Integrated Modeling Support
Delta Stewardship Council Contract #17400

Integrated Modeling in the Delta:
Status, Challenges and a View to the Future

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Prepared for:

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Executive Summary

Integrated modeling is a decision support approach where two or more models, typically with different areas of focus, are applied jointly as part of a quantitative analysis. This approach is often needed for system-level analysis of complex environmental problems that cross physical, chemical, biological, social and economic domains. Integrated modeling may be used for long-term facility and operations planning, short-term forecasting, regulatory decision-making, and developing or advancing scientific understanding of complex systems.

This document was developed in response to a vision laid out in the Delta Science Program's Science Action Agenda, Delta Independent Science Board recommendations, and by the Delta Stewardship Council's Integrated Modeling Steering Committee. This work evaluates the current state of integrated modeling in the Delta, identifies challenges to and potential approaches to facilitate integrated modeling in the region, and identifies related data and modeling needs. This information provides a foundation for specific recommendations for an integrated modeling strategy for the Delta. In this work, the Delta is a shorthand reference to systems that are connected to the Delta, either physically or socioeconomically, including, for example, the upper watershed and coastal regions.

Survey of Recent Integrated Modeling Applications in the Delta

A survey of recent and ongoing integrated modeling applications in the Delta was conducted by examining publicly available information on major ongoing or recently completed modeling studies and 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 large teams of interdisciplinary expertise. The 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. Our review of major project initiatives in the Delta found that model integration was being used widely, notably in the physical, chemical, and biological domains; our review also found growing opportunities in the economic domain and emerging opportunities in the other social sciences. In general, integrated modeling in the Delta was found to provide utility when evaluating complex, high-stakes initiatives if supported by sufficient resources and if the missions and goals of the participating agencies or organizations were aligned to the modeling needs.

We developed an inventory of models used in the Delta as part of our effort to evaluate the current state of integrated modeling in the Delta. The primary goal of the model inventory was to move towards developing a shared and interactive library useful for future modelers, model users, and other professionals while identifying opportunities for interaction between models. This model inventory is meant to be a living document. It is anticipated that the inventory will be updated over time as models are updated, new studies are completed, and new models are developed. The most up-to-date model inventory can be accessed online at:
https://cwemfwiki.atlassian.net/wiki/spaces/MI/overview.

Challenges for Integrated Modeling

Although integrated modeling across different spatial and disciplinary domains can be beneficial in addressing complex environmental problems, the added complexity of getting two or more models to effectively work together raises some practical challenges. These challenges are grouped into two broad categories: institutional and technical. Institutional challenges are primarily concerned with the human side of modeling and relate to the overall setting in which modeling occurs, the expertise needed to develop integrated models, the funding needs, and the engagement of stakeholders. Technical issues include computational and scientific challenges related to integration and are associated with model compatibility, data exchange and management, accessibility of models, overall complexity of integrated models, propagation of uncertainty across integrated models, and the overall limitations in model testing. An assessment of these challenges shows that model integration is not driven by modelers alone. Even when the technical challenges of integration are solvable by modeling teams, successful development of integrated models will require other participants in the modeling process, such as model sponsors and other stakeholders, to address institutional challenges.

Institutional and Technological Approaches to Facilitate Integrated Modeling

In our assessment of model integration challenges that arise around participating organizations and people, we identified different actions that can help stimulate the development of integrated models, including institutional commitment and leadership support, model community development, and education. Modeling 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. collaboratory). Community engagement across participating agencies is also fostered by various regional, state, and national forums that involve technical exchange among modelers and scientists. Institutional efforts for model integration also include education for current and future students, staff in participating organizations, as well as the broader stakeholder community. These institutional challenges, while distinct from technical challenges, are equally important to address for the long-term success of model integration in the Delta.

Several technological approaches to facilitate model integration were identified:

- Model documentation is an obvious and straightforward approach; this 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.
- User interfaces, while not essential for model integration *per se*, allow greater accessibility and understanding of data input and output needs, and is therefore beneficial for cross-disciplinary interaction.
- Data exchange standards are an essential element for creating frameworks that allow models to share information among one another in various dynamic formats. Several such 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 is a technological approach that can promote more informed use of model results in decision making. Such analysis can be highly computationally demanding and is currently the subject of research.
- Model emulation, an approach that replaces a complex model with a simpler approximation, reduces computational requirements. In many cases, emulators can be embedded within another model. Several emulation approaches are available, with some being used in the Delta.
- Adoption of big data approaches can facilitate integrated modeling. Related analysis tools are undergoing rapid development, especially in the commercial realm. Some environmental applications of these tools are beginning to appear, and, 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 combining data-based approaches and process-based models.

Overall, our assessment suggests that technological approaches to facilitate model integration are developing rapidly in the environmental domain and other related domains. These approaches offer many different avenues for linking models and creating new integrated modeling frameworks to support future decision-making needs.

As a practical step to facilitate integrated modeling in the Delta, this report provides guidance for best practices that are expected to enhance the utility of modeling efforts to decision-makers, stakeholders and the modeling community at large. The guidance offered here applies equally to both individual discipline-specific models and integrated models that combine knowledge from various disciplines. Many of these concepts are general and yet can be considered by non-modelers willing to understand the scope of a modeling application at its inception and to make a judgement as to the utility of the results upon its completion.

To encourage adoption of the best practices identified in this work, we provide three summary sheets, corresponding to different modeling stages. The first sheet, a checklist that could be employed at inception of a modeling effort, is to enable various participants to agree on the basic features of the work to be done. The purpose of the second sheet is to evaluate and score a modeling analysis upon completion. The final sheet is to assess the overall life cycle of a modeling framework.

Future Directions

Our survey of recent and ongoing integrated modeling applications demonstrates that it is an active area of decision support in the Delta; these recent and on-going efforts evaluate drivers and interactions that cross a spectrum of disciplinary boundaries such as engineering, 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. To this end, we identify future modeling needs and outline the basis for future actions.

Identified 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 this report, it is 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 environmental problems 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 on developing and maintaining such material will allow models to be useful to a broader community over a longer period.
- **Cost Savings**. A large part of the effort of model integration is getting models to "talk" to one another. Efforts to streamline model inputs and outputs for integration may require resources in the near term; however, these efforts will almost always save costs over the long term, as new model frameworks are envisioned and implemented.
- **New Scientific Development**. With greater recognition of the interactions between different environmental and anthropogenic drivers—such as water, energy, food, and communities—and recognition of constraints on sustainability, from local to global scales, there is a need for more sophisticated understanding of these relationships. This is best done through integrated models that encapsulate knowledge across different disciplines.

- **Incorporation of New Technological Developments**. As noted above, there are rapid advances in software tools that can enhance modeling in general, and modeling integration in particular. Adoption of these approaches will lead to new developments and generally benefit the decision-making role of models.
- **Understanding Feedbacks**. In many cases the dynamic feedbacks between human and natural systems are not studied or understood. As a result, model integration is performed in a more static manner, e.g., with fixed regulations in an operations model. This is often a constraint of how component models are integrated, with 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 the ideas described here are acknowledged by the modeling community but are not fully implemented because of institutional or resource constraints. A directed effort at coordinating actions among the community of modelers is more likely to lead to beneficial outcomes than a more organic, undirected approach.

Integrated Modeling Strategic Plan

Given our current understanding of the status of model integration, the primary participants, and anticipated future needs, we lay our four possible paths for future development, followed by specific actions to be implemented for each alternative. While these possible paths are in fact part of a single continuum, we present them in this report as discrete alternatives for purposes of discussion. These discrete alternatives are associated with different levels of commitment and resources (human and financial), in recognition of the fact that there will be practical constraints in what can be implemented over different time frames.

- **Alternative 1.** 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. Such an alternative would entail continued guidance by the IMSC, a voluntary committee, and with the DSC providing the primary staff resources.
- **Alternative 2**. The second alternative 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.
- **Alternative 3.** 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.

- **Alternative 4.** The fourth alternative is the development of a physical collaboratory. This alternative would have all the features of the virtual collaboratory (Alternative 3) as well as a physical home where staff from participating organizations could work together. The placement of staff in the collaboratory would be on delegation from partner agencies for fixed periods; these delegates could be supported by some level of dedicated staffing.

Specific task recommendations are provided for future implementation as part of this plan, with tasks related to one or more of the alternatives selected.

Glossary

Term	Definition
All-at-a-time (AAT)	A sensitivity analysis approach where all parameters can be varied at each iteration. Typically used with global sensitivity analysis.
Boundary condition	The solution of a differential equation over a finite space requires the definition of values at the boundary of the space, termed boundary conditions.
Calibration	The process of exploring the value-range of a quantitative model's parameters so model outputs match field observations or predefined baseline conditions.
Code	Representation of the theoretical formulation of a model in computer language that serves as the basis for developing an executable model. In many cases, even for public-domain models, the underlying codes are not in the public domain.
Code verification	The process of testing whether the computer representation of the theoretical formulation of a model is accurate. Typically, this is done by code examination, testing of bounding cases, and comparison against analytical solutions of underlying equations (when available).
Conceptual model	A high-level representation of inputs, interacting processes and drivers, and outputs for any kind of process (e.g., physical, biological, economic, etc.). Although a conceptual model may include quantitative information, it is often presented in non-quantitative form and serves to communicate the model structure in a transparent manner. A conceptual model may be developed as a communication tool following the completion of a modeling study, or, during the initiation of the project, the conceptual model serves as the basis for selection of or development of a quantitative model.
Emulator	A computationally simplified representations of a model's relationships between inputs and outputs. Emulators are typically developed to reduce the computational cost of model exploration.
Evaluation	A general term for a sequence of steps taken to understand the performance of a model following calibration. Evaluation may include comparison against independent input and output data sets, sensitivity analysis for key parameters, or uncertainty analysis.
Initial condition	The solution of a differential equation over time requires the definition of values at the inception of the solution, termed the initial conditions. Other types of formulations, such as time series models, may also need the definition of initial conditions.
Lumped model	A generic term referring to a model that combines multiple processes into a single or "lumped" form. There is no clear guideline on what constitutes a lumped model in the environmental domain, in that most model representations involve some level of simplification.
Model framework	A general term for the theoretical implementation of a process-oriented model. A model framework will usually need to be configured for application to a specific geographic setting. Many models in common use are general purpose frameworks that can be configured to represent the same set of processes in different regions (for example, watershed models), whereas others are developed from the ground up as applicable to a single location, and the configuration is embedded within the general setup.

Term	Definition
Model lifecycle	A term referring to the entire timeframe from conceptualization of a mathematical model to implementation in computer code, and to multiple cycles of application, revision, and reuse in one or many different domains. Major models generally require large investments and a lifecycle of many decades.
Model structure	The representation of model inputs, key processes and interactions, and outputs. A conceptual model may graphically communicate the model structure, but even where a conceptual model is not published, all process-based models require an underlying model structure. In the case of data-driven models, internal processes are generally not represented, and model structure refers to the inputs that are selected a priori to influence the outputs.
Model training	Similar to calibration and parameter estimation, but typically used in the context of machine learning. The process of adjusting empirical model constants to match model outputs and field observations. In the context of machine learning, the model constants may have no physical meaning.
Monte Carlo simulation	A general solution approach in modeling analysis where key values (for example, parameter values in a model) are sampled randomly over a defined space to provide a range of conditions for testing.
Numerical model	Many quantitative models are represented by differential equations that cannot be solved exactly because of the complexity of the equation or the domain. Numerical solutions (such as finite elements or finite differences) are a commonly-used approach to estimate the solutions of differential equations. Models that employ such numerical solutions are especially common in the representation of physical and chemical processes and are termed numerical models.
Parameter estimation	Similar to calibration. The process of adjusting parameter values in a model such that the model output matches field observations within an acceptable error range.
Parameters	Parameters in a quantitative model represent numeric constants associated with key processes. Typically, these processes represent a feature of a natural system (for example, reaction rates or hydraulic conductivities), and may be known within a range. The process of parameter estimation is to find values that enable the model to fit observed data within an acceptable range.
Sensitivity analysis	The process of adjusting model parameters or inputs within a realistic range to explore the effect on, or sensitivity of, model outputs. Model sensitivity in a multi-parameter model may depend on the states of other parameters, and individual model outputs may be more or less sensitive to different parameters. A common goal of sensitivity analysis is to identify parameter(s) that have the greatest impact on key model outputs.
Uncertainty analysis	Model inputs or parameter values are presented in a probabilistic form (i.e., as a distribution of values) to a calibrated model, and the effects on model output evaluated. Given that inputs and model parameters are known with different degrees of error, the goal of uncertainty analysis is to quantify the range of outputs in a modeling study.
Validation	A term in common use in many modeling communities, validation refers to the process of applying a calibrated model to an independent set of observed data to assess whether the model fit is acceptable. A criticism of the term validation is that the process does not prove that a model is valid, but rather demonstrates performance over a limited range of conditions. The term evaluation is sometimes recommended as an alternative.

1 Introduction

Report Goals

Because of the large number of individuals and teams involved in Delta modeling across different disciplines, there is considerable interest and management focus in improving coordination and integration. A priority action identified in the Science Action Agenda for the Delta Stewardship Council is the advancement of integrated modeling. The present work is a tangible step in moving forward with this agenda, with lessons learned from ongoing model integration to the outlining of a future strategy for integrated modeling.

Modeling—which refers to the quantitative representation of a natural, social, or engineered system—supports decision-making on a wide variety of issues related to the Sacramento-San Joaquin Delta (Delta), including water facility operations and regulations, infrastructure and restoration planning, and scientific development. Such modeling has been conducted in the Delta for decades, especially for the operation of California's water management system, and applications continue to expand in related disciplines. Notably, with increasing scientific and societal interest in the effects of water management on natural systems and human communities over the long term, modeling applications are growing in a variety of inter-related environmental domains. Modeling is performed by, and results interpreted by, virtually all environmental decision-making organizations, from governmental and non-governmental agencies to academia and private organizations.

1.1 Report Motivation

Because of the breadth of modeling activities in the Delta,[1] and the large number of individuals and teams involved, there is considerable interest in coordination and integration. Based on the direction from the Delta Plan Interagency Implementation Committee, the Delta Stewardship Council (DSC) formed an Integrated Modeling Steering

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[1] In this work, modeling for the Delta is a shorthand reference to systems that are connected to the Delta, either physically or socioeconomically, including, for example, the upper watershed and coastal regions.

Committee (IMSC) in 2017 composed of modelers across a broad spectrum of organizations. The IMSC was given the charge to develop a strategic plan for building a sustainable modeling community and a governance framework that links the short (1-5 years), intermediate (5-10 years) and long-term (10-30 years) decision universe with key management questions and management priorities while optimizing the available resources. Further high-level future direction for modeling is provided by the Delta Independent Science Board recommendations (Delta ISB 2015, 2016, 2018) and the Delta Science Program's Science Action Agenda, highlighting priorities through 2021 (Delta Stewardship Council, 2017). A priority action identified in this document particularly relevant to the present work follows:

Advance integrated modeling through efforts such as an open Delta collaboratory (physical or virtual) that promotes the use of models in guiding policy.

The present work is a tangible early step in the implementation of these concepts, particularly the IMSC's charge for developing a strategic plan for building a sustainable modeling community, and the Science Action Agenda goal of advancing integrated modeling. It is expected that integrated modeling will provide decision makers with the best possible insight into multi-faceted environmental problems.

The goal of this report is to assess the current state of integrated modeling in the Delta, identify the opportunities for such modeling to address Delta problems, identify key challenges and technological solutions to facilitate integration, and develop a strategic plan for future implementation by the DSC and the IMSC. This work is closely related to and complemented by another concurrent project by the Delta Independent Science Board, termed the Monitoring Enterprise Review. The goals of the Monitoring Enterprise Review are to review the various monitoring programs underway in the Delta, develop recommendations to improve current and future monitoring programs to meet decision-making needs, and to improve coordination among discrete monitoring programs.

Lamprey redd in Stanislaus River (Source: Cramer Fish Sciences)

1.2 Integrated Modeling vs. Discipline-Specific Modeling

For the purpose of this work, integrated modeling is conceived as a general approach to address complex environmental problems. We define integrated modeling as follows:

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

In contrast, we define discipline-specific modeling as an approach that originates in a specific field of study, with a focus on a limited set of processes (e.g. hydrology, fluid mechanics and hydrodynamics, hydrogeology, biogeochemistry, economics, etc.) It is recognized that, in many instances, sophisticated models already exist that integrate processes across disciplines, and thus the boundary between integrated and discipline-specific models is not a rigid one. Indeed, many good practices for developing integrated models may also apply to discipline-specific models, and vice versa.

1.3 Methodology

Given the breadth of potential modeling applications in the Delta, this work was executed through a multidisciplinary team with in-depth knowledge in key areas, including: water resources and hydrology, hydrodynamics, wetlands, water quality, geomorphology, fisheries, agricultural economics, and human ecology. The team also has expertise in cross-cutting themes related to all modeling, particularly statistical analysis and software development. Information on ongoing and completed projects was based on the team's knowledge of and participation in major modeling studies, supplemented with in-person interviews with key project participants. This process helped to characterize the performance of large-scale modeling studies, including how they were used in decision-making, and key challenges in integration. The team also interacted with the IMSC membership during the planning and execution of this work. This work was envisioned and implemented as a collaborative effort between the project team, the IMSC and the larger Delta modeling community, to ensure shared ownership of the resulting products across the community.

This work is premised on the understanding that integrated modeling is often useful for evaluating complex environmental problems, whose drivers and impacts may span large geographic areas and cover diverse natural science and social science domains. However, it is recognized that the approach may not be beneficial under all circumstances. In this work, over the course of gathering information on ongoing studies, and in developing strategic plan recommendations, the project team attempted to maintain an objective perspective on the utility of integrated modeling. Recommendations for future actions to enhance integrated modeling are provided in a stepwise manner to allow evaluation of incremental benefits.

1.4 Intended Audience

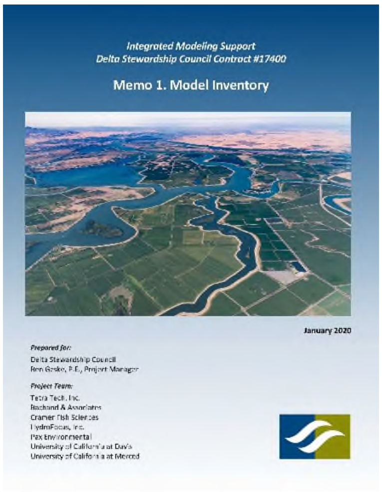
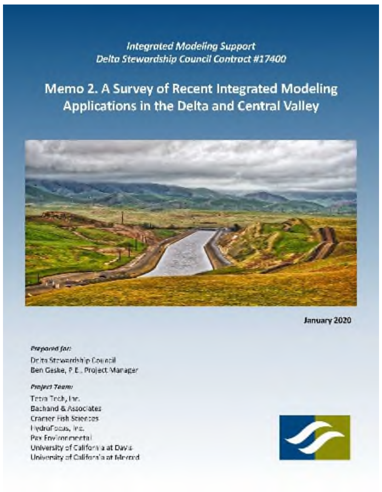
This report was written to serve a broad audience with common interest in integrated modeling in the Delta; this includes modelers as well as those who direct, sponsor, and use the results of modeling studies. Because of its broad disciplinary focus, this report should be of interest to modelers in the Delta who are experts in one or more discipline domains and are interested in issues that pertain to potential integration with other domains. This report provides modelers new to the Delta (or work in domains outside the region) with a general primer for modeling in the region, including an overview of recent major integrated modeling efforts and new opportunities for development. Other sections of the report are focused toward model sponsors (who fund and direct studies) and decision-makers and highlight institutional aspects of model integration as well as actions to implement the proposed integrated modeling strategic plan.

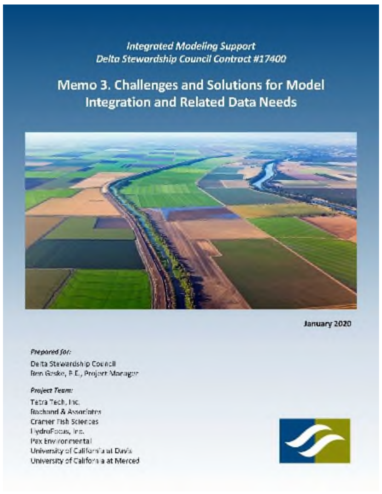
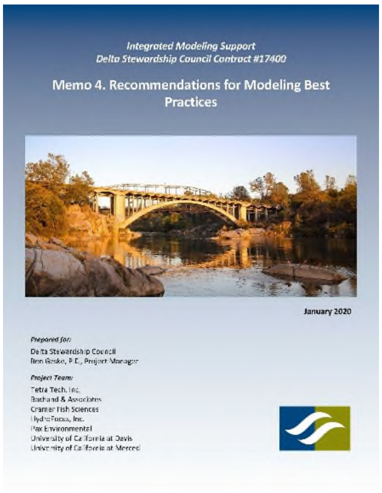
1.5 Report Organization and Other Resources

Chapter 2 presents an overview of integrated modeling and its potential applications for environmental problems in the Delta. Chapter 3 is a summary of ongoing or recently completed major model integration efforts in the Delta. This summary describes the primary drivers and challenges associated with the current practice of integrated modeling and forms the basis of future IMSC planning activities. Following this summary of ongoing efforts, Chapter 4 describes challenges associated with implementing integrated modeling in the Delta. Chapter 5 and Chapter 6 discuss institutional and technological approaches to facilitate model integration, respectively. Chapter 7, which highlights future needs for model integration, provides motivation for investing in an integrated modeling strategy over the long term. Finally, Chapter 8 outlines a proposed integrated modeling strategic plan, presented as a set of recommendations that can be implemented in whole or in part.

This report is a synthesis of several standalone documents which the reader may refer to for additional details of related topics. These documents and their primary areas of focus are described below:

- 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 this 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 this report.

Document	Overview
 *Integrated Modeling Support* *Delta Stewardship Council Contract #17400* Memo 1. Model Inventory 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	**Memo 1. *Model Inventory.*** The model inventory provides an initial step towards developing a shared and interactive model library useful for future Delta modelers. The model inventory includes models in current use in the Delta across a range of engineering, science, and social science disciplines. The model inventory is meant to be a living document. It is anticipated that the most up-to-date model inventory can be accessed online at: https://cwemfwiki.atlassian.net/wiki/spaces/MI/overview
 *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	**Memo 2. *A Survey of Recent Integrated Modeling Applications in the Delta and Central Valley.*** This memo presents a survey of how integrated modeling is being implemented in sixteen recent 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.

Document	Overview
 *Integrated Modeling Support* *Delta Stewardship Council Contract #17400* Memo 3. Challenges and Solutions for Model Integration and Related Data Needs 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	**Memo 3. *Challenges and Solutions for Model Integration and Related Data Needs.*** This memo evaluates the current state of challenges, potential solutions, and data needs within the context of Delta model integration. This information provides a foundation for specific recommendations for an integrated modeling strategy for the Delta. Data needs across a range of Delta-relevant domains for model integration are discussed, to provide a general reference for modelers working across disciplines and identifying data gaps where appropriate. Data needs were evaluated for several disciplines including: hydrodynamics, ecology, water quality, fish species, water budgets and consumptive use, agricultural economics, and socioeconomics.
 *Integrated Modeling Support* *Delta Stewardship Council Contract #17400* Memo 4. Recommendations for Modeling Best Practices 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	**Memo 4. *Recommendations for Modeling Best Practices.*** This document provides recommendations for best practices that are expected to enhance the utility of modeling efforts to decision-makers, stakeholders and to the modeling community in general. The guidance offered in this document applies equally to individual discipline-specific models and integrated models that combine knowledge from different disciplines. Many of these concepts are general and can also be considered by non-modelers who need to understand the scope of a modeling exercise at its inception and to make a judgement as to the utility of the results upon its completion.

2 Overview and Potential Opportunities for Integrated Modeling

Overview of Integrated Modeling

Integrated modeling has emerged as a sub-discipline within the larger field of environmental modeling. Model representation of complex interactions between human activities and natural systems is often needed to support various decision-making processes and science initiatives. This chapter provides an overview of the general concepts and the types of problems that may be addressed through integrated modeling.

There is greater recognition than ever before that human activities have a broad range of influences on natural systems, and conversely, human activities are affected by natural systems. Furthermore, independent of the human aspect, natural systems are complex, and a better understanding of their behavior transcends individual academic disciplines. Model representation of these interactions is often needed to support various decision-making processes (including facility planning, short-term forecasting, and regulation development and analysis) and science initiatives. Integrated modeling is conceived as a general approach to address these broad problems, where two or more models (typically with different areas of focus) are applied jointly in an analysis. The component models in an integrated modeling framework may emphasize the same processes over different geographic areas or may originate from different disciplines.

Over the past two decades, integrated modeling has emerged as a sub-discipline within the larger field of environmental modeling. Rapid decreases in the cost of computer resources, including flexible resources such as cloud computing and storage, mean that integration of models to address interdisciplinary problems is now computationally feasible. There is a growing global literature on integrated modeling methodologies and applications. Key aspirations for the growing field of integrated modeling include common terminologies for variables across different disciplines, data management strategies to allow efficient integration, common standards for data exchange between models, institutional infrastructure to permit integration across agencies, and scientific understanding of new challenges that arise from integration, such as the propagation of uncertainty and the difficulties of calibration across multiple models. This chapter provides an overview of the general concepts and the types of problems that may be addressed through integrated modeling.

2.1 Approaches for Model Integration and Associated Terminology

Three common approaches for model integration are shown in **Figure 1**. For the sake of clarity, this illustration assumes a simple case of two models. However, the concept can be generalized to a larger number of models.

- In Case 1, models may be linked to one another by means of external data transfer (i.e., through file exchange, typically performed with some manual intervention). This approach is also referred to as “off-line” coupling or “loose” coupling.
- In Case 2 (a more structured approach), models may be linked more directly through code. In this approach, data and model intermediate outputs are internally exchanged at the computational time step level with minimal external intervention using a common data exchange format. This approach is referred to as “in-line” coupling or “tight” coupling. The benefit of this approach is that required modifications to component model codes are limited to input-output routines.
- In Case 3, the models are re-written as a single code with internal data flows determined by the needs of the processes represented.

In Cases 2 and 3, data are exchanged internally and not necessarily reported to the user and a single set of output data is produced. Cases 2 and 3 both require access to the original component model source codes. These types of integration are needed when there is feedback between two different models, i.e. where the results of each model influence the results of the other model. In our review of existing integrated modeling efforts, we found that most instances of integrated model applications in the Delta area fall under Case 1, with some notable exceptions that fall under Case 3.

This report also refers to “upstream” and “downstream” models. In the context of model integration, an upstream model is one that provides input to a downstream model and is typically used in the case where there is no feedback, i.e., the results of the downstream model do not influence the upstream model.

