Modeling Science Workgroup White Paper

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

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Executive Summary

Management actions in the Delta related to nutrients could cost billions of dollars to implement in the coming decades depending on decisions that will come before the Central Valley Regional Water Quality Control Board (Water Board). The complexity of the Delta ecosystem and the range of questions to be addressed demand that numerical, processed-based water quality modeling be part of Delta management efforts. In light of this fact, the Water Board convened the Modeling Science Workgroup in 2015, and tasked it with advising on the development and use of water quality models as one component of the Water Board's Nutrient Research Plan. The Charge to the Modeling Science Workgroup (included in Appendix B) was to provide advice to the Water Board on:

- The types of models would be needed to answer the nutrient management questions raised by stakeholders,
- Organizational arrangements to support and maximize the benefits of models, and
- Cost estimates for the modeling task and how such work might be phased over time.

The key findings of the Workgroup for each of these topics are summarized below.

Types of Models Needed

To address the nutrient management questions in the Delta, modeling will need to include hydrodynamics, nutrient water quality, primary productivity, benthic and pelagic grazing, sediment transport, and macrophyte-related processes. Models should also have the desired characteristics of accessibility, credibility, scalability, and a large enough user community (including institutional support) to ensure continuity through time. Meeting all of these general and technical characteristics may not be possible with any one model; therefore, these characteristics are considered guidelines, not necessarily requirements. Answering the management questions sufficiently is the real performance standard. In certain cases, a simple model may provide sufficient answers when applied and evaluated by skilled analysts.

The existing hydrodynamic and water quality models that have been applied to the Delta were reviewed and evaluated for this report. However, none of the existing models include all the important processes, meet all of the desired model characteristics, or address each of the identified nutrient management questions explicitly.

Organization and Approach

Developing and maintaining the water quality models for the Delta will be a significant undertaking that will cost millions of dollars. Therefore, the modeling approach should be carefully planned to minimize costs and maximize benefits. With this in mind, the Modeling Science Workgroup identified the following recommendations.

- **A Successful Modeling Approach Cannot Focus Only On Modeling -- Support for Data Management, Data Synthesis and Monitoring Is Equally Important**. The success of a modeling program in the Delta will not be measured by numbers output from a model, lines of computer code written, or dollars spent, but rather through increased insight into the nutrient processes in the Delta. Robust data management, interdisciplinary data synthesis, and enhanced monitoring are essential for achieving this goal. Data managers and technologists are needed to prepare the datasets used by the models and to visualize both the inputs and outputs of the models. A team of chemists, biologists, hydrologists, engineers, statisticians, and other relevant scientists is needed to develop conceptual models and evaluate model output in light of the body of scientific knowledge about the Delta. Enhanced monitoring is needed to provide calibration and validation datasets for the models.

- **Establish a Good Governance Process.** A Steering Committee, such as the committees for the Regional Monitoring Programs, will be needed to guide the process and make decisions regarding best allocation of resources. The water quality management questions in the Delta present too many options and related issues that have yet to be fully defined. Moreover, the development and adoption of a modeling approach will be heavily influenced by available funding and information at that time as the work proceeds. A good governance process will be needed to guide the program through these uncertainties and ensure stakeholder buy-in.

- **Phased Implementation - Add Nutrients into Existing Models as a First Step**. A phased implementation approach should be followed with two general stages.

  The first stage should be to employ existing models as a platform to develop and test the desired logic and linkages for appropriate water quality processes. These existing models may be notably simpler than models required to address the more complex management questions. However, starting with basic tools provides a useful opportunity to test modules prior to implementing the more complex models. Adding nutrient-related modules to existing hydrodynamic models of the Delta will save time and money (estimated at approximately 6 person-years or $1.5 million total) and reduce risk of project failure.

  The second stage should be to refine and add complexity to the models, or transferring previously developed logic to more complex models, to improve system representation as needed. Once more complex models are developed, subsequent logic refinements may be added directly.

- **Select the Right Model for the Job – The Need for Multiple Models**. A variety of different types of models will be needed to answer all of the management questions. Highly resolved three-dimensional models may be necessary for some applications, while simpler, one-dimensional models may be sufficient for others. The appropriate model for each question should be used. Attempting to develop a single model to address all potential conditions, may not only be infeasible, but would be inefficient and uneconomical.

- **Implement Robust Quality Assurance Processes**. The model development process should follow widely accepted guidelines for quality assurance to produce accurate and transparent results, including external peer review**.** Regular peer review by external experts will ensure that program funding provides the highest quality answers to the management questions.

- **Hold an Annual Delta Nutrient Modeling Workshop:** There should be an annual workshop where modelers, scientists, field monitoring staff, and managers come together to share results, confirm conceptual models, and discuss model modifications and applications. The primary objective of the workshop should be to answer management questions and determine priority data gaps for monitoring. Interaction between these different groups should occur on a regular basis anyway. An annual workshop is a simple and effective approach step that can be taken to ensure interaction of all the parties. The workshop could be organized by the California Water and Environmental Modeling Forum.

Costs

The cost of the modeling effort is estimated to be $1,675,000 per year in 2015 dollars. The annual cost estimate is similar to, but higher than, past budgets and budget estimates for modeling ($600,000 to $1,500,000). The reason for the increased cost is that the proposed approach includes more than just modeling. It also includes data management, data synthesis, and monitoring. Ideally, total costs will be shared by multiple agencies and funders so that each participant will leverage significant outside resources. The program is expected to last for 10 years, split into two 5-year phases.

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 prioritize Delta nutrient activities. The potential problems identified in the Delta Plan include assessing whether changes in ambient nutrient concentrations in the Delta have resulted in (1) decreases in algal abundance and shifts in algal species composition, (2) increases in the abundance and distribution of macrophytes, including water hyacinth and Brazilian waterweed, and (3) increases in the magnitude and frequency of cyanobacteria blooms, or some combination of nutrient concentrations and other factors. The Water Board also formed several Science Workgroups to develop white papers to review the state of the science and identify high priority science activities that 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. The white papers and workgroup documents contain more information and are available on the Central Valley Water Board's website[2].

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 and test hypotheses regarding 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 (included in Appendix B) was to provide advice to the Water Board on what types of models would be needed to answer the nutrient management questions raised by stakeholders (see Table 3). Included in this charge was also to provide advice regarding potential organizational arrangements to support and maximize the benefits of models. Finally, the group was asked to provide cost estimates for the modeling task and describe how such work might be phased over time. The Charge provided explicit guidance for the Workgroup to avoid recommending specific models, and instead focus on describing the characteristics of models that would be necessary to answer the management questions raised by the stakeholders. For clarity, models considered by the Workgroup are mechanistic, process-based numerical models, and 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, state and local agencies, university researchers, private consultants, and non-profit institutions with an interest in water quality modeling in the Delta. The full

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

[2] http://www.swrcb.ca.gov/centralvalley/water_issues/delta_water_quality/delta_nutrient_research_plan/index.shtml

list of Workgroup participants and their affiliations is provided on the title page. The Workgroup held meetings on June 24, 2015, August 5, 2015 (teleconference), September 10, 2015, and October 14, 2015. 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 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 computer models in order to provide context for the Workgroup recommendations at the end of this document. In addition, the strengths and limitations of a modeling approach for managing water quality in the Delta are discussed.

An important consideration when applying and using models is that, while models are critical for understanding complex systems, models alone do not provide the answers. Rather, models are tools to organize information, relate various processes, improve the understanding and characterization of aquatic systems, and test hypotheses in conjunction with field studies and management actions. *People using models as tools will provide the insight needed to formulate answers to management questions*.

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). A model includes the computer code, data to operate the model, and the assumptions of the conceptual model that describe the coded processes. The development and application of computer models generally follows a multi-step process that includes conceptual model development, computer model development and evaluation, and model simulations (Figure 1).

Conceptual model development is a multistage process that involves developing the conceptual model that reflects the underlying science of the processes being modeled and defining appropriate space and time scales and the key constituents to be modeled.

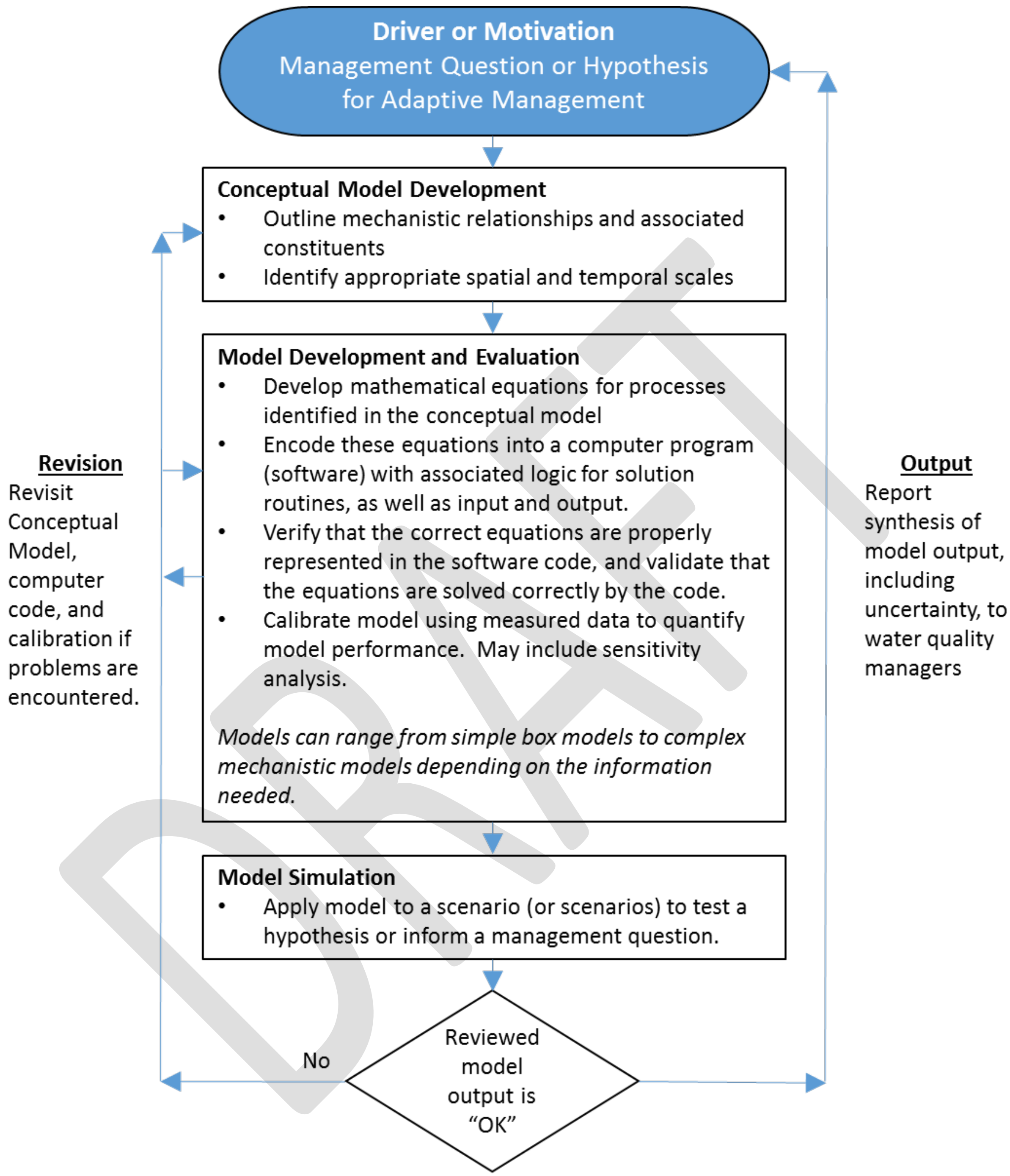
Computer model development and evaluation includes developing a mathematical representation of environmental processes in the conceptual model and encoding these mathematical expressions in a computer software program. The mathematical expressions typically include coefficients, constants, and parameters that represent rates, sources and sinks, constants, or other parameters. The software code requires verification that the correct equations were used and validation that they are solved correctly.

