm. Some environmental applications of these tools are beginning to appear. Given the potential utility of these tools for management and integrated data analysis, many future applications will likely develop. Such developments include standalone models as well as hybrid models that combine data-based approaches and process-based models.

We found that technological approaches to facilitate integrated modeling are developing rapidly in the environmental and related domains. These approaches offer many different avenues for linking models and creating new integrated modeling frameworks to support future decision-making needs. Institutional challenges, while distinct from technical challenges, are equally important to address for the long-term success of model integration in the Delta.

Future Needs for Integrated Modeling

Our survey of recent and ongoing integrated modeling applications demonstrates that, as an active area of Delta decision support, integrated modeling has been used to evaluate drivers and interactions that cross a spectrum of disciplinary boundaries such as engineering, hydrology, hydrodynamics, water quality, ecology, and the social sciences. Looking ahead, our comprehensive assessment is that decisions pertaining to a wide variety of Delta issues—relevant both today and in the foreseeable future—could be more effectively supported through an integrated modeling framework that goes beyond what is currently being utilized. Future modeling needs include continued support for regulatory actions under current laws, exploratory analyses and adaptation related to anticipated future conditions driven by climate change, developing better understanding of the interactions of different physical, chemical, and biological processes, and advancing techniques to more explicitly consider the dynamic role of humans in the landscape.

Based on the information gathered and presented in support of this project, we find it reasonable to argue for dedicated efforts to promote model integration (as well as good modeling practices) across the Delta. The main reasons for this recommendation are listed below:

- **Investment protection** – With the increasing complexity of decisions being addressed, model development and related analyses represent a large and growing investment of resources. Unlike databases of field observations, however, model results have limited shelf lives unless supported by adequate documentation, source codes, input files, etc. The adoption of good practices to develop and maintain such material will allow models to be useful to a broader community over a longer timeframe.

- **Cost savings** – A significant technological model integration challenge is to get models to "talk" to one another. Efforts to streamline model inputs and outputs for integration will require resources in the near term; however, these efforts will almost always be cost effective over the long term, as new model frameworks are envisioned and implemented.
- **Incorporation of new technological developments** – Rapid advances in software tools in the commercial realm (and more generally outside the Delta domain) have potential for enhancing Delta modeling in general and Delta model integration in particular. Adoption of these approaches will lead to new developments and will enhance the decision-making utility of models.
- **New scientific development** – With increasing recognition of the interactions between environmental and anthropogenic drivers (e.g. water, energy, food, and communities) and increasing recognition of constraints on sustainability (from local to global scales), a more sophisticated understanding of these relationships is needed. Developing such understanding can be effectively supported through integrated models that encapsulate knowledge across different disciplines.
- **Understanding feedbacks** – In many cases, dynamic feedbacks between human and natural systems are not studied or poorly understood. As a result, model integration is performed in a more static manner. This lack of understanding often constrains how component models are integrated, resulting in a one-directional flow of information. Even with the current suite of models in use, fuller consideration of feedbacks can lead to greater insight into future outcomes.
- **Focused leadership** – Many of these future modeling needs are acknowledged by the modeling community but are not fully implemented because of institutional or resource constraints. A directed effort to coordinate actions among the expert community (see *Alternatives to Advance Integrated Modeling* below) is more likely to lead to beneficial outcomes than a more organic, undirected approach.

Alternatives to Advance Integrated Modeling

Given the status of integrated modeling in the Delta and anticipated future needs as outlined in this report, Table 1 presents four possible paths for advancing integrated modeling. While these possible paths are in fact part of a single continuum, we present them here as discrete alternatives for purposes of discussion. These discrete alternatives, associated with different levels of commitment and resources (human and financial), inherently recognize practical constraints on what can be implemented over different time frames. We recommend that the IMSC and the

broader stakeholder community focus on a preferred alternative to pursue additional development in the near term. Key considerations associated with each alternative are presented in Table 2, including opportunities, limitations and funding resources needed.

The first alternative assumes an on-going “status quo” level of effort by active participants; this alternative does not require the creation of a new organization and does not need a new funding stream. Under this alternative, integration is need-based and led by individual teams, as done at present. However, this alternative provides limited exchange and learning opportunities across different organizations. This alternative would entail continued guidance by the IMSC (a voluntary committee) with the DSC providing primary staff resources.

The second alternative, which would also be led by the IMSC and DSC staff, would involve enhanced cooperation across the modeling community. In contrast to the first alternative, greater efforts would be made to reduce institutional barriers to cooperation, with specific attention to encourage staff from different organizations and specialties to work together. This alternative may require a greater level of staff support from the DSC (and associated funding) than at present.

