Modeling Science Workgroup White Paper

Working Title:
Recommendations for a Modeling Framework to Answer Nutrient Management Questions in the Sacramento-San Joaquin Delta

Report prepared for:
Central Valley Regional Water Quality Control Board

Report prepared by:
Modeling Science Workgroup

Authors:
Trowbridge, P.R.[a], M. Deas[b], E. Ateljevich[c], E. Danner[d], J. Domagalski[e], C. Enright[f], W. Fleenor[g], C. Foe[h], M. Guerin[i], D. Senn[a], and L. Thompson[j]

a. San Francisco Estuary Institute
b. Watercourse Engineering, Inc.
c. California Department of Water Resources
d. National Oceanic and Atmospheric Administration
e. United States Geological Survey
f. Delta Stewardship Council
g. University of California Davis
h. Central Valley Regional Water Quality Control Board
i. Resource Management Associates, Inc.
j. Sacramento Regional County Sanitation District

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Executive Summary

TBD – target audience will be senior managers and policy makers

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1. Introduction

The 2013 Delta Plan (DSC, 2013) called for the development of water quality objectives for nutrients in the Delta by January 1, 2018. The Central Valley Regional Water Quality Control Board (Water Board) staff responded to this call by writing a new five-year Delta Strategic Work Plan[1] to help prioritize Delta nutrient activities. The Water Board also formed several Science Workgroups to develop a series of white papers to review the state of the science and identify high priority science activities whose results would help resolve outstanding questions about the efficacy of nutrient management to control these problems. The recommendations from these white papers will be incorporated into a Nutrient Research Plan.

This white paper is the output of the Modeling Science Workgroup, which was tasked with advising on the development and use of water quality models as one component of the Nutrient Research Plan. The Modeling Science Workgroup was convened to address the recommendation from Water Board staff and stakeholders that a robust model – comprised of a hydrodynamic model linked to a suite of water quality and ecological modules for the Delta - was needed to holistically examine how nutrient loads, in combination with other physical and environmental factors, influence water quality and food webs in the Delta. A similar recommendation for an integrated model was made in 2009 by a CALFED independent Science Review Panel (Meyer et al., 2009).

The Charge to the Modeling Science Workgroup is shown in Appendix A. In short, the purpose of the Workgroup was to provide advice to the Water Board on what types of models would be needed to answer the nutrient management questions that have been raised by stakeholders. The group was also charged with making recommendations about the organizational and modeling frameworks that should be created to maximize the benefits of models. Finally, the group was asked to provide cost estimates for the modeling task and how the work might be phased over time. The Charge provided explicit guidance for the Workgroup to stop short of recommending specific models, and to instead focus on describing the specific characteristics of the models that would be necessary to answer the management questions. For clarity, the models to be considered and planned by the Workgroup are mechanistic, process-based numerical models, not conceptual or statistical models.

The Modeling Science Workgroup members were a mix of model developers and model users. The Workgroup had representatives from federal and state agencies, university researchers, private consultants, and non-profit institutions with an interest in water quality modeling in the Delta. The full list of Workgroup participants is provided in Appendix A. The Workgroup held meetings on June 24, 2015, August 5, 2015 (teleconference), September 10, 2015, and XX (last meeting TBD). In addition, the Workgroup reviewed the relevant scientific literature, recommendations for modeling from the Science Workgroups for cyanobacteria and macrophytes (Berg and Sutula, 2015; Boyer and Sutula, 2015) and

[1] http://www.waterboards.ca.gov/centralvalley/water_issues/delta_water_quality/strategic_workplan_baydelta/2014_delta_strategic_workplan.pdf

presentations at the Delta Science Program's workshop on Integrated Environmental Modeling of Estuarine Systems on May 21, 2015.

This White Paper reflects the consensus of the Modeling Science Workgroup. The primary audiences for the report are the Water Board, other agencies involved with Delta management, and interested stakeholders.

2. Background

The purpose of this background section is to give readers a common understanding of models in general to place identified specific recommendations in proper context. An important consideration when applying and using models is that while models are critical for understanding complex systems, models alone cannot provide all of the answers – they are tools to organize information, relate various processes and improve the understanding and characterization of aquatic systems.

a. General Information about Computer Models

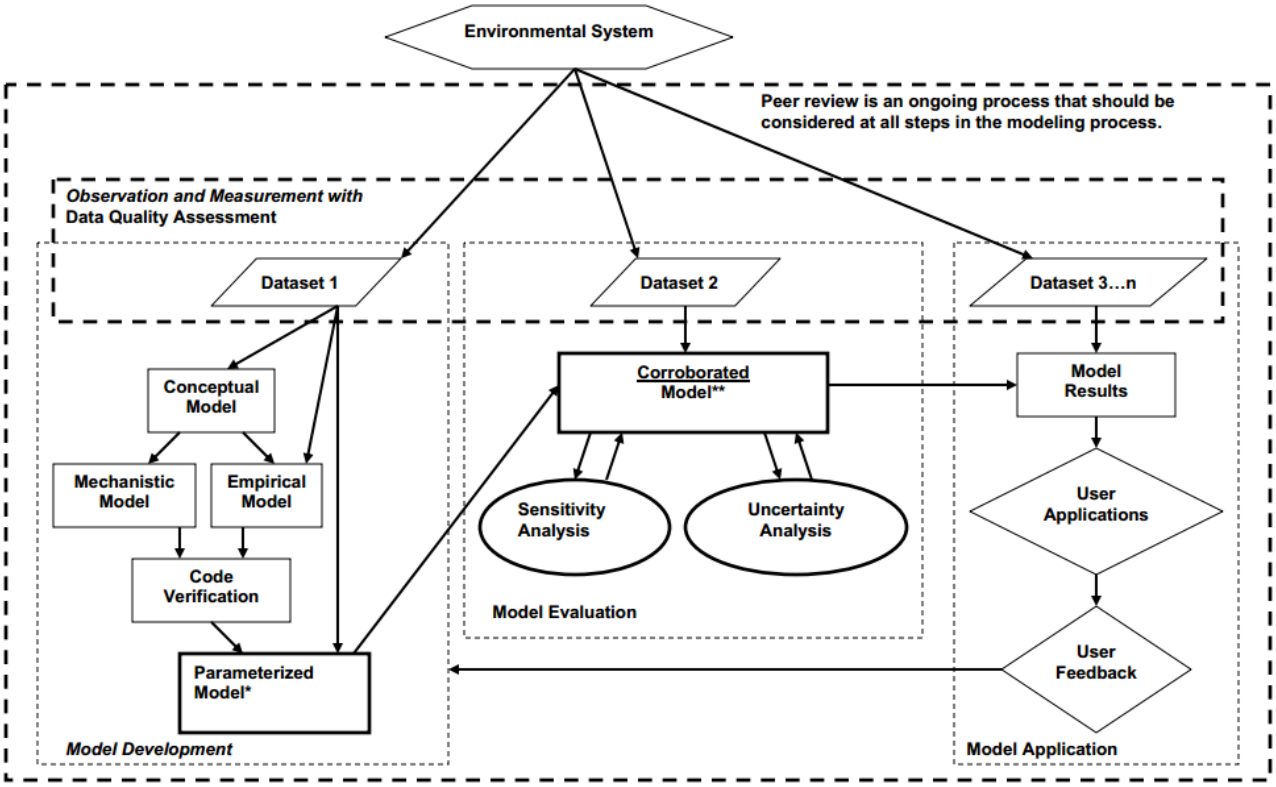
Computer models are mathematical representations of the real world. More specifically, the U.S. Environmental Protection Agency defines environmental models as a "simplification of reality that is constructed to gain insights into select attributes of a particular physical, biological, economic, or social system" (USEPA, 2009 at vii). The development and application of computer models generally follows a three step process of model development, model evaluation, and model application as shown in Figure 1 (USEPA, 2009).