Subsequently, the model is developed using this computer software and water body-specific field data describing the physical domain of the system and associated input data. During the model calibration process, the value for selected parameters can be adjusted so that the model predictions match measured values. There should be sufficient monitoring data to characterize model parameters, as well as a calibration data set to compare simulated and measured values. Because water body-specific information to define all model parameters is not typically available, parameter values are often defined using information from other systems, the scientific literature, and the professional judgment of the modeler. After calibration, an independent set of input data and calibration data (e.g., a different period of time) is used to verify the efficacy of the calibration. Quantifying the uncertainty in model results and evaluating the sensitivity of model output to certain parameters are also part of model evaluation. If challenges are identified during model development and evaluation, earlier activities in this phase can be revisited, or if necessary, the conceptual model phase.

Model simulation involves running the model and analyzing its outputs to inform a decision, hypothesis test or adaptive management. If after a review of outputs, model results are deemed acceptable or appropriate for the particular management objective, then the information is conveyed to managers. If outputs identify shortfalls in the effort, the conceptual model or model development and evaluation phase can be revisited.

An important distinction should be made between model software and model applications. Model software is generic computer code to represent environmental processes in the conceptual model. A model application is when the software is used to simulate conditions in a particular water body. The quality of the software and application are both important. High quality software can be inappropriately applied with poor quality output as a result. Likewise, simple software can be skillfully applied to provide useful information.

Figure 1: Diagram of the Modeling Process



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

Models are important tools for water quality managers. They have the potential to play a critical role in developing an improved understanding of ecosystem function in the Delta and thus informing Delta management decisions. Specifically, models can improve water quality management decision-making by multiple agencies, including the Central Valley Water Board, the Department of Water Resources, the Department of Fish and Wildlife, the National Oceanic and Atmospheric Administration, water contractors, dischargers, and municipalities. Other strengths of developing a modeling approach in the Delta include:

- Fundamentally, the Delta is too complex to comprehensively understand without models. Monitoring on the spatial and temporal scales necessary to fully characterize and assess management actions in the Delta is infeasible. Water quality monitoring data are typically collected at discrete points that are often separated by miles or tens of miles due to the size of the Delta. Further, data are collected at discrete times and may be collected at frequencies that range from hours to days to weeks. Models developed on finer spatial and temporal scales than measurement data predict conditions between monitoring stations and station visits, and provide a more comprehensive and continuous representation of water quality throughout a large model domain. Further, models provide the ability to sort out the effect of tides, which make understanding the Delta so difficult.

- Models can 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 are essential for allowing researchers to quantitatively explore how individual and multiple factors acting in concert can shape ecosystem response to nutrients. For example, an ecosystem perspective is essential to compare and understand the relative importance of clam and zooplankton grazing, transport (flow, settling, and routing), light limitation, residence time[3], water temperature, introduced species, and nutrients on algal biomass and algal species composition.

- Models can efficiently allow stakeholders to develop and assess management and planning scenarios to characterize the effect of nutrients over a range of conditions. For example, models could be used to assess complex spatial and temporal variability in response to 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.

[3] The cumulative amount of time a parcel of water is contained within a specified region (also known as exposure time). Determination in tidal systems can be defined in different ways and should be documented for each specific analysis/study. Useful guidance regarding definition and determination on residence time is provide by Monsen and Cloern (2002).

- Finally, models can be extremely valuable for communicating critical information to stakeholders, regulators, and resource managers, leading to a common understanding of complex systems. By organizing 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, they do have limitations. For example, accurately modeling all of the complex processes related to nutrients in the Delta is infeasible. In general, water quality models will not be as accurate as the hydrodynamic models that many managers currently use. Nevertheless, the water quality models will provide useful insights that will help managers make better decisions so long as the uncertainty in the model output is known and the following limitations are understood.

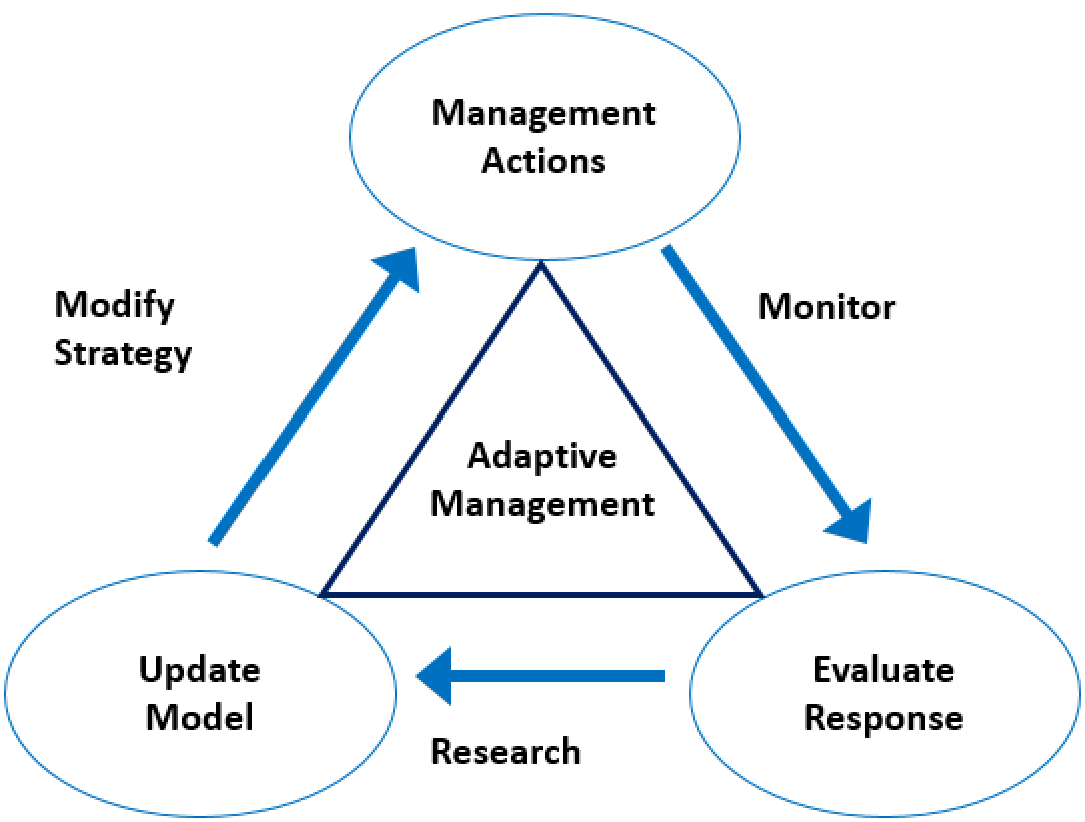
- Models by themselves will not provide answers; people using models as tools will provide answers. Models only generate output. Interdisciplinary analysis and synthesis of modeling results and related information, and communicating these findings to stakeholders provides the actual value of modeling for decision support and adaptive management actions (Figure 2). 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 considerable uncertainty. Uncertainty in model results originates 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. Mathematical formulations in models are imperfect representations of physical, chemical, and biological processes. Further, some processes may not be included, or are 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, such as one-dimensional (1-D) or two-dimensional (2-D) representations. For example, 1-D representations of Delta channels 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 the simulation time step is too large to capture processes of shorter duration, or if the temporal resolution and extent of available data do not match the time scale of the process being modeled. An important aspect of any modeling exercise is to effectively communicate model uncertainty to decision-makers.

- <u>Monitoring and modeling are complementary, and both activities are critical to understanding aquatic systems such as the Delta</u>. 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 have necessarily limited coverage in time and space but represent the measured state of the system. Model output can achieve much greater spatial and temporal coverage than data alone but can only approximate the measured state of the system. When monitoring data and model output are used together, scientists can come closer to a complete picture of a system and its processes. Therefore, when investing in model development and application, managers should also invest in monitoring programs needed to support the model. Further, both activities – modeling and monitoring – should undergo continuous review and refinement.

Figure 2: The Adaptive Management Process



3. Description of Existing Model Software and Applications to the Delta

There are several existing models that have been applied all or portions of the Bay-Delta. The following paragraphs summarize each of these models. While there may be other relevant models in use somewhere else in the world, they would just be software, not an application to the Delta. The CE-QUAL-W2 model is included in this assessment because it has capabilities that could be used in portions of the Delta, although it has not been applied to the Delta.

Principal attributes of the existing model applications are compared in Table 1. Table 2 summarizes the potential water quality capability or modules associated with each model. In order to simplify the summary tables, the following general assumptions were made:

- Training on how to use and apply the models was assumed to be available for all models. The group did not inquire about costs associated with model-specific training.
- Proprietary models have costs associated with them, but these costs may vary based on several factors, including, but not limited to: entity purchasing the code; number of users; term/duration of license; etc. As such, licensing costs were not determined.
- A level of technical expertise is required to develop and apply the models outlined herein, and there is a modeling community with sufficient expertise and experience with conditions in the Delta to support such tools. Regardless of model selected, this expertise and experience in Delta conditions is paramount to the successful use of any selected model(s).
- Post-processing software is an important element, but the specific needs of such post-processors can be identified during model selection and development. Specific details of each model post-processors were not included in the summary tables.

a. SCHISM (Semi-implicit Cross-scale Hydroscience Integrated System Model)

SCHISM is an open source, three-dimensional (3-D) model with horizontal unstructured triangular grid and terrain conforming vertical grid. SCHISM is based on the Oregon Health & Science University model SELFE (Semi-implicit Eulerian-Lagrangian Finite Element). SELFE uses a semi-implicit finite-element/volume Eulerian-Lagrangian algorithm to solve the Navier-Stokes equations. The model has several compatible water quality modules. The Department of Water Resources (DWR) has been the principal entity involved in model development and application to Bay-Delta, in collaboration with Virginia Institute of Marine Science (VIMS).

b. Suntans (Stanford Unstructured Nonhydrostatic Terrain-following Adaptive Navier-Stokes Simulator)

Suntans is an open source 3-D, unstructured triangular grid that employs the finite volume method to solve a non-hydrostatic representation of the Navier-Stokes equations. The model was developed and calibrated for the Delta by Stanford University and funded by the Delta Science Program. The model represents density, but not water quality (e.g., nutrients) at this time.

c. CASCaDE (Computational Assessments of Scenarios of Change for the Delta Ecosystem)

CASCaDE is a U.S. Geological Survey (USGS) application of the Delares Delft 3D software to the Bay-Delta. The modeling framework includes hydrodynamics based on a 3-D unstructured-mesh. The model is compatible with associated sediment and water quality modules. Various modules are in different stages of development. A developed 2-D hydrodynamic model application for the Bay-Delta is publically available.

d. DSM2 (Delta Simulation Model II)

DSM2 is an open source, finite difference, 1-D hydrodynamic model based on laterally and vertically averaged form of the St Venant equations. The model has been developed and applied in the Delta. Water temperature is modeled and nutrient modules are available, which includes the capability to model chlorophyll and dissolved oxygen. DSM2 is maintained by DWR.

e. RMA-2 Bay-Delta Model

The RMA-2 Bay-Delta Model is a proprietary 2-D, finite element, hydrodynamic model developed and calibrated for the Bay-Delta. The model solves the 2-D form of the St. Venant equations. The model has a compatible water quality and sediment transport models, RMA-11, that employs output from RMA-2 to determine fate and transport of a wide range of constituents. The model is maintained by Resource Management Associates (RMA).