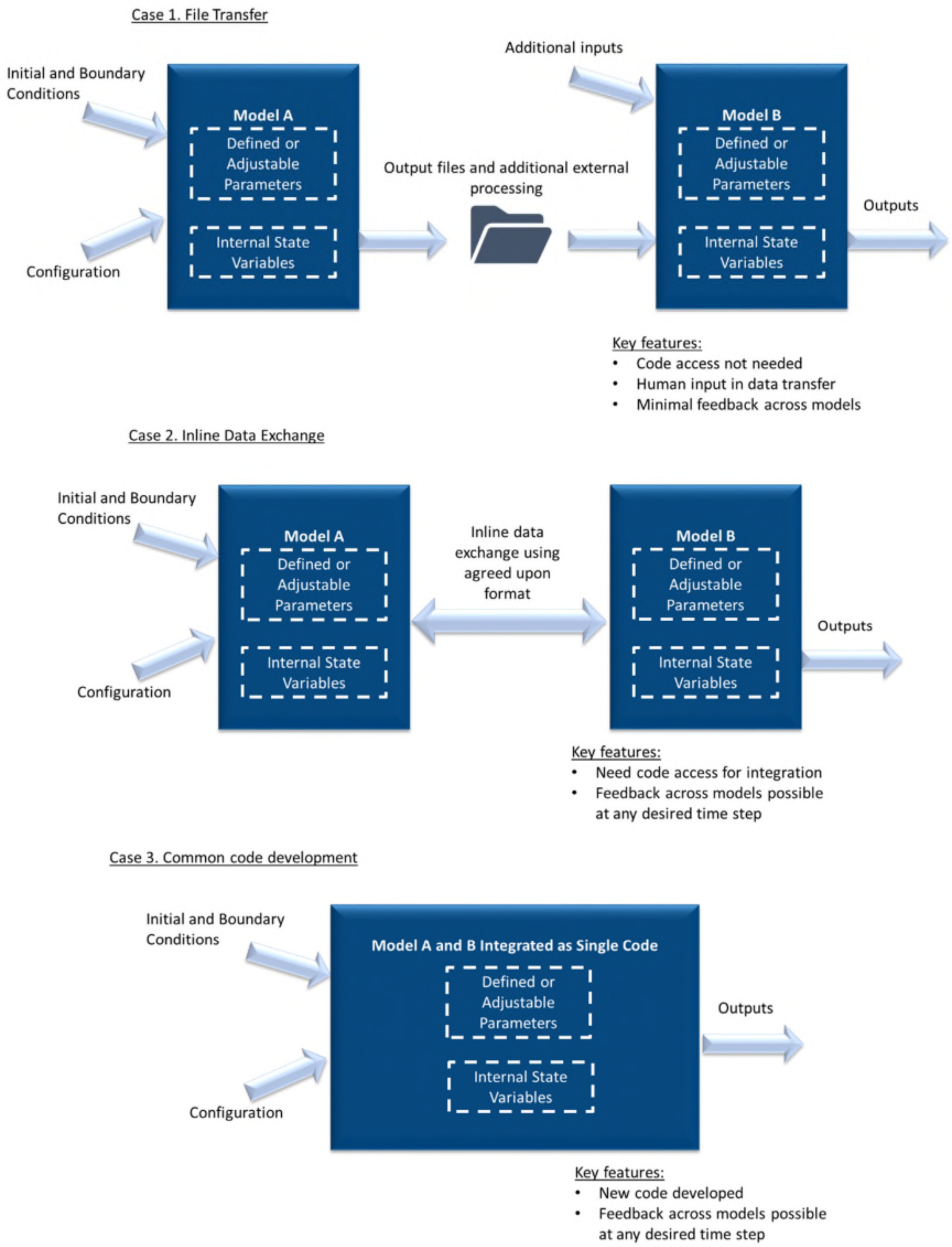


Figure 1. Three common approaches for model integration.

2.2 Types of Models to be Integrated

Table 1 summarizes a variety of modeling types or approaches used in the Delta. Selection of model type, as part of a model development process, is dictated by the potential availability of underlying theoretical frameworks and observations, the intended model use, and the technical discipline.

- Analytical or numerical models are often used where the underlying mechanisms can be explained through basic process representations. Numerical models, which solve differential equations over space and time, are in widespread use, especially in the flow and water quality domains. Over time, such models have tended to grow more complex, with greater spatial and temporal resolution, and associated computational demands. Analytical models normally consist of closed-form solutions to differential equations and have been used for relatively simple domains combined with a need for efficiency. Analytical solutions are also important for testing the computer implementation of numerical models, which are prone to solution errors (termed model verification).
- Statistical/empirical models are usually based on observed data and with limited underlying process representation. Larger datasets often improve performance of statistical models.
- Optimization-based models, notably water allocation models for the Central Valley (e.g. CalSim), have a relatively simple physical representation of processes (although the actual system may be very complex), and are focused around optimization of outcomes under specified constraints. In the case of CalSim, the outcomes are the water allocations to different users across the Central Valley and Delta, constrained by water availability, environmental flow requirements, and the hierarchy of water rights.
- Machine learning models, a class of statistical/empirical models, are identified here as a distinct model type because they offer a wide variety of emerging algorithms to find patterns or relationships in observed data. Unlike most statistical/empirical models, machine learning models may contain large numbers of fitting parameters that are not visible to a user.
- Agent-based models represent system with agents (e.g. organisms, individuals, or households) that have individual behavior and respond to external drivers or to each other.

The general task of model integration is to match component model input and output requirements within a single framework. **Table 1** identifies the key considerations in getting these different types of models to work with one another.

Table 1. Types of models to be integrated

Model Type	Feature	Key Considerations in Integration with Other Models
Analytical/Numerical	Solving a framework of process equations, either in closed analytical form or numerically; model parameters calibrated with observed data	Analytical models, because of the closed form nature of the solution of differential equations, often use limited spatial and temporal variation. Numerical models are often spatially and temporally detailed, with high-frequency outputs over fine grids (in 1-D, 2-D, or 3-D). Integration may need to match this scale of output by averaging over time or space.
Statistical/empirical	Limited process representation; model parameters calibrated with observed data	Less spatially detailed than analytical/numerical models; output often organized around scale of observations in the field. Other models may be constrained to work with this scale of output.
Optimization based	Focused on meeting key objectives under a range of input conditions	Constrained by optimization criteria, often defined at specific locations where compliance with specific targets is needed. Potentially less detailed representation than analytical/numerical models, and integration must align with the locations where optimization is focused on.
Machine-learning based	"Black-box" representation; trained on available data	Limited to specific locations or conditions, and other models needed to work with this constraint. Poor performance outside of training range must be considered in all phases of integration.
Agent-based	Represents behavior of organisms or populations (animal or human) in response to external factors.	Most experience is with exploring fish behavior with limited feedback with other models. Consideration of humans as an agent can create different feedbacks across models.

2.3 Model Integration Approaches

A variety of model integration efforts are underway in the Delta, as further described in Chapter 3 and in Memo 2, *A Survey of Recent Integrated Modeling Applications in the Delta and Central Valley*. Representative opportunities for model integration are described in this section at the process level, without delving into the details of specific models that may be used or data that might be needed to perform these calculations. These conceptual representations of integration illustrate the types of problems that may benefit from future investments in improving model integration.

Perhaps the most commonly used approach for integration relates to the management of Delta outflow and salinity (**Figure 2**). Individual models have been developed for the processes shown as icons in the figure. The flow of information in the integrated framework begins in the upper watershed models that provides the inflow for the major water supply and flood control reservoirs. Reservoir outflows, computed with optimization or rule-based models, are managed to maintain beneficial use targets for downstream riverine flows and outflows and salinity in the Delta. Resulting Delta tidal flows and salinity are calculated with a Delta hydrodynamic model. This structure of model integration is widely used for water resources planning related to current and long-term operations of the State Water Project and the Central Valley Project.

Another representative example of integration considers the effects of global warming on streamflows, reservoir operations, and stream ecosystems (**Figure 3**). Temperature changes may affect the timing and magnitude of snow-melt derived streamflows, which may lead to changes in reservoir operations. Downstream of the reservoirs, changes in flows and temperatures may affect ecosystems, notably temperature sensitive fish species.

Climate change effects, expressed as global warming and sea level rise, may also affect a variety of processes throughout the Sierra-Central Valley-Estuary-Coastal ecosystem, as shown in **Figure 4**. Each icon in this graphic can be represented by a specific model with flow of information upstream and downstream.

Changing fire risks due to global warming and impacts to communities and stream water quality are a growing concern in California. Long-term shifts in fire risks can be evaluated through landscape and streamflow models (**Figure 5**).

Large systemwide assessments of food, energy and water flows (termed the food-energy-water nexus) can be used to evaluate the sustainability of California under future drivers such as climate change, population growth, regulations to mitigate greenhouse gas emissions, and efforts to transition to a fossil-fuel-free power generation grid. These interactions are shown schematically in **Figure 6**.

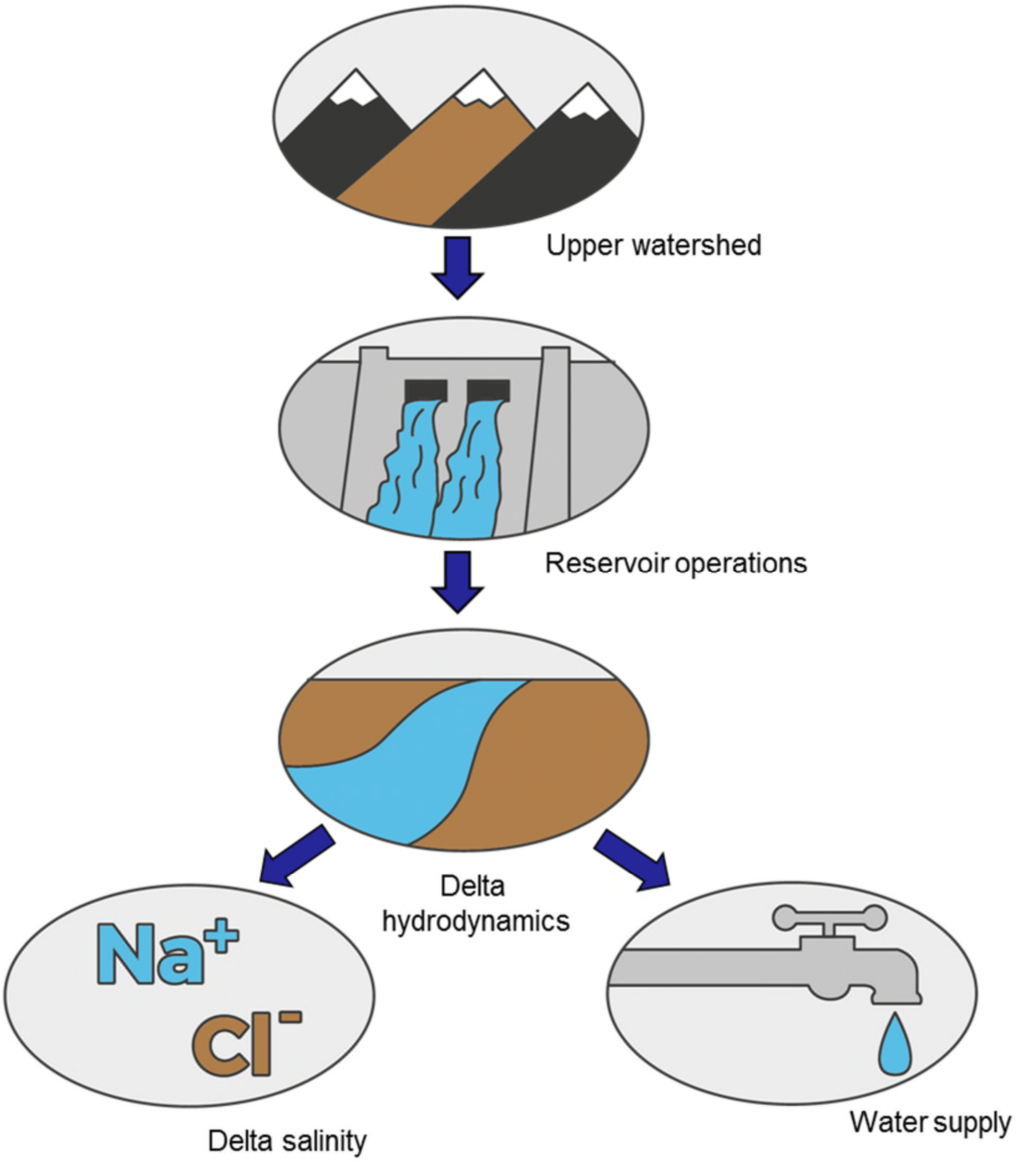


Figure 2. Modeling framework for reservoir operations and in-Delta water quality standards.

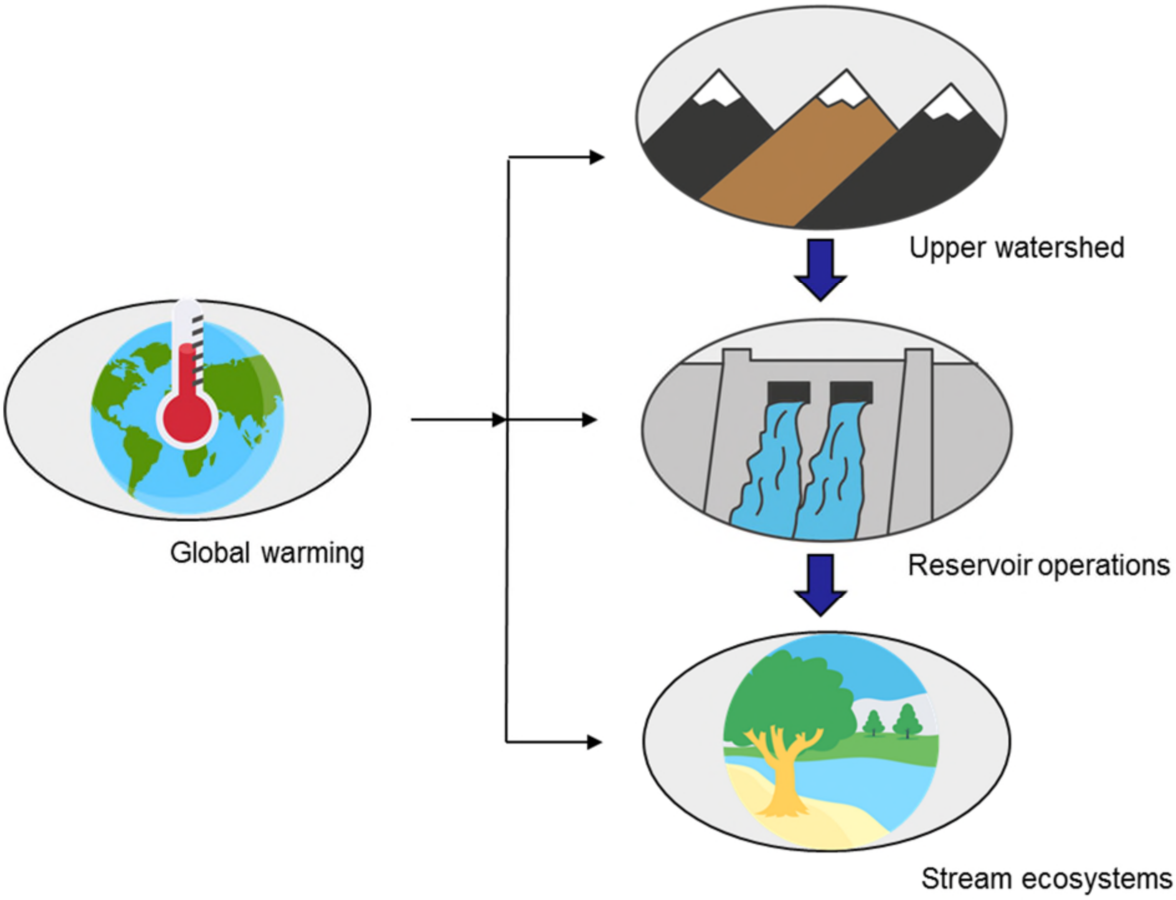


Figure 3. Aquatic ecosystem modeling, including consideration of flow and temperature. Global warming may affect instream flows, management of flows through reservoirs, and downstream aquatic ecosystems.

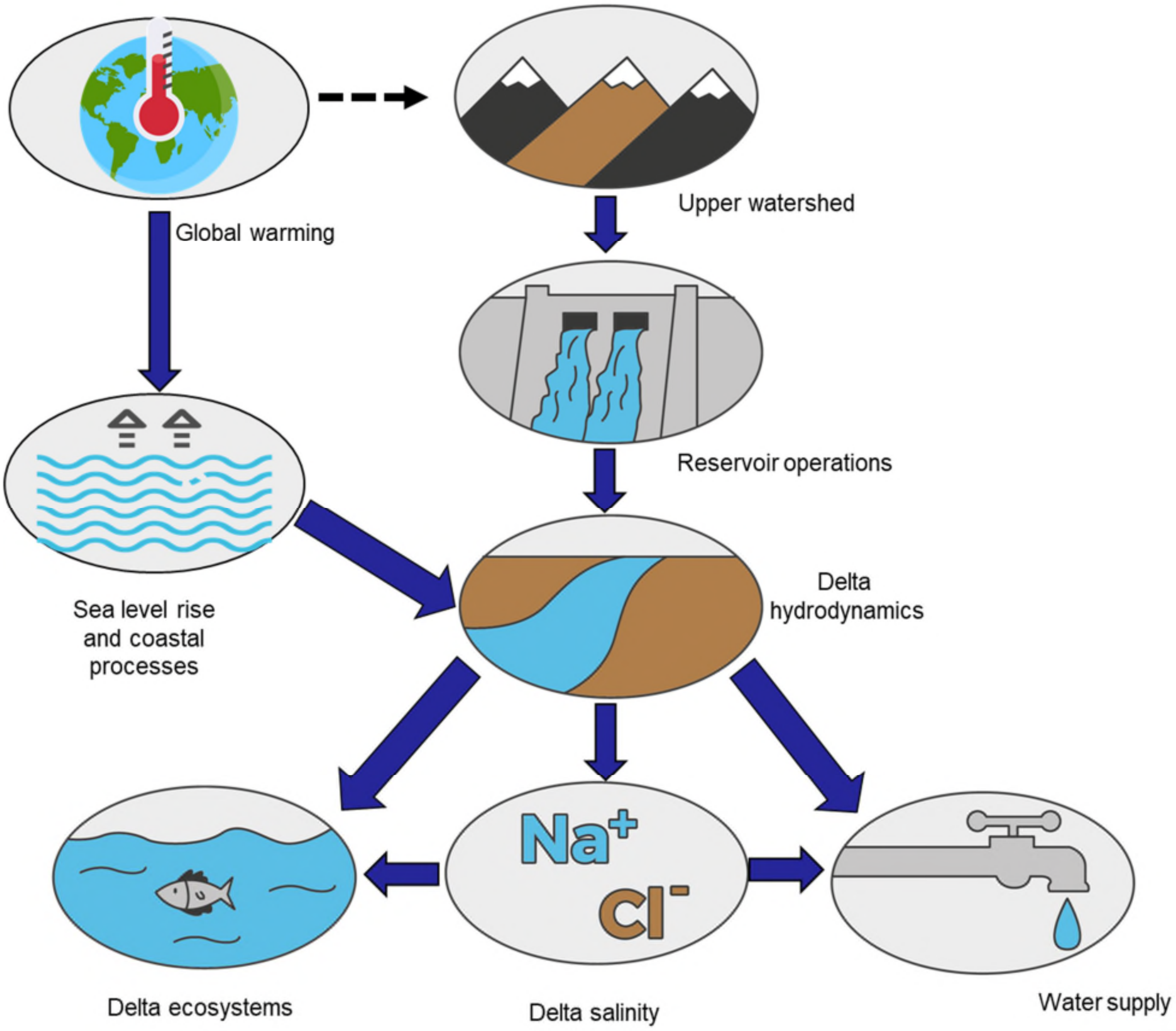


Figure 4. System-wide modeling of flow and salinity related to ecosystem impacts. Can also consider external drivers such as sea-level rise and warming.

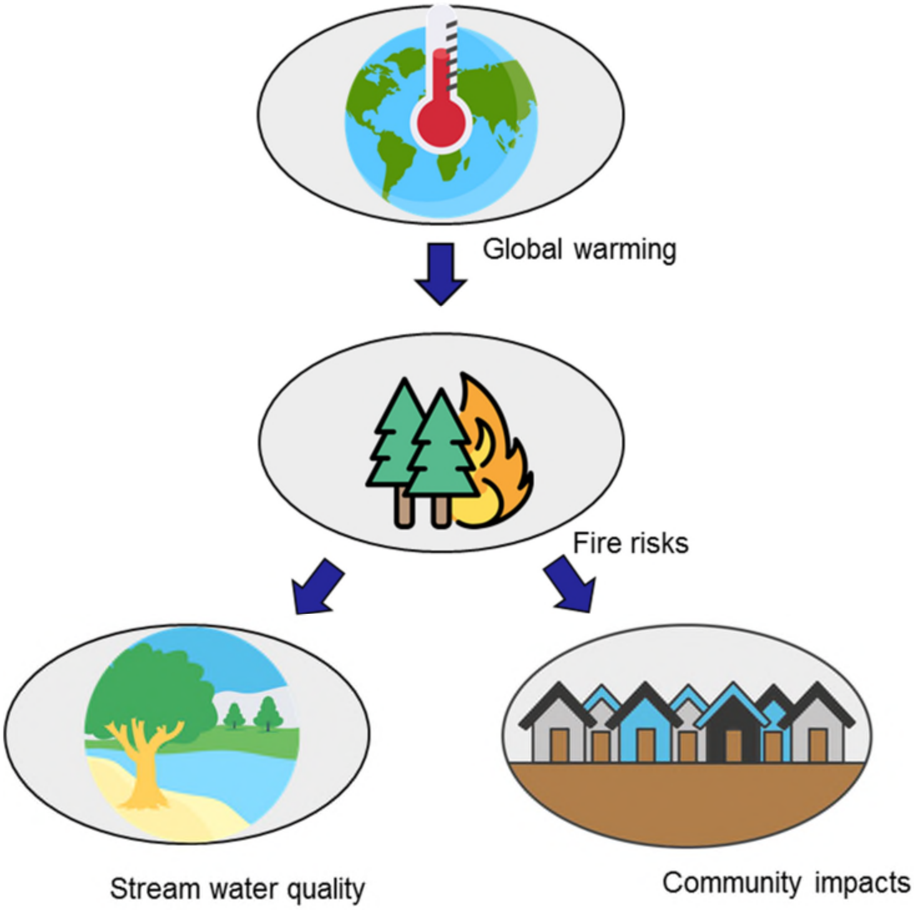


Figure 5. Changing fire risks due to global warming and impacts to ecosystems and communities.

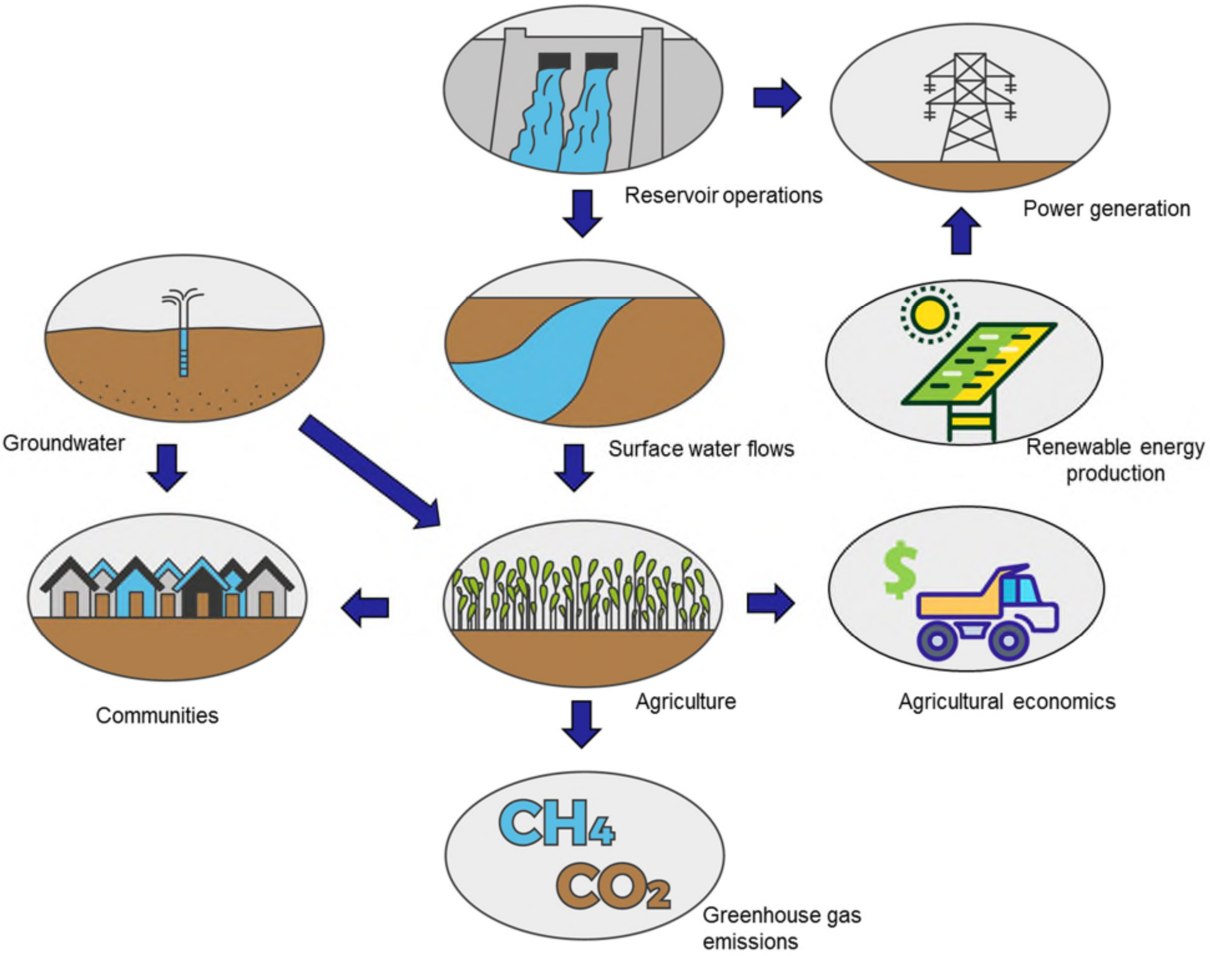


Figure 6. Modeling approach for the food-energy-water nexus, including consideration of renewable energy production, greenhouse gas emissions, and groundwater sustainability.

3 Findings from a Survey of Recent Integrated Modeling Applications

Integrated Modeling Applications in the Delta

A survey of recent integrated modeling applications in the Delta across major project initiatives reveals successes, challenges, and lessons learned, which can help guide future integrated modeling efforts in the Delta.

A survey was undertaken to explore how integrated modeling has been implemented in recent or ongoing projects in the Delta, or, in some cases, how it is planned to be implemented in the near future. The survey was conducted by examining publicly available information on major ongoing or recently completed modeling studies and 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. 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.

The following detailed information was pursued 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

The summary of sixteen project initiatives is presented in **Table 2** below, with a particular focus on challenges in model integration. Additional details on each of the initiatives is presented in Memo 2*, A Survey of Recent Integrated Modeling Applications in the Delta and Central Valley*. Specific models identified in this chapter are listed in Appendix A and described in greater detail in Memo 1*, Model Inventory.*

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. 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.

3.1 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 projects include restoration projects to meet endangered species goals and development of new water quality standards. Integrated modeling efforts are also driven by research considerations; in the Delta domain, these efforts are typically 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.