Model development involves developing the conceptual model that reflects the underlying science of the processes being modeled, developing the mathematical representation of that science, and encoding these mathematical expressions in a computer program. This step of the process includes defining the system in space and time, identifying the key constituents to be modeled, and representing the processes controlling the constituents with mathematical equations. Each equation can contain parameters that represent rate constants or other factors that affect the speed or magnitude of a process. During the model calibration process, the value for each parameter is adjusted so that the model predictions match measured values from a calibration dataset. Ideally, there should be sufficient monitoring data to fully characterize all of the parameters in the model, but this is rarely the case. Values for parameters are often set using information from other systems, the scientific literature, and the professional judgment of the modeler.

Model evaluation involves testing that the model expressions have been encoded correctly into the computer program and testing the model outputs by comparing them with empirical data. This step has traditionally been called model validation and involves comparing the results of the model to a measured dataset that was not used for the model calibration. Evaluating the uncertainty in the model results and the sensitivity of the model to certain parameters is also part of this step.

Model application involves running the model and analyzing its outputs to inform a decision.

Figure 1: Diagram of the Three-Step Modeling Process



Source: USEPA (2009) at 61

b. The Strengths of a Modeling Approach for Managing Water Quality in the Delta

Models are important tools for water quality managers, and have the potential to play a critical role in developing a greater understanding of ecosystem function in the Delta, and in informing Delta management decisions. The following is a list of ways in which models could improve water quality management in the Delta.

- Fundamentally, the Delta is too complex to describe and understand without models. Monitoring on the spatial and temporal scales necessary to characterize and assess management actions in the Delta is infeasible. Water quality monitoring data is typically completed at discrete points that are often separated by miles or tens of miles due to the size of the Delta. Models developed on a finer spatial scale could interpolate conditions between monitoring stations and provide a more comprehensive and continuous representation of water quality throughout a large model domain. In effect, models could multiply the insight from discrete monitoring data in space and time.
- Models could provide insight into the ecological significance of nutrient changes from an ecosystem perspective. The Delta is a large and highly complex system in terms of its hydrodynamics, water management, biogeochemistry, and lower food web response to physical and chemical drivers. In such a complex system, models would be essential for allowing researchers to quantitatively explore how these multiple factors act in concert to shape ecosystem response to nutrients, and to examine the effects of different potential management

actions. For example, an ecosystem perspective is essential to compare and understand the relative importance of clam and zooplankton grazing, transport (flow and settling, routing), light limitation, residence time, water temperature, introduced species and nutrients on algal biomass and algal species composition.

- Models could efficiently allow stakeholders to develop and assess management and planning scenarios that can characterize the relative effect of nutrients over a range of conditions. For example, models could be used to assess complex spatial and temporal variability in response multiple actions, e.g., "what will be the effect on blue green algal biomass if reductions in nutrients and global warming (increased water temperature, intensification of spring discharge and decreased summer/fall flows) simultaneously occur?" This type of scenario testing is limited, or even infeasible, using solely empirical data.
- Finally, models could be extremely valuable for communicating critical information to stakeholders, regulators, and resource managers, leading to a common understanding of complex systems. By organizing collective information and providing a means of systematically assessing alternative conditions, models can facilitate communication of complex topics in a simple, often visual, way.

c. The Limitations of a Modeling Approach for Managing Water Quality in the Delta

While models have the beneficial attributes of assisting in system characterization, describing conditions through large and complex regions, efficiently assessing a range of alternative conditions, and developing a common information base for stakeholders, such tools are not without limitations. The following is a list of important constraints on models as water quality management tools for the Delta.

- Models by themselves will not provide answers; people using models as tools will provide answers. Models just generate data. Interdisciplinary analysis, synthesis, and communication makes or breaks the value of modeling for decision support and adaptive management. A team of scientists, modelers and managers need to interact routinely, skillfully, and economically to optimize the benefits of modeling. The cost estimates presented later in this report include these interactions as an essential component of the modeling strategy.
- Not all processes can be effectively represented mathematically with our current knowledge base. Many ecological processes are incompletely understood; therefore, certain modeled processes are approximations based on limited understanding. Fundamentally, a model can only operate within the underlying equations and the observational data used to calibrate it (Ganju et al., 2015). Challenges in the Delta include spatially and temporally limited data sets; complex hydrodynamic, water quality, and ecological processes; and dynamic conditions (e.g., shifting bathymetry due to sediment erosion and deposition). Understanding these challenges is important to stakeholders, resource managers and others when considering the development and application of models in the Delta.
- While models produce extensive numerical output at a seemingly high-level of precision, such outputs may have notable uncertainty. Uncertainty in model results originate from many sources. Monitoring data can introduce uncertainty into a modeling process through sampling program design (spatial and temporal aspects, constituents sampled); collection techniques; and uncertainty in analytical methods or water quality instruments. Model mathematical formulations of physical, chemical, and biological processes are imperfectly represented in models. Further, some processes may not be included, or incompletely represented in certain

models. Spatial representation also plays a role - while aquatic systems express vertical, lateral, and longitudinal variations, model applications often assume simplified system conditions. For example, one-dimensional representations of Delta channels may assume vertically, and laterally averaged conditions, focusing on simulation of longitudinal variation. Such approximations can introduce uncertainty into model results. Likewise, temporal assumptions can introduce uncertainty if simulation time step is too large to capture the shorter duration processes. An important aspect of any modeling exercise is to effectively communicate uncertainty in results to decision-makers.

- Monitoring and modeling are complementary, and both activities are critical to understanding the aquatic systems such as the Delta. Models are only as good as the underlying data, and models provide a means to interpret monitoring data and improve sampling program design. Monitoring data has necessarily limited coverage in time and across sites, but represents the true state of the system. Modeled data can achieve much greater spatial and temporal coverage, but can only mimic and approximate the true state of the system. When monitoring and modeling data are used together, scientists can come closer to a complete picture of a system and its workings. Therefore, when investing in model development and application, managers should invest in both the modeling activities and the monitoring programs needed to support the models. Further, both activities – modeling and monitoring – should undergo to continuous refinement.