f. EFDC (Environmental Fluid Dynamics Code)

EFDC is an open source, 3-D, finite difference hydrodynamic model. The EFDC model solves the three-dimensional, vertically hydrostatic, free surface, turbulent averaged equations of motions for a variable density fluid (Hamrick 1992), and often referred to as the Euler's equations or Euler's transport equations. EFDC has compatible water quality and sediment models within the model. The application to the Delta was developed at VIMS, with development supported by the U.S. Army Corps of Engineers (USACE).

g. UnTRIM (Unstructured Tidal, Residual, Intertidal Mudflat Model)

UnTRIM is a proprietary, 3-D unstructured-grid, semi-implicit, finite-volume, model employing Eulerian–Lagrangian algorithms that solve the Navier-Stokes equations. The model has been calibrated to the Bay-Delta system and been applied to a wide range of problems. UnTRIM has been linked to water quality models to assess fate and transport of a range of constituents.

h. CE-QUAL-W2

CE-QUAL-W2 is an open source, 2-D model (laterally averaged). The governing equations are developed by performing a mass and a momentum balance of the fluid phase about a control volume. These equations are laterally averaged, representing vertical and longitudinal gradients. This model has not been applied to the Delta, but has been applied to other estuary settings. CE-QUAL-W2 resides in the public domain and is actively supported by Portland State University and the U.S. Army Corps of Engineers.

i. SI-3D (Semi-Implicit-3D Model)

SI-3D is a 3-D developed by Dr. Peter E. Smith at USGS to simulate portions of the Delta (e.g., Sacramento River in the vicinity of the Delta Cross Channel). The model uses a three-time-level, leapfrog-trapezoidal numerical scheme. A key feature of the scheme is that it does not rely on any form of vertical/horizontal mode splitting to treat the vertical diffusion implicitly. The model is designed for parallel processing on shared memory computers. A 3-D water quality model, SI3DWQ, can be coupled with SI-3D to assess fate and transport of a range of water quality constituents. A Java-based, 3-D particle-tracking model and interactive visualization toolkit are available for use with the model.

Table 1. Background information on existing or potential model platforms for Bay-Delta water quality assessments

Feature	SCHISM	Suntans	CASCaDE[1]	DSM2	RMA2[1]	EFDC[1]	CE-QUAL-W2	UnTRIM[1]	SI-3D
# of Dimensions	1-D, 2-D, 3-D	3-D	1-D, 2-D, 3-D	1-D	1-D, 2-D (depth avg)	1-D, 2-D, 3-D	1-D, 2-D (laterally avg)	1-D, 2-D, 3-D	1-D, 2-D, 3-D
Solver	SELFE	n/a	CASCaDE(I): Delta TRIM CASCaDE(II): Delft3D	n/a	n/a	n/a	n/a	n/a	n/a
Governing Eq.	Navier-Stokes	Navier-Stokes	Navier-Stokes	Saint-Venant	2D Saint-Venant	Euler's equations	Euler's equations	Navier-Stokes	
Solution Tech.	Semi-Implicit Finite-Element/Volume	Finite-Difference/ Volume	Finite Difference – Finite Volume	Finite Difference	Finite Element	External-Internal Mode Splitting	Finite Difference	Finite Difference – Finite Volume	Navier-Stokes equations
Horizontal Grid	Unstructured	Unstructured	Unstructured	Structured	Unstructured	Structured	Structured	Unstructured	Structured
Vertical Grid	Terrain Conforming	Terrain Conforming	Unstructured	n/a	n/a	Structured	Structured	Unstructured	Structured
Source Code	Open	Open	Open	Open	Proprietary	Open	Open	Proprietary	Open
Water Quality Modules/Nexus	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Ongoing development	Yes	Yes	Yes	Yes	Yes	No[2]	No	Yes	Yes
Computing Requirements	Cluster	Parallel	Parallel, Cluster	Single Computer	Single Computer	Single Computer	Single Computer	Single Computer	Single Computer
Domain	Bay and Delta	Delta	Bay and Delta	Legal Delta	Bay and Delta	Bay and Delta	n/a	Bay and Delta	Portions of Delta
Pre-Processors[3]	Yes, Open	Yes, Open	Yes	Yes	Yes, Proprietary	Yes, Proprietary	Yes, Open	Yes, Proprietary	n/a
Post-Processors[3]	Yes, Open	Yes, Open	Yes	Yes	Yes,	Yes, Proprietary	Yes, Open	Yes, Proprietary	Yes/Open
Documentation	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
Wide Range of Users in Delta applications[4]	Yes	No	No	Yes	Yes	No	No	Yes	No
Application Maintained by	DWR and VIMS	Stanford	USGS	DWR	RMA	VIMS and USACE (dynamic solution)	n/a	McWilliams, RMA, UCD	UCD/Stanford, Pete Smith
Software maintained by	DWR and VIMS	Stanford	Deltares	DWR	RMA	EPA (VIMS)	USACE/PSU	Casulli[5]	Pete Smith

[1]"RMA2" refers to the RMA2 Bay-Delta Model. "EFDC" refers to the Delta EFDC Water Quality Model. "UnTRIM" refers to the UnTRIM Bay-Delta Model. CASCaDE refers to the USGS application of Deltares' Delft 3D model to the Bay-Delta.

[2]No longer under development; moved to SCHISM

[3]"Open" refers to open source code for pre- and post-processors

[4]For purposes of this report a "wide range of users in Delta applications" refers to an active user-community of at least several people, i.e., not one or two people.

[5]Theory and solver maintained by Casulli, but user writes unique program for application.

See Appendix A for a glossary of modeling terms

Table 2. Potential water quality models or modules (in parentheses) available for selected models

Representation	**Parameter**	**SCHISM (CoSINE - HEM3D[3])**		**SUNTANS**	**CASCaDE (DELWAQ)**	**DSM2**	**RMA2 (RMA11)**	**EFDC**	**CE-QUAL-W2**	**UnTRIM (DELWAQ)**	**SI-3D (SI2DWQ)**
Density	*Salinity*	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Density	*Water Temp.*	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Nutrients	*Nitrogen*[1]	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Nutrients	*Phosphorus*[1]	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Primary Production	*Algae/Chloro-phyll a*[1]	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Primary Production	*Macrophytes*	No	No	No	No	No	No	No	Yes	No	No
Dissolved Oxygen	*Dissolved Oxygen*	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Sediment	*Sediments (bed)*[2]	No	Yes	No	Yes	No	Yes	Yes	Yes	Yes	Yes
Sediment	*Sediment transport*	No	Yes	Yes	Yes	No	Yes	Yes	No	Yes	No

[1] These parameters may be included in the main model or as an add-on or module to the main model. They be represented as a single aggregate term or more specific species may be included.

[2] Representation of sediment in the model or modules is not described in detail.

[3] CoSINE and HEM3D are two different water quality modules that could be used with SCHISM. They each support different parameters.

NOTE: This table summarizes the general capabilities (in a general sense), which water quality parameters are included within each model and/or its add-on/modules. Some models have parameters than can be included, but are not included in the current Bay and Delta applications. Other models list some parameters as under development, but not yet available for the current Bay and Delta applications. This table does not necessarily include all parameters included in the model.

4. Nutrient Management Questions and Modeling Objectives for the Delta

The impetus for any scientific investigation is the question or questions 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 B). As part of this effort, the Modeling Science Workgroup reviewed, refined, and reorganized the management questions to make them more applicable to modeling. The updated list of management questions is shown in Table 3. These questions are likely to change over time as priorities shift and new questions emerge.

The management questions have two parts: the scenario to test and the questions to be answered about that scenario. A scenario is a "what if" condition, typically in the future, for which managers want to know what will happen if a certain management action is taken. The scenarios that are included in Table 3 are:

A. Current conditions
B. Future conditions assuming already permitted reductions in nutrient loads from NPDES dischargers have been implemented[4]
C. Future conditions assuming nutrient reductions from in-Delta discharges, BMPs implemented in watershed, and other nutrient reduction efforts
D. Future conditions assuming changes in climate, Delta hydrology, wetland restoration, and nutrient loading from scenarios A, B and C

The management questions listed in Table 3 progress in a logical sequence from nutrient loading into 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).

For each of the questions, the Workgroup developed specific modeling objectives. Modeling objectives define the type of output desired from the model. The development of modeling objectives was necessary so that the technical requirements for models could be determined in Section 5 of this report.

[4] The largest change in permitted nutrient loads from NPDES discharges will occur in approximately 2020 when the upgrades to the Sacramento Regional Wastewater Treatment Plant take effect.

Table 3: Nutrient management questions, in increasing order of complexity, that (given sufficient data) a linked suite of hydrodynamic and water quality models might inform, and the modeling objectives and scenarios to be modeled for each question.

Management Scenarios*	**Management Questions**		**Modeling Objectives**
A. Under current conditions B. Under future conditions assuming already permitted reductions in nutrient loads from NPDES dischargers have been implemented C. Under future conditions assuming nutrient reductions from in-Delta discharges, BMPs implemented in watershed, and other nutrient reduction efforts D. Under future conditions assuming changes in climate, Delta hydrology, wetland restoration, and nutrient loading from scenarios A, B and C.	1	What are the main nutrient sources to the Delta and nutrient sources and sinks within the Delta?	Identify the internal and external loads and sources 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 using watershed models. Identify missing sources or sinks by comparing loads from watershed models to measured loads and fluxes.
	2	How much do nutrient loads from known sources contribute to ambient nutrient concentrations in different sections of the Delta during different times of the year and different river flow conditions?	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 rates of change of total and reactive nitrogen and phosphorus during different times of the year and different river flow conditions 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 effects and how does the relative importance of these factors vary with space and time? a) algal biomass and primary production rates; b) relative proportions of different groups of algal species; c) distribution and abundance of macrophyte species; d) magnitude and frequency of cyanobacteria and diatom blooms.	Characterize primary production (phytoplankton and macrophytes) and determine which factor(s) is (are) limiting or enhancing 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) may influence the magnitude of response to nutrient load reductions or increases.

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

5. Model Characteristics to Achieve Modeling Objectives for the Delta

The modeling objectives for each question identified in Table 3 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 the 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, continuity, completeness, and scalability (Table 4). Technical model characteristics include hydrodynamic representation, biogeochemical representations, ability to interface with other models, extent of spatial domain, temporal resolution, dimensionality, and other factors (Table 5).

A graphical representation of the desired characteristics of the model(s) from Table 5 is shown in Figure 3. Due to the complex flow regime in the Delta, model(s) will need a hydrodynamic component and a fate and transport component that includes water quality modules for nutrient water quality, sediment transport, and macrophytes. The nutrient water quality module is a conglomerate of water quality processes and sediment interaction that addresses nutrients and primary productivity. Some elements will have to be modeled qualitatively or with less accuracy because processes are not well understood and/or data are lacking. The model(s) should be compatible with external models such as watershed loading models, hydrodynamic and water quality models for San Francisco Bay, and the ecological models for fish communities.

None of the existing models of the Delta meet all of the characteristics in Tables 4 and 5. Most existing models of the Delta only include hydrodynamics (and density as salinity and/or temperature). Modules for nutrient water quality, sediment transport, and macrophytes in the Delta are either still being developed or do not exist (Table 2).

Managers can use the recommended characteristics in Tables 4 and 5 to ask informed questions during grant solicitations or other funding decisions. 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 actual performance standard for a specific model application. In some cases, a simple model can provide sufficient answers when applied and 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 any 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 desired levels for bias, mean absolute error, root mean squared error, Nash-Sutcliffe efficiency, or other metrics. The appropriate model performance metrics magnitudes can be iteratively refined during model development in response to the final selected model, available data, and other factors.