Table 2. Summary of project initiatives

Project Initiative	Project Description	Integrated Model Elements	Challenges
1. California WaterFix	Major proposed infrastructure project to construct tunnels under the Delta	Integrated modeling for the WaterFix project included the following technical disciplines: water project operations, hydrodynamics, water quality (temperature, salinity, sediments, nutrients, and trace contaminants), agricultural economics, ecology, and groundwater.	Model integration in WaterFix involved the flow of information between independently run models. Iteration between model runs was implemented manually, with the transfer of input and output files from one team to another. Iteration between any two models being integrated occurred following completion of both runs; thus, real-time feedbacks between models were not fully considered.
2. Levee Assessment, Storage, Flood Management and New Infrastructure	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	Integrated modeling focused on the following domains: climate modeling, watershed and runoff, reservoir operations, riverine hydraulics, floodplain mapping, economic loss avoidance, levee fragility and system performance assessments, pulse flow operational planning, and estuarine hydrodynamics and salinity.	Regulatory constraints for future conditions are speculative, making future conditions studies difficult. Where proprietary models are used, and the underlying assumptions are not transparent, it can be difficult to evaluate results. Data used to calibrate 3-D models is limited.
3. Socio-economic Issues (not a specific project)	Evaluation of challenges and opportunities surrounding integrated modeling as it relates to socioeconomic issues in the Delta	Although integration has been considered conceptually, no formal efforts at integration across other domains have been made.	Historical data do not provide an accurate account of current conditions; model integration is complex in relation to socioeconomic issues given the variety of regional constraints on economic and social development; the region lacks timely data to support socioeconomic modeling efforts on a continuous basis.
4. Bay-Delta Water Quality Control Plan Updates	Update of Delta flow and salinity standards	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 State Water Resources Control 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, which limits the types of evaluations that can be performed. The pool of available and qualified consultants to operate the models was limited.

Project Initiative	Project Description	Integrated Model Elements	Challenges
5. Water Rights, Consumptive Use & Water Budgets	Consumptive use modeling and measurement for crops and other land use cover in the Delta	Surface water and groundwater allocations for consumptive use estimates	Complex and detailed input data sets need standardization and a common storage solution.
6. Delta Smelt Biological Opinion	Modeling Delta Smelt behavior and population dynamics to support ongoing Biological Opinion re-consultation	The modeling framework uses 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.	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. Another challenge that is being addressed by the modeling team is to generate a compatible long-term zooplankton data series.
7. Central Delta Corridor/Future Carbon Markets	Proposed multi-agency effort to assess options for greater sustainability on publicly owned lands in the western and central Delta.	Modeling has not yet occurred on this project. 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.	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.
8. California EcoRestore	Multi-agency effort to restore 30,000 acres of habitat in a set of discrete projects across Delta islands	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.	There is no public repository for the models and data; the model studies are not in the public domain. There is a need for clear meta-data on the model outputs to minimize confusion when information is transferred from one model to another. It is difficult to interpret the significance of model results, i.e. is it meaningful or is merely within model uncertainty.
9. Yolo Bypass Models	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	Hydrodynamics, economics and agricultural production, fish and bird habitat, and migratory waterfowl	Disagreements between models have not always been resolved. Proprietary models used cause difficulties with model integration, stakeholder engagement, and communication.

Project Initiative	Project Description	Integrated Model Elements	Challenges
10. Delta Methylmercury Total Maximum Daily Load Modeling	Evaluation of methylmercury loads and concentrations as a function of water project operations	The primary model elements represent hydrodynamics, water quality and mercury cycling	Two different modeling approaches are used in the Delta and Yolo Bypass domains. In the Yolo Bypass, model runs are limited by what has already been running with the proprietary TUFLOW model. Since mercury is an expensive analyte to detect, there is relatively limited observed data in space and time to characterize transformations.
11. CASCADEII Model Framework	U.S. Geological Survey-led model study of climate, hydrology, hydrodynamics, sediment, phytoplankton, bivalves, contaminants, marsh accretion, and fish	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.	The Deltares D-Flow FM (flexible mesh) source code was in beta form at the inception of the project, and it required several years for completion, calibration, and validation; multiple dependencies between modeling elements result in downstream model development and application lagging that of upstream models.
12. AFRI Rice Agriculture Modeling	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.	Modeled domains included GHG fluxes (methane emission, photosynthesis, evaporation, net carbon exchange), levee stability, carbon sequestration, land subsidence, groundwater hydrodynamics, water quality and economics.	Nontechnical challenges included timing, coordination and organizational structures. Technical challenges arose from integrating proprietary model and difference in spatial scaling.
13. Modeling for Climate Change Vulnerability Assessment and Adaptation Strategy for the Sacramento-San Joaquin Delta and Suisun Marsh	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.	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), sediment transport and water supply modeling (CASCADE), and climate modeling (Cal-Adapt).	Primary challenges to the project include IT restrictions with State government limits to software that can be used on government computers, and dependence on outside modeling expertise.

Project Initiative	Project Description	Integrated Model Elements	Challenges
14. Managed Aquifer Recharge using Floodwater (FloodMAR)	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.	Integrated model elements are hydrologic models, reservoir models, river models, flood models, and irrigation demand models.	Challenges for model integration included both technical and non-technical challenges: gaining trust from stakeholders, leadership and communication, model screening, and selection and modifications to meet project goals.
15. Franks Tract Restoration Feasibility	Hydrodynamic and water quality modeling to evaluate effects of different conceptual restoration designs	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.	The primary modeling challenges related to the complexity and computational requirements associated with the SCHISM model, limiting use to specialists, and limited ability to integrate with other models.
16. Chinook Salmon Life Cycle Model	Mechanistic model evaluation of juvenile Chinook salmon life cycle	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 flow, salinity, temperature, daylight hours, turbidity, and dissolved oxygen. CalSim is used to estimate the habitat availability for rearing salmon in the Delta.	Challenges include incorporation of the wealth of information on salmon behavior and movement from laboratory and field studies, understanding and representing their behavior with modeling, and the complexity of the aquatic system being modeled.

3.2 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 answers to stakeholder questions and inspire confidence. Model transparency and accessibility and replicability of data and analyses are essential for building trust and consensus among stakeholders.

3.3 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.

3.4 Challenges

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

- Model use is sometimes tied to specific experts, e.g., the expert is the primary developer and the primary entity applying the model. This situation, which may occur even in cases where the model is not proprietary, 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 and robust results.

Aleutian cackling geese and sandhill cranes (source: Lee Eastman, USFWS)

- Model availability (including code, input files, and outputs) may be limited for different reasons. For planning studies, model code is often readily available, but inputs and output information for a specific application can be made available when the studies are complete. For scientific studies, the model code may be under development, and cannot be released until completion and formal publication, which may take years in some cases. Finally, some models are not in the public domain and are not expected to be.
- 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.

3.5 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.

3.6 Lessons Learned

Important lessons learned from recent and ongoing application of integrated modeling analysis in the Delta are summarized below:

- 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 projects include restoration projects to meet endangered species goals and development of new water quality standards. Integrated modeling efforts are also driven by research considerations; in the Delta domain these efforts are typically 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.
- 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), provided there is a common understanding of inputs and outputs to be shared for integration.
- The success and future utility of model integration efforts largely depend upon the overall stakes, the resources dedicated and the primary organization’s mission. For instance, integrated modeling efforts like California WaterFix and the Delta Levee Investment Strategy address the State’s water and its security and have significant implications for California’s economy. With large stakes, appropriate resources are provided to develop and maintain integrated modeling tools because of their central role in the decision-making process. DWR leads these efforts which fall squarely within its mission. 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 different initiatives. This includes model code, input files, configuration files, best estimates for key parameters, and representative output files for specific studies. While such information exists 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 U.S. Geological Survey).

4 Challenges for Integrated Modeling

Integration Challenges

Integration challenges identified in this chapter are classified into two categories: institutional issues and technical issues. While any modeling study may have challenges, the challenges described here are *specific to model integration* with two or more models.

Integrated modeling as a technique for addressing complex environmental problems has existed for at least two decades. As summarized in Chapter 3 and described in more detail in Memo 2, there are several notable examples of the use of integrated models for addressing a variety of Delta issues. The use of integrated models is expected to grow, in large part driven by stakeholder and decision-maker needs for developing a better understanding of the multi-faceted water resources problems they are required to address. Informed by the specific case studies in Memo 2 and the scientific literature on integrated modeling, we address here some of the practical challenges associated with developing true integration across model domains. While any modeling study may have challenges, the challenges described here are *specific to model integration* with two or more models. General modeling challenges and the practices that have evolved to address them are addressed in *Recommendations for Modeling Best Practices* (Memo 4) and summarized in Appendix B of this document.

Integration challenges are classified into two categories: institutional (“people”) issues and technical (“model”) issues. Approaches to address these challenges are presented in Chapters 5 and 6 and form the basis for recommendations presented in Chapter 8.

4.1 Institutional (“People”) Issues in Model Integration

Institutional challenges involve people, from organizational management to technical staff performing the modeling studies to stakeholders engaged in working with the outcomes of a modeling study. We describe these issues under the following headings: setting, modeling expertise, stable funding sources, and stakeholder engagement and trust.

4.1.1 Setting

4.1.1.1 Model development within "siloed" institutions

Models are often developed in a "silo" environment. They are maintained by individual organizations (or groups within larger organizations) utilizing a focused expertise for a focused purpose with priorities set within the organization's institutional mission. As such, there is a potential barrier to the broader development and use of such models by specialists in different disciplines. An integrated model, especially where it crosses disciplinary boundaries, may not have an obvious institutional host or supporting funding stream for model maintenance and development. Managers responsible for developing and using such models must formally address this gap through proactive measures such as cross-training of staff in relevant disciplines, regular exchange of modelers from different areas, and finding computer resources (servers, databases) to allow joint development of the integrated model.

4.1.1.2 Delta as a setting with competing needs

The Delta is an epicenter of competing needs. The region's waterways serve as a major conduit for California's complex water system. The region's resources support competing agricultural, environmental and ecological beneficial uses and bolster local and regional economies. Debate among local communities, downstream users, environmental interests, and water managers continues in the search for common ground. Stakeholder agreement on many competing interests is difficult to find.

4.1.1.3 Project-driven modeling and model continuity

The majority of model integration efforts in the Delta and Central Valley—performed by agencies as well as academic institutions— are project driven, focused on specific outcomes with restricted timelines. Typically, modeling teams are focused on delivering specific results required for decision-making, and development and retention of the underlying capabilities related to model integration play a secondary role. Because time is an important driver, most integration efforts seek the path with the greatest probability of meeting deadlines. Therefore, existing models (both proprietary and public-domain) are used to the greatest extent possible. Specific tools and approaches developed for integration across models, including tools for pre- and post-processing, may not be fully documented or readily available for future applications. Institutional continuity of model integration is also a concern: when model integration is achieved for a specific study goal across different participating groups (such as agencies, universities, and private entities), and where there are no established mechanisms to retain the integrated structure for the long term, and institutional knowledge is eventually lost.

4.1.2 Modeling Expertise

4.1.2.1 Discipline-specific training

Virtually all models in use today in the Delta emerged from specific disciplines such as hydraulics, hydrogeology, aquatic chemistry, and fisheries science. Complex models in these domains require a high level of discipline-specific training as well as model-specific knowledge. Availability of experts with the necessary background to perform these modeling analyses is often limited. Institutional expertise may also be a limiting factor for integrated modeling. Many specialized models are housed within specific organizations where there are appropriate mechanisms to hire, train, and maintain staff skills over time. Such a culture may work well for individual model development and use; however, it may pose a significant challenge for integration across models from different disciplines.

4.1.2.2 Rapidly changing science

The science underlying many models, especially those related to ecosystems and human-ecosystem interactions, is maturing and model representations continue to evolve. The potential benefits of integrating models with different levels of scientific maturity may be limited. An unpredictable amount of time may elapse between the science being peer-reviewed or published to putting that science into code.

4.1.2.3 Limited software engineering capacity

Salmon diversion dam on Feather River (source: iStock)

Today's models often have sophisticated graphical user interfaces (GUIs) at the front- and back-end for processing output data or interacting with databases to store and manage data on remote servers. For computationally complex models, there is a need to use new hardware (e.g cloud servers or dedicated server clusters) to promote acceptable run times. These needs come with the need for increasing sophisticated software development. Software professionals with the skills to develop model interfaces are in demand from many fields and therefore are in short supply. Additionally, some large organizations may be required to hire staff from rigidly defined technical background or degrees, which can limit their agility in hiring computer scientists or software engineers.

4.1.2.4 Lack of team learning

Team learning, in the context of integrated modeling, is defined as a process where participants across different disciplines work together to implement an analysis and learn about each others' disciplines and mental models along the way. Systems thinking is another term that has been used in the literature to identify this process. Systems thinking is a conceptual framework – a body of knowledge and tools that can be developed to help make patterns clear (Senge, 1990). Where opportunities for team learning exist, there is a greater potential for generating acceptable solutions that address multi-faceted problems. Time and resource constraints, institutional structures, and even different terminologies can limit effective team learning in many problem-solving settings.

Pollino et al. (2017) described case-study examples that illustrate the benefit of engaging team learning. For example, in a case example of understanding groundwater-surface water interactions, an integrated model was developed collaboratively by a team that included expertise in hydrology, ecology, economics, governance, and social sciences. The inclusive and integrative approach to model development was time consuming; however, it provided significant value and greater insight into the problem and a platform for discussion among stakeholder groups.

4.1.2.5 Lack of a global expert or champion

When model integration occurs across different disciplines, there is rarely (if ever) a single expert to help interpret the global results and implications to a broader audience. Such expertise is needed in the communication of complex model outcomes in settings with stakeholder participation and is often accommodated through discipline-specific expert panels. This lack of global expertise is also encountered in interdisciplinary research work, but the work products are often reported in formal settings, such as research papers, and do not require the same level of stakeholder interaction.

4.1.3 Stable Funding Sources

Development of integrated models that serve a broad user community require resources beyond those needed for development of domain-specific models, as illustrated by the following example: Modelers in a particular domain, such as hydrology, may have the necessary background and training to develop and implement hydrologic models relatively efficiently. However, integration of a hydrologic model with a fish-behavior model needs more time and interaction with other models to develop a novel integrated framework. Furthermore, this integrated framework must mature over time to be credible and useful in a real-world setting. A stable and sustained funding effort can enable this process to occur and can provide the incentive for modeling teams to embark on such an exercise. In many situations, even when funding has been set aside for modeling studies, high-priority or short-term tasks can often exhaust modeling resources, and thus limit the development of longer-term and more novel approaches for integration.

4.1.4 Stakeholder Engagement and Trust

Stakeholders and other participants play a vital role in establishing the credibility of models and in supporting their use in important decisions. With the broader use of modeling in support of environmental decision-making, the key role of stakeholder engagement has been emphasized in several published modeling guidelines. Stakeholders should be involved in various phases of modeling, from inception to the final evaluation of results. Thus, constituents should be involved in the development of conceptual models, and ideally, should be able to investigate models independently. This participation in the modeling process may include, for example, the ability to develop independent model results with alternative scenarios that are a greater interest to the stakeholder constituency. This is especially true for decisions that involve the regulated and regulatory community where both parties should be able to independently run and evaluate models. An approach for stakeholder involvement is described in Chapter 5. However, in the specific context of integrated modeling, some challenges arise. For example, when multiple models are involved in analysis, stakeholders are expected to develop an understanding of different models and their interactions to appropriately interpret results. This is difficult for domain experts and may be particularly challenging for a broader group of stakeholders. An integrated model, especially a new application, may not have the same level of stakeholder acceptance that a single domain model may have developed after years of use. These aspects may adversely impact stakeholder engagement. Thus, the potential challenges of stakeholder engagement must be balanced with the benefits derived from developing integrated models.

4.2 Technical Issues in Model Integration

Integrating models that represent different technical disciplines and span different spatial and temporal domains presents a major and unique set of challenges. Here, we term them technical or “model” issues. Broadly, these issues relate to model compatibility, model and data accessibility, computational complexity and uncertainty.

4.2.1 Inter-Model Compatibility

Inter-model compatibility relates to spatial and temporal aspects of model runs. Relevant issues are discussed below.

4.2.1.1 Differences in model purpose

Temporal aspects of modeling in the Delta take two forms and are related to the underlying purpose of the model:

- **Time dependent models for understanding the evolution of systems.** This is a common form of modeling dynamic systems where a model is used to study the response of natural system variables that retain a memory over a long period of time (such as groundwater levels or fish populations). Thus, long term simulations are dependent on the initial conditions of the variables of interest, the sequence of natural drivers provided to the model, and the human drivers that may change over time. In such a simulation one might predict, for example, the groundwater levels in an aquifer given natural drivers (primarily climate) and human drivers (irrigated area and volume of pumping). The time variable associated with model output is often linked to a real time with observations, and historical observations—where the natural and human drivers are known—are the basis of calibration. A model of this type may be mechanistic or statistical.

- **Level-of-development models for planning.** These models are driven by hydrologic time series that represent the natural year-to-year variability of California climate but assume fixed conditions on the ground (e.g., land cover, regulations, water withdrawals, etc.) that represent specific time frames. In Delta modeling applications, system operations models such as CalSim take this form. The goal of such modeling is to understand the response of a defined system—including infrastructure, operations, and regulations—to a range of future hydrology. Relevant outputs from such models may be a range of values, such as water deliveries at a certain location, in response to a range of hydrologic inputs. This type of modeling is conceptually appropriate when the system being modeled effectively "re-sets" itself periodically and carries minimal memory of preceding years. For long-term simulations, outputs from such models are less sensitive to initial conditions and the sequence of inputs. Furthermore, time in such models represents a statistical sampling of the hydrology and the model response. Output from such models should not be compared directly to real-time observations.

The coupling of these two model forms (time dependent and level of development) is not straightforward, and the difference in the representation of time must be understood by model participants. Thus, when output from a level-of-development model is used to drive a time-dependent model, it is important to recognize that time in the level-of-development model may not reflect changing conditions over the long term. Another constraint for future projections is that time-dependent models may have a need for more varied data that is typically available from level-of-development models, which are primarily focused on hydrologic variables.

4.2.1.2 Differences in model time step

As models become more sophisticated and computational resources increase, finer time steps may be used. These finer time steps allow the representation of more temporally detailed processes and allow for greater spatial resolution. This is often needed for specific dynamic problems. However, upstream or downstream models may not have the same temporal discretization. Examples include: (i) the linking of the CalSim hydrologic model at a monthly time step with an estuary hydrodynamic model at a daily or sub-daily time step, (ii) the linking of a monthly groundwater model with an agroeconomic model at an annual time step, or (iii) a daily flow and water quality model with a fish-response model, requiring sub-daily inputs. The timestep for a typical model input or output, in some cases, may be tied to the observed data used for formulating and calibrating the model. Linking models with different time steps can necessitate artificial refinement in datasets that is not substantiated by the model output timestep or the observed data.

4.2.1.3 Differences in calibration and validation

Each model in an integrated modeling framework may have undergone an independent process of calibration and validation through which key parameters are adjusted to get the best fits to observations (see Memo 4 for a description of this process). The calibration and validation may be based on different time periods or different scenarios that may limit the ranges over which models are credible. Another consideration in calibration is the type of condition focused on through the model; as an example, the same model framework used for flood peaks or low flows, may result in different calibrations. Coupling of models with independent calibration must consider whether there is compatibility in the conditions used. Furthermore, in some situations, there may be a need to re-calibrate an integrated model to improve the fits to observed data, which can be more challenging in an integrated framework. Special attention must also be paid to the values of shared model parameters, if such parameters are present in the component models.

4.2.1.4 Differences in time frames of published models

Some models have complex data requirements such that their set up and calibration is only performed for specific periods where all the relevant input data are available. In such instances, the extension of the model to different periods is time consuming and may be difficult to accomplish. This is a challenge when such models need be integrated with other models that may have data availability over different periods. This consideration also applies when a proprietary model has been set up and run for a specific time period but is not readily available for use over other time frames. Another consideration is that some models (such as CalSim) embed empirical relationships within them, where the relationships are also based on data from a specific period. Thus, extending the model simulation time requires a nuanced understanding of the model internals.

4.2.2 Data Availability and Exchange

Data commonly refers to alphanumeric values that are stored in some form, without regard to the origin of this information. In the environmental domain, the source of the data is also relevant, and observed data collected in the field are handled differently than data that are output from a model. Environmental model development, calibration, testing, and application is closely tied to the availability of relevant observed data. In the case of model integration, outputs from one model may serve as the input to another model. Where different types of data are needed to work with individual models in an integrated modeling framework, additional challenges arise as discussed below.

4.2.2.1 Geographic data limitations

Data collected for different domains are reported at different levels of spatial and temporal detail. Some types of physical data are collected at high frequency through automated sensors, on the order of minutes. With sensors becoming cheaper and more reliable, a more spatially intensive network can be envisioned. Other data, especially biological data, require considerable manual involvement, and may be reported at less frequent time scales, such as monthly and over a limited number of locations. Finally, economic and social data may be reported at annual time scales and specified over political boundaries. When models across these domains are to be integrated, a common basis for exchanging data must be found.

4.2.2.2 Management of model output

With the growing complexity of models, notably spatially resolved numerical models, large volumes of output data are generated that must be stored and processed into forms that are suitable for interpretation or as input to downstream models. Significant computer resources are needed to manage these data, especially if they are to be retained in a format that is accessible to a broader community. Furthermore, the manipulation of these data for input to downstream models can also be a time-consuming exercise.

4.2.3 Model Accessibility

When planning to conduct an integrated modeling study, reasonable accessibility of component models should be assured. While this need not mean that source code be available in all cases, other supporting documentation should be available to describe model conditions, scenarios, input-output file structures and units, etc. Model accessibility may be limited because of ongoing development, proprietary restrictions, and cost restrictions.

4.2.3.1 Searchability of Model-Related Information

To be able to use a model framework or a specific model application, the potential community of users should be able to access a certain amount of supporting information. Relevant supporting information for a model includes: model source code or executable files, input data files and configuration files, sample output files, observed data files for calibration, and example scenario files. While some of this information can be re-created, it is most helpful if the relevant files from prior modeling efforts are easily available from public repositories and can be re-used or modified. A typical challenge is that such information from prior, dated projects are very difficult to find, and must be re-developed.

4.2.3.2 Documentation

Models are developed and applied over years with the participation of different individuals. The basis for specific model assumptions may be lost over time if not properly documented. In the long term, this lack of documentation may lead to an inappropriate use of the model by future users or may result in future users being unable to modify the model for a new application. Lack of model documentation may also be a challenge to a wider community of modelers who are trying to understand the model inputs, outputs, data needs, units, assumptions, etc. and integrate with other components. There are numerous examples in the Delta of older models being rendered of limited value because of insufficient or missing documentation.

4.2.3.3 Model versions in flux

Many models are in continual development, or the models' development cycles may span several years. In such instances, even where the code is in the public domain, or is intended to be in the public domain, version control issues may limit accessibility for integration with other models.

4.2.3.4 Proprietary models

Rice field with egret in the Sacramento Basin (source: iStock)

Non-proprietary software is usually preferred for stakeholder-based environment modeling because it reduces potential barriers to new users and encourages open dialog. However, non-proprietary models may not be available for a particular application or, if available, may not be adequately reliable. Furthermore, proprietary models, by having a mechanism to be sustained financially and independently of a government agency or academic institution, may provide new opportunities for enhancement and long-term viability. If proprietary models are used, they should be subject to the same rigorous quality control and peer review that might be expected of non-proprietary models. This appears to be true in many Delta applications, and the use of proprietary models is reasonably common. However, from the standpoint of model integration, the inability of proprietary models to be independently run is a challenge. In most instances, such integration is expected to be performed by utilizing results from pre-existing runs (which limits the types of scenarios that may be considered) or by the developers of the proprietary model. The latter situation may occur when the model developers are not just software vendors but an integral part of the modeling team.

4.2.4 Computational Complexity

Model complexity continues to grow, matching the trend in greater computer speeds. This phenomenon is particularly true for numerical models that require gridded representations of systems in space and time. Several multi-dimensional hydrodynamic models of the estuary are computationally demanding, often placing an effective constraint on the length of a hydrologic sequence that can be evaluated. Models of such complexity also require specialized user expertise to operate. Both of these factors are a challenge to the potential integration of complex models within a larger modeling framework.

4.2.5 Propagation of Uncertainty Across Models

Models are simplifications of reality, thus making them subject to various forms of uncertainty. In environmental models specifically, these sources of uncertainty include: 1) parameters, 2) structure (model conceptualization), 3) initial state variables, 4) configuration and input variables, and 5) observation data used for training and testing the model. Further, the nature of uncertainty can be categorized into epistemic uncertainty and aleatory uncertainty or stochastic uncertainty (Walker et al., 2003). Epistemic uncertainties, which stem from a lack of knowledge, can be reduced with additional collection of data. In contrast, aleatory uncertainties originate from inherent variability and stochasticity of natural phenomena (e.g., climatic variability). Aleatory uncertainties cannot be reduced by collection of more data. For certain natural phenomena, this means that there is no direct way of getting perfect knowledge. Climate predictions over different time scales are perhaps the most common example of aleatory uncertainty in environmental models. Often any modeling application includes both epistemic and aleatoric uncertainties.

Although uncertainty is a well-recognized problem in modeling that must be addressed in any major modeling effort, it is of particular concern in integrated models. This is because the uncertainty in the outputs of one model result in uncertain inputs to a downstream model and this uncertainty continues to accumulate over a sequence of models. Lack of accounting for uncertainties will result in biased and unreliable model results which will directly affect the decisions made based on the modeling (Beven and Binley, 1992; Refsgaard et al., 2007; Bastin et al., 2013). Specific approaches to manage and evaluate uncertainty in modeling frameworks are described in the following chapter on solutions.

4.2.6 Limitations in Model Testing

Most models must undergo a variety of tests to assure that they are credible for the problem and the range of conditions that they are intended to evaluate. Memo 4 describes a series of steps that may be undertaken, depending on the model complexity and the importance of the decision being made using the model. Usually, rigorous testing of any model will require time and analyst resources. In the context of integrated modeling, it should be assumed that the component models have each been subject to testing and are individually considered credible. Even when component models are considered credible, integration may result in new issues that need to be considered. New issues may include propagation of uncertainty (discussed above) and occurrence of new conditions and new outcomes that have not been encountered in the component models. Best practices should include testing of integrated models in a manner consistent with component models. However, the added computational complexity of integrated models and the time and expertise taken to run them, especially when done through offline coupling (see Chapter 1 for description), severely limits the extent of testing that may be performed.

4.3 Summary

Although integrated modeling across different spatial and disciplinary domains can be beneficial in addressing complex environmental problems, the added complexity of getting two or more models to work together effectively raises some practical challenges. This chapter provides a summary of these challenges, informed by the general scientific literature and the specific case studies of integration in the Delta and Central Valley described in Memo 2. These challenges are grouped into two broad categories: institutional and technical. Institutional challenges are primarily concerned with the human side of modeling and relate to the overall setting in which modeling occurs, the expertise needed to develop integrated models, the funding needs, and the engagement of stakeholders. Technical issues include computational and scientific challenges related to integration and are associated with model compatibility, data exchange and management, accessibility of models, overall complexity of integrated models, propagation of uncertainty across integrated models, and the overall limitations in model testing. Based on these practical challenges in the implementation of integrated models, we provide specific solutions in the following two chapters, focusing on institutional issues and technical issues. This chapter illustrates that model integration is not driven by modelers alone. Even when the technical challenges of integration are solvable by modeling teams, successful development of integrated models will require other participants in the modeling process, such as model sponsors and other stakeholders, to address institutional challenges.

5 Institutional Approaches to Facilitate Integrated Modeling

Given the wide-ranging challenges associated with integrated modeling discussed in Chapter 4, we identify approaches to improve the institutional framework to facilitate integration of existing and future models. Institutional approaches involve people, including organizational managers, technical staff and educators. These approaches, which were compiled based on our experience, past work in the Delta, and documented successes in other systems, provide a foundation for the integrated modeling strategy presented in Chapter 8.