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3. Nutrient Management Questions and Modeling Objectives for the Delta

The impetus for any scientific investigation is the question to be answered. As a result, when the Stakeholder and Technical Advisory Committee for the Water Board's Nutrient Science Plan explored addressing nutrient modeling in the Delta, the group developed an initial set of nutrient management questions. These questions addressed specific nutrient and primary production topics and were included in the charge document for this Workgroup (Appendix A). As part of this effort, the workgroup reviewed, refined, and reorganized the management questions in the Charge document. One of the original questions ("Do the models indicate that all major sources of nutrients to the Bay are accurately being measured?") was removed. Nutrient sources are inputs to the models; therefore, models cannot determine whether these inputs are accurate. All the other questions were retained. The final list of management questions and modeling objectives is shown in Table 1.

For each of the questions, the Workgroup developed specific modeling objectives and potential modeling scenarios. Modeling objectives define the type of output desired from the model and scenarios are the possible alternative situations to be modeled. The development of modeling objectives and scenarios was necessary so that the technical requirements for models could be determined.

The management questions progress in a logical sequence from nutrient loading to the Delta (questions 1 and 2), to spatial patterns and rates of transformation (question 3), to the relative importance of nutrients on algal productivity, macrophytes, and harmful algal blooms (question 4). The fourth question is carefully worded such that the effects of nutrients should not be studied in isolation, but rather should be considered along with other relevant factors (e.g., hydraulics, meteorology). Moreover, all modeling activities should address uncertainty in model outputs due to uncertainty in input data and model structure, which is critical for interpreting model results in planning processes.

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Table 1: Nutrient management questions that a linked suite of hydrodynamic and environmental models might inform plus the modeling objectives and scenarios to be modeled for each question.

Management Question		**Modeling Objectives**	**Potential Model Scenarios***
1	What are the main sources and loads of nutrients to the Delta?	Identify the internal and external loads and sources (model boundary conditions) for total and reactive nitrogen and phosphorus to the Delta from major rivers, stormwater runoff into and within the Delta, point sources discharging to the Delta, atmospheric deposition, groundwater, and tidal flow from the Bay.	A. Current conditions B. Future conditions assuming already permitted reductions in nutrient loads from NPDES dischargers have been implemented* C. Future conditions assuming nutrient reduction BMPs implemented in watershed, in-Delta discharges, and/or other nutrient reduction prescriptions* D. Future conditions assuming changes in climate, Delta hydrology, wetland restoration, and nutrient loading from scenarios A, B and C. * <u>All modeled scenarios should take into account the variability of other relevant factors such as flow, and address variability and uncertainty in model outputs due to input data and model structure.</u>
2	How much do nutrient loads from known sources contribute to ambient nutrient concentrations in different sections of the Delta by season?	Quantify ambient nutrient concentrations throughout the Delta and assess seasonal concentrations (e.g., total and reactive nitrogen and phosphorus) present at long-term monitoring stations (and locations in between) in response to nutrient loads from known sources (see Management Question 1)	
3	What are the important processes that transport and transform nutrients in the Delta and what are the rates at which these processes occur?	Quantify seasonal rates of change of total and reactive nitrogen and phosphorus due to physical, chemical, and biological processes within different regions of the Delta based on calibrated models for hydrodynamics and nutrients (see Management Question 2)	
4	What are the main factors affecting the following potential nutrient related problems and how does the relative importance of these factors vary with space and time? a) The algal biomass and primary production rates; b) The relative proportions of different groups of algal species; c) The distribution and abundance of macrophyte species; d) The magnitude and frequency of cyanobacteria and diatom blooms.	Characterize primary production (phytoplankton and macrophytes) and determine which factor(s) is limiting the occurrence of the effect (at different locations in the Delta where the effect has been observed, for different seasons). Perform sensitivity analyses to understand how changes in the limiting factor(s) might change the manifestation of the effect, particularly the magnitude of response to nutrient load reductions	

*The model scenarios A, B, C and D are intended to be applicable to each of the four management questions.

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4. Model Characteristics to Achieve Modeling Objectives for the Delta

The modeling objectives for each question identified in Table 1 present the conditions that an individual model or group of models would be required to represent. Given these conditions, the next step is to define the type of models that are needed to complete this work. In its Charge, the Workgroup was precluded from recommending specific models to avoid conflicts of interest. Therefore, the Workgroup defined the model characteristics that would be needed to achieve the modeling objectives.

Both general and technical model characteristics that are important to developing and applying water quality models in the Delta were identified. General model characteristics address attributes such as model costs, peer review, if models are widely used, include appropriate processes to meet objectives, and scalability, and are included in Table 2. Technical model characteristics address hydrodynamic representation, biogeochemical representations, ability to interface with other models, spatial domain, temporal resolution, dimensionality, and other factors, and are included in Table 3.

Meeting all of these general and technical characteristics may not be possible with any one model; therefore, the characteristics should be considered guidelines, not necessarily requirements. Further, the actual requirements of a model may be limited by the question being posed and the available data to support a modeling effort. Being able to answer the management question sufficiently is the real performance standard. In some cases, a simple model could provide sufficient answers when evaluated by skilled analysts. The only required characteristic identified by the Workgroup is that the model computer code must be transparent and open for review, and that code developers agree to contracting requirements regarding licensing of copyrighted material developed using public funds.

One overarching technical concern is model accuracy and uncertainty. While requirements for model accuracy cannot explicitly be defined prior to developing a model, the relevant metrics for model performance and acceptable error magnitude can be defined for each modeling objective. Examples of model performance metrics may include bias, mean absolute error, root mean squared error, Nash-Sutcliffe efficiency, and others. Identifying the appropriate model performance metrics magnitudes can be iteratively refined during the model development in response to the final selected model, available data, and other factors.

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Table 2. Desired general characteristics for Delta water quality and hydrodynamic models

No.	Characteristic	Explanation
1	Reasonably accessible in terms of costs and learning curve for end user (**required**)	Source code, software and training can be obtained at reasonable cost. A knowledgeable technical user should be capable of running the model. Compliant with copyright licensing requirements if developed with public funds[2].
2	Track record and peer review	Models should have a history of successful applications addressing nutrient management questions. Model equations and software should be verified and validated through a California Water and Environmental Modeling Forum peer review process, or equivalent, prior to a large scale investment in model development.
3	Support for technical continuity over multi-year period	Active and sufficiently large user community, substantial institutional support, sufficiently state of the art (avoid the potential for obsolescence prior project completion).
4	Sufficiently resolved/mechanistic to model management scenarios	To be determined based on technical characteristics in Table 3.
5	Scalable	Platform(s) can accommodate iterative development, both in terms of complexity of the domain and the range of processes/constituents to be modeled.

Adapted from Senn et al. (2014)

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[2] For state and federal funding, the funding agency will typically reserve a royalty-free, nonexclusive, and irrevocable license to reproduce, publish or otherwise use, and to authorize others to use the copyright in any work developed under the grant and any rights of copyright which are purchased with grant support (see 40 CFR 31.34).