The third alternative would lead to the creation of a “virtual collaboratory”, which would be a server- or cloud-based repository of information related to modeling, including codes, data, training resources, etc. This alternative would require additional funding for dedicated staff to maintain and manage the associated materials and additional funding to run the facility on servers or on a cloud-based platform. The success of this alternative would depend on the engagement and support of the expert community at large. This would be more likely to happen if all participants were to see the long-term benefits of putting related materials on a single, and widely accessible, repository. The “virtual collaboratory” would provide internet-based access to all interested participants; however, no physical location for collaboration would be provided.

The fourth alternative is the development of a “physical collaboratory”. This alternative would have all the features of the “virtual collaboratory” as well as a physical home where staff from participating organizations could work together. The placement of staff in the physical home would be on delegation from partner agencies for fixed periods; these delegates could be supported by some level of dedicated staffing. The primary benefits of this alternative would be the opportunity to create multi-disciplinary interactions among individuals and greater visibility of integrated modeling and related research in the Delta.

Table 1. Alternatives for Integrated Modeling Strategic Plan: Overview

Alternative	Description
1. Continuing development	Integration continues to occur as needed, driven by regulatory needs or new research. Currently occurs on a case-by-case basis within agencies and in academic research studies. DSC engagement through staff participation and coordination.
2. Enhanced cooperation	An institutional effort (likely through the DSC) to enhance collaboration among disciplines and organizations. Enlarged DSC staff participation, but no new formal structures.
3. Virtual collaboratory	A living repository of information on Delta modeling (models, training resources, etc.), albeit virtual; a single point of entry to learn about and contribute to modeling in the Delta. (Example: SGMA web support tools)
4. Physical collaboratory	A common workplace for modelers to work together, dedicated staff (possibly on rotation) from other organizations; computer resources, as in the virtual collaboratory. (Example: San Francisco Estuary Institute)

Table 2. Alternatives for Integrated Modeling Strategic Plan: Opportunities, Limitations, and Funding Needs

Alternative	Opportunity	Limitations	Funding Resources Needed
1. Continuing development	No top down implementation; integration efforts are need-based and continue as at present; no additional costs imposed; no institutional changes needed.	Integration is primarily off-line; limited team learning opportunities; lack of shared modeling and data resources; limited iteration between models.	Staff time within DSC; additional staff are engaged on a project basis.
2. Enhanced cooperation	Focus on the human side of the integration issue; support and encouragement for staff to work together across disciplines; greater opportunities for integrated model development	May not be continued in the absence of clear leadership	Additional staff within DSC and/or greater level of involvement.
3. Virtual collaboratory	A general resource for modelers (codes, data training resources, etc.)—not tied to any particular project. A repository for model information that otherwise is easily lost. May result in cost savings over time as it matures and gets community support.	Needs clear and long-term support to get community involvement.	Dedicated staff, funding, and organizational host to develop virtual collaboratory; consistent ongoing support. Estimated costs $0.25-$0.5 million annually.
4. Physical collaboratory	A common workplace for modelers to work together, dedicated staff (possibly on rotation) from other organizations; computer resources, as above. Potential for creating a true multi-disciplinary team; greater interaction; greater visibility in the Delta.	Greater cost and institutional support to initiate and sustain over the long term.	All of the above needs, with additional resources for maintaining a physical space. Estimated costs $1.5 to $2 million annually.

Going beyond these high-level alternatives, Table 3 outlines ten recommended actions for the DSC, the IMSC, and other stakeholders to implement an Integrated Modeling Strategic Plan. Selection of Alternative 1 would signify implementation of the first two actions, whereas selection of Alternative 4 would signify implementation of all ten actions.