Institutional Approaches

Model integration is not limited by technology alone; often there are institutional constraints. Institutional approaches to improve model integration involve people, including organizational managers, technical staff, educators and the modeling community. Institutional approaches outlined in this chapter are important to address for the long-term success of model integration in the Delta.

5.1 Institutional Commitment and Funding

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. Sustained funding recognizes that most integration efforts will take additional time and resources to be fully evaluated for real-world application. In most cases, these factors (leadership and commitment) are likely to be present when the institutions' missions and the goal of the specific integrated modeling exercise are well-aligned.

5.2 Community Development

Within the context of modeling and model integration, it is helpful to think of distinct roles in a larger modeling community: individuals/teams who develop and maintain specific models; individuals/teams that apply existing models to specific situations; individuals/agencies who direct and use model results and drive the need for integration across disciplines, but are not directly involved in running models; and other stakeholders who are affected by model outputs in some form. Indeed, the system in the Delta can be thought of as a “federated” system (borrowing a term from the data management literature) where modelers in different domains interact with one another, and are aware of each other’s needs, even though there is not one top-down model structure that everyone adheres to. Engaging this community’s shared focus around important challenges can be accomplished with various approaches listed below.

5.2.1 User groups

Model user groups typically focus on problem solving and development issues related to specific high-use models. The formation of additional user groups to support high-use models or domains would benefit model development and user training in much the same way as existing user groups have. Some currently active user groups are identified below.

Delta Modeling User Group – This user group was created by and receives ongoing support from DWR to facilitate the exchange of ideas and problem solving around the use of Delta hydrodynamic models. The user group is open to any interested parties and holds meetings three times a year. The website archives meeting presentations, notes, and annual newsletters (DSM2UG).
http://baydeltaoffice.water.ca.gov/modeling/deltamodeling/dsm2usersgroup.cfm

Integrated Water Flow Model (IWFM) – This user group, hosted by DWR and USBR, focuses on the development and understanding of the IWFM and IDC models. The group holds quarterly meetings, records of which are archived on the California and Environmental Modeling Forum (CWEMF) website.
https://water.ca.gov/Library/Modeling-and-Analysis/Modeling-Platforms/Integrated-Water-Flow-Model/IWFM-User-Group

Water Evaluation and Planning (WEAP) – This online user group was created to support WEAP model implementation. With over 30,000 members and many thousands active on forums, the website provides a virtual community for the model in addition to tutorials and user manuals. https://www.weap21.org

Groundwater Exchange —This online resource is a community/information site to share information related to the implementation of the Sustainable Groundwater Management Act (SGMA), including planning documents, data, and models.
https://groundwaterexchange.org/

5.2.2 Virtual community of practice

The “virtual” or online community provides a vast network of development and support for modelers in the Delta. Online forums and user groups have filled the local gaps in technical support and many regional models have roots in the broader modeling literature and community. Additionally, the virtual community has benefited from online resources such as code repositories and cloud storage and computing. The online code repository **GitHub** has allowed for the open storage and sharing of code, methods, tools and datasets. Cloud storage and sharing, such as **Box**, **Dropbox**, **SharePoint**, and **Google Drive**, have also allowed for more efficient transfer files and data and collaboration. Transparency and open communication about models have been enhanced through these tools and continue to be utilized by regional modelers. In the future, integrating existing virtual infrastructure utilized by the modeling community will facilitate efficient engagement.

An important challenge that must be addressed for all virtual communities is continuity and retention of information. In most cases, information starts to become harder to retrieve with the passage of time upon completion of a project and after an immediate need is met. Implementing processes for managing and archiving information for future use will require dedicated staff time in an organized framework.

5.2.3 Communication and physical collaboratory

The complexity and breadth of modeling in the Delta has brought to light many issues shared among modelers in the region. Although groups have formed organically to support the concurrent efforts of researchers within modeling domains, another identified approach is of a more centralized and coordinated social and physical infrastructure to support modeling in the Delta. This infrastructure, referred to as a collaboratory, provides a physical location for individuals to work together on a focused set of problems, along with the necessary virtual infrastructure to host related scientific information.

Two collaboratories have been established across California, including the Southern California Coastal Water Research Project (SCCWRP) and the San Francisco Estuary Institute (SFEI) (Medellin-Azuara et al., 2017). SCCWRP, founded in 1969, is a research institute that works to improve management of aquatic systems in Southern California and other regions. SCCWRP has been developing strategies, tools and technologies used broadly by the water management community. SFEI, founded in 1986 under a different name (Aquatic Habitat Institute), is similar to SCCWRP with a focus on San Francisco Bay. SFEI staff collect data and develop models and solutions for managing the Bay’s aquatic resources. SFEI scientists are also involved in projects across the Bay watersheds, including the Delta. Both SCCWRP and SFEI are financially supported by the local wastewater discharger community as well as project-specific funds.

Integrated working groups have proven effective in other complex estuary management regions in the U.S. such as Chesapeake Bay, the Great Lakes, Long Island Sound, and the Gulf of Mexico. These groups, several of which have been active for decades, are generally funded through federal or state agencies. These working groups support monitoring, modeling, project implementation, and stakeholder engagement in a particular region, i.e., modeling is not the sole focus of the collaboration. Activities are summarized in Boxes 1 through 4. The Chesapeake Bay Program (CBP) has special relevance to the integrated modeling focus in this work. The CBP modeling workgroup has successfully united a diverse modeling community and developed a portfolio of models for the Bay, including a comprehensive watershed model and a physical space for collaboration and model development with US EPA (see Box 1).

In response to the growing interest for collaboration mechanisms in the Delta, UC Davis Center for Watershed Sciences hosted a National Science Foundation/Delta Science Council co-funded workshop intent on gaining consensus within the multi-disciplinary modeling community on how best to enhance the modeling efforts across the Delta (Goodwin et al, 2015). The primary recommendation in Goodwin et al. (2015) was the formation of a Delta Modeling Collaboratory (DMC). Growing from the foundations of CWEMF, the proposed DMC would offer both an expansion to and an enhancement of the existing virtual network. More importantly, the proposed DMC would provide the infrastructure required to advance the quality and role of Delta models, learning and collaboration.

The following vision of the DMC was laid out in Medellin-Azuara et al. (2017) although the future implementation may differ on specifics. The DMC's proposed primary role would be as a technical support center for modeling in the Delta (Medellin-Azuara et al, 2017). Through an association of university, agency, NGO, and private sector players, the DMC would provide support in several avenues:

- Centralized physical space intended for meetings, work, education, and in-house computational infrastructure.
- Technical staff and working teams focused on addressing existing and developing issues within and across model domains. As a virtual and physical forum on models, these teams would provide capacity for both the continual evaluation and updating of existing models, but also individualized technical support when possible.
- Educational resources for all levels of modeler as well as project managers and decision makers. Focusing on project-based learning (Thomas, 2000), the DMC would be providing a learning environment focused on applied problem-solving for current research project and management needs.

Although the concept had been proposed following the 2015 workshop, limitations in physical infrastructure and funding have not yet enabled the development of the DMC.

Box 1. Chesapeake Bay Program

Chesapeake Bay was the first estuary in the nation targeted by Congress for restoration and protection. Following an initial research effort that identified excessive nutrients as the main driver of ecosystem impairment, the Chesapeake Bay Program was formed in the late 1970s with an agreement among the states bordering the Bay (represented by the governors of Maryland, Pennsylvania and Virginia, and the mayor of the District of Columbia), the U.S. EPA, and the Chesapeake Bay Commission. Delaware, New York and West Virginia joined the program in 2000. The program has an office in Annapolis, Maryland, and is staffed by employees from federal and state agencies, non-profit organizations and academic institutions (https://www.chesapeakebay.net/).

In 2010, the EPA established the Chesapeake Bay Total Maximum Daily Load (TMDL). The TMDL sets limits on the amount of nutrients and sediment that can enter the Bay and its tidal rivers to meet water quality goals from a multitude of point and non-point sources. Each of the member states has created a Watershed Implementation Plan to meet these pollution reduction goals by 2025.

Chesapeake Bay restoration is one of the largest such programs in the nation, and it is estimated that approximately $2 billion was spent on restoration in fiscal year 2017 from federal and state sources (https://chesapeakeprogress.com/funding).

Because of the variety and diffuse nature of nutrient sources to Chesapeake Bay, from land and from atmospheric deposition, modeling is an essential part of the process for quantifying loads. Modeling is also needed to evaluate biological impacts. The Chesapeake Bay Program Integrated Models workgroup consists of models for the airshed, watershed, estuary, key biota, and climate change. These integrated models assess effects of watershed management efforts on changes in nutrient and sediment loads delivered to the Bay, and the corresponding effects on Chesapeake Bay water quality and living resources.

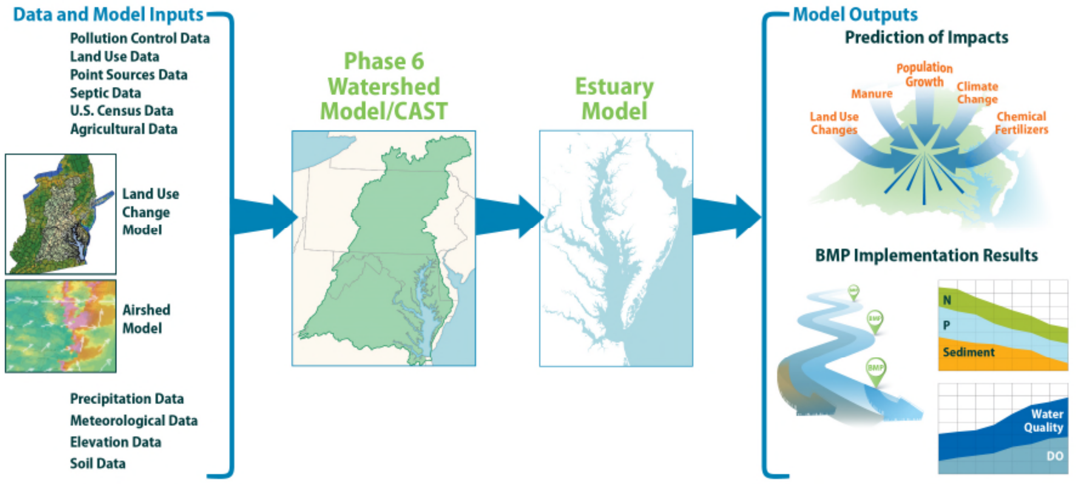


Figure Box 1. Models integrated for Chesapeake Bay nutrient loading (Source: Chesapeake Bay Program).

Box 2. Long Island Sound Study

Water quality in Long Island Sound has improved since the 1970s through a focus on point-source pollution. To continue the improvements, a cooperative effort – the Long Island Sound Study (http://longislandsoundstudy.net/) – was formed in 1985 by US EPA and the states of New York and Connecticut to focus on overall ecosystem health. The Study is a bi-state partnership consisting of federal and state agencies, user groups, concerned organizations, and individuals. In 1994, the Study developed a Comprehensive Conservation and Management Plan to protect and restore Long Island Sound (revised in 2015). The EPA Long Island Sound office is located in Stamford, Connecticut, with partners working from different locations in the Sound watershed. The Study supports and coordinates a variety of projects related to water quality and ecosystem monitoring, sea floor mapping, and modeling related to water quality, tidal marsh inundation, and climate change.

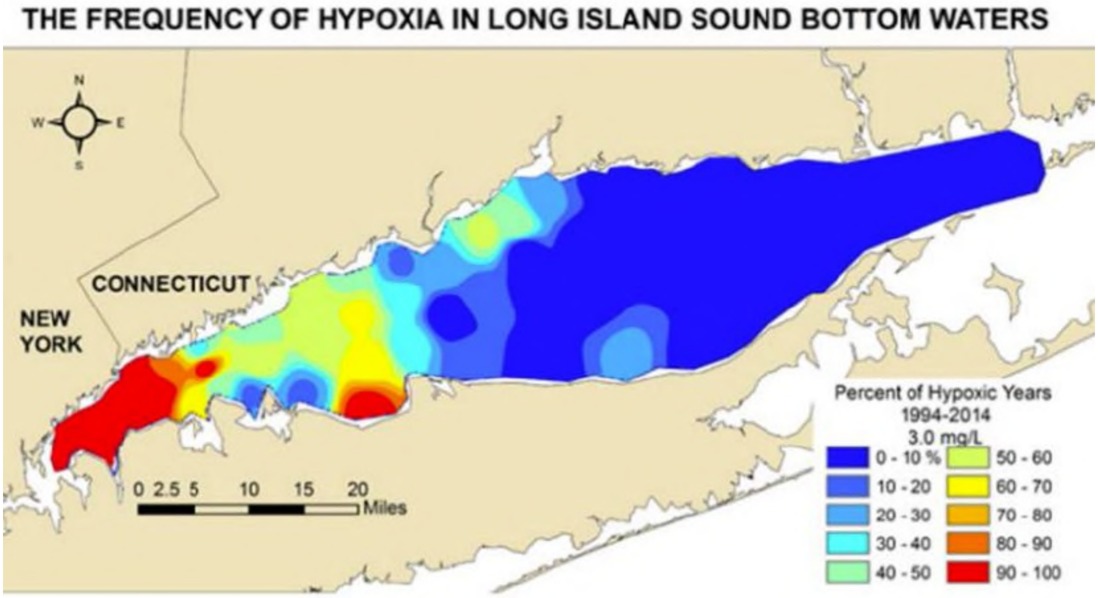


Figure Box 2. Hypoxia in Long Island Sound (Source: Long Island Sound Study).

Box 3. The Center for the Integrated Modeling and Analysis of the Gulf Ecosystem (C-IMAGE)

The Center for Integrated Modeling and Analysis of Gulf Ecosystems (C-IMAGE) is a research consortium of 19 U.S. and international partners studying the effects of oil spills on marine environments (https://www.marine.usf.edu/c-image/). The C-IMAGE consortium received funding from the Gulf of Mexico Research Initiative (GoMRI) in response to the Deepwater Horizon blowout of 2010. Funding was initiated in 2011 and is now in its final phase. The center is housed in the University of South Florida.

The C-IMAGE research goal is to advance understanding of the processes and mechanisms involved in marine blowouts and their environmental consequences, ensuring that society is better-prepared to mitigate future events. Research has focused on the chemical and biological processes related to two major oil spills, the Deepwater Horizon event of 2010 and a spill of similar magnitude in the Bay of Campeche in 1979. The research includes chemical evolution and biological degradation of the petroleum/dispersant systems and subsequent interaction with coastal, open-ocean, and deep-water ecosystems, and the environmental effects of the petroleum/dispersant system on the sea floor, water column, coastal waters, beach sediments, wetlands, marshes, and organisms.

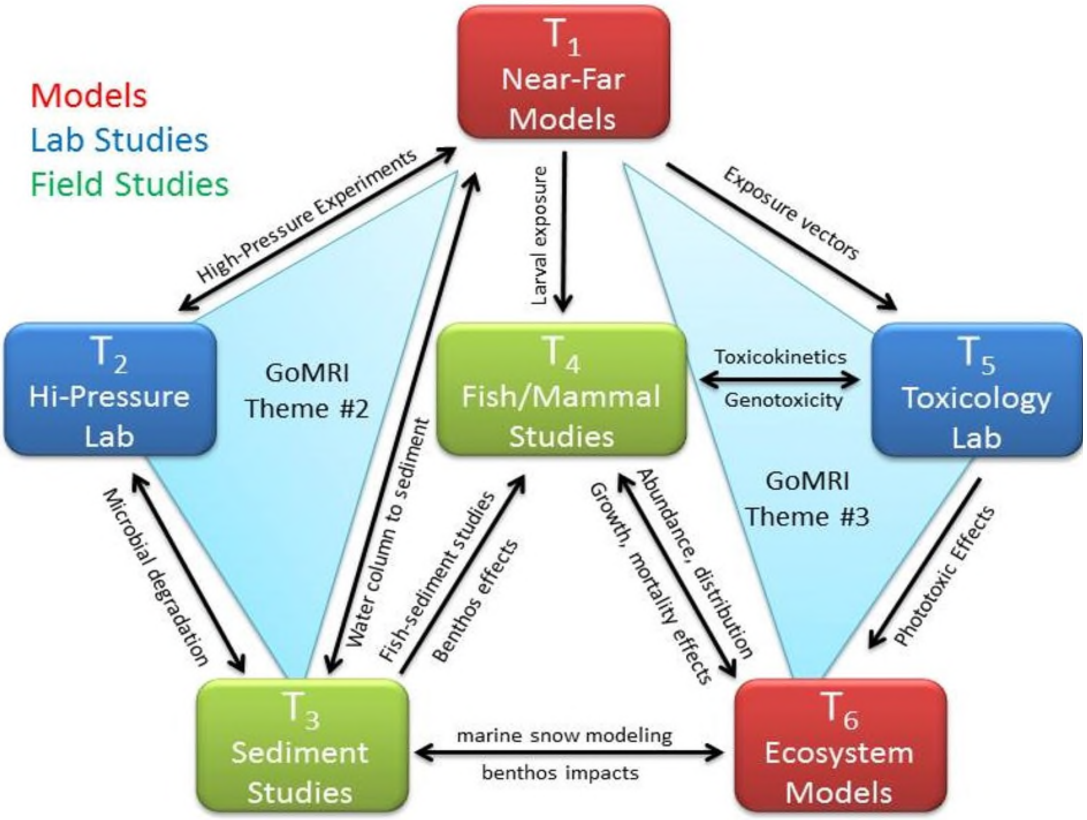


Figure Box 3. Modeling and data collection in lab and field studies as part of the C-IMAGE research program (Source: University of South Florida).

Box 4. Great Lakes Restoration Initiative

The Great Lakes Restoration Initiative (https://www.glri.us/) is focused on protection and restoration of what is the largest system of fresh surface water in the world. The Great Lakes contain 20 percent of the world's fresh surface water and span more than 750 miles west to east, with a 10,000-mile coastline.

The Great Lakes National Program Office (GLNPO), established in 1978, was the first EPA office with ecological rather than political or media boundaries. Its mission is to restore and maintain the chemical, physical, and biological integrity of the waters of the Great Lakes Basin ecosystem. Past and present problems in the ecosystem include excessive nutrient input (algal blooms, nuisance algae, hypoxia in Lake Erie and in large bays); bioaccumulative toxics, and invasive species. GLNPO programs include monitoring, Lakewide Management Plans (LaMPs), Areas of Concern, the Great Lakes Binational Toxics Strategy (GLBTS), the Great Lakes Legacy Act (to reduce contaminated sediments), the Cooperative Science and Monitoring Initiative (with Canada), and large-scale modeling programs. Work is coordinated through five-year action plans (the current plan is the third such plan) with a focus on the following areas: toxic substances and areas of concern; invasive species; nonpoint source pollution impacts on nearshore health; habitats and species and foundations for future restoration actions.

In addition to the EPA program office, monitoring and research functions related to water quality and ecosystem are independently performed by two other groups. The first is the National Oceanic and Atmospheric Administration (NOAA) Great Lakes Environmental Research Lab (https://noaaglerl.blog/) located in Ann Arbor, Michigan. The second is the U.S. Geological Survey's Great Lakes Science Center (https://www.usgs.gov/centers/glsc), also based in Ann Arbor, that has focused on biological research in the Great Lakes for more than 50 years.

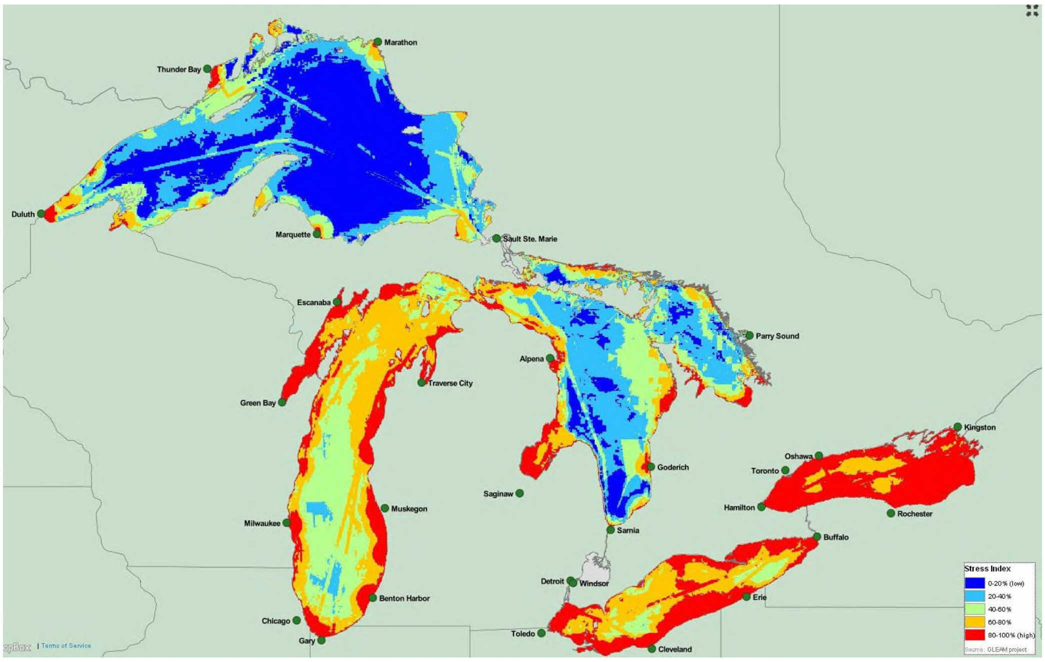


Figure Box 4. Stress in the Great Lakes mapped using 34 indicators (Source: University of Michigan).

5.2.4 Regional forums

The Delta Science Program's **Integrated Modeling Steering Committee** (IMSC) was recently established to provide guidance and strategy for integrated modeling efforts in the Delta. The IMSC, along with the DSC, is the driver of the current study. As a consortium of agency representatives, researchers, and consultants, the IMSC builds on the increased interest in collaboration and Delta-specific solutions. As of 2017, the IMSC held monthly meetings to address key ecosystem modeling concerns and projects. As part of the updated Delta Science Plan (revised October 2018), the IMSC is intended as a stepping stone to a greater regional modeling community. The Delta Science Program has also provided an annual regional forum for Delta research through the Bay-Delta Science Conference, as has the San Francisco Estuary Partnership via the State of the Estuary Conference. Both forums have created a venue for sharing and obtaining feedback on modeling for the Delta's agencies, researchers, and consultants.

The **Interagency Ecological Program** (IEP) has facilitated interagency research in the Bay and Delta since the 1970's. With a strong focus on fisheries, the program has been a critical collaborative organization for the development of monitoring and models. The organization has emphasized science, synthesis, and service in its operations and been an important component of stakeholder outreach in the region. IEP hosts an annual workshop, publishes quarterly newsletters, and provide strategic documents for ecological programming in the Bay/Delta area.

5.2.5 State/national forums

California Water and Environmental Modeling Forum (CWEMF) has been an integral component of California's modeling community since 1994. The mandate of the non-profit has been to increase usefulness of models, pool and distribute technical information, mediate technical disputes, and provide impartial peer reviews of models for the community. CWEMF hosts an annual meeting to allow for a physical forum on the state of modeling in California. These three-day events provide an opportunity for modelers to exchange ideas, highlight new approaches, and receive updates from model developers. In addition to the annual meeting, CWEMF hosts model-specific workshops and training opportunities.

Professional associations also provide forums on a state and national basis. The **Groundwater Resource Association of California** (GRA) is a network of managers and researchers focused on the topic of groundwater in the state. The GRA hosts numerous conferences and summits throughout the year, including technically-focused interdisciplinary forums. At a national level, **The American Society for Civil Engineers** (ASCE) includes several California chapters and a specialized **Environmental & Water Resource Institute** (EWRI), which hosts targeted forums, publications, and workshops. Similarly, the **American Water Resource Association** (AWRA) hosts several conferences and workshops each year throughout the U.S. and publishes the widely-read Journal of the American Water Resources Association. The National Science Foundation's **Consortium of Universities for the Advancement of Hydrologic Science** (CUASHI) serves as both an online and physical forum for national water resource scientists and holds a variety of annual events. The **International Association for Great Lakes Research** (IAGLR) hosts an annual conference on Great Lakes Research that provides an opportunity for workshops and sessions on cross-cutting modeling and analysis tools. The **American Geophysical Union** (AGU) hosts a major conference each year that allows for specialized groups from across the nation to gather in focused sessions, including significant representation from modelers. At a broad scale, these organizations offer forums for modelers to exchange knowledge and approaches to addressing regional issues. The creation of additional regional, state, and national forums which assemble users in a particular model domain would provide an ideal venue for providing domain-specific support, technical training, and workshops.

5.3 Education

Currently, the training of modelers is fragmented and dependent on existing expertise within an organization (Medellin-Azuara et al, 2017). Synergy between universities, public agencies, and private consulting is highly dependent on the experts or organizations involved and could be enhanced by increasing communication between domain experts (within public agencies and private consulting firms) and training institutions. Active feedback to university curriculums by domain experts, engagement of students through internships, and targeted workshops for novice modelers could improve training outcomes for the next cohort of modelers in the region.

5.3.1 Staff

Training is often provided within organizations that utilize a specific model or by modeling/professional associations. Many of the regional, state, and national organizations previously discussed offer model-specific workshops. These workshops provide time for direct interface with model experts, other domain modelers, and experts within the participant's own organization. With expert retirements affecting model use within organizations (Medellin-Azuara et al, 2017), these workshops fill an important training role. Organizations like CWEMF often offer modeling training workshops with regional and statewide applications often related to the Delta.

5.3.2 Students

The University of California (UC) and California State University (CSU) offer programs with foundations in modeling. Many programs offer opportunities for students to interact and participate in internships with regional, state, and federal agencies tasked with water resource management (e.g. USACE). Graduate programs often provide opportunities for mentorship with academic modelers and provide a training ground for many of the modelers in both public agencies and private consulting. However, with many models developed within agencies and consulting companies, graduates with strong modeling foundations often learn modeling within the workplace. Incorporating the following into course curriculum could enhance training in the university setting: cross disciplinary courses; introduction to the technical challenges of integrated modeling; and computer science training in integrated model development.

5.3.3 Stakeholders

Stakeholder education through training and workshops is a necessary part of the overall education framework. In the Delta, such education has been performed successfully and cost-effectively by CWEMF, the Water Education Foundation and by other state agencies.

5.4 Summary

This chapter focuses on model integration challenges that arise around participating organizations and people. We identify different actions that can help stimulate the development of integrated models, including institutional commitment and leadership support, model community development, and education. Modeling 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. collaboratory). Community engagement across participating agencies is also fostered by various regional, state, and national forums that involve technical exchange among modelers and scientists. Institutional efforts for model integration also include education for current and future students, staff in participating organizations, as well as the broader stakeholder community. These institutional challenges, while distinct from technical challenges, are equally important to address for the long-term success of model integration in the Delta.

6 Technological Approaches to Facilitate Integrated Modeling

Technological Approaches

This chapter is intended to serve as a point of reference for technological solutions to the integration of models. This guidance, which will enhance the ability of modelers to integrate existing and future models, is organized along themes of documentation and nomenclature standards, interfaces, uncertainty propagation, model data exchange standards, model emulation within integration frameworks, and big data analysis approaches.

