CASCaDE II: Computational Assessments of Scenarios of Change for the Delta Ecosystem

1. Project Purpose

In recent years, two guiding principles have been established regarding the future management of the Sacramento-San Joaquin Delta. First, Governor Schwarzenegger's Blue Ribbon Task force recommended that "the Delta ecosystem and a reliable water supply for California are the primary, co-equal goals for sustainable management of the Delta" [36], and this principle recently became state law [14]. Second, fundamental changes in the external forcings (e.g. climate) and physical configuration of the Delta are inevitable [33,52]. These guiding principles lead to the fundamental **question** we propose to address:

How will future changes in physical configuration and climate affect water quality, ecosystem processes, and key species in the Delta?

In particular, we propose to test the **hypothesis** that: *Climate induced changes in hydrology, sea level, and local meteorology, combined with new water conveyance structures or increased numbers of flooded islands, will impact water transport and water quality (e.g. salinity, temperature, and turbidity) in the Delta. These changes will further influence ecological processes and key species (e.g. primary productivity, distributions and effects of invasive bivalves, marsh sustainability, contaminant dynamics, and success of native and alien fish populations).* We propose to test this hypothesis by building on the work of the CASCaDE I project. CASCaDE I was conceived as a step toward developing the capabilities and understanding needed to assess potential responses of the Bay-Delta ecosystem to external (climate) and internal (e.g., Delta configuration) changes over the long term. Model simulations and results from CASCaDE I focused on climate as the primary driver. The approach taken was to link numerical and statistical models of the major components of the Bay-Delta-River-Watershed (BDRW) system, representing both physical and biological aspects.

A large part of the effort in CASCaDE I was devoted to numerical model development and linkage, as appropriate models of several components of the BDRW system were not yet available. In particular, this resulted in the following new datasets and modeling capabilities:

- A "constructed analogues" statistical downscaling technique was further developed, tested, and applied to downscale global climate model (GCM) temperature and precipitation [34,13,57], resulting in gridded daily values of multiple meteorological quantities over California for the 21st century [24]. The constructed analogues technique was adapted to other variables, including short wave radiation and humidity over the Bay, Delta and associated watershed.
- A model of water levels at San Francisco, based on empirical relationships [65] and GCM output, was developed and applied to produce hourly sea-level projections for the 20th and 21st centuries [13]. A hydrodynamic model was used to propagate these time series throughout San Francisco Bay, and detailed regional maps of inundation vulnerability were produced [43].
- The California Department of Water Resources operations model, CALSIM (http://modeling.water.ca.gov/hydro/model/index.html), was modified to be driven directly by a hydrologic model of the watershed [42]. The result is a new capability to simulate the response of California's freshwater management infrastructure to individual 100-year scenarios of climate change.
- A new modeling approach for hindcasting and forecasting morphodynamic development was applied to San Pablo Bay [83,84] and Suisun Bay [31,30] by calibrating and validating 3D morphodynamic models (ROMS and Delft3D) against 150-year datasets of bathymetric development.

- Life history parameters and relationships to environmental factors were established for *Corbula amurensis* and *Corbicula fluminea*, forming a basis for dynamic modeling of benthic bivalves.
- A new approach to calculating phytoplankton production and growth [following 17,18,10,38] was implemented, tested, and compared to more classical approaches, taking advantage of productivity measurements and high-correlation empirical relationships specific to the Delta.
- A new graphical and mathematically simple conceptual model of the general relationship between algal biomass, residence time, growth rate, and loss to grazing was developed. At the heart of this conceptual model is a simple index capturing 1) whether a habitat is algal growth dominated or loss dominated; and 2) how phytoplankton biomass will respond to changes in residence time [50].
- A conceptual and quantitative model for predicting food web response to changes in Se exposure was developed from local data and a comprehensive analysis of the global literature [54,64]. The time series of Se concentrations in *C. amurensis* in Suisun Bay was extended to present, spanning a range of hydrodynamic conditions critical for model refinement [64] and hypothesis testing [77].
- Outputs from many of the above models were used to assess habitat conditions for selected fish species, including salmonids in the Sacramento Rivers, Sacramento splittail in Yolo Bypass, and delta smelt in the Sacramento-San Joaquin Delta.