Table 3: Desired technical characteristics for Delta water quality and hydrodynamic models

No.	Characteristic	Explanation
1	Model(s) must have a hydrodynamic platform and modules for biogeochemistry, sediment transport, and macrophytes.	Meyer et al. (2009) concluded that a Bay-Delta model was needed to integrate hydrology, nutrients, herbivory, phytoplankton production and community composition. Some components will have to be modeled qualitatively or with less accuracy because processes are not well understood and/or data are lacking.
2	Biogeochemistry modules must simulate primary productivity from phytoplankton and grazing by zooplankton and benthic invertebrates.	Nutrient dynamics (water column and benthos) and how they relate to primary production are required to assess management actions. Underlying physical models of hydrodynamics, salinity, and water temperature are necessary to support the biogeochemistry module.
3	Biogeochemistry modules must be compatible with higher trophic level ecological models (e.g., food for fish models), but not necessarily model higher trophic levels directly.	Model output should be at an appropriate temporal and spatial scale to support higher trophic level ecological models. For example, the output of the biogeochemistry module should provide useful inputs to the models of fish growth and behavior developed by NOAA and other resource agencies.
4	For typical applications, model(s) must be capable of having a spatial domain that covers the majority of the legal Delta, including flooded islands and marshes.	Water exchange between the channels and flooded islands and marshes affect both the hydrodynamics and biogeochemical conditions. More localized applications may also needed to answer specific management questions.
5	For typical applications, model(s) must be capable of resolving processes at an hourly temporal resolution.	The majority of modeling objectives will require hourly simulations to represent diurnal patterns in temperature, salinity and flow, which are critical inputs to chemical and biological models. However, not all model applications will require hourly resolution. In particular, modeled scenarios for climate change may require computations on a daily or longer interval to simulate extended periods of time in a computationally efficient way.
6	For typical applications, model(s) must be capable of up to 3-dimensional representation to accommodate the various channel forms in the Delta.	Modeling objectives may require 3-D representation in deeper, wider areas to characterize longitudinal, lateral, and vertical variability. 2-D representations (depth averaged) may be useful to characterize wide, shallow areas (e.g., flooded islands) that experience little or no vertical stratification. 1-D representations may be effective in relatively narrow, shallow channels where vertical and lateral gradients are minimal.
7	Macrophyte module representations should be linked to both biogeochemistry and hydrodynamics modules.	Because macrophytes can affect hydrodynamics (e.g., through increased channel roughness) and aquatic system biogeochemistry, linkages between the macrophyte representations and these other modules is necessary.
8	Model(s) should be compatible with other hydrodynamic and water quality models selected by the San	To the extent possible, consideration should be given to existing models for the Bay to leverage and provide synergy with ongoing efforts. For hydrodynamics and

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	Francisco Regional Board for use in Suisun and San Pablo Bays, and with watershed models of river loads to the Delta	certain water quality models, integrated models of the Bay-Delta are strongly preferred to capture interactions and fluxes between the Bay and the Delta. At a minimum, models should be compatible in geography, be compatible in the processes modeled, and provide independent hydrodynamics and water quality outputs that can be exported/imported to other, appropriate software platforms.

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5. Description of Existing Models for the Delta

Review Note: This section of the report is still in outline form. It will be completed after the summaries of existing models (Appendix B) have been edited and reviewed by the Workgroup.

- There are several existing models that represent all or portions of the Bay-Delta.
- None of the existing models are currently capable of answering the nutrient management questions.
- Appendix B contains short summaries for each of the existing or potential modeling platforms. This information has been summarized below.

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6. Recommendations for Modeling Framework and Approach

To answer the management questions about nutrients in the Delta will take multiple years. During this time, new information will come to light, monitoring programs will be modified, and modeling methods will evolve. An adaptable modeling framework and approach will be needed to efficiently adjust to these changes. The Workgroup identified the following recommendations for the framework and approach that should be followed.

a. Organizational Framework

The modeling effort should have an umbrella organization to provide purpose and continuity and to be responsible for model maintenance, data synthesis and interpretation. The structure of and duties of this organization are listed in the following bullets.

- The umbrella organization should have a steering committee of key stakeholders from agencies, academia, and private industry. The group should have a clear mission and charter that includes model development, model maintenance, and synthesis of modeled results.
- The responsibility for model maintenance should be clearly defined and funded. Model code will evolve over time, especially if it is open source. Without a plan for maintenance, the initial investment in model development could be lost as the code becomes outdated and fragmented across many users. The following are three options for model maintenance.
    - One institution with active management. This institution would be responsible for managing license requirements, editing the source code as requested by users, validating suggested edits offered through the open source environment, managing modeling system version control, and distributing the most current version of the model. At least two programmers who know the code well enough to make changes would need to have this responsibility as part of their jobs.
    - Shared resource among a group of developers across multiple organizations. The developers group would have the same responsibilities as listed in the preceding bullet but the effort would be distributed across multiple agencies. While the technical work for each agency will be light, there will be increased resource time for coordination and governance. This approach would be favored if multiple models are in use and the expertise for the different models is not all within one agency.
    - None. Open source software “in the wild”. This option requires no effort but will result in confusion because the differences between model versions may be poorly documented. Therefore, it is not recommended.
- Data synthesis and interpretation of model outputs should be funded as part of the modeling effort. Models are able to produce large amounts of data. If funding for modeling does not include the cost of data synthesis, only a fraction of the insight that would be possible would be obtained. Data synthesis may require statisticians, chemists, biologists, and engineers. The workgroups for cyanobacteria and macrophytes have recommended that there be good interaction between modelers and scientists who are studying the underlying mechanics.

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b. Modeling Approach

In addition to the organization and governance, the Workgroup developed recommendations for how to go about developing the models and the principles that the Steering Committee should follow. The Workgroup recommendations are listed below, grouped by topic.

Mechanistic, Process-based Models

- Models should be mechanistic, but may require refinement or be adapted to incorporate processes of interest. The key characteristics are that (i) processes be represented mechanistically to the extent possible, and (ii) processes can be selectively enabled/disabled in order to efficiently support a wide range of modeling objectives. The four main modules should be:
  - Hydrodynamics: including processes of advection, diffusion, stratification, bed stress, and wind effects;
  - Sediment transport: non-cohesive and cohesive sediment transport (morphodynamics is not considered a high priority);
  - Biogeochemistry: including water column nutrients and carbon, phytoplankton, dissolved oxygen, and light transmission; and
  - Macrophytes.
- The four modules should be developed iteratively: starting with simple models and then adding detail. Table 4 outlines a three phase development plan for each of these modules.