In this chapter we propose guidance and identify approaches that will enhance the ability of modelers to integrate existing and future models. Based on our review of present-day integrated modeling efforts, some of these proposals are already in use and are noted below. However, others are not, and this chapter is intended to serve as a point of reference for technological solutions to the integration of models. This chapter focuses on the challenges of model integration specifically; guidance to improve the robustness of modeling in general is presented in Appendix B and Memo 4, *Recommendations for Modeling Best Practices*. The approaches are discussed along the following themes: documentation and nomenclature standards, interfaces, uncertainty propagation, model data exchange standards, model emulation within integration frameworks, and big data analysis approaches.

6.1 Documentation and Nomenclature Standards

6.1.1 Documentation for model data exchange

Meta-data standards are needed for individual model inputs and outputs, similar to standards set for observed data. These metadata should include brief descriptions of the type, temporal and spatial scale, and units of the input/output data. Although such information is often available within model documentation, it may not be necessarily transparent to non-specialist users of the model. Specifically, implications of inconsistencies between the input/output data for different components of the integrated model and required data modifications should be explicitly communicated. Making this information clearly available will minimize the potential misuse of a model where it is being integrated to represent different processes.

6.1.2 Documentation for model processes

Documentation standards for model processes apply at two levels: first for general purpose model frameworks and second for specific applications to a geographic area. In some cases, the two are conflated, where a single model is developed for a specific geographic area.

Documentation for model frameworks needs to provide enough theoretical background on the processes being represented. Usually, presenting the general conceptual model is valuable for effectively communicating the processes modeled. Moreover, basic information on transformation of the conceptual model to a mathematical model, and then a potential computer model, should be presented clearly. For any model that is being used to support an environmental decision affecting the Delta ecosystem and communities, this level of information should be in the public domain, and there should be no mystery as to the processes being represented. In many cases, a typical user will not need to drill down to the implementation level of a model in the form of computer code, and this information need not be in the public domain. However, such documentation is needed to allow model maintenance, support, and improvements over an extended period of time where many different people may be contributing to the changes. Rigorous documentation is also important where a single individual or a small team is responsible for development and support of the model, when due to transitions and staff and retirements, there is an increased risk of loss of model background information.

For specific model applications (e.g. those applied to particular geographic areas or those applied for fundamental scientific understanding), there is an additional need to clearly document application-specific characteristics and methods such as: site conditions, model setup decisions, calibration and evaluation approach, and model uncertainty. These needs are outlined in more detail in Memo 4, *Recommendations for Modeling Best Practices*. It is important to point out that good practices in the development of individual models directly translate to greater ease of integration across models when the need arises.

6.1.3 Common nomenclature

Consistent terminology for similar model processes and data, including reporting units, is desirable to promote effective communication and minimize loss of information across models. It is unrealistic to expect that all models will use the same terminology, but it is reasonable to require that terminology be fully defined before it is used in each case, listing relevant information such as: linkage to specific theoretical or empirical framework, form of measurement, temporal and spatial frequency, etc. An effort to compile terminology for individual models will greatly facilitate communication among models and modelers. The online model inventory (see Memo 1 *Model Inventory*) is a good virtual location where key and commonly used terms can be defined with typical units and general context.

6.2 Interfaces

6.2.1 Front end interfaces

While interfaces are not a central part of model integration, improved and accessible user interfaces almost always reduce barriers to entry and encourage broader adoption of models. Few public domain technical models in use in the Delta today have reasonably intuitive user interfaces, with the exception of tools being developed for support of the Sustainable Groundwater Management Act (SGMA) and selected general purpose tools developed by the U.S. Army Corps of Engineers for hydrology, hydraulics, and flood risk evaluation (see Memo 1). It is recognized that the development of user interfaces is a resource intensive task. However, there is a payback in wider use and greater stakeholder involvement over the long term.

6.2.2 Post-processing tools

Tools that efficiently and intuitively present model results greatly benefit the process of model development and testing and the utility to model users. As with front-end user interfaces, these back-end tools take resources to develop and are not central to model integration; however, they enable integration by encouraging adoption across a broader community.

6.3 Model Data Exchange Standards

Component models considered for integration, in most cases, will have independent histories, having been developed independently based on the subject area needs. In additional to the domain information embedded in each model, we expect the component models to differ in the following areas:

- spatial and temporal computational resolution,
- input data,
- programming language and development environment,
- units and assumptions,
- output results, and
- user interfaces for inputs and display or results.

The task of integrated modeling entails linking models with the above differences together into an operational model chain. In the simple case of manual exchange, the models are run separately in sequence and the outputs from one model are parsed to the next (see Case 1 in **Figure 1**). Upon completion of an upstream model run, outputs, following transformation if needed, serve as inputs to a downstream model. The component models are not modified and are run in a standalone manner. Typically, this sequence of runs is not iterative, i.e., one set of upstream model results are fed to downstream model (more than two models may be involved, but the same concept applies). As noted in Memo 2, *A Survey of Recent Integrated Modeling Applications in the Delta and Central Valley*, this is a common approach for many projects in the Delta today.

The more general requirement is of a fully integrated network with loops and feedbacks, where models or even modules within models pass data to each other dynamically. These integration approaches require interoperability to be addressed at technical, semantic, and dataset levels (Belete et al., 2017). Interoperable frameworks are a major focus of research in the field of integrated modeling. Key concepts in code development for data exchange in integrated environmental models and common data exchange platforms are discussed in further detail below.

6.3.1 Code development for data exchange in integrated models

The approach of running models in sequence is adequate when there are no feedbacks between processes and where the decision-making process does not require an optimal analysis of multiple processes simultaneously. In some integrated modeling efforts, there may be a need for feedback among processes, such as between a reservoir-operations model and models of specific responses downstream of the reservoir, such that the operations can be modified to meet conditions downstream. Where dynamic feedback between components is an essential part of the conceptual model, some form of process integration at the code level is required.

Flood irrigation for almonds (source: iStock)

A large portion of code development efforts for integrated models is concerned with data exchange and data manipulation which are fundamental to integrated modeling systems (Argent, 2004; Leimbach and Jaeger, 2005). These efforts are often constrained by technical and conceptual challenges. Technically, individual models are designed to serve as stand-alone components that serve unique purposes and goals. Conceptual challenges include resolving the different ways modelers and science domains represent data and knowledge. Inter-operability of models can also be provided at different levels. At the technical level, models should ideally be able to 'talk to each other' which requires automating data exchange, making models jointly executable, and ensuring repeatability and reproducibility of model chain configuration and processing (Knapen et al., 2013). At the semantic level, models should 'understand each other' by identifying and, if possible, bridging semantic differences in an automated manner. After semantic reconciliation, the datasets should be compatible between the models. This often entails unit and format conversion, aggregation or disaggregation, interpolation, etc. to prepare the data for exchange between model.

Code development for integrated models often involves the following steps: (i) modification of individual model modules (subroutines) usually with the purpose of adding intermediary arrays to store variables that need to be passed between the models, (ii) creating new modules or subroutines that control the communication between the individual models at each integrated model iteration, and (iii) creating modules or subroutines for processing and writing the output data from the integrated model. This approach gets more complicated when the models to be integrated are developed in different programming languages. Under these circumstances, extensive programming skills are required to reconcile the inconsistencies that stem from different programming languages for the models. However, this level of programming skill may not be available in all cases. Another approach that can facilitate model integration is application of platforms that are developed for standardizing the data exchange between various models, as described below.

6.3.2 Platforms for data exchange in integrated environmental models

Several model integration platforms (or frameworks) allow creation of dynamic feedbacks through a plug-and-play mechanism by connecting submodels and components of various models. The term plug-and-play in this context, does not necessarily mean a fully ready to use platform that various models can be plugged into and operate together. Rather, it implies that the level of effort to develop interactions and feedbacks between various components of the integrated model is reduced due to automation and standardization of data exchange procedures. There may still be a need for performing code revisions inside the individual models when these platforms are used, but the effort is considerably less than when models are integrated by only revising the model codes. Intuitively, the ideal situation is to have a platform that is completely model-independent and can be applied to a wide range of models with different capabilities with minimal level of effort for modification.

Table 3 lists key features of commonly used integration platforms. This document provides an overview of these platforms, and the potential benefits of such an approach, although the specifics of implementation of each is beyond the scope of this work. Jagers (2010) summarizes the main differences between these platforms, and notes that there is wide variety of alternative solutions due to conflicting priorities (e.g., performance, ease of use and generality). It is important to recognize that when deciding on a platform for integrating existing models, there is often a tradeoff between convenience and reusability. For example, the effort required to standardize the interface of a legacy code for one of the platforms below can be substantial, but the resulting usability of the model can be greatly increased, since it may then be easily wrapped and combined with other models. A summary of the available platforms for model integration is provided below. The frameworks discussed range from model-independent frameworks such as the Open Model Initiative to discipline-specific frameworks such as Earth System Modelling Framework (ESMF).

Table 3. A list of model integration technologies

Approach	Language(s) and service interfaces	Description	Key features	Reference
Open Model Initiative (Open MI)	C# or Java interfaces, wrapped C/Fortran	A collection of programming interfaces for components.	It consists of a list of function names or method signatures called initialize, update, input items, status, etc. that enable the model being wrapped to request data from other models and respond to requests for data.	Moore and Tindall (2005)
Community surface Dynamics Modeling System (CSDMS)	C, C++, Fortran, Java, or Python	Developed to simplify conversion of an existing model to a reusable, plug-and-play model component.	It has two levels of specification: (1) Basic Model Interface (BMI) developed to provide model metadata to the next level and (2) Component Model Interface (CMI) communicates with BMI functions as well as with Service Components and the CSDMS Framework	https://csdms.colorado.edu
Open Geospatial Consortium Web Processing Service (OGC WPS)	NA	Specifications on how inputs and outputs of geospatial services are handled.	It has three mandatory operations that should be implemented by all services: Get Capabilities, Describe Process, and Execute.	Schut and Whiteside (2007)
Kepler, Taverna, Vis Trails, and Trident	Java, PMML, WSDL, BPEL, wrapped C/Fortran, Python	Workflow tools providing user-friendly GUIs that can be used to process and arrange data entries, mapping inputs to outputs, and defining control/break conditions	The workflow can be stored, published, shared, and exposed as encapsulated models, while the component models themselves must simply expose a WSDL document describing each process, and its input and outputs.	More details in Bastin et al., 2013
FRAMES, TIME, SME, MCT, ESMF	Native C interface with bindings for Java, .NET, Fortran, VB6 and Python, Open MI, Wrapped C/Fortran, C++	Discipline-specific frameworks for combining models and controlling their execution	They include standard modules for hydrological or climate modelling. The recent versions generate wrappers and control code wrappers for model sequences based on standardized model metadata.	More details and comparisons in Bastin et al., 2013; Whelan et al., 2014

- Initiatives such as Open Model Initiative (OpenMI) in hydrology (Blind et al., 2005) focus on standardizing the interface to give a clear vision of requirements and limitations. Recent adaptations to the OpenMI standard (Buahin and Horsburgh, 2018) pay particular attention to these common issues of interoperability: for example, allowing more abstract inputs and outputs, and permitting inputs which have no specific time frame, thus opening up the tools for use with non-time stepping models.
- The Community Surface Dynamics Modeling System (CSDMS), focused on earth system models, is a platform that employs state-of-the-art architectures, interface standards and frameworks that make it possible to convert stand-alone models into flexible "plug-and-play" components that can be assembled into larger applications (Peckham et al., 2013). The CSDMS model-coupling environment offers language interoperability, structured and unstructured grids, and serves as a migration pathway for surface dynamics modelers towards High Performance Computing.
- The Open Geospatial Consortium Web Processing Service (OGS WPS) Interface Standard provides rules for standardizing how inputs and outputs (requests and responses) for geospatial processing services, such as polygon overlay. The standard also defines how a client can request the execution of a process, and how the output from the process is handled. It defines an interface that facilitates the publishing of geospatial processes and clients' discovery of and binding to those processes. The data required by the WPS can be delivered across a network or they can be available at the server.
- General purpose workflow tools such as Taverna, Kepler, Vis Trails, and Trident provide user-friendly GUIs within which modular processing or data entities can be arranged, inputs mapped to outputs and control/break conditions defined (Table 3). The resulting workflow chains can be stored, published, shared and exposed as encapsulated models, while the component models themselves must simply expose a document describing each process, and its inputs and outputs. Thus, these tools can be used as engines for interacting with other workflows, as well as compiled C code or R scripts.
- Finally, there are also a host of discipline-specific frameworks (Table 3) for combining models and controlling their execution, such as FRAMES (Framework for Risk Analysis of Multimedia Environmental Systems, Laniak et al., 2013), SME (Spatial Modelling Environment, Maxwell and Constanza, 1997), TIME (The Invisible Modelling Environment, Rahman et al., 2003), MCT (Model Coupling Toolkit, Larson et al., 2001), and ESMF (Earth System Modelling Framework, Collins et al., 2005). Many of these frameworks include standard modules for applications such as hydrological or climate modeling.

There is no existing one-size-fits-all platform for the wide range of integrated modeling potentially needed in the Delta, spanning natural and social science disciplines. Moving forward, however, a platform can be modified from the available options above for future use and require participants to develop future models or modify existing models that meet a public specification. Borrowing from the experience of past efforts, a new system can be developed that is modular, extensible, and adaptable over the long term. For example, using web pages or web services, the system would provide an open, extensible dictionary of field types, a model registration service, unit conversion service, and data transfer capabilities—all pertaining to the Delta region. An extensible model file format would be defined to provide both general and model specific fields. When large amounts of data are produced, the model information would provide a database connect string and select statements. Models located locally or remotely could be chained together for coordinated execution – remote models launched using web services. These actions require specialized programming expertise to set up, and there are upfront costs for adoption. In the long run, however, they provide extensive opportunities for integrated modeling, and may be considered as the needs for such modeling mature in the Delta.

6.4 Uncertainty Propagation Across Integrated Models

All environmental models face challenges related to uncertainties. Approaches for analyzing uncertainty are described in Memo 4, *Recommendations for Modeling Best Practices*. These challenges are magnified in the case of complex integrated environmental models as described in Chapter 4. Uncertainty assessment in integrated modeling consists of two stages: 1) assessing uncertainties associated with individual models, and 2) assessing propagation of uncertainties from individual models through the integrated system. The decomposition of aggregated uncertainties is challenging due to multiple models being involved.

Uncertainty assessment methods fall under one of two classifications: forward uncertainty propagation and inverse uncertainty quantification. In forward propagation methods, uncertainties in model inputs are propagated to the model outputs. In inverse uncertainty quantification methods, posterior distribution of model parameters is derived based on discrepancies between model simulations and observations and values of likelihood function. Inverse quantification of uncertainty is much more complex than forward propagation of uncertainty, as the modeler is essentially solving the problem in reverse (similar to calibration). However, the method provides some important benefits: in most cases the uncertainties associated with various model elements (parameters, inputs, etc.) are initially unknown and, using an inverse approach, the modeler can estimate the most consequential uncertainties, and select them for further evaluation. Thus, these uncertainties can be propagated to simulations through a forward approach. In most inverse uncertainty quantification applications, the overall modeling uncertainties are quantified as a lumped value, as quantifying the uncertainties associated with each model component is very time-consuming and in some cases impossible. Specifically, in highly complex integrated environmental models, decomposition of uncertainty and attributing portions of total uncertainty (total error) to various sources of uncertainty is an extremely challenging task and remains a subject of extensive ongoing research (Bastin et al., 2013).

Bayesian-based methods are among the most commonly used assessment techniques for conducting uncertainty analysis for complex environmental models (Jia et al., 2018). Bayesian uncertainty analysis methods, rooted in Bayes' Theorem, quantify parameter uncertainty by deriving the posterior parameter distribution from a combination of prior parameter distribution and a likelihood function. In most environmental models, specifically more complex models, the analytical solution to derive the explicit functional form of the posterior distribution is infeasible. Hence, a sampling is often used to derive the posterior distribution. The Markov Chain Monte Carlo (MCMC) sampling schemes provide efficient algorithms to derive the posterior parameter distribution (Rath et al., 2017; Tasdighi et al., 2018). In this regard, multi-chain MCMC methods have proven superior performance and efficiency in sampling the parameter space and deriving the posterior distributions. Application of multiple Markov chains enhances the efficiency of the search algorithm and reduces the chance of being trapped in local optima (Ter Braak, 2006). Two common multi-chain MCMC algorithms frequently used for environmental models are the DiffeRential Evolution Adaptive Metropolis (DREAM) algorithm (Vrugt, 2016) and the Shuffled Complex Evolution Metropolis (SCEM) algorithm (Duan et al., 1992). While multi chain MCMC algorithm have been employed in conducting uncertainty analysis for various environmental models, their application to integrated model frameworks remain very limited due to computational burden (Tscheickner-Gratl et al., 2019).

A significant challenge to applying sensitivity and uncertainty analysis techniques to integrated models is the high computational burden. Nearly all sensitivity and uncertainty analysis techniques require numerous model iterations. In the case of integrated models, this issue is exacerbated as several models are working jointly in each model iteration. Facing these high computational burdens, modelers must use manual techniques that use a very limited number of model runs or resort to more advanced computational techniques as described below.

6.5 Model Emulators to Represent Complex Models

When computationally intensive models are integrated, the combined model run time can be time-prohibitive on desktop machines and alternative approaches such as cloud computing may need to be considered. Another alternative that has gained some currency in the literature is to use an emulator for one or more models within an integrated modeling framework. Emulators need some resources to develop, but once created, they may allow certain types of model integration that may not be possible with the original models. Emulation approaches, summarized in **Table 4**, range from simple linear regression to sophisticated deep learning artificial neural networks.

Emulators represent the input/output relationships in a model with a statistical surrogate to reduce the computational cost of model exploration. In this approach, the computer model is viewed as a black box, and constructing the emulator can be thought of as a type of response-surface modeling exercise (Box and Draper, 2007). The approach establishes an approximation to the input-output map of the model using a limited number of complex model runs. Of course, as with any approximation, emulators produce less accurate estimates. Therefore, model developers must consider this trade-off between accuracy and computational cost.

Table 4. Model emulation approaches

Algorithm	Description
Linear Regression	Linear regression is a ubiquitous technique that estimates one numerical variable as a linear function of one or more other variables. It is conceptually simple and computationally efficient for datasets of almost any size. Assumptions on data structure are quite restrictive compared to some of the other more complicated algorithms listed below; thus, the ability to make full use of the theoretical results about a linear model is generally unlikely on real-world data. Nevertheless, linear regression models can serve as useful building blocks in more complex models. In principle, approaches such as regression should be limited to the range of data used to develop the regression, and not extrapolated beyond.
Logistic Regression	Logistic regression is a type of regression for binary (yes/no) variables. The estimated parameters of the model are still linear with the input variables, but a sigmoidal function maps the underlying linear predictor to fall within the range of 0–1. The value that a given combination of input variables outputs is the probability that the corresponding output variable has value 1 (e.g., yes/true). The use cases of logistic regression for binary variables are similar to those of linear regression for continuous variables: it is a conceptually simple and computationally efficient model that has restrictive assumptions compared to other more complex algorithms. Logistic regression is often a building block in artificial neural networks (ANNs) discussed below. Both linear and logistic regression fall in a family of techniques called “Generalized Linear Models,” but these two are the most common.
Bayesian Inference	Bayesian inference isn’t a specific model but rather a method for estimating model parameters that can be specified by probability distributions. In practice, many of the models that practitioners in water resources might be interested in using fall into this category, the main exceptions being “nonparametric” procedures like the Mann-Kendall rank-based trend tests. The main strengths of Bayesian inference are that uncertainties for the estimated parameters are automatically generated in a straightforward manner and that it is possible to incorporate prior information (e.g. expert knowledge, results of previous studies) as a regularizing effect to improve estimates on parameters in more complex models where the data alone might be insufficient. Bayesian inference is also one of the best ways to fit structured *multilevel* models, where the data is organized in a hierarchical fashion: e.g., a model of water samples from several lakes in a region might be organized so that the samples from the same lake are in the same group and share information with each other.
Markov Chain Monte Carlo (MCMC) Techniques	A simple algebraic expression for the properties of a probability distribution generally only exists for the simplest examples. In other cases, including many of the Bayesian models that one would like to use in practice, alternative methods must be used to estimate the necessary calculations. MCMC refers to a state-of-the-art family of methods that explore probability spaces with a sequential (Markov) chain. These methods are particularly good at evaluating high-dimensional spaces that come up in real-world multivariate problems. However, they tend to be computationally intensive and can require some fine-tuning on the part of the analyst to ensure that they have converged.
Spline Methods	There is often a need to estimate the relationship between variables with unknown but nonlinear functional form. Splines are one way to do this—they are unknown smooth functions evaluated at a limited number of points (knots) that have some constraints on their degree of smoothness, often expressed as a penalty on the second derivative of the function. Splines can be computationally less expensive than other techniques discussed below, but the determination of where to place the knots can be difficult or arbitrary. Generalized Additive Models (GAMs) often use spline functions as a basis for expressing unknown smooth functions.

Algorithm	Description
Gaussian Processes	Gaussian Processes is another method to estimate smooth functions. In contrast to being evaluated at a discrete set of points like splines, Gaussian Processes are parameterized in terms of a known (or assumed) covariance function between pairs of observed data points. This is often conceptually more elegant and sidesteps that question of knot placement, but it is computationally expensive in the general case and approximations often must be made on all but the smallest of datasets. Kriging techniques, often used by GIS practitioners, are a type of Gaussian Process.
Artificial Neural Networks (ANNs)	ANNs encompass a broad class of models that represent relationships among data in a fashion that has some similarities to biological neurons: variables correspond to nodes and the parameters of the model correspond to connections between the different nodes, usually between intermediate nodes that represent internal model state. The relationships that ANNs can represent are very general—they are often described as "black box" models—and the complexity of those relationships is determined by the structure of the connections between the nodes in the network. ANNs are very flexible models that can pick out unknown relationships among multiple variables, but they are computationally expensive to train. Non-deep networks (deep networks are described below) can require expert knowledge and pre-processing of data to get accurate, structurally valid, and generalizable models.
Deep Learning	Software and hardware innovations since the early 2010s have greatly expanded the size and complexity of ANNs that are feasible to train in a reasonable amount of time. Specialized ANN architectures with many connected layers of nodes are referred to as "deep networks" and machine learning using these networks is deep learning. The distinction in terminology comes from the fact that the depth of these networks induces qualitatively different behavior compared to traditional ANNs. They can generalize beyond the training data much better and are able to extract relevant information from raw, unprocessed data much more successfully. In general, these networks must be trained on specialized hardware. It has become commonplace to rent cloud computing resources to train these models. Selection of an appropriate deep learning architecture should be guided by the particular applications. Thus, architecture selection requires some expert knowledge, even if the final model itself can handle raw, unprocessed data. For example, deep recurrent neural networks (RNNs) can be used to estimate relationships between and predict time series variables and convolutional neural networks (CNNs) can be used to process image-like data.

6.6 Data Analysis Frameworks in Support of Model Integration

Data analysis is the process of systematically applying statistical and/or logical techniques to describe, condense, illustrate, and evaluate data. Data analysis and integration frameworks can be used as comprehensive tools to manage model input and output and display results. Commercial tools for data analysis and integration include Tableau, Qlik, Palantir, and Matlab. The R programming language is the most widely used non-commercial, or open source, programming environment for data analysis and graphics. These frameworks allow for integration of technical code and provide a means for managing the flow of input and output files. Data or model results can be tabulated or visualized by model stakeholders through the use of "data dashboards", some of which can be freely published on the internet.

According to Shamoo and Resnik (2003), data analysis procedures “provide a way of drawing inductive inferences from data and distinguishing the signal (the phenomenon of interest) from the noise (statistical fluctuations) present in the data”. Technological advances are driving exponential growth in volume and speed of data generation, giving rise to the concept of “Big Data”. Big data, although informal in origin, has come to serve as a term to describe data that are high in volume, velocity, and variety, requiring new technologies and techniques to capture, store, and analyze.

In the integrated environmental modeling realm, the big data concept primarily pertains to techniques to capture, process, analyze, and visualize large structured and unstructured datasets in a reasonable amount of time. When analyzed properly, big data can enhance decision making, provide insight and discovery, and support integrated model applications.

Another approach that has potential is the use of data-driven (i.e. black box) models with process-based models, building on the strengths of each modeling methodology. Big data analysis tools can be used to reconcile the strengths of black box and process-based modeling approaches and may allow mixing of models with different levels of information (**Figure 7**). The inter/multi-disciplinary nature of the integration problem necessitates the merging of large, disparate datasets (model inputs/outputs) which eventually must be analyzed to make inferences about the system being modeled.

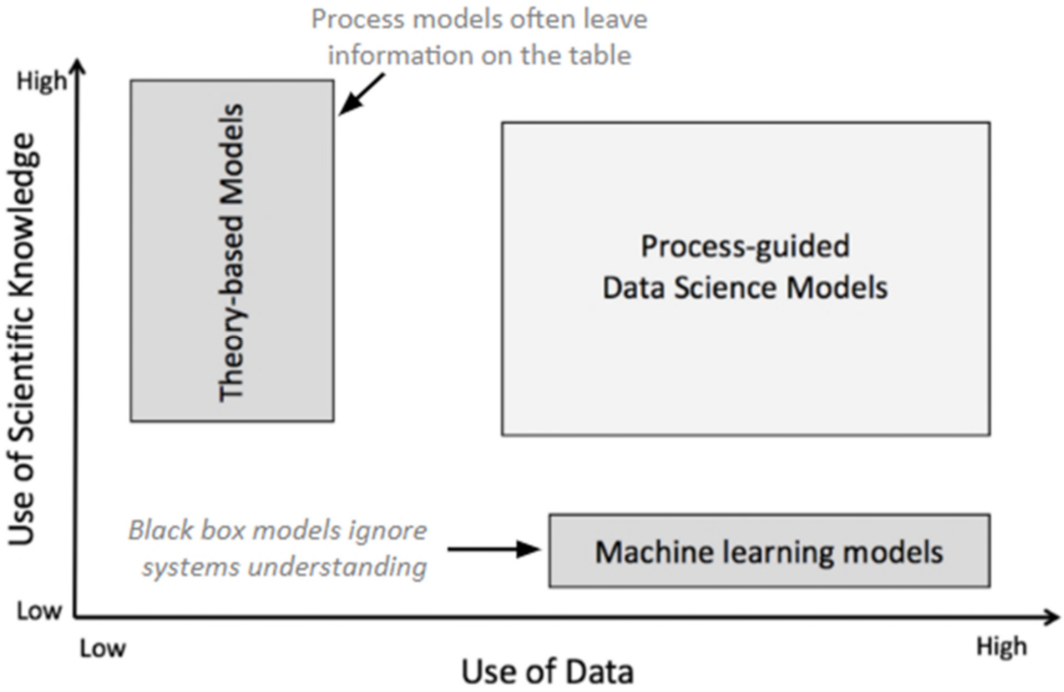


Figure 7. Big data analysis can help benefit from both black box and process-based modeling approaches. Adapted from Karpatne et al. 2017.

6.7 Big Data Analysis Technologies and Applications

There is a variety of available big data analysis tools and frameworks that can be used for integrated models. Considering the large data requirements and computational power demand of integrated models, application of big data analysis tools is expected to create new efficiencies and new opportunities, such as the hybrid modeling approach described above. This section provides a list of the most popular big data analysis frameworks in use that have potential applicability in the environmental domain. There are some published environmental applications of specific tools (as noted below), although for many of these tools, their use in environmental applications has not been documented in the scientific literature.