Table 4. Desired general characteristics for Delta hydrodynamic and water quality 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[5].
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.
4	Sufficiently resolved/mechanistic to model management scenarios	To be determined based on technical characteristics in Table 5.
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)

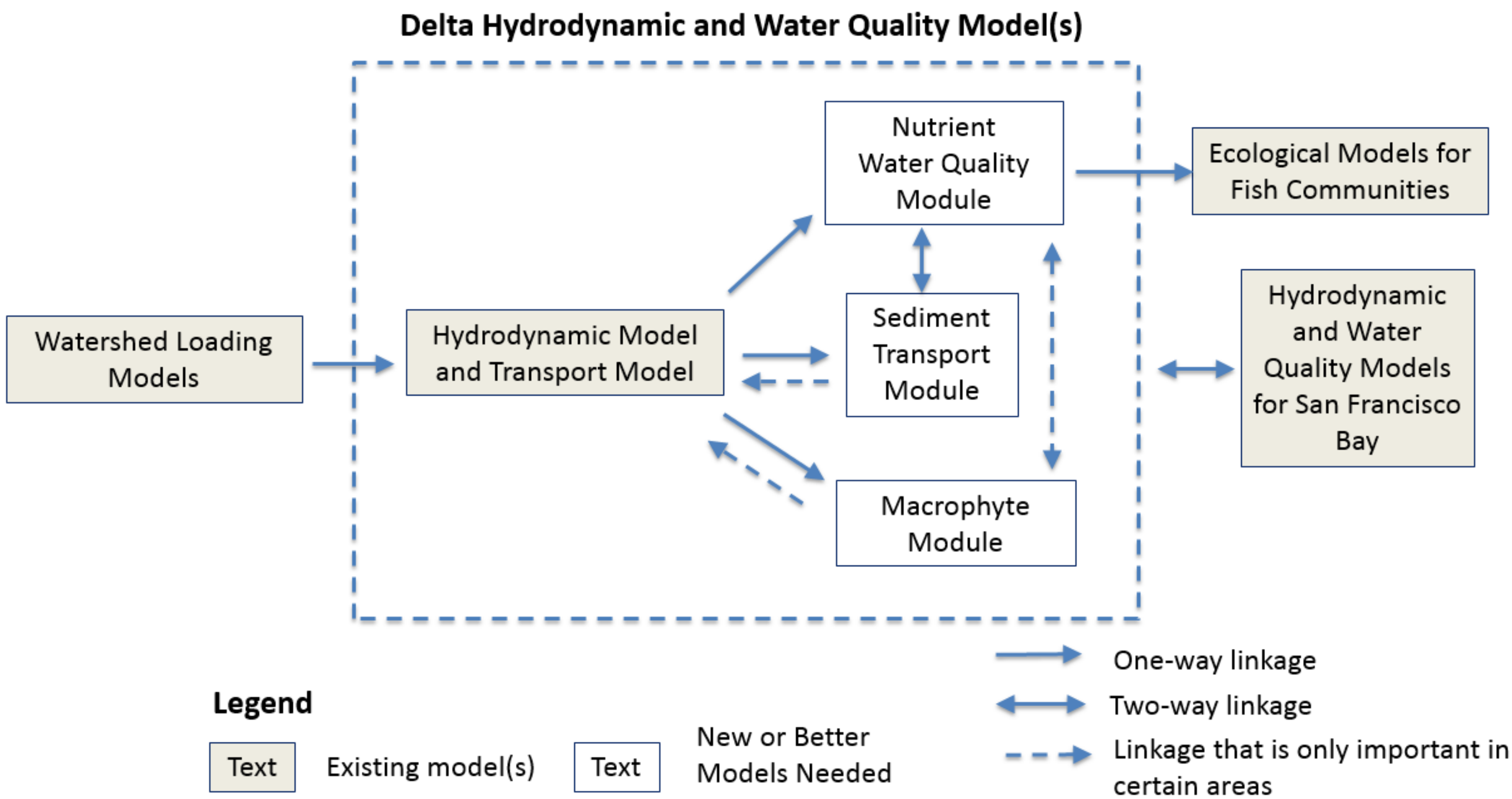
[5] For state and federal funding, the funding agency will typically reserve a royalty-free, nonexclusive, and irrevocable license to reproduce, publish or otherwise use, and to authorize others to use the copyright in any work developed under the grant and any rights of copyright which are purchased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

Table 5: Desired technical characteristics for Delta hydrodynamic and water quality models

No.	Characteristic	Explanation
1	The model(s) must have a hydrodynamic platform and transport component. For most applications, the spatial domain of the hydrodynamics model should cover the majority of the legal Delta, including flooded islands and marshes.	Water exchange between the channels and flooded islands and marshes affects both the hydrodynamics and biogeochemical conditions. To answer some specific management questions fine scale models that only cover a part of the Delta may be more appropriate.
2	The model(s) must have water quality modules for nutrient water quality, 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.
3	The nutrient water quality module must simulate nutrient and carbon transformations, 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 water quality module.
4	The nutrient water quality module should 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 water quality module should provide useful inputs to the models of fish growth and behavior developed by NOAA and other resource agencies.
5	The sediment transport module should be capable of two-way linkages with the nutrient water quality module.	Suspended sediments can influence nutrient biogeochemical reactions through exchange between the water column and sediments, transport of nutrients with the sediment, and influence on water clarity.
6	The macrophyte module should be capable of two-way linkages to both the nutrient water quality module and the hydrodynamics and transport model.	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.
7	The dimensionality (e.g., 1-D, 2-D, or 3-D) and temporal resolution of the model(s) must be appropriate for answering the management questions.	Some 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.

		The majority of modeling objectives will require hourly output (though simulation time step may be considerably shorter) 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.
8	Model(s) should be compatible with other hydrodynamic and water quality models selected by the San Francisco Regional Board for use in Suisun and San Pablo Bays, and with watershed models of river loads to the Delta	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 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.

Figure 3: Diagram of the model components for nutrients in the Delta



6. Recommendations for Developing Water Quality Models for the Delta

The previous sections of this report identified modeling objectives for the Delta, limitations of existing models, and the characteristics of the new models that are needed. Developing new or refined models will be a significant undertaking that will cost millions of dollars (estimated costs are provided in Section 7 of this report). Therefore, the modeling approach should include a careful planning and review process to minimize costs and maximize benefits. With this in mind, the Workgroup identified the following recommended approach.

a. A Successful Modeling Approach Cannot Focus Only On Modeling -- Support for Data Management, Data Synthesis and Monitoring Is Equally Important

The success of a modeling program in the Delta will not be measured by numbers output from a model, lines of computer code written, or dollars spent, but rather through increased insight into the nutrient processes in the Delta. Robust data management, interdisciplinary data synthesis, and enhanced monitoring are essential for achieving this goal. Therefore, the modeling program should have the following core functions.

MODELING SUPPORT. Model developers/programmers will be needed to write or review computer code and maintain models and model components. These staff will also be responsible for model evaluation and running the models for different management scenarios. While writing computer code is a necessary task, maintaining the code over time is equally important. Model code will evolve over time both within this framework and from external sources as well: especially if it is open source code. Without support for maintenance, the initial investment in model development could be lost as the code becomes outdated and fragmented across many users. These staff would also be responsible for managing license requirements, editing the source code as requested by users, validating suggested edits offered through the open source environment, documentation, managing modeling system version control, and distributing the most current version of the model and associated data sets.

DATA MANAGEMENT SUPPORT. Data managers and technologists will be needed to prepare the datasets used by the models and to visualize both the inputs and outputs of the models. There is a critical need for standardized and interoperable databases of measured input time series (velocity, stage, inflows and outflows, salinity, water quality constituents, etc.) and digital elevation models that multiple groups can use for one or more models. These datasets can be time consuming and challenging to prepare. Raw data are first screened for outliers and other bad data. Subsequently, data gaps are filled using estimation techniques to provide continuous time series for model simulation. Finally, the database needs to include metadata defining basic data information and quality assurance for transparency and data sharing. Maintaining these datasets with proper metadata would benefit the modeling and scientific community as a whole. The development of high quality, complete model application data (boundary conditions, calibration data sets, model parameters) consumes an inordinate amount of time. Development of common, accepted data sets/libraries available to model users would be economical, lead to more efficient model applications (shorter project timelines), and increase opportunities innovation because more resources would be available for modeling. Models often produce large amounts of output in tabular form (e.g., time series). Tools to visualize model outputs are needed for the analysts to interpret model results, as well as to more effectively communicate the results to managers and the scientists involved with data synthesis. Without good visualization tools, efficacy of model applications would be markedly reduced.

DATA SYNTHESIS SUPPORT. An interdisciplinary team of chemists, biologists, hydrologists, engineers, statisticians, and other relevant scientists will be needed to develop conceptual models and evaluate model output in light of the body of scientific knowledge about the Delta. Absent this data synthesis and interpretation of model outputs, only a fraction of the insight from modeling would be obtained. The interdisciplinary team could also serve as a forum for developing recommendations for monitoring and special studies.

MONITORING PROGRAM SUPPORT. Enhanced monitoring data will be needed for model calibration and validation datasets. In addition to long term monitoring, short-term, intensive studies will be needed to understand the underlying mechanics of nutrient dynamics in certain areas or during certain periods of the year. Therefore, existing monitoring programs in the Delta, such as the Delta Regional Monitoring Program and the Environmental Monitoring Program (EMP), should receive increased funding to collect the identified modeling data needed. The interaction between modeling and monitoring should be reciprocal, with the monitoring program highlighting priority data gaps to be refined through monitoring (locations, frequency, parameters), and the monitoring programs providing field measurements in the Delta to further ground truth the models.

b. Establish a Good Governance Process

A Steering Committee, such as the committees for the Regional Monitoring Programs, will be needed to guide the process and make decisions regarding best allocation of resources. The water quality management questions in the Delta present too many options and related issues that have yet to be fully defined. Moreover, the development and adoption of a modeling approach will be heavily influenced by available funding and information at that time as the work proceeds. A good governance process will be needed to guide the program through these uncertainties and ensure stakeholder buy-in.

The specific governance structure for the modeling program will depend on how the program is funded. However, the Steering Committee of the Delta Regional Monitoring Program could serve as one option. For example, the Steering Committee could consist of funders of the modeling effort plus key stakeholders, such as regulatory and resource agencies, and be charged with allocating program funds and providing oversight of the final products. The committee members would represent a balance of interests. Governance processes would be established in a formal Charter. A Memorandum of Understanding would be used to formalize the partnership and facilitate transfer of funds.

c. Follow a Phased Implementation Approach - Add Nutrients into Existing Models First

Scientific studies of the Delta were initiated more than a hundred years ago with a variety of different objectives. Over the past century the Delta has been continually studied, with objectives evolving as priorities changed, knowledge increased, monitoring techniques improved, and new tools in the form of computer models were developed. Modeling has become firmly established as a standard approach in complex water quality studies, and will be for the foreseeable future. However, for planning purposes, the Working Group estimates that 10 years of concentrated effort will be needed to address the immediate management questions related to nutrients. Some questions will be answered relatively quickly, while others will be answered in stages over several years, ideally with ever-increasing levels of certainty. The work should be completed in two 5-year phases.

1. The first stage should be to employ existing models as a platform to develop and test the desired logic and linkages for appropriate water quality processes. These existing models may be notably simpler than models required to address the more complex management questions. However, starting with basic tools provides a useful opportunity to test modules prior to implementing the more complex models. Adding nutrient-related modules to existing hydrodynamic models of the Delta will save time and money (estimated at approximately 6 person-years or $1.5 million total) and reduce risk of project failure.