Multiple Models

- A variety of different types of models will be needed to answer all of the management questions. Highly resolved 3D models may be necessary for some applications, while 1D models may be sufficient for others. The best model for each question should be used, rather than investing in only one model to answer all questions.
- Development of ensembles of models (i.e., multiple models that predict the same thing) should be encouraged where possible (Ganju et al., 2015). Comparison between multiple models provides insights into processes and established the envelope of likely ecosystem response. From a management perspective, duplicate models are not necessarily duplication of effort because they use different approaches and the different results provide insight into how much uncertainty there is the predictions.
- Operational models may be more useful for predicting macrophytes and harmful algal blooms. Operational models are continuously re-run with updated information (such as real-time remote sensing data) as inputs to predict future conditions.
- Updating existing models should be the default first step because it will save time. However, if a new model has much better functionality, early adoption of that model may yield cost-savings over the long-term.

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Adaptability

- Models will and should change over time as new information and data become available and to adapt to changes in system conditions. Meyer et al. (2009) recommended a modeling approach that was flexible in order to accommodate future stressors and changes.
- Model implementations should be modular where possible. Modularity simplifies code changes and allows for easier testing of the module. This enables both iterative development and comparison of differing mathematical representations, if available, to be readily compared.
- Decoupling models as much as possible can provide flexibility and efficiency. However, decoupling models prevents interaction between model components, which may not be appropriate if an interaction is important.

Quality Assurance

- Model representation, assumptions, and parameters/coefficient must be included in a Design Document (outside of computer code) to allow peer review of the underlying model basis.
- The model development process should follow widely accepted guidelines for quality assurance to produce accurate and transparent results. A recent U.S. Environmental Protection Agency guidance document recommended four specific practices for developers of environmental models used for regulatory decision-making (USEPA, 2009 at vii):
    - Subject the model to credible, objective peer review;
    - Assess the quality of the data used in the model;
    - Corroborate the model by evaluating the degree to which it corresponds to the system being modeled; and
    - Perform sensitivity and uncertainty analysis.

Monitoring

- There should be strong links between Delta monitoring and modeling programs. Modelers should communicate priority data gaps to monitoring programs such as the Delta RMP and the Environmental Monitoring Program (EMP). Results from models should be presented to monitoring programs in order to refine monitoring locations, frequency of monitoring, and parameters measured.

Data Formats

- There is a need for a standardized database of measured input parameters (flows, inflows, salinity, etc.) that many groups can use for multiple models.
- Model input and output files should be standardized or at least compatible using formats such as netCDF (http://www.unidata.ucar.edu/software/netcdf/docs/ncFAQ.html).

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Translation of Model Outputs

- Models often produce large amounts of date in tabular for or time series. Tools to visualize model outputs are an important in the communication of results to stakeholders. Visualization tools should be funded as part of modeling projects.
- Models or their output should be translated into decision support tools that managers and stakeholders can use to run their own simulations of scenarios (Ganju et al. 2015).

Scope

- Models should be useful for evaluating identified beneficial uses, e.g., drinking water, recreation, aquatic life. By addressing the wide array of potential model applications, a wider group of stakeholders and users will be involved, increasing support for the modeling and associated efforts.

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Table 4: Phased development plan for hydrodynamic and water quality mechanistic models

Module	**Phase 1**	**Phase 2**	**Phase 3**
Hydrodynamics	Advection, diffusion, stratification, bed stress, wind effects (stage, velocity, temperature, salinity, eddy diffusivity) Water withdrawal operations (i.e. variable pumping rates)	Refine spatial domain: Hydrological connectivity between river main stems, bypasses, sloughs, barriers Wetting/drying of intertidal areas	Continued refinement of spatial domain
Sediment Transport	None	Integrated water column and bedded sediment model	Accretion and burial of water quality constituents Erosion and remobilization of water quality constituents
Nutrient Biogeochemistry	Water column nutrients and carbon species (NO3, NH4, DON, PON, PO4, PP, DOC, POC) Phytoplankton growth and decay (total biomass) Dissolved Oxygen Light transmission (empirical relationship)	Nutrients, carbon and oxygen exchange with sediments (empirical relationships) Zooplankton grazing Benthic grazing Impacts of toxic contaminants (e.g., pesticides) on algae Light transmission (scaling law)	Integrated water column and sediment model for nutrients, carbon, oxygen Phytoplankton speciation HABs/toxins Light transmission calculated from sediment, phytoplankton, carbon models
Macrophytes		Macrophyte effects on flow	Macrophyte growth and decay

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7. Cost Estimates

In order to estimate the costs to implement a credible modeling program, the overall modeling effort was broken into four tasks. It was assumed that the cost of the program was predominantly the cost to hire and retain skilled employees to complete these tasks. Licensing fees are expected to be negligible compared to the labor costs. Moreover, the costs associated with enhanced monitoring needed to calibrate and validate the models are not included in this estimate.

The four tasks for the modeling effort are listed below.

- **Model development, upgrades and applications**: For this task, modeling specialists will either develop new models or upgrade existing models to meet the characteristics from Tables 2 and 3. Then, the modelers will apply the models to the Delta to answer management questions. It is important that there be redundancy of skills across multiple specialists with at least 2-3 skilled modelers in the program. For budgeting purposes, the staffing needs have been estimated to be 2 full time equivalent employees (FTE) if existing models will be upgraded and 3 FTE if entirely new models are developed. It was assumed that fewer FTEs would be needed to upgrade existing models because staff from agencies or organizations would also support the effort.
- **Model maintenance and governance**: For this task, modeling specialists will actively manage the code for the models either in one institution or across multiple institutions (see description of model maintenance in Section 6 of this report). For cost estimates, it has been assumed that 0.25 FTE will be needed for this task regardless of whether existing models are upgraded or new models are developed. There is a no cost option if open source software is not maintained but this option is not recommended.
- **Synthesis and analysis of model output**: For this task, field staff, data analysts, GIS technicians, statisticians, and research scientists will review the model outputs, visualize the results, and communicate with collaborators and managers. While not technically modeling, this task is critical for reaping the benefits of modeling investments and making good adaptive management decisions. For budgeting purposes, it was assumed that 1 FTE would be needed for this task.
- **Peer Review by external advisors**. All major investments benefit from external peer review. For the budget, honoraria payments for external advisors and panels were assumed to be approximately 5% of the total project cost per year.

The total cost depends on how long the modeling program will last. While there will likely always be a need for modeling, the end point of the nutrient modeling effort will be when there is sufficient information for each of the management questions listed in Table 1. A ten year period to answer these questions seems reasonable given the complexity of the problem and the pressing concerns about nutrients in the Delta. Some questions will be answered quickly, while others will be answered in stages with increasing levels of certainty. For budgeting purposes, it has been assumed that building off the existing models will provide a several year head start over developing new models.

Based on these assumptions, the cost per year range from $862,500 to $1,112,500 for upgrading existing models and developing new models, respectively (Table 5). Since the cost is driven by staffing, there will not be an initial “start up” cost followed by lower cost maintenance. The annual cost is expected to remain relatively constant for as long as the models are being actively developed or used. Assuming that existing models can be successfully adapted to answer the questions in 10 years, the total cost of the program would be $8.6 million. In this case some of the cost of the program may be borne by

in-kind contributions of modeling staff from agencies (DWR, USGS, USBR, etc.) and post-doc researchers at universities. To develop new models will take at least 12 years and cost $13.3 million.