- **Apache Hadoop:** The Apache Hadoop software library is a framework that allows for the distributed processing of large data sets across clusters of computers using simple programming models. It is designed to scale up from single servers to thousands of machines, each offering local computation and storage. Hadoop is open source and many large organizations are already implementing its capabilities. Hu et al. (2015a) coupled a multi-agent system model with an environmental model for watershed modeling with Hadoop-based cloud computing. They reported an 80% reduction in runtime for the coupled model. The practice showed a good potential for scalable execution of the coupled model through application of Hadoop. Hu et al. (2015b) also used Hadoop-based cloud computing for global sensitivity analysis of a large-scale socio-hydrological model. They were able to reduce the computation time of 1000 simulations from 42 days to two hours.
- **Apache Spark:** Apache Spark is an open-source distributed general-purpose cluster-computing framework. Spark provides an interface for programming entire clusters with implicit data parallelism and fault tolerance. Spark facilitates the implementation of both iterative algorithms (which visit their data set multiple times in a loop) and interactive/exploratory data analysis, i.e., the repeated database-style querying of data. Omrani et al. (2019) implemented the Apache Spark framework to reduce the high computational burden of land change simulation model across a large region and span of time. Their results showed significant computational performance improvements compared to running the model out of the Spark framework.
- **Apache SAMOA:** Apache SAMOA (Scalable Advanced Massive Online Analysis) is an open-source platform for mining big data streams. SAMOA provides a collection of distributed streaming algorithms for the most common data mining and machine learning tasks such as classification, clustering, and regression, as well as programming abstractions to develop new algorithms.
- **Microsoft Azure HDInsight:** Azure HDInsight is a Spark and Hadoop service in the cloud. It provides an enterprise-scale cluster for the organization to run their big data workloads.
- **Teradata Database:** Teradata database allows analytic queries across multiple systems, including bi-direction data import and export from Hadoop. It also has three-dimensional representation and processing of geospatial data, along with enhanced workload management and system availability. A cloud-based version is

called Teradata Everywhere, featuring massive parallel processing analytics between public cloud-based data and on-premises data.

- **IBM Watson:** Watson Analytics is IBM's cloud-based data analysis service. When data are uploaded to Watson, it asks questions it can help answer based on its analysis of the data and provide key data visualizations immediately. It also does simple analysis, predictive analytics, smart data discovery, and offers a variety of self-service dashboards. IBM has another product, SPSS, which can be used to uncover patterns from data and find associations between data points.
- **Skytree:** Skytree is a big data analytics tool that allows the development of data-driven models using machine learning approaches. The tool provides capabilities for data scientists to visualize and understand the logic behind machine learning decisions. Skytree provides model interoperability capabilities and allows access through a GUI or programming in Java.
- **Talend:** Talend is a big data tool that simplifies and automates big data integration. Its graphical wizard generates native code. It also allows big data integration, master data management and checks data quality. Talend is open source and provides various software and services for data integration, data management, enterprise application integration, data quality, cloud storage and Big Data.
- **Domo:** Domo is a big data analysis and visualization tool that automatically pulls in data from spreadsheets, on-premise storage, databases, cloud-based storage, and data warehouses and presents information on a customizable dashboard. It has been lauded for its ease of use and how it can be set up and used by a wide range of users, not just a data scientist. It comes with several preloaded designs for charts and data sources to get moving quickly.
- **R:** R is a language and environment for statistical computing and graphics. It is also used for big data analysis and provides a wide variety of statistical tests. R provides effective data handling and storage facility, a range of matrix operations, several big data tools, and great visualization capabilities. Many R packages for machine learning are also available off the shelf.
- **Matlab:** MATLAB is a multi-paradigm numerical computing environment and proprietary programming language developed by MathWorks. Matlab has numerous designated data analysis toolsets. Statistics and Machine Learning Toolbox provides functions and apps to describe, analyze, and model data. Regression and classification algorithms provide the capability to draw inferences from data and build predictive models. The toolbox provides supervised and unsupervised machine learning algorithms for big data, including support vector machines (SVMs), boosted and bagged decision trees, k-nearest neighbor, k-means, k-medoids, hierarchical clustering, Gaussian mixture models, and hidden Markov models. Matlab also has superb visualization capabilities which is essential for big data analysis.
- **Python:** Python is an interpreted, high-level, general-purpose programming language. Similar to R and Matlab, Python has numerous data analysis toolsets including NumPy, pandas, and Scikit-Learn. Scikit-Learn implements a wide-range of machine-learning algorithms and allows them to be plugged into actual applications. A range of functions are available through Scikit-Learn such as regression, clustering,

model selection, preprocessing, classification and more. Scikit-Learn in in widespread use today for big data analysis.

- **Tableau:** Tableau is a widely used data analysis and visualization tool. Tableau queries relational databases, online analytical processing cubes, cloud databases, and spreadsheets to generate graph-type data visualizations. The tool can also extract, store, and retrieve data from an in-memory data engine. Tableau also has a mapping functionality with the ability to plot latitude and longitude coordinates and connect to geospatial information such as Esri Shapefiles, Google Earth KML files, and GeoJSON.
- **Plotly:** Plotly, or Plot.ly, is focused on data visualization without requiring programming or data science skills. Its GUI is designed for importing and analyzing data and uses the D3.js JavaScript library for all of its graphics. Its dashboards can be generated in real-time as well as from existing data pools, and it supports exporting to a variety of visualization tools as well, including Excel, SQL databases, Python, R, and MATLAB.

6.8 Summary

This chapter discusses several technological approaches to facilitate model integration, summarized as follows:

- Model documentation is an obvious and straightforward approach; this 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.
- User interfaces, while not essential for model integration *per se*, allow greater accessibility and understanding of data input and output needs, and is therefore beneficial for cross-disciplinary interaction.
- Data exchange standards are an essential element for creating frameworks that allow models to share information among one another in various dynamic formats. Several such 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 is a technological approach that can promote more informed use of model results in decision making. Such analysis can be highly computationally demanding and is currently the subject of research.
- Model emulation, an approach that replaces a complex model with a simpler approximation, reduces computational requirements. In many cases, emulators can be embedded within another model. Several emulation approaches are available, with many being used in the Delta.
- Adoption of big data approaches can facilitate integrated modeling. Related analysis tools are undergoing rapid development, especially in the commercial realm. Some environmental applications of these tools are beginning to appear and 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 combining data-based approaches and process-based models.

Overall, our review suggests that technological approaches to facilitate model integration are developing rapidly in the environmental domain and other related domains. These approaches offer many different avenues for linking models and creating new integrated modeling frameworks to support future decision-making needs.

7 Future Directions

Future Modeling Needs

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.

Our survey (see Chapter 3) demonstrates that integrated modeling analysis is an active area of decision support in the Delta; these recent and on-going efforts evaluate drivers and interactions that cross a spectrum of disciplinary boundaries such as engineering, hydrodynamics, water quality, ecology, and the social sciences. In subsequent chapters, we identified challenges associated with integrated modeling and approaches (both institutional and technical) to facilitate advances in integrated modeling. 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. In this chapter, we identify future modeling needs and outline the basis for future actions.

7.1 Future Modeling Needs

The 2017-2021 Science Action Agenda (DSC, 2017) identifies the advancement of integrated modeling as a goal to support policymaking in the Delta. Numerous organic efforts at model integration are already underway in California; nonetheless, identifying activities that may benefit from integrated modeling remains as important as ever.

Based on our comprehensive assessment of integrated modeling in the Delta, we identify a list of future modeling needs **Table 5**. These 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. This list spans project areas that employ some form of integrated modeling for policy-oriented as well as research-oriented support and decision making. Many of these research-oriented project areas may evolve into policy-oriented project areas in the future. Based on our present understanding, these project areas will remain active in future decades, even as conditions in the Delta evolve and improvements in data gathering and computational capabilities are made.

Yolo bypass bird habitat (source: Bachand & Associates)

Future modeling needs for project areas listed in **Table 5** are expected to involve solutions drawn from a wide variety of disciplines which have their own, well-developed modeling frameworks. To address this range of topics, we recognize that it is not generally practical to develop single models encapsulating more and more relevant processes. These mega-models would likely be difficult to create and manage and would not make use of existing models and insights developed through them. Integration of available models is thus a reasonable alternative and can be advanced through one of the three approaches shown in **Figure 1**. While integration of available models is not without its challenges, the typical experience in the Delta and elsewhere is that the use of existing models as modules or building blocks (within a more complex model framework) is a practical solution for meeting future needs.

The information summarized in **Table 5** provides the motivation for future investments to support integrated modeling in the Delta. While unanticipated needs may arise, the general methodologies for integration will continue to remain relevant.

Table 5. Example integrated modeling needs

Modeling Need	Description of Modeling Need
1. Development of Delta salinity standards.	Salinity is regulated at different compliance locations in the Delta by the State Water Resources Control Board to meet various ecological and human beneficial uses. These regulations are subject to regular updates; updates are currently in progress.
2. Development of biological opinions for key endangered aquatic species present in the San Francisco Estuary.	Biological opinions are developed by the U.S. Fish and Wildlife Service and National Marine Fishery Services to propose conditions for the sustainability of threatened and endangered species. Updates to these opinions are driven by conditions in the field.
3. Climate change impacts on water supplies, water demands, and flooding in the Central Valley and Delta.	Climate change impacts on sea level, precipitation volume and timing, and temperatures, are expected to have complex effects on agroecosystems, flooding potential, estuarine water quality, the water supply system, and municipal and agricultural demands. Climate change will also have a variety of impacts on communities dependent on the Delta. Modeling is needed to understand the range of inter-related impacts across these sectors under climate change.
4. Climate adaptation planning, costs and relationship to Delta communities.	Adaptation efforts include changes in water systems operations, regulatory actions, and engineering approaches. Changes are applied at different spatial scales. Modeling is needed to relate adaptation to future impacts (previous item above), explore changes in the Delta, and to develop cost estimates across strategies.
5. Impacts from implementation of the Sustainable Groundwater Management Act (SGMA) on groundwater-surface water systems, agricultural production and regional economics.	The management of groundwater across California is undergoing dramatic change as a result of the implementation of SGMA. The need for modeling is anticipated across groundwater and surface water basins, groundwater dependent ecosystems, as well as agricultural patterns and economic impacts.
6. Impacts of wetland restoration on Delta flows, water levels, water quality, ecosystems, and Delta communities.	Efforts to restore natural tidal wetlands on some Delta islands is envisioned as part of EcoRestore (see Memo 2). Potential impacts associated with these efforts are investigated through models, including direct impacts to Delta hydrodynamics, flooding, and water quality and indirect impacts on ecosystems and Delta communities.
7. Impact of Delta island subsidence on the future agricultural economy and water quality of the region.	Rapid subsidence on Delta islands, especially those with the highest organic content soils, poses levee failure risk. This risk affects Delta agricultural production, local communities, water quality, and the economy at large.
8. Impacts of new reservoir regulations and project operations on water quality and endangered species.	Changes in reservoir regulation for various reasons (e.g. FloodMAR and climate adaptation) have downstream effects on ecosystems and water quality that can be examined through models.

Modeling Need	Description of Modeling Need
9. Effects of nutrients on Delta food webs and endangered species.	The effects of nutrients (specifically nitrogen and phosphorus species) on the aquatic ecosystem are of growing interest in the Delta and in downstream waters such as the Bay and coastal ecosystem. Effects include changes in algal communities and overall food web, harmful algal blooms, and low dissolved oxygen. These effects are evaluated through a mix of hydrodynamic, water quality, and food web models.
10. Effect of emergency events such as levee failure or spills on water supply, water quality, project operations.	Emergency events in the Delta—driven by earthquakes, major storms, spills, and even sunny-day failures—may have broad ranging impacts across its different uses. Modeling across disciplines, ideally with structures set up in advance, are needed to evaluate the varied impacts.
11. Changes to water allocation given changes in hydrology (in the near term), regulations (in the medium term) and to climate change (in the long term).	Modeling project operations in conjunction with estuarine processes requires analysis across different time scales to evaluate responses due to hydrologic variability, regulatory changes for water quality and biological opinions, and changes in precipitation and mean sea level due to climate change.
12. Integrated management of flood peaks and groundwater recharge to improve groundwater sustainability.	Large flood flows that occur in some wet years are an opportunity to capture additional water supplies in California. Related planning activities require the integration of models for reservoirs, surface flows, and groundwater basins.
13. Effect of changing crop types on water use, water quality in Central Valley groundwater and impacts downstream.	Variations in cropping patterns across the Central Valley, driven by economics at the farm scale, as well as new regulations (such as SGMA noted above), have effects on water demands and water quality in surface and groundwaters. For long-term planning, integrated modeling is needed to evaluate these changes.
14. Impacts of innovation in monitoring, data collection, telemetry on water resources management in the Delta.	New data collection techniques driven in part by new sensor technologies on the ground, improved and more accessible remote sensing technologies, and new communication technologies potentially allow an entirely different perspective on monitoring. Data may be collected at much finer spatial and temporal scales and across a wider range of parameters, and with an associated need to assess with new integrated models.
15. Integrate biogeochemical processes across the Sierras, the Central Valley, Delta, Bay, and coastal regions.	There is growing scientific interest in biogeochemical processes which integrate flows, water quality, and ecosystem impacts over a large scale and requires understanding of human drivers at regional and global scales. These analyses require integration of larger earth system scale models with more localized models.
16. Sociohydrologic modeling to study the co-evolution of human and hydrologic systems.	Modeling typically assumes human behavior as fixed. However, there is growing research interest in incorporating human behavior as a variable in water resources modeling; this relatively new research field is termed sociohydrology. Integrated models of natural and human systems can aid exploration of the future evolution of communities across the Delta region.

7.2 Basis for Future Actions

As noted in Chapter 1, this work was undertaken with an objective perspective on the future utility of integrated modeling, without necessarily assuming that it is beneficial for all environmental applications. Based on the information gathered and presented in this report, it is 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 environmental problems 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 on developing and maintaining such material will allow models to be useful to a broader community over a longer period of time.
- **Cost Savings.** A large part of the integration effort is to get models to “talk” to one another. Although efforts to streamline model inputs and outputs for integration may require resources in the near term, these efforts will almost always save costs over the long term as new model frameworks are envisioned and implemented.
- **New Scientific Development.** With greater recognition of the interactions between different environmental and anthropogenic drivers (e.g. water, energy, food, and communities) and recognition of constraints on sustainability (from local to global scales), there is a need for more sophisticated understanding of these relationships. Developing such scientific understanding is best done through integrated models that encapsulate knowledge across different disciplines.
- **Incorporation of New Technological Developments.** There are rapid advances in software tools that can enhance modeling in general and modeling integration in particular. Adoption of these approaches will lead to new developments and generally benefit the decision-making role of models.
- **Understanding Feedbacks.** Dynamic feedbacks between human and natural systems are, in many cases, not studied or understood. As a result, model integration of such systems is performed in a more static manner, e.g., with fixed regulations in an operations model. This is often a constraint of how component models are integrated, with 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 the ideas described here are acknowledged by the modeling community but are not fully implemented because of institutional or resource constraints. A directed effort at coordinating actions among the community of modelers, such as those outlined in the following chapter, is more likely to lead to beneficial outcomes than a more organic, undirected approach.

8 Proposed Integrated Modeling Strategic Plan

Following the identification of future modeling needs and the basis for future actions as presented in the previous chapter, we recommend future activities to encourage model integration in the Delta. These activities are presented in the form of a strategic plan. This plan is intended to lay out a menu of possible actions which may be undertaken at different times and evaluated for success before proceeding. It is envisioned that the leadership for implementing this plan will be provided by the IMSC in collaboration with the DSC.

Integrated Modeling Future

Given current modeling activities and future modeling needs in the Delta, focused efforts to enhance model integration are expected to benefit the community of modelers, decisionmakers, and other stakeholders. This section outlines four alternative future directions and specific steps for enhancing integrated modeling in support of future decision-making in the Delta.

8.1 Alternatives for Future Development

Given our current understanding of the status of model integration, the primary participants, and anticipated future needs, we lay out four possible paths for future development in **Table 6**. 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 are associated with different levels of commitment and resources (human and financial), in recognition of the fact that there will be practical constraints in what can be implemented over different time frames. It is important that the IMSC focus on a preferred alternative to pursue additional development in the near term. Key considerations associated with each alternative are presented in **Table 7**, including the opportunity, the limitation and funding resources needed.

Table 6. Description of Alternatives for Integrated Modeling 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 7. Alternatives for Integrated Modeling 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.

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, as we have noted, most integration is off-line, and, with some exceptions, there is limited exchange and learning opportunities across different organizations. Such an alternative would entail continued guidance by the IMSC, a voluntary committee, and with the DSC providing the 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 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 modeling 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 (Alternative 3), plus a common workplace where staff from participating organizations could work together. The placement of staff in the collaboratory 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 and beyond.

8.2 Recommended Actions

We define here a set of recommended actions for the DSC, the IMSC, and other participants from the modeling community to implement an Integrated Modeling Strategic Plan. These actions, numbered 1 through 10, are listed in **Table 8** with further expansion of each action in the following sections. 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 8. Recommended Actions for implementing alternative

<table>
<tr><th>Recommended Action</th><th colspan="4">Alternative</th></tr>
<tr><td>1. General IMSC Actions</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></tr>
<tr><td>3. Staff Development</td><td></td></tr>
<tr><td>4. Operations Model Improvements</td><td></td></tr>
<tr><td>5. Implementation of Enhanced Model Integration</td><td></td></tr>
<tr><td>6. Education Plan</td><td></td><td></td></tr>
<tr><td>7. Interaction across Modeling Communities</td><td></td><td></td></tr>
<tr><td>8. Integrated Modeling Research Program</td><td></td><td></td></tr>
<tr><td>9. Creation of a Virtual Collaboratory</td><td></td><td></td></tr>
<tr><td>10. Creation of a Physical Collaboratory</td><td></td><td></td><td></td></tr>
</table>

8.2.1 Recommendation 1 - IMSC Actions

These actions consist of steps that the IMSC would take to implement the concepts in this plan. The recommendations for IMSC actions are divided into near-term components (to take place in the next year) and medium-term components (to take place over the next two to five years).

8.2.1.1 Near Term

We recommend these near-term IMSC actions as a fundamental component of all four alternatives moving forward. A key component of Recommendation 1 is to assess opportunities where integrated modeling is needed, now and in the future, based on prospective applications identified in this work (Chapter 7).

We recommend that the IMSC conduct stakeholder outreach to develop support for the strategic plan outlined in this document, including the modeling community, and decision-makers and managers in participating agencies that will need to provide funding and staff for any future efforts. The IMSC should recommend different levels of support (in terms of human resources and monetary resources) for different alternatives needed over the short term (1-5 years) and intermediate term (5-10 years) time horizons, and which organizations will provide this support.

Interaction with other wide-ranging DSC planning activities is a key piece of recommended IMSC actions over the next year. These planning activities may include those related to adaptive management, structured decision making, and monitoring enterprise review.

8.2.1.2 Medium Term

We recommend that the IMSC support implementation of enhanced model integration for selected key projects. These key example projects will highlight the benefits to be achieved from enhanced model integration and will highlight the best modeling practices outlined in Memo 4 and summarized in Appendix B of this report.

The IMSC should continue to evaluate costs and benefits of individual options. Within the two- to five-year time frame, we recommend that the IMSC select an initial path forward.

8.2.2 Recommendation 2 - Improve Modeling Robustness

Modeling best practices, expected to enhance the utility of modeling efforts to decision-makers and stakeholders, are discussed in Memo 4 and summarized in Appendix B of this report. Modeling best practices apply equally well to individual discipline-specific models as well as integrated models that combine knowledge from different disciplines. We recommend that the IMSC adopt standards for modeling best practices developed in this study, especially for large-scale modeling efforts with relevance to economically consequential decisions. The adoption of robust and consistent modeling approaches across different domains will enable integration over time.

Appendix B presents three templates based on best practices for modeling discussed above. We recommend that these three templates be utilized in the following way:

- Template 1 is a checklist for defining model purpose at the inception of a modeling project.
- Template 2 is designed for evaluating completed model applications, with higher expectations from large, consequential modeling efforts.
- Template 3 is designed to help evaluate the long-term sustainability of a modeling framework.

8.2.3 Recommendation 3 - Staff Development

We recommend that the IMSC promote a formal staff development and training program as well as a succession program. Training is often delivered within organizations that utilize models or by modeling and professional associations. Many of the regional, state, and national organizations previously discussed offer model-specific workshops. These workshops provide time for direct interface with model experts and networking with other domain modelers in addition to the expertise that may be available within the learner’s own organization. With expert retirements affecting model use within organizations (Medellin-Azuara et al., 2017), these workshops fill an important role in training and aid in succession plans for each organization. Organizations like CWEMF, GRA, and university systems offer modeling training workshops with regional and statewide applications related to the Delta. The development of web-based training tools will provide an easy-to-use repository of institutional knowledge on model application. In addition to the development of staff training protocols, we recommend the rotation of staff within agencies to provide cross-disciplinary training and a broad knowledge base.

8.2.4 Recommendation 4 - Operations Model Improvements

Operations models such as CalSim are widely used in ongoing model integration efforts, often with a constrained set of inputs. Because of the significant role of reservoir operations in California streamflows, operations models will continue to be central to large-scale modeling endeavors in the State. 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.

We recommend that the IMSC develop a long-term operations model development pathway in consultation with a broad base of stakeholders that are likely to use this model or other future successor models. Based on our survey of recent integrated modeling applications in the Delta (see Chapter 3), we offer the following specific recommendations:

- A mechanism should be developed to relate fixed level-of-development operations modeling approaches to models that have a strong memory of conditions from year to year (such as ecosystem models or groundwater models).
- Data and model development efforts should be initiated to reduce the time step of CalSim and other operations models from monthly to daily. While we recognize such an effort will require significant resources, we believe such an advancement is needed for integration with many water quality and ecosystem models.

8.2.5 Recommendation 5 - Implementation of Enhanced Model Integration

Technological solutions to facilitate integrated modeling are discussed in Memo 3 and summarized in Chapter 6 of this document. These solutions include model standards, integrated code development, model emulators to represent complex models, and data analysis and integration frameworks, all designed to improve the ability of models to work together. We recommend that the IMSC implement these technological solutions for enhanced model integration.

- **Model standards** can be further broken down into three key components: data exchange standards, documentation standards, and use of common, well-defined nomenclature. It is important to point out that good practices in the development of individual models directly translate to greater ease of integration across models when the need arises. In addition to Memo 4 (*Recommendations for Modeling Best Practices*) prepared as part of this work, the California Water and Environmental Modeling Forum (CWEMF) is also in the process of developing modeling protocols to help standardize modeling activities.
- **Integrated code development** ensures that future efforts require participants to develop future models or modify existing models that meet a public specification. Borrowing from the experience of past efforts, a new system can be developed that is modular, extensible, and nearly future proof.
- Another alterative that has gained some currency in the literature is to use **model emulators to represent complex models** within an integrated modeling framework. Emulators need some resources to develop, but once created, they may allow certain types of model integration that may not be possible with the original models.

- **Data analysis and integration frameworks** allow for integration of technical code and provide a means for managing the flow of input and output files. Through the use of "data dashboards", some of which can be freely published on the internet, data or model results can be tabulated or visualized by model stakeholders.

The IMSC can take the lead toward the development of common terminology to allow different specialties to understand one another. A consistent terminology for similar processes and observations, including the reporting units, is desirable to minimize loss of information across models, and to allow consistent communication across stakeholders. It may be unrealistic to expect that all models will use the same terminology, but it is reasonable to require that the terminology be fully defined before it is used in each case. The online model inventory (see Memo 1 *Model Inventory*) is a good place where key and commonly used terms can be defined with typical units, in the form of standardized dictionaries.

8.2.6 Recommendation 6 - Education Plan

Integrated modeling will need special training for a new generation of practitioners. We recommend that the IMSC develop an education plan that incorporates learning resources in both in and out of the classroom setting. Key elements of such a plan are discussed below, with additional details to be developed.

The University of California (UC), the California State University (CSU), and other university systems in the state offer programs with foundation in modeling. Many programs offer opportunities for students to interact and participate in internships with regional, state, and federal agencies tasked with water resource management (e.g. US Army Corps of Engineers). Graduate programs often provide opportunities for mentorship with academic modelers, providing the training ground for many of the modelers in both public agencies and private consulting. However, with many models developed within agencies and consulting companies, graduates with strong modeling foundations often learn modeling isolated within the workplace. Development of partnerships with universities beyond California would bring fresh perspective to integrated modeling applications and broaden the pool of skilled technical staff.

The development of new course content or additions to existing courses in California universities would encourage cross-disciplinary applications. Incorporating the following into course curriculum could enhance training in the University setting: cross disciplinary courses; introduction to the technical challenges of integrated modeling; and computer science training in integrated code development.

There are also needs and opportunities for training outside the classroom, especially directed at practitioners. It is envisioned that training in specialized models would be encouraged and perhaps facilitated by the IMSC, with the goal of creating a community of modelers with some familiarity with models outside their specific domain. Such training could occur as workshops or provided virtually through training materials online. Not all individuals trained would become advanced users but would learn enough about models in different domains to identify new integration opportunities. Encouragement for such training should be provided to individuals and to organizations participating in modeling in the public and private sectors.

8.2.7 Recommendation 7 - Interaction across Modeling Communities Inside and Outside the Delta Region

Modeling communities inside the Delta region can draw upon experience and lessons learned from projects and experts beyond the Delta. Interaction across modeling communities inside and outside the Delta region can leverage tools and human resources from a larger network of participants beyond the Delta. We recommend that the IMSC encourage interaction across modeling communities inside and outside the Delta region

Focusing on the human aspect of model integration, it is helpful to think of distinct roles in a larger modeling community: individuals/teams who develop and maintain specific models; individuals/teams that apply existing models to specific situations; individuals/agencies who direct and use model results and drive the need for integration across disciplines, but are not directly involved in running models; and other stakeholders who are affected by model outputs in some form. Engaging the shared common focus around important challenges can be accomplished with these methods. User groups in the region are typically focused on problem solving and development for specific high-use models. Regional forums, such as the Interagency Ecological Program (IEP) and more recently the IMSC, were founded to facilitate interagency and integrated modeling research in the Bay and Delta. State and national forums, such as the California Water and Environmental Modeling Forum (CWEMF), The Groundwater Resource Association of California (GRA), the American Geophysical Union (AGU), and the American Society for Civil Engineers (ASCE), host annual meetings, conferences, and technically-focused interdisciplinary forums that offer opportunities for modelers to exchange knowledge and approaches to their regional problem-solving. The benefits of such interaction and collaboration include the engagement of a larger pool of technical experts, participation in the development of model interoperability standards that are applicable globally for specific technical disciplines, leveraging common tools for modeling, analysis, data management, and visualization, and transfer of lessons from practices adopted in other regions.

8.2.8 Recommendation 8 - Integrated Modeling Research Plan

Complexities arising from integrated modeling are not fully understood and need focused research. We recommend that the IMSC undertake an integrated modeling research plan to further investigate the following issues:

- Understand the complexities arising from integrating different models, such as calibration and uncertainty propagation, and to explore when added complexity benefits system insight and decision-making;
- Support social-science oriented research to understand human-environment interactions over different time horizons; and
- Evaluate the role of new technologies, such as computation through cloud computing, new software tools, data management and visualization tools, and incorporation of new data collection technologies.