In CASCaDE I, several of these new modeling capabilities were linked and applied to evaluate the response of the BDRW system to multiple climate-change scenarios that spanned a range of projected futures. This resulted in projections of hydrologic responses, sea-level-rise impacts, changes in sediment supply and geomorphology, and fish population responses under projected climate change. These scientific results and their implications for our conceptual model are discussed in the next section. Links to relevant publications and data can be found at the CASCaDE Project web site: http://cascade.wr.usgs.gov. In CASCaDE II, we intend to build upon, update, and extend the work of CASCaDE I with coordinated efforts toward the following **objectives**:

1. Generate updated scenarios of meteorological forcings, watershed flows and stream temperatures, and downstream sea levels based on new GCM outputs corresponding to the upcoming Intergovernmental Panel on Climate Change 5th Assessment Report, as these data become available.
2. Develop and apply a new model of sediment transport in the Bay-Delta watershed to better understand upstream sources of sediment, and to project future patterns of sediment transport into the Delta under scenarios of climate change.
3. Apply a new model of Bay-Delta hydrodynamics and sediment transport, Delft “UNSTRUC”, to evaluate key quantities such as residence time, salinity, water temperature, and turbidity under scenarios of climate change and alternate physical configurations of the Delta.
4. Enhance UNSTRUC to include capabilities for simulating coupled phytoplankton dynamics and non-native clam distribution, biomass, and grazing rate, and extend the evaluations in (3) to include these quantities. Use output from these new coupled models to support contaminant modeling.
5. Include a peat accretion modeling component to evaluate the survival of existing and restored marshes under climate change.
6. Incorporate results from (1)-(5) to refine and update assessments of survival likelihoods for native and alien fish populations, including species not considered in CASCaDE I.

Linking the capabilities developed in CASCaDE I with the new capabilities proposed in CASCaDE II will enable a more complete and accurate evaluation of the response of the BDRW system to updated climate change scenarios. Importantly, the incorporation of a robust hydrodynamic model of the Delta capable of simulating key physical and biological processes will also allow the evaluation of ecosystem impacts of scenarios of Delta configuration change (alternate freshwater conveyance infrastructure, flooded islands), in combination with the climate change scenarios. These are the **goals** of CASCaDE II.

Specific scientific **questions** relating to the scenarios of climate and Delta configuration changes to be addressed in CASCaDE II include:

- Which downscaled meteorological changes are robust across climate models? Which are not? What does this imply about projections of hydrologic and other downstream changes?
- How will upstream hydrologic changes combine with sea level rise to affect inundation patterns in the Delta region? How will peak stage change relative to levee heights?
- What is the likely trend of the future sediment yield from the Sacramento River? Has a post-dam equilibrium been established?
- What and where are the major sources in the Sacramento River watershed that supply sediment to the Delta? How might the rates of supply from these sources change due to climate change?
- What are the dominant suspended sediment (SS) transport processes within the Delta? How will these change under the scenarios considered?
- Will rates of vertical peat accretion in various Delta marshes be high enough to sustain marshes under conditions of future sea-level rise or will certain marshes eventually be drowned?
- Will increased shallow habitat significantly influence propagation of tides (as suggested by J. Burau, USGS)? How will transport processes through the Delta be affected?
- Under which scenarios will the Delta be more susceptible to salinity intrusion?
- How do the distributions of *Corbula* and *Corbicula* change with salinity distribution under the scenarios considered? How does the change in grazer biomass distribution affect phytoplankton biomass and contaminant bioaccumulation and availability to higher trophic levels?
- How will future changes in hydrodynamics (e.g. residence time, stratification), water clarity, grazing, and distribution of habitat depths affect phytoplankton biomass and productivity?
- How do changes in residence time, potential sources of Se (San Joaquin Valley, refineries, local streams) and composition of suspended particulate material (phytoplankton and inorganic particles) impact Se accumulation in *Corbula amurensis* in Suisun Bay and how could those relationships change with different scenarios of climate and infrastructure change?
- What are the likely effects of flooded island and "alternate conveyance" scenarios on fish populations? How will key habitat attributes for fish (e.g. temperature, turbidity, salinity) change in response to the combination of a changing climate and physical configuration?