The cost estimates for the proposed modeling effort in this paper ($0.8 to $1.1 million per year) are within the range of past experience and estimates. The USGS has reported the cost to develop the CASCaDE model was $5.5 million between 2011 and 2015 (or ~$1 million per year). In 2008, UC Davis estimated a $1.8 to $3 million start-up cost over 2 years (or $0.9 to $1.5 million per year) to develop the capacity for 3D hydrodynamic modeling in the Delta. Preliminary budget estimates from the Department of Water Resources for adding sediment and water quality modules to SCHISM are in the same range (roughly 10 Person Years over 3 years or ~$0.8 million per year). The nutrient modeling component for the San Francisco Bay Nutrient Management Strategy is currently funded at $0.6 million per year. These cost estimates from comparable programs demonstrate that the budget estimates in Table 5 are reasonable.

Table 5: Estimated cost of modeling task over 15 years. Costs shown in 2015 dollars. The labor cost of a full-time employee (FTE) was assumed to be $250,000 per year. Equipment costs and license fees are not included but are assumed to be negligible compared to the labor costs. Costs for enhanced monitoring for model calibration and validation are not included.

	Options	
	A. Build off existing models as much as possible	B. Develop new models
Expected Duration of Modeling Effort		
Years	10	12
Task: Model development, upgrades and applications		
# FTEs	2	3
Cost/Yr	$500,000	$750,000
Task: Model maintenance and governance		
# FTEs	0.25	0.25
Cost/Yr	$62,500	$62,500
Task: Synthesis and interpretation of model results		
# FTEs	1	1
Cost/Yr	$250,000	$250,000
Task: Peer Review by External Advisors		
Honoraria ($5K-$10K each)	$50,000	$50,000
Totals		
Total Cost/Yr	$862,500	$1,112,500
Total Cost for Whole Effort	$8,625,000	$13,350,000

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8. Summary and Key Observations

To be determined.

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Appendices

Appendix A: Charge to the Modeling Science Workgroup

Appendix B: Summary of Existing Hydrodynamic and Water Quality Models for the Bay-Delta

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Review Note:
These model summaries were provided by individuals and have not been edited or verified.

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Appendix B. Background Information on Existing Model Platforms for the Bay-Delta

SCHISM	
General Description	Open source 3-dimensional hydrodynamic model with horizontal unstructured grid and terrain conforming vertical grid. Has compatible water quality modules. DWR involved in model development and application to Bay-Delta, in collaboration with Virginia Institute of Marine Science. http://baydeltaoffice.water.ca.gov/modeling/deltamodeling/models/bay_delta_schism/ SCHISM is based on the OHSU model SELFE.
Strengths	· Open source (Apache license). · Second generation unstructured, semi-implicit algorithm enjoying a good balance between maturity and active development. The current form of the algorithm and mesh has been deployed over numerous estuaries worldwide for 5-10 years, but is also being enhanced at VIMS and by users across several institutions. It is more numerically dispersive and less numerically diffusive than most other algorithms in the estuary. · Unstructured horizontal mesh with no orthogonality constraint and terrain following vertical mesh. This makes it possible to efficiently represent bathymetric features and conform to flow fields in channels at moderate resolution without blending fast and slow regions together as in an orthogonally-constrained or curvilinear mesh. · 3D model calibrated for salinity and temperature in the Bay-Delta. Continuously refined by DWR with releases of new capabilities annually. · DWR provides sustained support for upkeep and training in the Delta Modeling Section. · Model resolution is driven by a carefully articulated goal to resolve the primary flow field in major channels of the Delta. · Three ecosystem modules in the suite: o EcoSim 2.0: Dense model with six phytoplankton species, iron, nutrients and simple model of light. SELFE/SCHISM applications in literature but not in SF estuary. o HEM3D: Developed by VIMS to represent direct coupling of hydrodynamic with eutrophication. Variable include DO, 3-5 phytoplankton species, TSS Phosphorus. Estuary tilt emphasizes interaction with sediment, phosphorus and role of DO. o CoSINE: Carbon, Silicate, Nitrogen, two phytoplankton groups (small and diatoms), zooplankton. Currently being coupled to EcoLight for applications in San Francisco estuary. No DO or sediment coupling or phosphorus species, nitrogen cycle is a lean model focusing on ammonia and nitrites. · SCHISM (with CoSINE) Utilized in two multidisciplinary, multi-agency applications to the San Francisco Estuary and beyond: SESAME (http://oceanview.pfeg.noaa.gov/sesame), a DEB ecosystem model for salmon; and NASA-HICO (http://wilkerdalelab.weebly.com/nasa--hico.html), a nutrient model emphasizing remote sensing and the role or light. · Demonstrable scaling on high performance systems, including accolades on parallel performance in the SURA tsunami benchmark process. · DWR plugin for VisIT allows visualization of associated native or NetCDF output

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	using LLNL VisIt across a variety of architectures.
Weaknesses	· Bay-Delta SCHISM is most efficiently run on high performance systems or clusters. · Toolset is dispersed over 2 graphical tools for mesh development and visualization plus a set of scripts for other simulation setup chores. · The Yolo module is still in preparation. · Calibration thus far has emphasized low-medium tidal flows and meshing choices. Work on larger floods is in progress. · The finite element discretization is globally but not locally mass conserving. · None of the modules has benthic grazing term for invasive clams. Initial representation for this will be a simply parameterized sink term.
Other Comments	The nutrient models to date have been developed to run nutrients and water quality variables in line with the hydrodynamics. The arrangement requires re-running hydrodynamics, but offers the full high performance of SCHISM and no storage overhead. DWR is considering creating a standalone version and piping in flow from a database of hydrodynamics results, but this mode will be inefficient when simulating a large number of constituents in a high performance computing environment or when experimenting with a variety of hypothetical flow inputs. The DWR priorities for SCHISM nutrient modeling: · Augment CoSINE with important HEM3D features in a user-modifiable framework amenable to experimentation and modification. · Extension of NASA-HICO work through the upper estuary including light and sediment/turbidity. · Inclusion in CoSINE of a grazing rate for bivalves and zooplankton in keeping with recent research such as Kimmerer and Thompson (2014).