2. The second stage should be to refine and add complexity to the models, or transfer previously developed logic to more complex models to improve system representation as needed. Once more complex models are developed, subsequent logic refinements may be added directly.

Phase I modeling and investigations are expected to take approximately five years, roughly from 2016 to 2020. The end date for this phase coincides with the planned changes in nutrient loading from the Sacramento Regional Wastewater Treatment Plant. Phase II modeling is expected to last another five years, from 2021 to 2025. These dates are planning estimates and are likely to change as the phased work is implemented and new information and management questions evolve through time. However, it is important to have working models in place by 2020 to guide adaptive management and to test hypotheses about Delta responses to major changes in nutrient loading. Table 6 compares and contrasts the types of modules that could be used for Phase I and Phase II modeling.

d. Select the Right Model for the Job – The Need for Multiple Models

A variety of different types of models will be needed to answer all of the management questions. Highly resolved 3-D models may be necessary for some applications, while 1-D models may be sufficient for others. The appropriate model for each question should be used. Attempting to develop a single model to address all potential conditions, may not only be infeasible, but would be inefficient and uneconomical.

Models will and should change over time as new information and data become available and to adapt to changes in system conditions and management direction. Meyer et al. (2009) recommended a modeling approach that is flexible in order to accommodate future stressors and changes.

e. Implement Robust Quality Assurance Processes

The model development process should follow widely accepted guidelines for quality assurance to produce accurate and transparent results. A USEPA 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.

External peer review of the models and model outputs should be completed regularly. From the conceptual models to the interpretation of model outputs, major products of the modeling effort should be critiqued by experts who are not doing the work. Regular reviews will keep the effort on track and credible. The most efficient process for peer review is to convene an expert panel and provide them with a clear charge to guide their review.

All modeling activities should address uncertainty in model outputs associated with uncertainty in input data and model structure. Input data, derived from field measurements, include uncertainty due to sampling location and frequency, as well as from measurement and laboratory equipment. Uncertainty can be introduced through the model structure from both simplifications of complex processes or inaccurate conceptual models of how the system works. Consideration of such uncertainties is critical for interpreting model results in planning processes.

A wide range of modeling efforts has already occurred in the Delta. These multiple modeling efforts provide a level of redundancy that can be beneficial. From both management and technical perspectives, duplicate models are not necessarily duplication of effort because they often employ different approaches and assumptions, and the difference in results provides insight into the range of uncertainty in the predictions. While Ganju et al (2015) argues that development of ensembles of models (i.e., multiple models that predict the same thing) is to be encouraged where possible, a less formal approach can fulfill this role where multiple models with similar purpose occur in response to a wide range of agency and stakeholder interest as occurs in the Delta.

As a process step, mathematical equation and logic, assumptions, and parameters/coefficients should be included in a Design Document (outside of computer code) to allow peer review of the underlying model basis.

Model components should be modular wherever possible. The key characteristics of modularity are that the code can be replaced with another implementation, can be updated without affecting other parts of the model, and can be turned on/off without affecting the other parts of the model. 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.

f. Hold an Annual Delta Nutrient Modeling Workshop

There should be an annual workshop where modelers, scientists, field monitoring staff, and managers come together to share results, confirm conceptual models, and discuss model modifications and applications. The primary objective of the workshop should be to answer management questions and determine priority data gaps for monitoring. Interaction between these different groups should occur on a regular basis anyway. An annual workshop is a simple and effective approach step that can be taken to ensure interaction of all the parties at least once per year. The workshop could be organized by the California Water and Environmental Modeling Forum.

Table 6: Recommended plan for phased implementation of hydrodynamic and water quality mechanistic models

Module	**Phase 0 – Existing Models (no cost)**	**Phase I**	**Phase II**
Hydrodynamics and Transport Model	Hydrological connectivity between river main stems, bypasses, sloughs, barriers (water level, flow velocity, water temperature, salinity) Water withdrawal operations, barriers, and gates (i.e. variable pumping rates)	Continued refinement of spatial domain as needed for the specific application	Continued refinement of spatial domain as needed for the specific application
Nutrient Water Quality	Nutrient water quality models are in the development stage for some Delta models.	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 Zooplankton grazing Benthic grazing Impacts of toxic contaminants (e.g., pesticides) on algae Phytoplankton speciation Algal toxins Light transmission calculated from sediment, phytoplankton, carbon models
Sediment Transport	None	Integrated water column and bedded sediment model	Accretion and burial of water quality constituents Erosion and remobilization of water quality constituents
Macrophytes	None	Macrophyte effects on flow using field data on the locations of dense macrophytes	Macrophyte growth and decay through nutrient water quality module

7. Cost Estimates

To estimate costs of implementing a credible modeling program, the principal assumption was that the program cost was predominantly associated with the cost to hire and retain skilled employees to complete the core functions of the program. Other costs, such as licensing fees, are expected to be negligible compared to the labor costs over the life of the project. Specific assumptions for each component of the program include:

- **Steering Committee**: No cost. Members of the Steering Committee would be assumed to be funded by their own organization.
- **Modeling Support**: This task will require funding for 2 Full-Time Equivalent (FTE) employees. To provide program stability, at least two programmers/developers will be needed. Some of the programming will likely be covered by staff at partner agencies. However, since programming is a specific and high-demand skill, funding for a minimum number of dedicated staff will be needed.
- **Data Informatics Support**: Funding for 0.5 FTEs. Compilation of modeling datasets (including digital elevation models) and maintenance of modeling code is a specific task that is essential for this collaborative program. Dedicated funding to either hire a part-time employee or partially fund an employee in another organization will be needed.
- **Data Synthesis Support**: Funding for 2 FTEs. While the interdisciplinary team will have more than 2 participants, these participants will not be full-time and some of their time on the project may be paid for by their own organization.
- **Monitoring Program Support**: Enhanced monitoring should be conducted by existing monitoring programs. A rough approximation of the increased funding needed to support a nutrient modeling effort is $500,000 per year. This cost estimate will be refined through the Regional Board's Nutrient Science Plan process and Delta Regional Monitoring Program nutrient synthesis studies. However, the Workgroup made an estimate of this cost to avoid underestimating the full cost of the program.
- **Peer Review Panel**: Common practice for obtaining peer-review of a program is to pay each advisor an honorarium of $5,000 to $10,000. Assuming that 5-10 advisors will be needed each year, the total cost for honoraria and travel would be $50,000 per year.
- **Cost per FTE**: The labor cost of a FTE, including benefits, was assumed to be $250,000 per year in 2015 dollars.

Based on these assumptions, the proposed level of effort will require funding for 4.5 FTEs ($1,125,000) plus $550,000 for peer review and enhanced monitoring, resulting in an annual cost of $1,675,000. Since staffing drives the cost, there will not be an initial "start up" cost followed by a lower maintenance cost. However, some of these costs may be borne by in-kind contributions of staff from participating organizations. Over the 10 years of expected effort, the total program would cost $16.7 million, divided into two, 5-year phases, each with a cost of approximately $8.4 million.

The annual cost estimates for the proposed modeling effort in this paper ($1.7 million per year) are similar to, but higher than, past experience and estimates would indicate. The reason for the increased cost is that the proposed approach includes more than just modeling. It also includes data management, data synthesis, and monitoring. USGS reported the cost to develop the CASCaDE model was $5.5 million between 2011 and 2015 (or approximately $1 million per year). In 2008, UC Davis estimated a $1.8 to $3 million start-up cost over two years (or $0.9 to $1.5 million per year) to develop the capacity for 3-D 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 approximately $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 7 are reasonable.

Table 7: Estimated cost of modeling task over 10 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.

Program Component	**# FTEs**	**Cost**
Steering Committee	0	$0
Interdisciplinary Science Team	2	$500,000
Model Development Staff	2	$500,000
Data Informatics Staff	0.5	$125,000
External Advisors (Peer Review)	0	$50,000
Modeling Program Subtotal	***4.5***	***$1,175,000***
Increased Monitoring to Support the Modeling Effort (approximate)	0	$500,000
Total Cost per Year		***$1,675,000***
Total Cost for Phase I (5 years)		$8,375,000
Total Cost for Phase II (5 years)		$8,375,000
Total Cost		$16,750,000

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Appendices

Appendix A: Glossary of Modeling Terms

Appendix B: Charge to the Modeling Science Workgroup

Appendix A: Glossary of Modeling Terms

Glossary of Modeling Terms

Accuracy — A measure of model performance whereby simulated values are compared with field observations (or other measured data). A function of both bias and precision.

Algorithm — A step-by-step procedure for solving a mathematical problem using a computer.

Bathymetry — Topographic map showing depth contour lines, typically in a reservoir.

Bias — The difference between observed (field measurements) and simulated values. Often termed error, and may be represented by an average.

Boundary Condition — Data required by the model at each time step at all locations where flow, water quality conditions, or other modeled variable enters or leaves the system.

Code, Source Code — A code is a set of instructions and algorithms written in a language for a computer to understand that solves a particular set of mathematical equations. In the case of water quality, the source code solves the equations describing flow and transport of water quality constituents.

Calibration Data — Measured data collected within the model domain to calibrate the model and assess model performance. Calibration data are not required to run a model (unlike boundary and initial condition data).

Coefficient / Constant — A number generally derived from empirical formulations that approximate part of a process. The terms coefficients and constants are often used interchangeably to define true physical constants (like the number pi), as well as numbers that vary over a range. Typically, coefficients and constants are selected from literature or determined in the field and then maintained at one fixed value (or in some cases a few values) throughout the modeling exercise. (Or, determined from laboratory experiments)

Data, types of — Several different types of data are needed to develop a model, including: geometry, boundary condition data, initial condition data, and calibration/validation data. Such information may be stored in a data library to form a common data set for analyses or archival purposes.

Diffusion — A time-dependent random process characterized by a net movement of atoms or molecules in space, typically from a region of high concentration to a region of low concentration

Diffusion (turbulent) — Scattering of a constituent by turbulent motion, considered to be statistically similar to molecular diffusion, roughly analogous but with "eddy" diffusion coefficients (that are larger than molecular diffusion coefficients). Sometimes called mixing coefficient. One for each principal direction.

Dispersion Scattering or spreading of a constituent by diffusion in an aquatic system. (Compare with numerical dispersion, below.)

Eulerian A stationary frame of reference that observes particles moving past a point (e.g., as in time series).

Explicit Scheme Explicit schemes represent spatial derivatives with known information (i.e. at the current time step). These schemes offer an efficient numerical solution, with fast computational times, and are easy to code.

Finite Difference A numerical method to solve the complex governing equations of flow and fate and transport. The method requires that the domain be divided into a discrete number of points (nodes) representing the system. The differential terms of the governing equations are representing with finite difference approximations based on truncated Taylor Series expansions. By using the physical properties of the system and the appropriate physical laws a set of simultaneous equations in the unknown quantities at the element boundaries is formed. The result is a large banded matrix, readily solved on a computer.

Finite Element A numerical method to solve the complex governing equations of flow and fate and transport. The method requires that the domain be divided into a number of finite elements (or links) that are joined at a discrete number of points (nodes) along their boundaries – together, termed a mesh. By using the physical properties of the system and the appropriate physical laws a set of simultaneous equations is developed that is readily solved on a computer.

Finite Volume A numerical method to solve the complex governing equations of flow and fate and transport. The method requires that the domain be divided into a meshed geometry defined by discrete points (nodes). Finite volume refers to the small volume surrounding each node point in the mesh. By using the physical properties of the system and the appropriate physical laws a set of simultaneous equations is developed that is readily solved on a computer.

Formulation A systematized statement or expression, i.e. "a mathematical formulation".