8.2.9 Recommendation 9 - Creation of Virtual Collaboratory

The creation of a virtual collaboratory is the capstone of Alternative 3 and incorporates all the previous recommendations. 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. Regardless of choice, the computer resources will require continued financial support. The virtual collaboratory could have limited staff of its own but draw upon assigned leads within existing organizations.

The virtual collaboratory would serve as a living repository of information on Delta modeling, including models, documentation, and training resources. Over time, it would become a single point of entry to learn about and contribute to modeling in the Delta.

8.2.10 Recommendation 10 - Creation of a Physical Collaboratory

A physical collaboratory would provide a physical place 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.

In response to interest in this concept, UC Davis Center for Watershed Sciences hosted a National Science Foundation/Delta Science Council co-funded workshop to gain consensus within the multi-disciplinary modeling community on how best to enhance the modeling efforts across the Delta (Goodwin et al, 2015)[2]. Goodwin et al. (2015) stated that a physical collaboratory would provide support for integrated modeling by several means:

- Centralized physical space intended for meetings, work, education, and in-house computational infrastructure.
- Technical staff and working teams focused on addressing existing and developing issues within and across model domains. As a virtual and physical forum on models, these teams would provide capacity for both the continual evaluation and updating of existing models, but also individualized technical support when possible.
- Educational resources for all levels of modelers as well as project managers and decision makers. Focusing on project-based learning (Thomas, 2000), the collaboratory would provide a learning environment focused on applied problem-solving for current research project and management needs.

Going beyond the vision above, the concept of the collaboratory may evolve over time, in particular with regards to the composition of its staff and the kinds of roles it would play in future modeling efforts. However, its primary feature, that of a physical location for interaction among modelers, is expected to remain a part of the concept. Regardless of

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[2] See also: https://watershed.ucdavis.edu/project/integrated-environmental-modeling

the near-term decision on the creation of a physical collaboratory, it may take several years for the facility to develop and build the staff capabilities to take a leading role in environmental modeling integration.

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Appendix A: Inventory of Models in Use in the Delta

A first step in model integration efforts for this project was the development of an inventory of models used in the Delta and the Central Valley. The primary goal of the model inventory was to move towards developing a shared and interactive library useful for future modelers, model users, and other professionals while identifying opportunities for interaction between models. The model inventory includes models in current use in the Delta across a range of engineering, science, and social science disciplines. This inventory was developed through the combined expertise of individuals working in the different domains identified.

The model inventory highlights how models have been used in a decision-making context (e.g., land- and water use planning, ecosystem restoration, multi-purpose flood risk reduction, climate change adaptation and hazard assessment, water pricing and trading) to address management questions in the Delta, and for relevant issues in the Delta watersheds and the Bay.

The models, presented in **Table A-1**, are divided into the following categories:

- Reservoir operations models
- Hydrodynamics models
- Human ecology and economics models
- Groundwater - surface water models
- Fisheries and ecosystems models
- Greenhouse gas emissions and land use models
- Water quality models

- Soil chemistry and salinity models
- Consumptive use models
- Processing and visualization tools

Within the model inventory, a distinction was made between general model frameworks and Delta-specific models. Thus, under each broad heading category listed above, the inventory is further classified into 'model frameworks' and 'Delta specific models.'

Each model description contains a brief summary and features that are pertinent to future model integration. The general criteria for characterizing each model are shown in **Table A-2**.

This model inventory is meant to be a living document. It is anticipated that the inventory will be updated over time as models are updated, new studies are completed, and new models are developed. The most up-to-date model inventory can be accessed online at: https://cwemfwiki.atlassian.net/wiki/spaces/MI/overview

Table A-1. Models in the inventory

Model Category	Model Type	Model Name
Reservoir Operations Models	**Model Frameworks**	WEAP (Water Evaluation and Planning)
		WRIMS (Water Resource Integrated Modeling System)
	Delta Specific Models	CalSim II
		CalSim 3
		CALVIN
		SacWAM (Sacramento Water Allocation Model)
Hydrodynamics Models	**Model Frameworks**	Delft3D-FM (Finite Mesh)
		EFDC (Environmental Fluid Dynamics Code)
		RMA2
		SCHISM (Semi-implicit Cross-scale Hydroscience Integrated System Model)
		SUNTANS (Stanford Unstructured Nonhydrostatic Terrain-following Adaptive Navier-Stokes Simulator)
		TRIM/UnTRIM (Tidal, Residual, and Intertidal Mudflat/Unstructured)
	Delta Specific Models	DSM2 (Delta Simulation Model 2)
		ANN Model Emulators for DSM2
		FDM (Fischer Delta Model)
		RMA3D San Francisco Estuary Model
Human Ecology and Economics Models	**Model Frameworks**	HAZUS-MH (HAZUS Multi-Hazard Model)
		IMPLAN (IMpact Analysis for PLANning)
		REMI (Regional Economic Models, Inc)
		SWAP (Statewide Agricultural Production Model)
	Delta Specific Models	DAP (Delta Agricultural Production Model)
		F-RAM (Flood Rapid Assessment Model)
Groundwater - Surface Water Models	**Model Frameworks**	IWFM (Integrated Water Flow Model) / IDC (IWFM Demand Calculator)
		MODFLOW (USGS Modular Groundwater Flow Model)
		MODPATH
		MT3D
		PHAST (PHREEQC And HST3D)
		STANMOD
		SUTRA (Saturated-Unsaturated TRAnsport)
	Delta Specific Models	C2VSIM (California Central Valley Groundwater-Surface Water Simulation Model)
		CVHM (Central Valley Hydrologic Model)
		CVHM-D (Central Valley Hydrologic Model - Delta)
Fisheries and Ecosystems Models	**Model Frameworks**	ELAM (Eulerian-Lagrangian-Agent Method)
		inSALMO (Improvement of Salmon Life-Cycle Framework Model)
	Delta Specific Models	Delta STARS (Survival, Travel Time, and Routing Simulation)
		DPM (Delta Passage Model)
		DSLCM (Delta Smelt Life Cycle Model)

Model Category	Model Type	Model Name
		EFT (Ecological Flow Tools)
		ePTM (Enhanced Particle Tracking Model)
		IOS (Interactive Object-Oriented Simulation)
		SacPAS Fish Model
		SALSIM (Salmon Simulator)
		WRLCM (Winter Run Life Cycle Model)
Greenhouse Gas Emissions and Land Use Models	**Model Frameworks**	CANVEG
		DAYCENT (Daily CENTURY Model)
		DNDC (DeNitrification DeComposition)
	Delta Specific Models	PEPRMT-DAMM (Peatland Ecosystem Photosynthesis, Respiration, and Methane Transport – Dual Arrhenius Michaelis-Menten)
		SUBCALC
Water Quality Models	**Model Frameworks**	CE-QUAL-W2
		HEC-5 and 5Q (Hydrologic Engineering Center)
		HEC-RAS (Hydrologic Engineering Center's River Analysis System)
		HSPF (Hydrological Simulation Program FORTRAN)
		PHREEQC (pH-REdox-Equilibrium)
		SWAT (Soil & Water Assessment Tool)
		VIC (Variable Infiltration Capacity)
		WARMF (Watershed Analysis Risk Management Framework)
	Delta Specific Models	SBWQM (South Bay Water Quality Model)
		USRWQM (Upper Sacramento River Water Quality Model)
Soil Chemistry and Salinity Models	**Model Frameworks**	Hydrus
		Watsuit
Consumptive Use Models	**Model Frameworks**	Cal-SIMETAW (California Simulation of Evapotranspiration of Applied Water)
		CIMIS (California Irrigation Management Information System) and AmeriFlux
		DisALEXI (Atmosphere-Land Exchange Inverse (ALEXI) flux disaggregation approach)
		ITRC-METRIC (Mapping of EvapoTranspiration with Internal Calibration)
		SIMS (TOPS Satellite Irrigation Management Support)
	Delta Specific Models	DETAW (Delta Evapotranspiration of Applied Water)
		DICU (Delta Island Consumptive Use)
Processing and Visualization Tools		Groundwater Vistas
		HEC-DSSVue (Hydrologic Engineering Center's Data Storage System Visual Utility Engine)
		ModelMuse
		PEST
		T-PROGS (Transition Probability Geostatistical Software)
		USGS Model Viewer
		Visual MODFLOW

Table A-2. Criteria used for evaluating models

Criterion	Explanation
General Description	Brief overview of model.
Model Domain	Physical domain of the model.
Developer	Name of company/agency/individual that developed the model.
Hardware computing requirements	Specific computational requirements, if available.
Code language	Language the model was coded in.
Original application	Focus of the original model, type of processes and conditions modeled.
Public/proprietary and cost	Whether model and source code are public and modifiable, or if proprietary. Where available, specific licensing costs were reported.
Process or empirically based	Whether the underlying formulation of the model solves mechanistic equations, or is based on an empirical formulation. Both types of model are considered.
Mathematical methods used	Mechanistic or empirical approaches used; numerical approaches used for solutions.
Input data requirements	Typical input data needs, and difficulty of preparing these data sets from publicly-available information.
Outputs	Nature and format of outputs (spatial and temporal detail and formats used).
Pre-processing and post-processing tools	Available processing tools that are provided with the model or by a third-party.
Representation of uncertainty	How uncertainty analysis is integrated into the modeling framework.
Prevalence	How common is the model; are there many known applications (not just peer-reviewed publications)?
Ease of use for public entities	What are the barriers to the widespread use of the model, in terms of training or specialized supporting hardware and software?
Ease of obtaining information and availability of technical support	Is the model actively supported with an engaged user group or commercial help desk?
Source code availability	Is the source code available for modification if needed?
Status of model development	Whether the model is developed and available for immediate use; this may include models that continue to be updated. What is the future direction of model updates?
Challenges for integration	What are the challenges or barriers to integration with other models?

Appendix B: Best Practices for Modeling

An underlying theme of this report is the growing use of environmental models to assess the most societally important environmental problems. This chapter provides guidance for best practices that are expected to enhance the utility of modeling efforts to decision-makers, stakeholders and to the modeling community in general. The guidance offered in this chapter applies equally to individual discipline-specific models and integrated models that combine knowledge from different disciplines. Many of these concepts are general and can also be considered by non-modelers who need to understand the scope of a modeling exercise at its inception and to make a judgement as to the utility of the results upon its completion. This chapter is focused on applications in San Francisco Bay, the Central Valley and Sacramento-San Joaquin Delta that pertain to areas of interest of the Delta Stewardship Council; however, the recommendations for best practice are applicable outside of this geographic domain.

This work provides a summary of actions that need to be undertaken to improve the robustness of virtually all modeling exercises, including efforts that are relatively modest in scope. These actions include: defining modeling purpose; developing conceptual models to provide a compact and transparent representation of key processes to communicate with stakeholders and other technical specialists; preparing standardized datasets that can be used to replicate a modeling study and compare across models; verifying code to ensure that the theoretical framework has been correctly implemented; documenting the model calibration process; and evaluating model performance over new data sets. This work also recommends a broader exploration of model structure and bias, going beyond routine calibration and evaluation/validation exercises, especially when observed data do not adequately match model predictions. Finally, this work recommends that adequate documentation be developed and made readily available to meet the needs of users as well as current and future modelers.

Additional practices can be adopted to improve modeling, but imposing requirements for such actions may not be practical for all studies. Additional actions for major modeling studies (i.e. those studies tied to large societally consequential decisions) are identified separately. These additional actions include: peer review of model studies at various stages of implementation; model sensitivity analysis to identify key drivers; model uncertainty analysis; consideration of novel approaches to meet sensitivity and uncertainty analysis needs of complex models and model frameworks; consideration of alternative models for model studies (where available); post-audits (i.e., review and evaluation of historical model predictions in light of new field observations); and development and compatibility with exchange standards to enable data sharing across models.

The technical strength of a model can be established through the above steps. Nonetheless, there remain several non-technical issues that should be addressed to meet the broader goals of a modeling exercise. These non-technical issues include: development of a communication strategy for a modeling study; consideration of bias in many aspects of the model formulation; presentation of results across many audiences; building trust across the community that will be using the model results; overall user-friendliness of the modeling framework; and practices for sustaining the usefulness of a model over a long-term horizon.

To encourage adoption of the best practices identified in this work, we provide three summary sheets at the end of this chapter, corresponding to different stages of modeling. The purpose of the first sheet, designed as a checklist to be employed at inception of a modeling effort, is to enable various participants to agree on the basic features of the work to be done. The purpose of the second sheet is to evaluate and score a modeling exercise upon completion. The final sheet is to assess the overall life cycle of a modeling framework.

B.1 Overview of Best Practices

Models in general, and environmental models in particular, must strike a balance between the competing needs of accessibility and comprehensiveness (**Figure B-1**). A model formulation that is more readily understandable or accessible may focus on key processes and provide a more simplified system representation at the expense of omitting some more complex relevant drivers. A more comprehensive model formulation may represent many drivers and capture system complexity at the expense of greater challenges to implement, test, and explain.

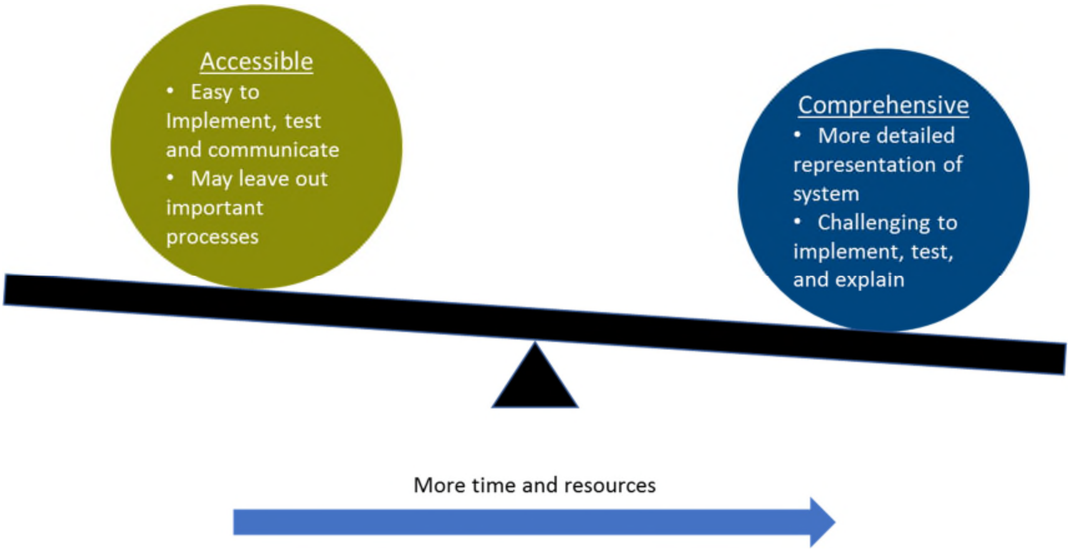

Figure B-1. Balance between accessible and comprehensive models.

Several different mathematical approaches may be applied in the development of quantitative environmental models as shown in **Table B-1**. The broad classes of mathematical approaches in use include analytical/numerical solution of process equations over a defined domain; statistical/empirical models that are based on relationships between observed data but typically contain little to no process representation; optimization based models that seek to meet key objectives subject to a set of defined constraints; machine learning based models, a sub-class of statistical/empirical models with a wider range of algorithms and capacity to handle disparate data sets; and agent-based models that represent behavior of organisms or populations (animal or human) in response to external factors. Several of these approaches may be combined within a single modeling system, resulting in a "hybrid" model. As described in the following chapters, the underlying approach adopted within a particular modeling framework affects the applicable best practices for development.

Table B-1. Types of models used for environmental modeling

Model type	Feature
Analytical/Numerical	Solving a framework of process equations, represented algebraically or numerically.
Statistical/Empirical	Based on finding relationships between observed data.
Optimization based	Focused on meeting key objectives under a range of input conditions
Machine-learning based	Trained on finding patterns or relationships in available data, but with minimal process-oriented representation. These are an extension of the statistical/empirical models, but with a greater variety of emerging algorithms to represent increasingly complex data sets.
Agent-based	Represents behavior of organisms or populations (animal or human) in response to external factors over time and space.

The steps necessary to model a specific problem depend on the nature and history of the problem being studied. When basic principles of the problem are well understood and mature, a model study will likely utilize an existing model framework, customized for a specific location of interest. When basic science associated with the problem is still developing, modeling will likely focus on the creation of new models, new model components, and/or the development of new codes. Both types of problems are evaluated through model studies in the Delta and are described further below.

Figure B-2 diagrams the sequence of steps that might occur for a problem with well-defined basic theoretical principles, mathematical representations, and computer implementations in place. The main steps, explained in greater detail in the following chapters, involve using observed data from the field to configure and calibrate the model; apply to various scenarios; and report results. Model results are compared against field data and can be subjected to a variety of tests to evaluate performance. To provide additional specificity for these modeling best practices, we separate the evaluation step into two phases: an initial evaluation that is expected to be applied for all model applications, and additional evaluation such as sensitivity and uncertainty analysis, requiring more resources and time, that are better suited for larger and more consequential exercises. Many applications fall into the category of applications shown in **Figure B-2**, where a modeling framework (such as MODFLOW or C2VSIM, for groundwater flow modeling[3]) is customized for a specific geography. Although the basic theory for this class of models is well-established, there are nonetheless many areas that are the focus of improved performance and research. These include collection of more spatially and temporally resolved field data to better configure the model; improving the calibration of the model to better fit observations; more efficient model run times; improved visualization and interpretation of results; and more sophisticated evaluation of performance as described in the following chapters. Over time, models in this category, while using the same theoretical equations to represent the underlying processes, are becoming more spatially and temporally detailed and resulting in greater computational requirements.

Figure B-3 diagrams the sequence of steps that may occur for a problem where the underlying scientific understanding is evolving. The primary difference between an evolving problem and a well-defined problem is that, at the inception of such a study, model structure, data needs, or even outputs are less certain. Here the focus is on collecting more data (typically new types of indicators to improve scientific understanding) and developing conceptual models to explain relevant processes and drivers for a variable of interest. A conceptual model may be thought of as a compact graphical representation of the key processes of interest in a modeling study. Benefits of a conceptual model are described below. A conceptual model may be converted to a quantitative model structure, thereby formally describing how inputs and outputs are related and then implemented in computer code. Such models may then be calibrated and evaluated in a manner consistent with more mature models. The modeling best practices proposed in this work apply to both newly-defined and well-established modeling processes. The distinction **Figure B-2** and **Figure B-3** is made not to downplay the role of evaluating and testing practices in models with evolving science, but rather to

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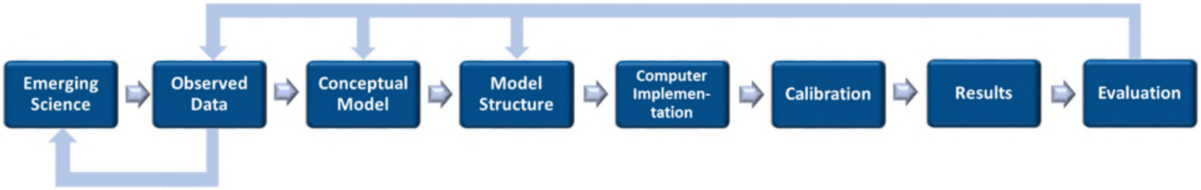
[3] See Memo 1, *Model Inventory*, for additional details on these and related frameworks.

point out that the primary attention may often be focused on improving the basic understanding and representation of the processes of interest.

Areas of Focus:
- More resolved observed data
- Improved model configuration
- Improved calibration
- More efficient performance
- Visualization of results
- Additional evaluation

Figure B-2. Modeling steps for a topic with well-developed theoretical frameworks and computer implementation.



Areas of Focus:
- Additional data collection
- Conceptual model
- Model structure

Figure B-3. Modeling steps for a topic where the scientific understanding is still evolving.

B.2 Improve Model Robustness for Typical Applications

Model studies vary greatly in time requirements and resources available for execution. Time requirements may range from weeks to many years, depending on the complexity and the importance of the underlying questions being asked. In this chapter, we identify a set of practices that help to address model robustness and are applicable to virtually all types of modeling activities, including applications that are relatively limited in time and scope. In this work, we refer to robust modeling exercises as those that are credible among the community of modelers and users and stand the test of time.

B.2.1 Define the Purpose of a Modeling Exercise

At the inception of a study, it is important to clearly define the specific purpose of a modeling exercise. While this practice appears obvious, it is often not explicitly addressed up-front among modelers and stakeholders. A clear specification of purpose is especially needed for modeling efforts that are not focused on open-ended research. An important goal of this practice is to constrain acceptable outcomes. The stated purpose should, at a minimum, allow stakeholders to agree on a broad scope of work, including: what processes will and will not be modeled, what data are needed, what form the results will take, and what the expected accuracy and uncertainty will be. Importantly, a modeler needs to understand the stakeholders' viewpoint of how the model results will be used. The model study's purpose can be defined with greater clarity when the task at hand consists of customizing an existing framework, rather than creating a completely new model. The more specifics are outlined early, the more efficiently the modeling exercise will progress. In many situations, elements of the modeling scope are not well-defined up-front and are later selected by decisionmakers based on the results obtained, likely resulting in a less-than-optimal use of the modeling effort.

B.2.2 Develop Conceptual Models and Transparent Model Formulations

Conceptual models, as used in the environmental domain, are abstractions of reality, ranging from a schematic representation of processes to a more detailed description of the state of science related to a specific environmental concern. Developing a conceptual model, even a simple schematic representation, is recommended as a first step in building a model and writing documentation. A conceptual model is a communication tool that guides model development, experimentation, and evaluation. Moreover, conceptual models may provide a good tool for communicating about a model with stakeholders, particularly when the conceptual model represents processes graphically and highlights key quantitative information. A good conceptual model improves understanding of the system and creates a point of reference for model developers to revisit when considering changes to the model.

In addition to enhancing communication, under certain circumstances, a well-designed conceptual model may more readily accommodate formal hypothesis-testing relative to a computer implementation of a conceptual model. A good conceptual model may lead to the early realization that development of a quantitative system model would be premature due to data and knowledge gaps.

In some instances, conceptual models play a role following the synthesis of data and after completion of a modeling study. Typically, the initial conceptual model would be refined over the course of model application, and more quantitative information provided in the revised conceptual model. Such a model can serve as a basis for further communication with stakeholders. Graphical representation of modeled processes, with key quantitative information being highlighted when available, is a significant aid to communicating with stakeholders.

B.2.3 Verify Code

Code verification is the process of determining how accurately a computer program correctly solves the equations of a mathematical model. It is assumed that most established model frameworks in common use will have undergone this test, and thus, this task is appropriate when a new code or module is being developed for a specific application. Code verification also provides an opportunity to evaluate or reevaluate the efficiency of the code, which may enable its use for situations that require multiple model runs, such as for sensitivity analysis. Typically, computer codes are verified with well-documented data sets and the results of published and documented analytical or semi-analytical models. Within many large-scale computational models, opportunities exist to perform verification studies that reflect the hierarchy or collection of these models. For example, code verification can fruitfully employ “unit tests” that assess whether the fundamental software building blocks of a given code correctly execute their intended algorithms. Documentation of code verification, especially for newer models or for models where modifications are being made to established codes, is an important part of establishing model robustness.

B.2.4 Prepare Standardized Observed Datasets for Analysis

Observed data are a fundamental part of sound modeling practice. In most instances, environmental models contain parameters that are defined independently or are adjusted as part of the model setup. Parameters that cannot be determined independent of the model (e.g. a reaction rate for a chemical process within a water body or a roughness coefficient for a stream bed) are estimated through the process of model calibration (described below), which involves tuning the parameters to obtain a good fit between the model and observed data. Thus, data that are credibly measured, have good quality and measured with an established quality assurance protocol, have been cleaned of potential erroneous values, and well documented for limitations are an essential part of the modeling process. California Assembly Bill 1755 (Open and Transparent Water Data Act, AB 1755) is a large step toward such a data resource. The bill requires California state agencies to make data publicly available and to develop protocols for data sharing, documentation, quality control, and promotion of open-source platforms and decision support tools related to water data. Once fully implemented, AB 1755 may provide observed data in a form that is suitable for model studies (i.e., for calibration and testing). Additionally, the California Water Quality Monitoring Council has requirements for quality assurance program plans that must be used in collecting water quality data.

B.2.5 Accommodate Appropriate Model Complexity

In most modeling situations encountered in the Delta, more than one approach may be taken for model development. Where the task requires use of an existing model, more than one model may be available for use. Where the task requires the development of a new model, the modeler has some discretion on the level of process complexity to be used. In both cases (existing or new model), the modeler has the flexibility to determine the level of spatial, temporal and process detail incorporated. As an example, a dynamic model may compute and report values at timesteps of minutes, days, or longer. A spatially detailed model may contain a grid with sizes ranging from square meters to hundreds of square kilometers. An appropriate level of model complexity is a function of multiple factors, including but not limited to objectives of the modeling exercise, knowledge of the system, and data availability. A useful rule of thumb for deciding on the level of complexity *a priori* is that the model outcomes should be testable by observed data spatially and temporally. For example, when choosing between a simple lumped model and a more sophisticated distributed model, a model developer should be able to 1) support the added complexity by more detailed input data available for the distributed model (e.g. distributed measurement of related properties), and 2) test whether this added complexity is providing an additional benefit by comparing the simulations with available observed data.

Figure B-4 illustrates the conceptual relationship between model complexity, data availability, and predictive performance. The term "data availability" implies both the amount and quality of the data in terms of its use for model testing. Within the context of hydrology, access to spatial patterns of surface runoff data is considered "high" availability while scarce streamflow measurements as aggregated runoff implies "low" availability. The term "model complexity" means detail of process representation and spatial/temporal detail. Complex models include more processes and report values at greater spatial and temporal density. As illustrated in **Figure B-4**, for a given data availability, there is an optimum level of model complexity giving the highest predictive performance; additional complexity leads to concerns with identifiability or equifinality. For a given model complexity, more data availability results in better predictive performance up to a point, beyond which there is not more information from the data to improve the model with that level of complexity. Under these conditions, a model user may wish to consider a more complex model to better exploit the information from the available data.

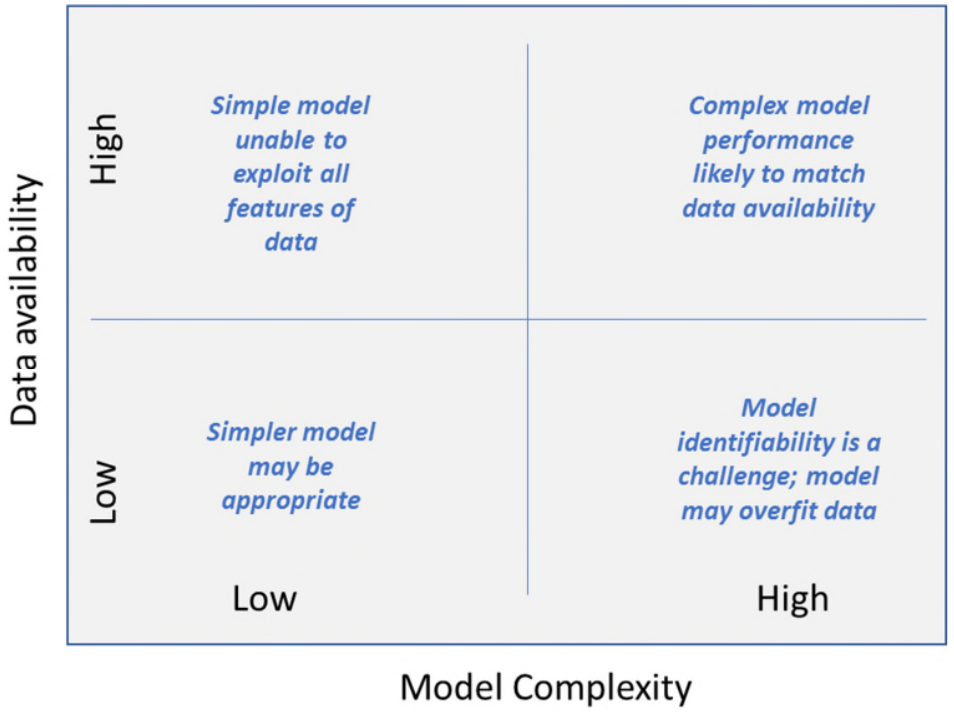


Figure B-4. The conceptual relationship between model complexity, data availability, and performance (modified from concepts in from Grayson and Blöschl, 2001).