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Suntans	
General Description	3-dimensional, unstructured grid (horizontally but not vertically), hydrodynamic model calibrated for Delta. Developed by Stanford University and funded by the Delta Science Program. Open source. It is a non-hydrostatic Navier-Stokes equation solver utilizing the Boussinesq approximation and Reynolds Averaged Navier-Stokes turbulence parameterization of the resolved motions.
Strengths	-3D unstructured grid fully nonlinear and non-hydrostatic model. It can resolve channel junctions in detail to assess the relative importance of localized, supertidal flow features which determine junction mixing via shear, separation, flow bifurcations, turbulent mixing layers, and secondary circulations induced by curvature. These mechanisms can them be compared to dispersion from tidal flows induced at the junction by flow phasing in connecting channels. -Suntans is open source enabling continuity among users as source codes can be examined, improved and shared. It also enables interdisciplinary collaboration since scientists can incorporate their discipline modules into the existing implementation. - The code is highly parallelized and can be run on multiprocessor parallel computers.
Weaknesses	-Suntans relies on a triangular C-grid method and various related alternatives. Numerical noise in the vertical component of velocity (horizontal divergence noise) continues to be a challenge. This affects resolution of secondary flows especially in real applications. Careful grid selection and filtering is required as yet. Triangular C-grids require very high resolution grids to represent turbulent processes (especially in weeds, rocks, walls) making > tidal time-scale simulations infeasible.
Other Comments	-Suntans has been used to quantify dispersion at channel junctions to better understand fundamental transport phenomena--including secondary flows and grid choices. He analyzed the mechanisms of intra-junction mixing and the usefulness reduced-order dispersion models (Wolfram 2013). He found that 2D models capture the dispersion mechanisms in junctions sufficiently. Also, among several key mechanisms, junction flow phasing appears to be the dominant dispersion mechanism. - Used to categorize how tidal forcing and inflows affect stratification and mixing for a simplified system (Fringer et al., 2006) - The premise underlying the development of Suntans is that Delta-scale dispersion is driven primarily by dynamics at channel junctions. Dispersion coefficients of low dimensional models lump too many processes to be useful for mechanistic study. With sufficient resolution, numerical models that include much if not all, of the relevant physics can simulate flow behavior at junctions, enabling model predictions of Delta-scale dispersion that do not require tuning.

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CASCaDE	
General Description	3-dimensional, flexible-mesh hydrodynamic model. Curvilinear grid approach (appropriate to narrow, sinuous channels) melds with unstructured grid approach (which works well in broad, open water areas). Has compatible sediment and water quality modules. Open source. Software is developed by Deltares, and adapted and applied to SF Bay-Delta by CASCaDE team, in close collaboration with Deltares. Various modules are in different stages of development. Currently, calibrated 2D hydrodynamic model for Bay-Delta is available for download (http://www.d3d-baydelta.org/).
Strengths	· Flexible mesh (unstructured+curvilinear) is ideal for Delta. · Models are under development for Bay-Delta by CASCaDE team in collaboration with Deltares. This includes the development of spatial grids and boundary condition files. · State-of-the-art. · Open source. · Biogeochemical modules exist for modeling multiple phytoplankton groups/species and their interactions with nutrients, light, hydrodynamics, and grazers. Phytoplankton model being adapted for Bay-Delta is currently in deep R&D mode and currently focuses on interactions with hydrodynamics, light (including light attenuation by dynamically computed sediment), and grazers. (Nutrients are not a current CASCaDE focus). Many of the necessary model linkages and Bay-Delta specific approaches for providing measurement-based input to these models are being established by CASCaDE team in collaboration with Deltares. · Multiple ecosystem processes can be modeled in an integrated manner within a single modeling framework. In some cases, the "coupling" between models is relatively direct; in other cases, translation of output from one Deltares model into appropriate input format for other models is a multi-step process. The inter-model "infrastructure" exists, or is under development, to provide this communication between models. · 2D hydrodynamic-sediment model for Delta has been calibrated and published (http://www.hydrol-earth-syst-sci-discuss.net/12/1507/2015/hessd-12-1507-2015.html). · Multiple other modules exist for ultimate expansion of processes considered (e.g. macrophytes, contaminants, dissolved oxygen, microphytobenthos, etc.) · A parallel version of the hydrodynamic model has been developed and is being used by CASCaDE to facilitate long simulations. A "stitching" tool has been developed by Deltares to merge parallel subdomain hydrodynamic outputs into single-domain files for use by water quality and ecological models. · Water quality and ecology modules can be run "offline" (i.e. driven by saved hydrodynamic outputs), for maximum efficiency. · Deltares has developed tools to translate hydrodynamic and water quality outputs into inputs for HABITAT, software that is being used by CASCaDE team to assess habitat suitability for fish and bivalves. Preliminary results for Bay-Delta are encouraging.

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	· Several GUI's, pre- and post-processors, plotters, and viewers are available for use with Deltares models. · Deltares scientists and developers are keen collaborators. · 3D hydrodynamic model for Bay-Delta is currently undergoing calibration and validation, and will ultimately be released for broader use. SFEI is intending to implement Deltares/CASCaDE models as foundation for SF Bay Nutrient Modeling effort.
Weaknesses	· Flexible-mesh software for hydrodynamics---and thus for water quality and ecology---is very new. As a result, intra- and inter-model hurdles are still being crossed to optimize performance, accuracy, flexibility and capability (e.g. vertical Z-layers, grid aggregation). Such challenges continue to be resolved over time. · Understanding of and modifications to actual software are not as easy, from the user standpoint, as if user was implementing own code.
Other Comments	· The mathematical method for characterizing phytoplankton competition is based on a linear programming optimization approach, which is quite different from many other (e.g. partial differential equation + Monod based) phytoplankton models. Comparison of the two approaches by Deltares developers indicates, if formulated consistently, that they provide the same results and that the LP approach is efficient and stable. · The Deltares grazing module currently being implemented by CASCaDE for zooplankton and benthos is not a dynamic model of grazer *populations* or *biomass*, but rather is being used to provide reasonable *grazing rates* on the phytoplankton. A goal of CASCaDE is to ultimately develop a dynamic bivalve model based on the DEB approach, but other alternatives may be considered.

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DSM2	
General Description	Calibrated 1-dimensional hydrodynamic model for Delta. Water temperature can be modeled. Has a nutrient module, which includes the capability to model chlorophyll and dissolved oxygen. Developed and maintained by DWR. Open source
Strengths	· Historical hydrodynamics and salinity are well-calibrated by Delta Modeling Section (DMS) staff in DWR. · The source code is available. · Boundary conditions input is in DSS data format which allows easy modification to boundary conditions and easy BC development. · Model output is calculated in the DSS data format. · There is a very active user group that is supported by the DMS in DWR. · Fairly comprehensive user documentation is included with the model set-up, which can be downloaded by the user for several of the most recent versions. · The model set-up facilitates ease of use – the model is not very difficult to learn for a technically competent user. · Salinity transport, represented as EC, is calculated in by the QUAL water quality module separately from hydrodynamics. · Transport of water temperature included in the QUAL module. · Nutrient dynamics (PO4, Organic_P, NH3/4, NO3, NO2, Organic_N, CBOD, DO, algae, EC) included and temperature dependent. · Rate parameters for processes are spatially discrete (vary by channel) · Calculations are very fast, allowing decades to be simulated easily · The conceptual model of nutrient dynamics matches available data, although there is sparse data for some processes · The nutrient conceptual model is simple, well-understood and has been used in many water quality models (and has been peer reviewed in other models) · There is a simple particle tracking module that uses the hydrodynamics output directly in its calculations
Weaknesses	· The application to the Delta is one-dimensional. · Water bodies are represented as zero-dimensional fully-mixed objects, which is inadequate in some areas of the Delta (such as Liberty island) · Only the legal Delta is represented (i.e., the Bay is not included) · Tidal wetting-and-drying at the boundaries of the estuary in not included, so representation of Suisun Marsh, for example, is inadequate for some applications. · Hydrodynamics is independent of the salinity field, making representation of the salinity intrusion in the western Delta less than adequate in low outflow situations. · Meteorology is specified as a global BC, but analysis of water temperature data vs. model output clearly indicates that multiple meteorological regions are needed (this is a significant problem as some processes are sensitive to