Geometry A mathematical description of the physical shape and location of an aquatic system. For example, in the Delta this information would consist of a bathymetric representation of the channels, waterways, flooded islands and other inundated areas describing the elevation of the bottom.

Governing Equations The set of mathematical expressions that describes the pertinent physical processes. Examples include formulations of the conservation of mass and momentum equations for flow, and the advection-diffusion equation for fate and transport of constituents.

Gradient Change in some quantity per unit distance. May occur in the longitudinal, lateral, and/or vertical direction(s).

Mesh or Grid Mathematical representation of the geometry or bathymetry of a water body for simulation modeling. Can be represented by nodes, links, and/or elements. May be structured (e.g., rectangular grid with consistent dimensions) or unstructured (e.g., irregular shapes or combination of different shapes (triangles and quadrilaterals)).

Governing Equation See “hydrodynamic model”

Hydrodynamic Model Hydrodynamic models are based on the solution of the partial differential equations of unsteady open channel flow. These equations include various forms and associated assumptions. Examples include the Navier Stokes equations, St. Venant equations, and Euler equations, and include the conservation of mass and momentum formulations.

Implicit Scheme Implicit numerical schemes represent spatial derivatives at the future time step. Implicit schemes simultaneously solved a system of equations at each time step, making them more cumbersome to code and less computationally efficient. However, they are generally more accurate – perform better – than explicit schemes.

Initial Condition Conditions specified for or determined by the model to represent the initial state of the system at the beginning of a simulation.

Lagrangian A moving frame of reference that follows a particle through a system (e.g., particle tracking).

Lateral Direction The direction perpendicular to the flow direction, e.g., in streams, from bank to bank. Sometimes termed transverse direction.

Logic Sometimes used interchangeably with *code* or *algorithm*. The approach a computer model takes to solving a problem.

Longitudinal Direction In the same direction as bulk flow, e.g., in streams, downstream.

Mathematical Model A quantitative formulation of physical processes that simulates the actual system.

Model Application	The process of using the model (after calibration and validation) to examine potential outcomes of alternative management scenarios.
Model Calibration	The process of establishing specific values for parameters in the model's mathematical equations and algorithms. Often a statistically acceptable comparison between model results and field measurements; adjustment of model parameters is allowed within the range of experimentally determined values reported in the literature.
Model Domain	Area or region represented by the model, often defined by available data. See also "study area."
Model Implementation	The process of preparing data for input into the models, selecting default parameters, and testing. The end result of model implementation is a functioning, but uncalibrated model.
Model Inputs	Forcing functions or constants required to run the model (e.g. flow, meteorological conditions).
Model Validation	A statistically, or other, acceptable comparison between model results and a second (usually independent) set of field data for another period or at an alternate site; model parameters are fixed and no further adjustment is allowed after the calibration step. Verification and validation are often used interchangeably, but strictly speaking are different processes).
Model Verification	The process of checking the individual pieces of the model to ensure that they are all functioning properly. This often includes checking the formulation of the governing equations and sensitivity of model parameters. Model verification should occur during the construction of a model (i.e., occurs before model calibration).
Module	A distinct computer program code that accomplishes a specific task. May be incorporated into the computer code. See also "Routine."
NPDES	National Pollutant Discharge Elimination System (NPDES) is a permit program that controls water pollution by regulating point sources that discharge pollutants into waters of the United States.
Numerical Dispersion	Numerical dispersion is error introduced into the solution as a byproduct of approximations. The impact of numerical dispersion is to smooth out steep concentration gradients.
Numerical Solution/Method	A method used to solve the governing equation(s) in a model by replacing terms with numerical approximations for efficient solution
Parameter	Often referring to any of several values used in modeling, e.g., a parameter could be a constant or coefficient.

Pre- and Post-Processors	Pre-processors assist in reviewing and developing the input data for models. Post processors assist in tabulating, viewing (e.g., graphical, animation), and analyzing model output. Certain processors may also assist in running the model.
Precision	How closely individual computed values agree with each other, e.g., "scattered" values represent low precision, "clustered" values represent high precision.
Program	A sequence of coded instructions (or collection of routines and/or modules) for processing on a computer.
Residence Time	The cumulative amount of time a parcel of water is contained within a specified region (also known as exposure time). Determination in tidal systems can be defined in different ways and should be documented for each specific analysis/study.
Discharge	Water entering an aquatic system after utilization. Examples include return flow from agricultural fields, cooling water discharge from industrial applications, and wastewater discharge.
Routine	A section of a computer program code that usually accomplishes a specific task. See also "Module."
Sediment Diagenesis model	A model that represents bed sediments and associated constituents, as well as interactions (inputs to and outputs from the bed) with the water column.
Sensitivity Analysis	Determination of the effect of a small change in a model parameter, coefficient, or input on the results (state variable) either by numerical simulation or mathematical techniques.
Simulation	Use of a model with an input data set (even hypothetical) and not requiring calibration or verification with field data.
Solver	A computer program routine or module that solves a mathematical problem.
Solution Technique	The numerical approximation used to solve the governing equations in a computer model. See also "Finite Difference," "Finite Element," and "Finite Volume."
Source Code	The computer code associated with a specific model. Source codes may be "open" or "proprietary." Open source codes are typically free of charge and the code is "open" for viewing and modification.

Proprietary codes are typically available for a charge and the source code cannot be readily viewed.

Spatial scale (model) The spatial resolution of a model. May differ in the longitudinal, lateral, and vertical directions. Certain model formulations may place limitations on the spatial and temporal scales.

Stratification The vertical segregation of a water body due to density gradients, typically due to salinity, temperature or suspended solids. Stratification can affect hydrodynamic, water quality, and ecological conditions.

Temporal Scale (model) The temporal discretization of a modeling period, e.g., hourly, daily. Sometimes referred to as "time step." Certain model formulations may place limitations on the spatial and temporal scales.

Validation Validation is a step in code development that assures the correct equations are represented in the code. Validation is also a stage in model evaluation that follows calibration. In this case, the model is typically tested and model performance assessed for an independent period without changing any of the model coefficients or parameters set during calibration.

Verification Verification is a step in code development that tests if the equations are solved correctly in the code.

Vertical Direction The vertical direction in an aquatic system. Often used to describe water bodies that exhibit vertical density or concentration gradients

Appendix B: Charge to the Modeling Science Workgroup

Charge to Modeling Science Work Group.

Background

In 2009 the California legislature passed the Delta Reform Act creating the Delta Stewardship Council. The mission of the Council is to implement the coequal goals of the Reform Act and provide a more reliable water supply for California while protecting, restoring, and enhancing the Delta ecosystem. The Council wrote and adopted a Delta Plan in 2013 to implement these goals. Chapter 6 of the Delta Plan deals with water quality and contains recommendations to implement the coequal goals of the Delta Reform Act. Recommendation # 8 states, in part,

> *"…the State Water Resources Control Board and the San Francisco Bay and Central Valley Regional Water Quality Control Boards should prepare and begin implementation of a study plan for the development of objectives for nutrients in the Delta … by January 1, 2014. Studies needed for development of Delta… nutrient objectives should be completed by January 1, 2016. The Water Boards should adopt and begin implementation of nutrient objectives, either narrative or numeric, where appropriate, in the Delta… by January 1, 2018.***

The potential problems identified in the Delta Plan includes assessing whether (1) decreases in algal abundance and shifts in algal species composition, (2) increases in the abundance and distribution of macrophytes, including water hyacinth and Brazilian waterweed, and (3) increases in the magnitude and frequency of cyanobacteria blooms are the result of changes in ambient nutrient concentrations in the Delta. White papers are being prepared on each of these topics assessing whether long term changes in ambient nutrient concentrations have contributed to these conditions and whether future changes in nutrient management might remedy the situation.

In the spring of 2014 Water Board staff wrote a new five-year Delta Strategic Work Plan to help prioritize Delta activities. The five-year plan was presented as an information item at the February 2014 Board meeting. Item five in the Strategic Plan lays out tasks, schedule and deliverables to begin implementing the nutrient recommendations in the Delta Plan (Figure 1). The Strategic Plan included the formation of a Technical Advisory

Committee and a Stakeholder Advisory Group (which was later combined into the Stakeholder and Technical Advisory Group or STAG) to help respond to Delta Plan recommendations and to identify additional issues of concern. The Water Board also formed several Science Work Groups to help develop white papers on the three potential nutrient related problems. White papers will include recommendations for research to resolve outstanding questions about the efficacy of nutrient management to control these problems. These recommendations will be incorporated into a Nutrient Research Plan. Draft white papers and a draft Nutrient Research Plan will be available for review by the STAG and the State Board's Independent Science Review Panel in 2015. A final Nutrient Research Plan addressing all review comments is anticipated to be completed and presented as an information item to the Central Valley Regional Water Board and, if requested, the Delta Stewardship Council in 2015.

Need for a Model

The STAG, a CALFED independent Science Review Panel and Water Board staff all recommend that the Research Plan include development of a hydrodynamic model linked to a suite of environmental modules for the Delta. The previously described white papers and associated research will provide valuable information on whether ambient nutrient concentrations in the Delta contribute to present problems and can be managed in the future to remedy them. However, these one dimensional nutrient centric results cannot provide a holistic understanding of the relative effect of nutrient loads acting in combination with other physical and environmental factors on water quality and food webs in the Delta. Only robust hydrodynamic models coupled with a suite of water quality modules can accomplish this.

In 2009 CALFED assembled an independent science review panel to recommend a research plan to determine the role of ammonia in the Delta[1]. The panel prepared a final document entitled, "*A Framework for Research Addressing the Role of Ammonia/Ammonium in the Sacramento San Joaquin Delta and the San Francisco Bay Estuary Ecosystem*". A high priority recommendation of the panel was development of a coupled hydrodynamic water quality model. The authors state, "*We believe that the most important gap to be filled in the Bay-Delta research program is the development of an overarching, integrative model of the major drivers controlling the Bay-Delta Ecosystem. This modeling effort is especially needed because a wide variety of non-*

[1] http://www.science.calwater.ca.gov/events/workshops/workshop_ammonia.html

convergent perspectives remain about the major controls on POD species and the Bay-Delta food web". The 2014 Delta Stewardship Council's Workshop on *Delta Outflow and Related Stressors* Panel[2] also recommended development of a hydrodynamic biological model to tease apart the effect of nutrients, grazing, and outflow on algal species composition and biomass. Unfortunately, limited progress has been made in developing such models for the Delta, although model development has started for Suisun Bay as part of the San Francisco Bay Nutrient Management Strategy.

Investment in a suite of environmental models will provide multiple benefits. First, such models would allow an understanding of the ecological significance of changes in nutrients from an ecosystem perspective. 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. A second benefit of such models is that they would allow researchers to build and test management planning scenarios, based in part on future reductions in nutrient loads already "baked into" the system as the result of past regulatory and management decisions. For example, the models could be used to inform questions like, "*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*"? Finally, the models will help in the design of field experiments and in the interpretation of their results. All this information will be essential for evaluation, and if needed, the development of a robust nutrient management plan and associated nutrient objectives for the Delta. Development of such models may also be useful for other researchers as they investigate non-nutrient related issues. At present there are no environmental models being used to perform these functions.

The suite of water quality models will depend on the types of questions being asked. A potential framework for how the hydrodynamic/water quality models might be linked and an initial set of questions are included in Figure 2 and Table 1. Both the figure and list of questions will likely be revised and expanded upon by the Modeling Work Group, other science work groups and STAG. For example, each of the other three science

[2] http://deltacouncil.ca.gov/sites/default/files/documents/files/Delta-Outflows-Report-Final-2014-05-05.pdf

work groups has been asked to review Table 1 and provide additional questions for the modeling group to consider. The present list has been divided into questions that are of immediate and longer term significance. Information on both time scales is important as development of a nutrient management plan and adoption of nutrient objectives for the Delta are intended to protect aquatic resources now and in the future.