B.2.6 Calibration: Formal Process for Parameter Estimation in Models

As previously discussed, environmental models often use parameters that are not known ahead of time but are derived on a site-specific basis from the observed data. Models use parameters within equations to relate various influences and responses (e.g., rainfall to runoff). Some of these parameters may be readily determined based on field measurements or other observations. Often, however, many model parameters are either too difficult to measure (specifically with proper spatial resolution) or practically impossible to measure (non-measurable parameters). An example of a parameter that is too difficult to measure with adequate spatial resolution includes the hydraulic conductivity in aquifers (used for groundwater modeling). An example of a non-measurable parameter is the Manning's n coefficient in surface water bodies (used for streamflow modeling). Furthermore, some domains, notably in the biological, economic, and social sciences, inherently use parameters that are lumped and location specific, and not known *a priori*.

Depending on the level of complexity, models can be posed with a small number of parameters or can be posed with a very large number of parameters – in extreme cases numbering in the thousands. The task of calibration—also termed training—is to find the set of best-fit parameters that describe the observed data with a given model. Formally, calibration is the mathematical process of searching for a solution that minimizes or maximizes an objective function (i.e. a function quantifying a measure of error based on model simulations and observed data), by adjusting the values of n unknown parameters, i.e., a search in n-dimensional space. The general goal is to find a global best-fit, but in complex models this is often difficult, and it is not uncommon to find model calibration codes settling in local minima. Superficially, local minima have some features of a global minimum, but formally, they do not represent the best parameter fit.

B.2.7 Quantitative Model Evaluation and Validation

The term validation has traditionally referred to the process of comparing model predictions with a data set that is independent of model calibration. While this process can provide a generally reasonable evaluation or assessment of the model performance, interpretation of validation results should be developed with care. Because there is inherent uncertainty in all models, the term validation is somewhat a misnomer. Because of the term's root (i.e. "valid"), the process of model validation implies an unjustified assertion of legitimacy (e.g. Oreskes and Belitz, 2001). According to this argument, the use of the word validation is misleading in the context of assertions or implications that models accurately reflect underlying natural processes and can be used to provide reliable input for policy and decision making. For example, there is unavoidable uncertainty associated with the subjectivity of what constitutes acceptable error (Konikow and Bredehoeft, 1992).

B.2.8 Non-Quantitative Model Evaluation and Validation

Going beyond the evaluation of numeric results and data as identified in the previous section, given our experience with environmental models, a broader set of considerations may be applied:

- **The bias of stasis.** When model parameters are adjusted to obtain a best fit with historical data, a bias is created towards existing trends, even when driving forces indicate that the model will diverge from existing conditions. A relevant example for modeling hydrology in California and the Delta is hydrologic effects from climate change. Changing climate is affecting driving forces including evapotranspiration trends, the frequency and magnitude of precipitation events, and changes in groundwater and surface water pumping in response. These driving forces are outside the typical range in the historical record and thus the future conditions may diverge outside of a model built on past conditions. It will often be important to run models with varying assumptions about driving forces.

- **Capturing causal processes.** If the underlying causal processes are important, as is the case with most hydrologic and ecosystem models, the model must capture them to be reliable. Model post-audits (see next chapter) can serve to provoke curiosity about why the model does or does not make accurate predictions.
- **Conceptualization.** Models may match observations but still be conceptually flawed. Advances in computational power may help with this in the sense that if a model is run using an exhaustive sampling of parameter values and comes up short, a conceptual error is likely. This is perhaps the thorniest of modeling issues and a difficult one to address, and the reason post-audits are so important.
- **Overparameterization.** The level of model complexity and number of parameters should be commensurate with the available data and required predictive resolution. Model developers refer to the concept of “model parsimony,” which is the development of models with the least number of parameters that adequately explain a relevant phenomenon. While more complex models can be made to fit observed data, this “over-fitting” approach may result in limited model ability to generalize.

Model “validation” should not only include a post-audit but also a close look at the model conceptualization, the ability to capture causal processes, biases (including biases towards stasis), and parameterization.

B.2.9 Model Documentation for Users and Developers

Documentation may apply to a general modeling framework and to a specific application. With respect to a framework, in many cases model frameworks are developed and maintained over years, sometimes with different individuals or teams with changing composition. Good model documentation should serve the needs of developers and users and may be accomplished by the same set of documents. Ideally, documentation should be prepared in a manner that contains enough information to allow for the long-term evolution of a model, both within the organization and external to it. From the perspective of external users in particular, documentation should explain the basis of the model and its use, including how key input variables are selected. Such documentation should include representative input files and result files to allow a user to reproduce a basic set of scenarios.

In the case of a specific application, documentation needs to be oriented toward explaining the best practice elements that are outlined in this section, including, model purpose, input data used, calibration approach, model evaluation, and model results in the context of the intended purpose.

Writing model documentation is an essential step in model development. However, under short timelines and tight budgets, preparing documentation may become a low priority, particularly for models developed for a specific application with no expectation of re-use. Missing, inadequate, or out-of-date documentation is a barrier to model integration and may result in duplication of effort because a potentially suitable model may be overlooked for inclusion in an integrated modeling process.

B.3 Improve Model Robustness for Key Applications

The previous section summarized actions that need to be undertaken to improve the robustness of virtually all modeling exercises. Additional actions are recommended beyond those previously summarized when model applications entail greater complexity (e.g. integrated models) and/or when model applications are used to support critical decision making that will have significant societal consequences in terms of benefits, costs, and risks. These additional actions will almost always require more time and resources to complete, and this should be clearly scoped with the model sponsors and stakeholders. While greater costs are associated with these actions, the resulting model outcomes will be more robust and more generally accepted by the modeling community and model users.

B.3.1 Peer Review

Peer-review is the process of soliciting input from experts who are not involved in a particular study but are familiar with the general topic. Peer review should provide timely, open, fair and helpful input and should ideally occur at various stages of the modeling life cycle, including conceptual model development, model implementation in code, and model application to specific geographic area or problem.

Experience indicates that peer review is most helpful when the following conditions are met: i) peer review is conducted in an atmosphere of transparency, collaboration and shared sense of purpose; ii) the review team reviews the source material and modelers' responses to their comments; iii) adequate time is budgeted for review; and iv) the review team contains some interdisciplinary membership to allow for a broader evaluation of basic assumptions and utility of the exercise. If a sincere commitment to obtaining constructive feedback is not made through the above steps, there is a risk that peer-review becomes more of a rubber-stamp than a positive contribution to a modeling study.

We recommend that most complex and consequential model studies in the Delta be subject to peer review. Usually such reviews are conducted by the organization sponsoring the model study. For newly developed model frameworks, the process of anonymous peer review required by scientific journals serves as the touchstone for validation of a modeling study and is also recommended.

B.3.2 Sensitivity Analysis

Sensitivity analysis explores how changes in model inputs—most generally, boundary conditions, parameters, or configuration—affect the variation in model outputs.

Sensitivity analysis can illustrate which parameters have the least effect on results of interest, and in some cases, may allow for reduction of model complexity, by streamlining process representation. Sensitivity analysis also complements model calibration, which involves selecting parameter values based on the fit between model output and actual observations. Performing sensitivity analysis after model calibration helps to identify which fitted parameters are close to optimal estimate because low sensitivity indicates high uncertainty in the fitted parameter estimate. Both sensitivity and uncertainty analysis require the running of a model multiple times with a range of inputs. Specific steps for uncertainty analysis are described in the following section.

Sensitivity analysis is often used prior to conducting uncertainty analysis to increase the efficiency of uncertainty analysis by reducing the dimensionality of the model. Using sensitivity analysis, the modeler determines which model parameters have the highest impact on simulations (Saltelli et al., 2008). This will help the modeler to decide which model parameters should be included in the uncertainty analysis procedure, thereby increasing the efficiency of uncertainty analysis. Because sensitivity analysis of complex models can be highly computationally demanding, it is a focus of current research to help improve efficiency and applicability.

B.3.3 Uncertainty Quantification and Propagation

Models, as simplifications of reality, are subject to various forms of uncertainty. In environmental models specifically, these sources of uncertainty include: i) parameters, ii) structure (model conceptualization), iii) initial state variables, iv) configuration and input variables, and v) observation data used for training and testing the model. Further, the nature of uncertainty can be categorized into epistemic uncertainty and aleatory uncertainty or stochastic uncertainty (Walker et al., 2003). Epistemic uncertainties stem from our lack of knowledge and they can be reduced with additional collection of data. In contrast, aleatory uncertainties originate from inherent variability and stochasticity of natural phenomena (e.g., climatic variability). Aleatory uncertainties cannot be reduced by collection of more data. For certain natural phenomena, this means that there is no direct way of getting perfect knowledge. Climate predictions over different time scales are perhaps the most common example of aleatory uncertainty in environmental models. Modeling applications typically include both epistemic and aleatoric uncertainties.

Uncertainty assessment methods fall under one of two classifications: forward uncertainty propagation and inverse uncertainty quantification. In forward propagation methods, uncertainties in model inputs are propagated to the model outputs. In inverse uncertainty quantification methods, posterior distributions of model parameters are derived based on discrepancies between model simulations and observations and values of likelihood function. Inverse quantification of uncertainty is much more complex than forward propagation of uncertainty, as the modeler is essentially solving the problem in reverse (similar to calibration). However, the method provides essential benefits when modeling as in most cases the uncertainties associated with various model elements (parameters, inputs, etc.) are initially unknown and using an inverse approach, the modeler can estimate the most consequential uncertainties, and select them for further evaluation. Thus, these uncertainties can be propagated to simulations through a forward approach. In most inverse uncertainty quantification applications, the overall modeling uncertainties are quantified as a lumped value, as quantifying the uncertainties associated with each model components is very time-consuming and in some cases impossible. Specifically, in highly complex integrated environmental models, decomposition of uncertainty and attributing portions of total uncertainty (total error) to various sources of uncertainty is an extremely challenging task which still is a subject of extensive ongoing research (Bastin et al., 2013).

B.3.4 Frameworks for Model Calibration, Sensitivity, and Uncertainty Analysis

Most model evaluation techniques are built around iterative approaches that entail running the model multiple times. For large models with long run times, iterative approaches can be very challenging. Integrated environmental models pose particular challenges as they are highly parametrized and often have multiple component models that work jointly to generate results. General approaches to address this issue include 1) employing more computational power (more computational capacity from software and hardware), and 2) revising the model evaluation algorithms to be more efficient in exploring the model response space. Often, both approaches are needed for evaluating complex models. A summary of common tools for conducting model evaluation is presented below.

B.3.5 Novel Approaches for Confronting Computational Burden of Sensitivity and Uncertainty Analysis for Complex Model Frameworks

Conducting sensitivity and uncertainty analysis for complex model frameworks is often challenging due to the high computational cost of running them. Indeed, continually exercising the simulator to carry out tasks such as sensitivity analysis, uncertainty analysis, and parameter estimation is often infeasible (Baustert et al., 2018). Modelers are then faced with only a limited number of model realizations for conducting their analysis. A common approach sometimes used to overcome this pitfall is application of model emulators. Application of cloud-based platforms and parallel computing are also becoming possible with more computational power from supercomputers and clusters. These are further discussed as follows:

- **Emulators.** Emulators basically represent the input/output relationships in a model with a statistical surrogate to reduce the computational cost of model exploration. In this approach, the computer model is viewed as a black box, and constructing the emulator can be thought of as a type of response-surface modeling exercise (Box and Draper, 1986).
- **Greater Computational Resources.** Another approach for confronting the high computational demand of complex models and integrated model frameworks is cloud-computing. Cloud-computing is the on-demand availability of computer system resources, especially data storage and computing power, without direct active management by the user. The term is generally used to describe data centers available to many users over the internet.

B.3.6 Alternative Models

For key problems, it is possible (and even preferable) to consider different models to evaluate scenarios. Where multiple models are available—as is case with models for simulating hydrodynamics, watersheds, and groundwater—ranging in theoretical formulation, complexity, availability and accessibility, it is worthwhile to perform comparative studies and evaluate model performance under different conditions. This may be especially beneficial when the modeling effort is being used to support a major, consequential decision. Differences across models provide insight into potential sources of error or inadequate representation in the conceptual model. In some cases, more complex models (e.g., three-dimensional fluid flow models versus two- or one-dimensional models) may provide more nuanced results, but in other cases simpler models may be easier to communicate with decision-makers and stakeholders. Indeed, where possible, there is a benefit to supporting a hierarchy of models with different levels of complexity to better communicate with different users and potentially to allow different levels of integration across models.

B.3.7 Post Audit: Compare Model Results to Future Data Being Collected

For models that are used to make near-term forecasts, but also for longer-term predictions, it is important to revisit model outcomes and to compare field observations with previously made model predictions. This process is termed a post-audit, and its importance has been highlighted in other modeling guidance as well, notably, the *Guidance on the Development, Evaluation, and Application of Environmental Models* (USEPA, 2008). For major models which are often in use for a decade or longer, and where supporting observed data continue to be collected, a post-audit is not very difficult to implement. A post-audit can provide insight on conditions under which model performance was acceptable and in line with prior calibration history, thus providing credibility to the model and related modeling studies. A post-audit may also result in the opposite outcome. Under conditions where model performance was poorer than expected, the post-audit provides an excellent opportunity to revisit the fundamental conceptual model and/or the model calibration. Indeed, a post-audit can provide an excellent basis of future model improvements.

B.3.8 Compatibility with Existing Data Exchange Standards

Even where models are not used within an integrated framework, a model's outputs are rarely used in isolation. Therefore, it would be beneficial to have common frameworks for exchanging data between different models and data processing/visualization tools. Agreed upon standards exist in specific disciplines, such as the DSS standard in hydrology and multiple standards for geospatial and other model data exchange (see Memo 3 for specific frameworks). However, over the broad range of disciplines considered in this work, there are major differences in how data are represented in space and time, and how data are stored and transferred between models. Thus, for most integrated modeling studies, it is not unusual for a large amount of analyst time to be spent in moving data across formats. Where these data transfer processes cannot be automated, there are clear limitations to model integration. To address this practical challenge, focused efforts and collaboration across developers in different areas are needed to provide tools that enable standardization in data, documentation, and efficient exchange across a variety of models.

B.4 Broader Issues in Modeling

Because models are employed within a larger decision-making framework in the Delta, it is helpful for modelers and model users to think beyond the strictly numerical and even conceptual frameworks addressed in Sections 6.2 and 6.3. Even when many of the steps identified in the preceding sections are implemented, a model study may not achieve the support and credibility that it needs to be successful. Here we focus on a set of issues, going beyond the technical aspects of model development and testing, to develop effective products that are useful for decision-makers and stakeholders. Attention to these issues will allow model results to be accessible to a broader audience, including the scientific and educational communities in the region. This chapter provides some general insights based on our experience on working with complex, multi-faceted modeling problems in the Delta region.

B.4.1 Communication Strategy for Model Study

At the inception phase of a modeling study, during project execution, and at its completion, it is important to think through the overall communication approach with model sponsors and stakeholders, and the larger community of technical experts and the general public. Some of these steps are outlined elsewhere in this document and are summarized below:

- **At project inception:**
  - Outline expected use and purpose of the model to sponsors and stakeholders; run through a model evaluation checklist.
  - Define conceptual model and communicate key processes and unknowns at the start of the study. For major studies, solicit peer review and feedback on the conceptual model.
- **During project execution:**
  - Solicit peer review at key interim steps of the modeling process, focusing on items such as data available, assumptions, and methodology.
  - Update stakeholders on progress and changes in approach from initial plan.
- **At project completion:**
  - Perform peer review of results, including calibration and evaluation, as well as further evaluation such as sensitivity and uncertainty analysis.
  - Prepare documentation on modeling study.
  - Review and update conceptual model and share with stakeholders. Conduct workshop to share results.
  - Develop summary sheets for a broad, general audience. The summary should describe the problem and outcomes with minimal technical jargon.

B.4.2 Consideration of Model Bias

Modeling is a human activity and is inherently subject to bias. It is essential to acknowledge this bias and attempt to minimize it. This general concern has been addressed in other published guidance as well (Glynn, 2017). Several biases worthy of attention in modeling of complex systems are listed below. Not all these biases can be addressed through the steps listed above, and it is important that modelers and model users keep these in mind when considering the practical consequences of a modeling study:

- **Confirmation bias.** Modelers often focus on and highlight observations that confirm a pre-existing conceptual model and are less willing to seek data that will counter the model. This is also termed as “group-think” and is associated with a resistance to new approaches for analysis.
- **Temporal insensitivity bias.** Decision makers may have more interest in predictions that are one to two generations in the future than in the distant future.
- **Steady-state bias.** Modeling approaches often assume constancy in conditions or assume that known variability will continue into the future. In the current literature, this assumption of stationarity is questioned most often by the increasing realization of climate change impacts on aquatic ecosystems. However, this bias is not limited to climate change alone and could involve virtually any social or economic system.
- **Disciplinary bias.** Modelers tend to focus on topics that they know most about even in the case of a framework where multiple models are being integrated.
- **Separation between man and nature.** Mechanistic models of natural systems often do not explicitly account for changes in human behavior during the period of simulation. Thus, regulatory actions are implemented in models as fixed drivers, but not as variables themselves. There is growing interest in developing models that represent as dynamic actors, with responses changes as natural conditions change.

B.4.3 Results Gauged to Different Audiences

Model findings will be used by and will need to satisfy the information needs of different audiences, from technical specialists to members of the general public. Therefore, it is important that modelers are also engaged at different levels of this process such that the right information is transferred to each audience. Furthermore, audiences may weigh in on a modeling study during various phases of the project. Considerations for different audiences at project inception and completion are described below:

- **At project inception:**
  - **Technical specialists.** Such audiences will need to understand why the modeling is needed and the approach to be used. Some of the items in the project inception checklist may serve to aid this goal. It is also important to convey the novelty of a modeling exercise, and how it extends current thinking.
  - **Stakeholders.** Such audiences will need to know the specific answers to be obtained through the modeling, whether similar answers can be developed without modeling. They will need to know the costs, time frames, and major unknowns. Modelers should use this opportunity to highlight known and

potential uncertainties, and how this might affect the outcome of the findings. Conceptual models can be used as a tool to highlight the areas of focus of the modeling exercise. In communication with stakeholders, it is important to have clear definitions, and minimize use of jargon as far as possible.

- **Near completion:**
  - **Technical specialists.** Such audiences will expect to see many of the technical steps described in Chapters 2 and 3, such the basis of the model, specific assumptions used, the results of testing and evaluation of uncertainty. It is also important to convey the novelty of a modeling exercise, and how it extends current thinking. The presentation of key model studies as peer-reviewed publications provides additional credibility and also provides archival benefits for a modeling exercise. Finally, audiences may want to understand next steps or the long-term plan for the study (additional modeling or data collection, etc.).
  - **Stakeholders.** Such audiences need a high-level overview of key findings that can be quickly understood across broad range of people, expertise and experience. Good results are simple and memorable and tell the key elements of a story in a compact manner. A new or updated conceptual model is a good summary of the overall exercise. Additional graphical resources, beyond the conceptual model, may also be developed to help readers understand important findings. It is helpful to describe what was achieved through the modeling and what remains unknown.

B.4.4 Building Stakeholder Engagement and Trust

With the growing adoption of models in support of socially consequential decisions, it is becoming increasingly important that models be considered credible by the stakeholder community. This is a feature of modeling applications worldwide, and a trend away from technocratic decision-making to a more participatory framework (Voinov and Bosquet, 2010; Voinov et al. 2016; Parrott et al., 2017). Because of the complex and well-established interaction of many environmental processes in the Delta (e.g., water supplies and ecosystems), stakeholders for a modeling exercise include a range of participants, from government agencies at different levels (local, state, and federal) with different areas of focus, as well as non-governmental and individual participants with different levels of expertise and different interests. Decision-makers are often faced with situations where some stakeholders are not convinced of the benefits or the credibility of a model used to support a decision; thus, social as well as scientific credibility should be pursued for a model and related studies. Systematic engagement with stakeholders on various aspects of a modeling exercise—such as modeling purpose, conceptual model, calibration and evaluation, and peer review (as described above) – may provide such credibility and support over the long-term.

B.4.5 Model Utility and Friendliness

As a model becomes used more frequently and/or used within a larger stakeholder community, the justification for resources to support documentation and solid practices becomes stronger and more obvious. Model accessibility, including utility and friendliness, has an influence on how frequently and/or broadly a model is used. Below are design considerations for increasing model accessibility:

- **User-friendliness and lower barriers to entry.** All models require certain levels of expertise and skills. High barriers to entry and poor user-friendliness (e.g. poor documentation, arcane technology) limit the pool of people that will utilize and leverage the model. Making models more user-friendly broadens that pool and brings greater value to society. This consideration has been a factor in some of the more successful technical models in use today.
- **Models to provide initial scoping results.** Simple and easy-to-build models can be useful as tools to quickly assess a situation with early results that provide initial scoping information. These scoping results can provide a foundation for considering more complex models in subsequent analyses. These types of models can find broad audiences for smaller problems akin to the broad use of spreadsheet analyses today. Models for initial scoping may be helpful to engage stakeholders and are preferable to a situation where even initial results are dependent on a model that takes a long time to develop.
- **Fun, Entertaining and Accessible.** Technology becomes more attractive when it is fun, entertaining and accessible. Graphs that can be displayed on phones or tools that can be readily accessed on the web are thus more likely to be used. Augmented reality (AR) tools that present model results in the context of the real world will allow greater engagement and understanding of outcomes. An example of this is the model SimBasin, which overlays the WEAP water resources modeling software. SimBasin uses a model of an actual basin and is designed to facilitate communications and engagement between stakeholders and scientist when considering different policy impacts.

B.4.6 Model Sustainability over Long Time Horizons

Models represent large intellectual and financial investments, but in most instances, their long-term viability is unknown. Models are often developed to serve a specific need, and access to these models and related analyses rapidly diminishes over time. For key foundational models and related efforts, long term sustainability should be addressed early in its life cycle to make best use of the investments being made. This life cycle planning should identify the responsibilities, accountabilities, and resources needed to support a model over the long term, potentially over decades. This life cycle planning should also contemplate development of new versions and ongoing model evaluation. Because of the resources and long-term commitments required to sustain a model over time, this is an issue that extends beyond the modelers and should be brought to the attention of decision and policy makers early in the process.

B.5 Encouraging Adoption of Best Practices

Many of the concepts identified in the preceding chapters are perhaps known to most modelers but are not widely adopted. This may be due to time and resource limitations associated with virtually all modeling studies; this may also be due to the lack of specific expectations in the broader community of modelers and model users. Thus, model users may not know what specific and reasonable requests to make of modelers to guide a model study toward greater credibility and usefulness.

To encourage adoption of the best practices identified in this work, we provide three relatively compact summary sheets. The purpose of the first sheet (**Table B-2**), designed as a checklist to be employed at inception of a modeling effort, is to enable various participants to agree on the basic features of the work to be done. The purpose of the second sheet (**Table B-3**) is to evaluate and score a modeling exercise upon completion. A final sheet (**Table B-4**) is designed to help evaluate the long-term sustainability of a modeling framework.

The first sheet is designed with Yes/No responses, although additional narrative information can be provided. While there are no correct answers associated with the model study pre-audit, the questions are designed to flag issues that may need to be resolved before significant modeling study resources have been expended.

The second sheet contains a list of questions that may be answered with narrative responses or with numerical scores. If the numerical scoring approach is used, a model study with a higher score is more desirable. A numerical scoring approach may be useful for comparing multiple model studies that employ the same type of domain modeling. However, this approach is of limited value when a unique or one-of-a-kind model study is to be evaluated. The questions provided in these sheets are offered as starting points to be modified as needed for specific agencies or applications. However, we expect many of the essential items will apply to most modeling studies.

The third sheet is focused not on modeling *per se*, but on questions that help evaluate the long-term sustainability of a model framework. It is not intended to evaluate a single study, but to assess whether the framework used in one or more studies is well supported into the future.

Table B-2. Model study initial appraisal

Item	Description	Response
1	Do we know how the model results will be used?	Yes/No
2	Is the model to be used defined?	Yes/No
3	Has a conceptual model been developed?	Yes/No
4	Have the criteria for selecting the model been defined?	Yes/No
5	Is an existing model going to be modified?	Yes/No
6	Is a new model to be developed?	Yes/No
7	Are the time frames known for initial model development, calibration, testing, and review?	Yes/No
8	Are data associated with intended model inputs available?	Yes/No
9	Does the model need calibration?	Yes/No
10	Are data associated with intended model outputs available (to support model calibration)?	Yes/No
11	Are time frames of the input and output data known and consistent with one another?	Yes/No
12	Are the errors in data measurements known?	Yes/No
13	Is the level of error in the expected results known?	Yes/No
14	Are the model stakeholders known?	Yes/No
15	Will stakeholders be part of the modeling process?	Yes/No
15	Have users of the model output met together?	Yes/No
16	Will documentation be prepared upon completion of the model?	Yes/No
17	Will the information embedded in questions 1-15 be used to prepare a memo describing the model's purpose?	Yes/No

Table B-3. Model study post-completion appraisal

Item	Description	Response (Numeric Score or narrative)
1	Is the model a new formulation or the application of an existing code? If a new formulation, what has been done to test and verify the code?	
2	Has a conceptual model been developed for this effort and has it been updated following completion?	
3	Are observed data used in the modeling exercise (input and output data) documented and available for review?	
4	Has the calibration approach been described?	
5	Has the model performance following calibration been adequately evaluated using test data?	
6	Has the sensitivity of major variables been evaluated?	
7	Has model output uncertainty been evaluated?	
8	Were any novel approaches used to evaluate the sensitivity and uncertainty of the model response to inputs?	
9	Were the model results compared and contrasted with other models (if available)?	
10	Does the model study documentation adequately explain the approach, assumptions, and findings?	
11	Was a peer review performed and responded to?	
12	What were the stakeholder's reactions to the model results?	
13	Are the model summary documents easily understandable by a variety of audiences?	

Table B-4. Model framework lifecycle evaluation

Item	Description	Narrative Response
1	Are all source codes and supporting files stored in a single location and archived in a manner that enables future access?	
2	Are the source codes documented, even if this documentation is not in the public domain?	
3	Is the model development dependent on a single individual? What is the long-term transition plan for the expertise in this model?	
4	Is the model framework applied by a community or by a single team? Is there a mechanism to share knowledge about the model application over time, such as a virtual community, trainings, etc.?	
5	Is there a defined plan for making updates to the model framework?	
6	For a public-domain model framework, is there a funding mechanism to support staff that would work on the model?	
7	For a proprietary model framework, what is the mechanism to support the code development over the long-term?	