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	water temperature (*e.g.*, DO) · There are other parameters used in the nutrient and/or water temperature calculations that are global, but should be allowed to vary by channel · Only one general algal group is included · pH is not included in the water quality model · Sediment-water column interactions are extremely simple (although this is not a big problem, as there is no data to support them) · No sediment transport · Visualization tools are inadequate. · Model failure errors (i.e., model crashes) are tricky to interpret and require some user experience · Particle tracking module has some conceptual problems at channel junctions that make its use questionable in some applications
Other Comments	DMS staff have used the hydrodynamics and salinity modules successfully for many years and these two applications are in wide general use - these results are widely accepted as sufficiently accurate for most purposes. Even though the nutrient model is simple, this is not a problem given nutrient data availability – there is a fairly good match between the conceptual model and available nutrient data. *I.e.*, the simplicity of DSM2 for hydrodynamics and water quality is both a strength and a weakness. DMS staff are subject to the whims of politicians, so model upgrades to anything other than hydrodynamics or salinity are slow in arriving (if at all). The source code (for QUAL) is generally well-written, so modifications to the conceptual model should be straight-forward for an experienced developer. Thus, any lack of availability to DMS staff time should not be an issue.

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RMA 2-D Bay-Delta model	
General Description	Calibrated 2-dimensional, finite element, hydrodynamic model for the Bay-Delta. Has compatible water quality and sediment models. Maintenance and ongoing development at Resource Management Associates.
Strengths	· The RMA Bay-Delta model calibration for hydrodynamics and salinity transport has been ongoing for many years, and is well-documented and widely accepted (RMA2 calculates the hydrodynamics and RMA11 calculates transport). · The hydrodynamic and salinity model results are well-accepted by the modeling community · The hydrodynamics and salinity modules can either be run with or without density-dependent calculations (i.e., without density dependence, the codes are run sequentially, with it they are run concurrently) · Model output analysis tools are well-developed. · Visualization tools are very well-developed · Particle tracking modeling and visualization tools are well-developed, widely used, and well accepted by the modeling community · Particle tracking modeling includes some behavioral additions to the transport of particles to mimic the assumed behavior of fish · Boundary conditions input is in DSS data format which allows easy modification to boundary conditions and easy BC development. · Model output is calculated in the DSS data format. · Some aspects of model set-up can be automated · The company has historically been willing to support external use of the executable codes, and has made the particle tracking applications available to some clients · There is a nutrient model available (in RMA11) that is generally of the same form as the nutrient model in DSM2. · The nutrient module has been applied in several applications outside of the Delta, and the results have been well-accepted. · Parameterization of RMA11 (water quality, transport model) is under user control, so all parameters can be made spatially explicit · The nutrient model can be altered in a straight-forward manner to include additional processes and RMA staff have expertise in modifications to the RMA11 code · There is a compatible sediment model in RMA11.
Weaknesses	· Model documentation is dated and inadequate for current uses. · The source code is not free · Being a higher dimensional model, most applications require a fairly sophisticated user · Model set-up has some tricky aspects that require a fairly sophisticated user

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	· The Bay-Delta application is mixed one and two-dimensional, NOT 3-D · Run times can be limiting for applications running more than several years at a time · RMA11 set-up can be time-consuming, and requires some user expertise · Model failure errors (i.e., model crashes) are tricky to interpret and require user expertise
Other Comments	The RMA modeling suite has been applied broadly for many important applications in the Delta. It is flexible in its ability to be adapted to changes in Delta bathymetry. The RMA modeling staff have among them many decades of experience in Bay-Delta model applications, and are considered as experts in the modeling community. The staff are also expert in interpreting the basic hydrodynamic and water quality data needed as the backbone of any model development project.

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Delta EFDC Water Quality Model	
General Description	Calibrated 3-dimensional, structured grid, hydrodynamic model for Delta. Has compatible water quality and sediment models. Developed at Virginia Institute of Marine Sciences, local calibration supported by the U.S. Army Corps of Engineers. Open source
Strengths	It is a well-established computational engine for curvilinear grids.
Weaknesses	Only the EFDC computational code is open source, not the pre-and post- processor tools required to use the software. A curvilinear grid has some limitations for the Bay-Delta geometry. The grids demonstrated in the last two USCAE 'shows' have an incomplete network and ignored most structures altogether. The 'local calibration' supported by the USACE falls way short of demonstrating any efficacy of modeling the Bay-Delta system. Most data shown have been near boundary conditions and not that favorably. The model has no provision for simulating structures (gates, barriers, culverts) and as such is really limited to simulating known flow conditions where structures can be handled by withdrawals and inflows. Tedious model input file structure requirements
Other Comments	

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UnTRIM Bay-Delta model	
General Description	The UnTRIM code is a 3-dimensional solver developed by Vincenzo Casulli. Current the 3-dimensional hydrodynamic model developed by Michael McWIlliams is the most strongly calibrated and utilized 3-D model of the Bay-Delta system. Michael has coupled sediment, waves and water quality into the model of the Bay-Delta Estuary. Michael has also created a lower resolution model from his original using sub-grid bathymetry techniques incorporated in the UnTRIM solver. Not in the public domain. RMA and UC Davis has also developed a model suing the UnTRIM solver that incorporates a resolution between the two of McWilliams that also uses sub-grid bathymetry.
Strengths	Currently the McWilliams UnTRIM Bay-Delta model is the best developed 3-D model being used. The high-resolution model has been sued for extensive studies including sediment transport. The lower-resolution scheme has been used to replicated the work of Fleenor et al. in the modeling work done for the Comparing Futures book. A second UnTRIM Bay-Delta model has been developed by RMA and UC Davis and is a medium grid-resolution model that is using sub-grid bathymetry to provide improved resolution. To date this model has been limited in use to modeling limited current Delta bathymetry and a 1850s bathymetry. Additional development is underway. The biggest strength of the UnTRIM code, other than being what SCHISM and SUNTANS are trying to replicate, is its ability to operate on an inexpensive workstation with reasonable computations times rather than requiring a cluster or cloud.
Weaknesses	It is currently not public domain or open source requiring a substantial investment in software, but not in hardware.

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Other Comments	

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