A preliminary list of hydrodynamic models that might be coupled with water quality modules is included as Table 2. Some important criteria for the preferred suite of hydrodynamic and water quality modules are listed in Table 3. The STAG and Modeling Science Work Group should review and expand on both Tables 2 and 3.

Charge to the Modeling Science Work Group.

The purpose of the Modeling Science Work Group is to provide advice to the Water Board on the important criteria for models to inform nutrient management questions and on the characteristics of the institution(s) where such models would be housed. The deliberations and recommendations of the work group will be captured in a white paper. The white paper will not recommend the preferred suite of models nor the institution responsible for housing and maintaining the model. Instead, the Modeling Science Work Group will (1) examine and expand upon the types of questions that the model(s) will need to inform, (2) assemble a list of important criteria the models should meet, (3) assemble a list of available hydrodynamic and water quality models, (4) evaluate available models against these criteria, discussing the pros and cons of each suite of models and the improvements that would need to be made to develop hydrodynamic-water quality models to inform management questions, (5) provide advice, if possible, on the cost and amount of time required to successfully develop linked hydrodynamic water quality models. Finally, (6) integrating the various models, validating and calibrating them is likely to be an expensive, multi-year, multi-phased effort. The work group should provide advice on how to successfully phase model development and identify key tasks that should be included at each phase of the project. Actual model selection would be left to the funding authorities to determine in a competitive bid process.

Similarly, the Modeling Science Work Group will not recommend the institution(s) responsible for developing and housing the model(s). The work group will (1) assemble a list of potential institutions interested in being responsible for developing and maintaining the model(s) and (2) assemble a list of criteria the preferred institution(s) should possess. Again, selection of the institution(s) responsible for developing and maintaining the model would be left to the funding institutions.

It is likely that multiple models will be needed to inform all of the nutrient management questions listed in Table 1. Models that can provide high spatial and temporal detail cannot also provide multi-year simulations of the whole Delta with reasonable computational processing times. Therefore, the work group is not expected to recommend one single type of model to inform all of the management questions.

Stakeholder Comments

At the last STAG meeting Stakeholders reviewed the charge and had a suggestion for the Modeling Work Group. One Stakeholder commented, "*My experience with the development and application of such models in the Delta ecosystem makes me concerned that more effort will be devoted to producing a model than will be dedicated to validating and calibrating that model. Predictions from quantitative models should not be used to inform management or make recommendations until the model has been tested to verify that it can accurately predict outcomes of scenarios that were not used to develop the model.*

This may be a bit premature, since the charge of the STAG is to identify a process for developing the model. But this appears to be the most funding-challenged of the proposed projects, and at a minimum, we'll want to ensure that the work plan and budget for model development includes sufficient resources to calibrate the final model".

The Modeling Work Group should attempt to achieve the charge while being mindful of Stakeholder recommendations.

Work Group Process

Mike Deas of Watercourse Engineering will serve as the Chair of the Modeling Work Group. Philip Trowbridge, San Francisco Estuary Institute, and Water Board staff will attend all meetings, take notes and be responsible for drafting the white paper. The white paper will summarize the deliberations and recommendations of the group (see Attachment A for a draft outline of the white paper). All materials sent to the Modeling Work Group will be made available on the Water Board's project webpage and will also be shared with the STAG.

The Modeling Work Group will meet three times in 2015. The approximate schedule and desired outcomes from each meeting are summarized below. Note: This schedule may need to be adjusted if pre-identified Science Work Group members decline to participate and replacements cannot be readily identified and confirmed.

Work Group Meeting #1 (Mid-June 2015)

Desired Outcomes:

- Review and comment on the outline for the white paper (Attachment A).
- Review and comment on the nutrient management questions prepared by the Regional Board, Stakeholders and other work groups (see Table 1 for initial list) to determine whether they can be practicably addressed through modeling.
- Review and comment on the draft list of important criteria for the preferred suite of models (Table 3).
- Review and comment on the draft list of available hydrodynamic and water quality models (Table 2).
- Gather information from the Modeling Work Group to initially populate a table with the following information for each different management question:
  a) the important criteria for a model(s) to inform the specific question;
  b) the existing hydrodynamic and water quality models that meet or can reasonably be adapted to meet the criteria from step (a);
  c) the pros and cons of the existing model(s) from step (b); and
  d) the estimated time and cost to modify existing models or to develop new models to inform the management question.

Work Group Meeting #2 (Early September 2015)

Desired Outcomes:

- Review and comment on the first draft of white paper. The white paper will contain tables of the important criteria and existing models that were discussed at the first meeting. The group will carefully review these tables. Any items in the tables that do not have concurrence from the group will be identified as a data gap or area of uncertainty. (Note: the draft white paper will be distributed to the STAG for comments at the same time.)
- Provide recommendations for phasing the development of hydrodynamic and water quality models over multiple years.
- Provide recommendations on the characteristics for institution(s) to house and maintain the model(s).
- Provide recommendations for developing coordination among modeling efforts across agencies/institutions.

Work Group Meeting #3 (Early October 2015)

Desired Outcomes:

- Review and comment on the final draft of the white paper.
- Polish language in the executive summary.

A final session may be scheduled to review suggested changes to the white paper after comments from the STAG and from the State Board Independent Science Review Panel (tentatively scheduled for late fall) have been received.

Products of the work group process will include:

1. Science Work Group white paper and prioritized research recommendations.
2. STAG comments and recommendations.
3. State Board Independent Science Panel comments and recommendations.
4. Final white paper and research plan after comments from the State Board Independent Science Panel and STAG have been received and addressed.

This package is intended to support the transparency of the process and ensure that Regional Water Board staff and other interested parties have a complete suite of information needed for their consideration and decision making.

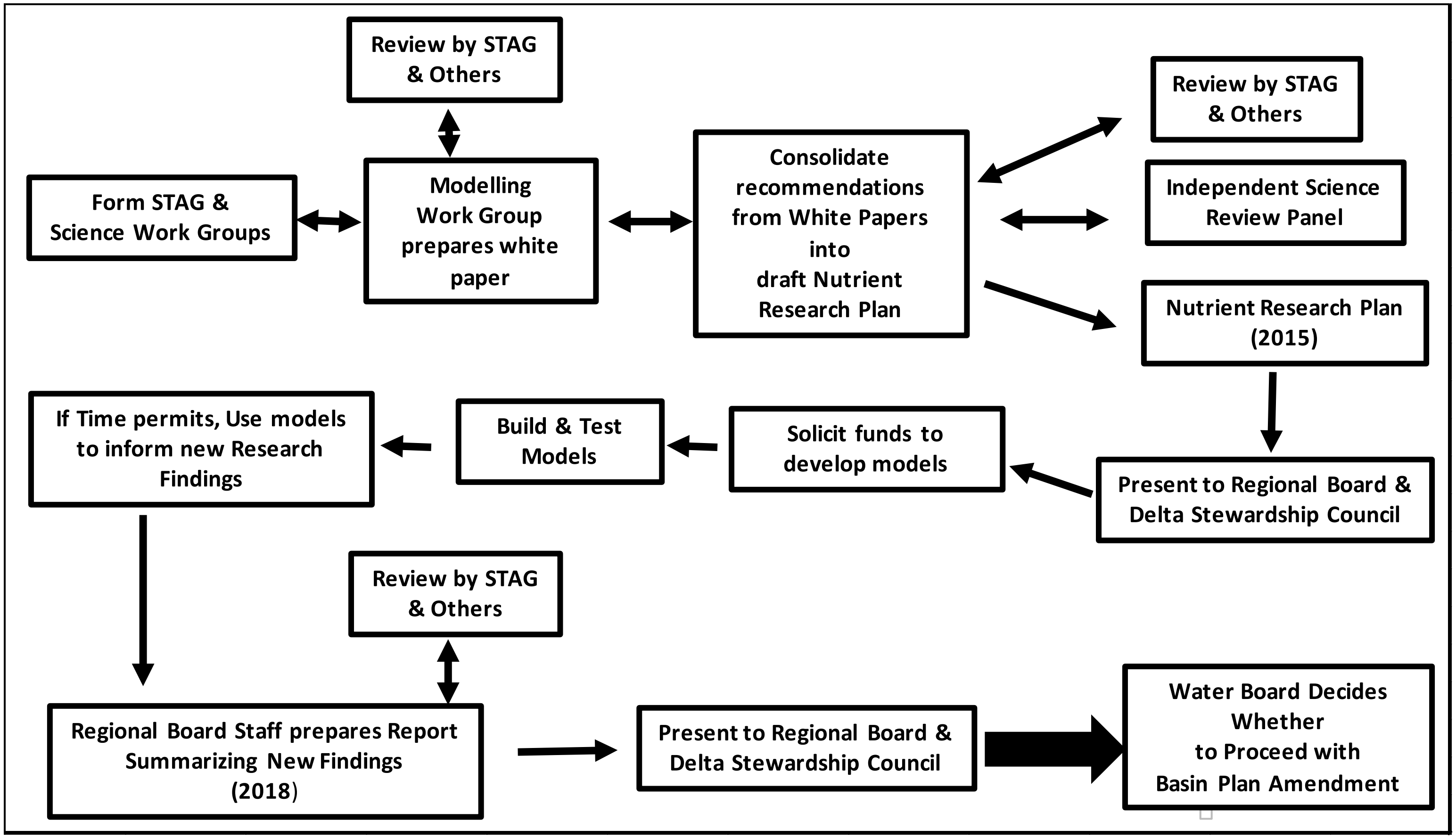
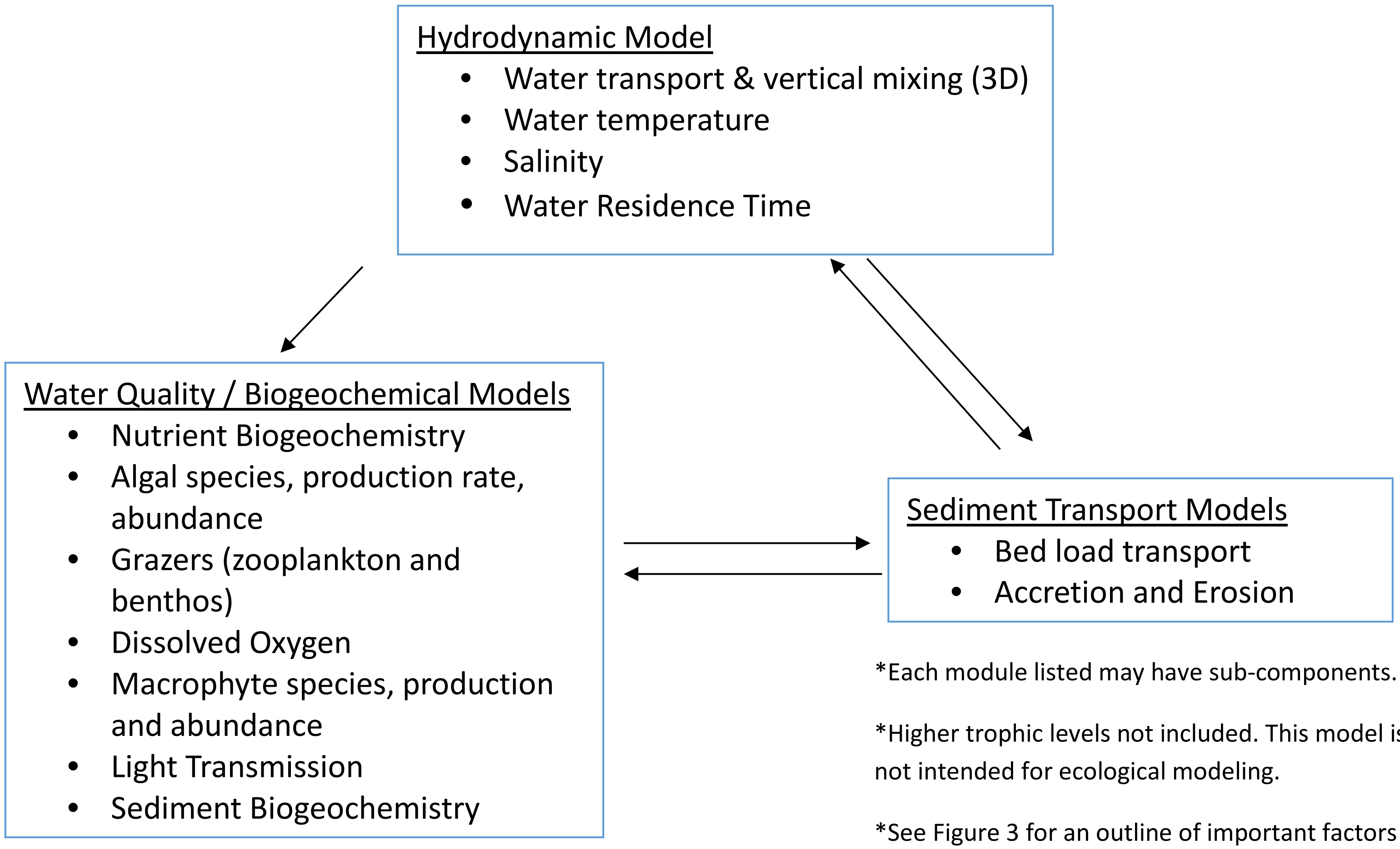