Table 3. Recommended Actions for Implementing Strategic Plan Alternatives

<table>
<tr><th>Recommended Action</th><th>Description</th><th colspan="4">Alternative</th></tr>
<tr><td>1. General IMSC Actions</td><td>Steps the IMSC would take to implement the concepts in this plan, in the near-term (to take place in the next year) and medium-term (2-5 years).</td><td rowspan="2">Alternative 1</td><td rowspan="5">Alternative 2</td><td rowspan="9">Alternative 3</td><td rowspan="10">Alternative 4</td></tr>
<tr><td>2. Improve Modeling Robustness</td><td>Recommendation that the IMSC adopt standards for modeling best practices, especially for large-scale modeling efforts with relevance to economically consequential decisions.</td></tr>
<tr><td>3. Staff Development</td><td>Encourage promotion of a formal staff development and training program as well as a succession program within organizations.</td><td rowspan="8"></td></tr>
<tr><td>4. Operations Model Improvements</td><td>Operations models of California reservoirs are central to large-scale modeling endeavors. Over the long term, improving the robustness of these models to varying inputs and improving ease of use over different conditions is key to enabling integration.</td></tr>
<tr><td>5. Implementation of Enhanced Model Integration</td><td>Implementation of technological solutions for enhanced model integration, in the following areas: model standards, integrated code development, model emulators to represent complex models, and data analysis and integration frameworks</td></tr>
<tr><td>6. Education Plan</td><td>Development of an education plan that incorporates learning resources in both in and out of the classroom setting, for students as well as practitioners.</td><td rowspan="5"></td></tr>
<tr><td>7. Interaction across Modeling Communities</td><td>Interaction across modeling communities inside and outside the Delta Region to leverage tools and human resources from a larger network of participants beyond the Delta.</td></tr>
<tr><td>8. Integrated Modeling Research Program</td><td>Complexities arising from integrated modeling need focused research, including in areas such as calibration and uncertainty propagation, human-environment interactions, and incorporation of new data collection technologies.</td></tr>
<tr><td>9. Creation of a Virtual Collaboratory</td><td>A virtual collaboratory provides the virtual framework for exchange of model information and computer-based resources to host and manage models and related materials. The computer resources could involve dedicated servers housed at a participating agency or a cloud-based solution, without a physical server footprint at any local agency.</td></tr>
<tr><td>10. Creation of a Physical Collaboratory</td><td>A physical collaboratory would provide a common workplace for modelers to interact and would create the potential for creating a true multi-disciplinary team with dedicated staff (possibly on rotation) from other organizations. Computer resources hosted by the physical collaboratory could provide the same point of entry as the virtual collaboratory, but in addition could house additional computer resources for computationally intensive model runs, plus meeting and training workspace.</td><td></td></tr>
</table>

Other Resources

This report is a management summary of the Delta Stewardship Council (DSC) document "*Integrated Modeling in the Delta: Status, Challenges and a View to the Future.*" Background information is provided in the following supporting documents:

- **Memo 1** – *Model Inventory* is a summary of models in use in the Delta today, with a focus on considerations related to their integration with other models. An abridged version of this memo is provided in Appendix A of the full DSC report; the appendix is linked to a web-based model inventory (a living document) that is expected to be revised and updated over time.
- **Memo 2** – *A Survey of Recent Integrated Modeling Applications in the Delta and Central Valley* presents the current state of practice of Delta integrated modeling.
- **Memo 3** – *Challenges and Solutions for Model Integration and Related Data Needs* is based on our review of ongoing integration and serves as the foundation for efforts to improve integration.
- **Memo 4** – *Recommendations for Modeling Best Practices,* as suggested by the title, recommends best practices for model development which apply equally to individual discipline-specific models and to integrated models. An abridged version of this memo is provided in Appendix B of the full DSC report.

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.

We acknowledge input from individuals associated with the following specific project initiatives: *California WaterFix* – Chandra Chilmakuri (MWD), Marin Greenwood & Rick Wilder (ICF), Erik Reyes (DWR); *Levee Assessment, Storage, Flood Management and New Infrastructure* – Michael Mierzwa and Laura Hollender (DWR); *Bay-Delta Water Quality Control Plan Updates* – Matt Holland, Subir Saha and Scott Ligare (SWRCB); *Water Rights, Consumptive Use and Water Budgets* – Tariq Kadir (DWR), William Fleenor (UC Davis); *Delta Smelt Biological Opinion* – Li-Ming He & Matt Nobriga (USFWS); *Central Delta Corridor/Future Carbon Markets* – Campbell Ingram (Delta Conservancy); *California EcoRestore* – Erik Loboschevsky (DWR); *Yolo Bypass Models* – Robyn Grimm (EDF), William Fleenor (UC Davis) and Doug Brown (Douglas Environ.); *Delta Methylmercury Total Maximum Daily Load Modeling* – Carol DiGiorgio (DWR); *CASCADEII Model Framework* – Noah Knowles & Lisa Lucas (USGS); *Delta Rice Agriculture Modeling* – Dennis Baldocchi (UC Berkeley), William Horwath (UC Davis), Lucas Silva, Patricia Oikawa, Amy Merrill, Paul Jacobs, and Sandra Bachand; *Modeling for Climate Change Vulnerability Assessment and Adaptation Strategy for the Sacramento-San Joaquin Delta and Suisun Marsh* – Kate Anderson (DSC); *Managed Aquifer Recharge using Floodwater (FloodMAR)* – Ajay Goyal, David Arrate, Romain Maendly, Rich Juricich (DWR); *Franks Tract Restoration Feasibility* – Eli Ateljevich (DWR); *Chinook Salmon Life Cycle Model* – Vamsi Sridharan and Eric Danner (NOAA). We also acknowledge input from the following individuals on various cross-cutting themes related to Delta integrated modeling: Drs. Jay Lund (UC Davis), John DeGeorge (RMA), and Eli Ateljevich (DWR).

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

Endnotes

[i] An inventory of models in current use was created for this project and can be accessed online at: https://cwemfwiki.atlassian.net/wiki/spaces/MI/overview

[ii] Delta Science Plan 2019. Online at: http://www.deltacouncil.ca.gov/pdf/2019-delta-science-plan.pdf