Figure 1. Tasks and schedule for developing and implementing the Nutrient Research Plan as outlined in the 2014 Delta Strategic Work Plan. Staff will solicit input at a 2018 Regional Board meeting whether nutrient objectives are needed for the Delta and whether staff should begin their development.



*Each module listed may have sub-components.

*Higher trophic levels not included. This model is not intended for ecological modeling.

*See Figure 3 for an outline of important factors and variables for the models.

Figure 2. Preliminary framework for the hydrodynamic, water quality/biogeochemical, and sediment transport models and sub-models needed to inform nutrient-related questions. Others researchers may use the model to investigate non-nutrient related issues.

Table 1. Potential list of the types of questions that a linked suite of hydrodynamic and environmental models might inform. The Science Work Groups and STAG should review and propose additional questions for evaluation. Purpose of compiling a list of questions is to ensure that the appropriate hydrodynamic model(s) and suite of water quality modules are selected for use in the Delta.

	Current Nutrient Sources, Hydrodynamic Transport and Rates of Transformation
1	What are the main sources and loads of nutrients to the Delta now?
2	How much do nutrient loads from known sources contribute to ambient nutrient concentrations in different sections of the Delta by season?
3	Do the models indicate that all the major sources of nutrients to the Bay are accurately being measured?
4	What are the important processes that transport and transform nutrients in the Delta and what are the rates at which these processes occur?
	Which Factors are Most Important
5	What are the main factors* affecting: • The algal biomass and primary production rates; • The algal species composition; • The distribution and abundance of macrophyte species; • The magnitude and frequency of cyanobacteria and diatom blooms. How does the relative importance of these factors vary with space & time?
	Effects of Nutrient Load Reductions
6	After the already permitted reductions in nutrient loads from NPDES dischargers have been implemented: a) What will be the main sources of nutrients in the Delta? b) What will be the new ambient nutrient concentrations in different sections of the Delta in each season? c) How much will nutrient loads from known sources contribute to ambient nutrient concentrations in different sections of the Delta by season?

<table>
<tr><td>7</td><td>After the already permitted reductions in nutrient loads from NPDES dischargers have been implemented, what changes and what magnitude of beneficial response are expected for:
The algal biomass and primary production rates;
The algal species composition;
The distribution and abundance of macrophyte species;
The magnitude and frequency of cyanobacterial and diatom blooms.
How will these changes vary with space and time?</td></tr>
<tr><td colspan="2">Effects of Long-Term Climate and Hydrology Changes</td></tr>
<tr><td>8</td><td>What effect will predicted climate change, changes in Delta hydrology, and wetland restoration have on the following effects (1) under current nutrient loads and (2) under a future predicted nutrient load scenario:
The algal biomass and primary production rates;
The algal species composition;
The distribution and abundance of macrophyte species; and
The magnitude and frequency of cyanobacterial and diatom blooms?</td></tr>
</table>

*see Figure 3 for a list of some, but not necessarily all, of the important factors and variables relevant to the types of questions that a linked suite of hydrodynamic and environmental models for the Delta might inform.

Figure 3. Driver-Pressure-State-Impact-Response (DPSIR) model outlining some, but not necessarily all, of the important factors and variables relevant to the types of questions that a linked suite of hydrodynamic and environmental models for the Delta might inform

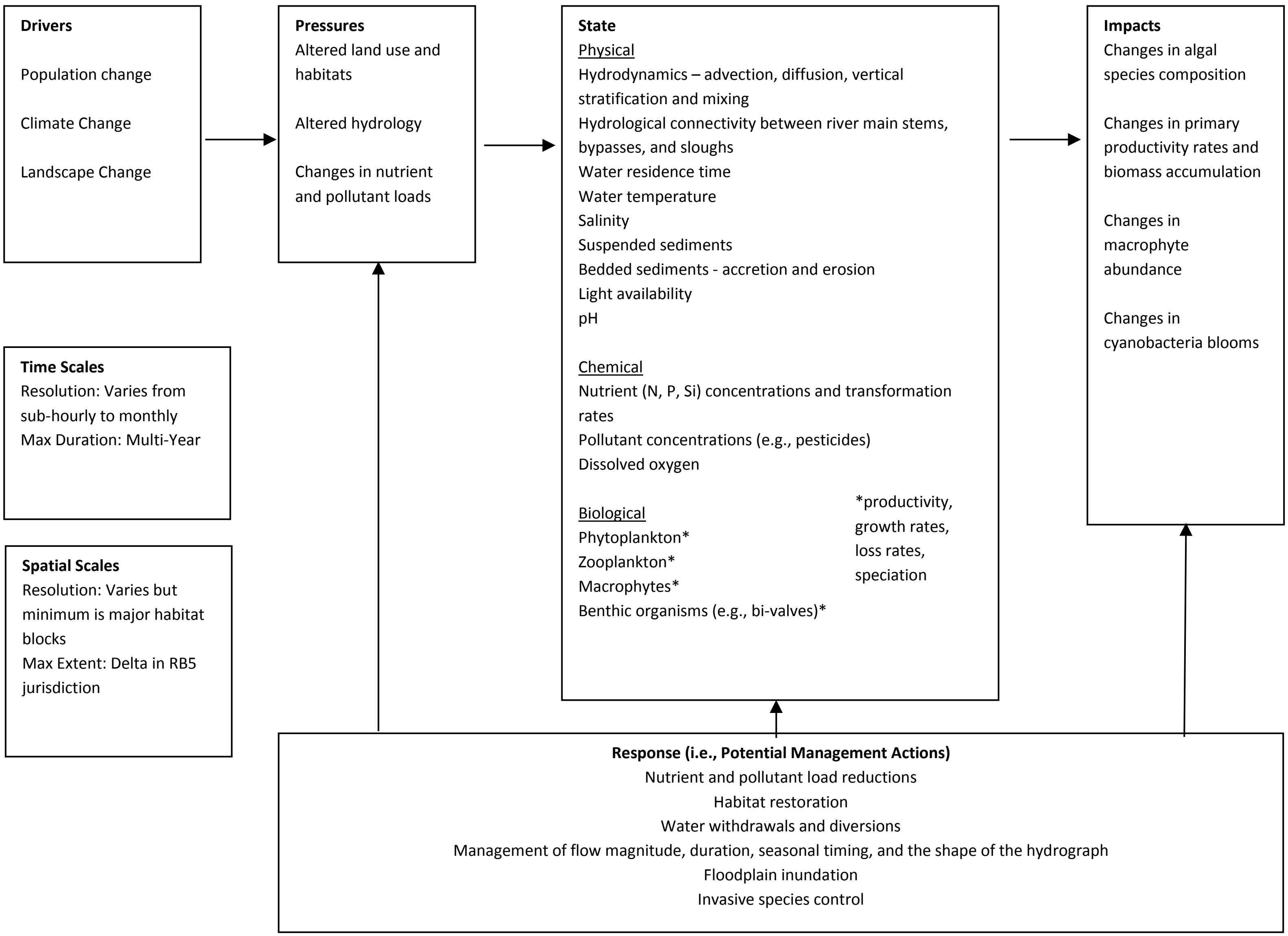


Table 2. Partial List of available hydrodynamic models.

Model	Description
SCHISM	3-dimensional, unstructured grid, hydrodynamic model. Has compatible water quality modules. DWR involved in model development and calibration. Open source.
Suntans	3-dimensional, unstructured grid (horizontally but not vertically), hydrodynamic model calibrated for Delta. Developed by Stanford University and funded by CALFED. Open source.
Deltares Flexible Mesh	3-dimensional, unstructured grid, hydrodynamic model. Has compatible sediment and water quality modules. Developed by Deltares in collaboration with USGS Menlo Park. Open source.
DSM2	Calibrated 2-dimensional hydrodynamic model for Delta. Has nutrient, chlorophyll and dissolved oxygen modules. Developed and maintained by DWR. Open source
Delta EFDC Water Quality Model	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
UnTRIM Bay-Delta model	3-dimensional hydrodynamic and sediment model of the Bay-Delta Estuary. Not in the public domain

Table 3. Preliminary list of desirable criteria for the linked hydrodynamic and water quality modules.

1	Public domain
2	Open source
3	Model successfully employed elsewhere or otherwise peer-reviewed
4	Compatible* with other hydrodynamic and water quality models selected by the San Francisco Regional Board for use in Suisun and San Pablo Bays and with watershed models of river loads to the Delta
5	Calibration for the Delta preferred
6	Model technical support and training available for end users
7	Spatial Extent - Model covers the majority of the legal Delta
8	Temporal Extent - Model can be applied to short duration studies, or long-term (e.g., decadal) analyses.
9	Hydrodynamic model results need to support environmental models representing water quality, sediment biogeochemistry, and sediment transport modeling.
10	Spatial scalability—model can be started at a simple, coarse grained, large-cell version, with finer scale resolution and complexity added as the need arises and data allow.
11	Temporal scalability—model can accommodate time scales from short (e.g., hourly, daily) to long-term (e.g., monthly, annually).
12	Development status – model could potentially start to be used to inform preliminary nutrient management questions as early as mid-2018.

*Different options for evaluating compatibility: Basic ability to pass loads of nutrients and other constituents between models; using the same space and time steps; using the same period of analysis; and modeling the same processes.

Table 4. List of Individuals for the Modeling Science Work Group.

Individual	**Agency**	**Modeling Work Group**
David Senn	San Francisco Estuary Institute	X
Joe Domagalski	US Geological Survey	X
Chris Enright	Delta Stewardship Council	X
Lisa Thompson	Sac Regional County Sanitation District	X
Bill Fleenor	UC Davis	X
Phil Trowbridge	San Francisco Estuary Institute	X
Edward Gross / Marianne Guerin	Resource Management Associates	X
Michael Deas	Watercourse Engineering, Inc	X
Eli Ateljevich	Department of Water Resources	X
Paul Hutton	Metropolitan Water District	X
Eric Danner	NOAA Fisheries	X

Key: X = Individual agrees to participate in work group.