2. Background and Conceptual Models

Our evolving conceptual model of the Delta ecosystem has been informed most recently by key CASCaDE I findings, including:

- From an examination of several climate model projections, temperatures over California were found to warm significantly during the 21st century, with 1) marked increases in the frequency, magnitude, and duration of heat waves and sea level rise extremes; 2) a strong inclination for higher warming in summer than winter and greater warming inland than along the coast; 3) a tendency in several simulations for drier conditions to develop during mid-and late-21st century in Central and Southern California, with a decline in winter wave energy along the coast [13].
- In San Francisco Bay, high sea levels during the first half of the 21^{st} Century are mainly caused during events when winter storms and high Sierra runoff coincide with high astronomical tides. These events become more extreme through the 21^{st} Century due to accumulating effects of sea level rise [13].
- Hydrological model projections yield larger floods by the end of the 21st Century for both the Northern and Southern Sierra Nevada. These increases appear to derive from increases in large-storm

sizes, storm frequencies, days with more precipitation falling as rain and less as snow, and antecedent winter soil moisture [21].

- A loss of snowpack leads to more runoff during flood management season, though strong drying trends in some scenarios counteract this by leaving more flood control space in the reservoirs. Models show that reductions in freshwater supply would require an increased reliance on groundwater supplies at unsustainable levels unless significant management changes occur.
- Future turbidity and geomorphic change in the estuary depend on sediment supply [30,84]. In all scenarios examined, Suisun Bay deposition is less than a low estimate of sea level rise (2 mm/yr) and Suisun Bay deepens [30].
- Decadal morphodynamic developments in Suisun Bay and San Pablo Bay can be predicted with reasonable skill [31,84] by applying reasonable estimates of model input parameter values.
- Increased residence time does not necessarily result in more phytoplankton biomass; in fact, if a habitat is overrun with bivalve grazers, an increased residence time could result in *less* phytoplankton biomass [50]. In order to predict how phytoplankton biomass will respond to a change in hydrodynamics, we must know the rates of algal growth and loss to grazing and/or sedimentation [50].
- Distributions of the exotic bivalves *Corbicula* and *Corbula* overlap and, therefore, one or the other species is found throughout the system. Changing salinity distribution changes the distribution of the two species but will not remove the bivalves. Both species can control phytoplankton biomass in shallow water. Population growth of both species is food-limited; increasing phytoplankton availability/ biomass is likely to increase bivalve biomass [80,81].
- Climate change will challenge Chinook salmon due to increases in water temperatures in the watershed and long term persistence of Delta Smelt will be challenged by changes in the salt field, turbidity and water temperature.
- The best indicators of selenium contamination in the system are Se concentrations in bivalves and Se in suspended particulate material. Time series of Se concentrations in bivalves indicate multiple sources of Se in the estuary, each with their own temporal shifts, that have contributed to the changes in contamination that have occurred in the last 15 years.
- “Integrated modeling” is much more complex than having a model that produces a “parameter” needed by another model. The synchronization of spatial and temporal scales, and consistent time periods and conditions between models is a complex and time-consuming endeavor. Moreover, designing model runs describing possible future scenarios (especially for climate) requires careful planning and synchronization of multiple boundary forcings.

Shaped by these CASCaDE I lessons, the CASCaDE II project described here is based on a **conceptual model** (see Fig. 1) built from the following principles:

1. San Francisco Bay, the Sacramento-San Joaquin Delta, their tributary Rivers and Watersheds are one system of interconnected landscapes (we refer to this as the BDRW system).
2. The primary medium linking these landscapes is surface water including precipitation, runoff, streamflow, and effects of storage, conveyances, consumption, and estuary-ocean exchanges.
3. These hydrologic and hydrodynamic processes are primary drivers of change in the chemical, sedimentological, and biological properties of the BDRW system.
4. BDRW hydrologic processes will change during the 21st century due to altered global-scale external forcings and regional-to-local scale internal forcings.
5. External forcings will reach the BDRW from the atmosphere (as variable air temperature, solar radiation, winds, precipitation, pressure) and from the coastal ocean (regional currents, sea level, tides, temperature).

6. Internal forcings include modifications of land use (associated with economic and population trends), structural alterations within the Delta (levee failures, new storage or conveyance facilities or constructed habitats), and altered water operations.

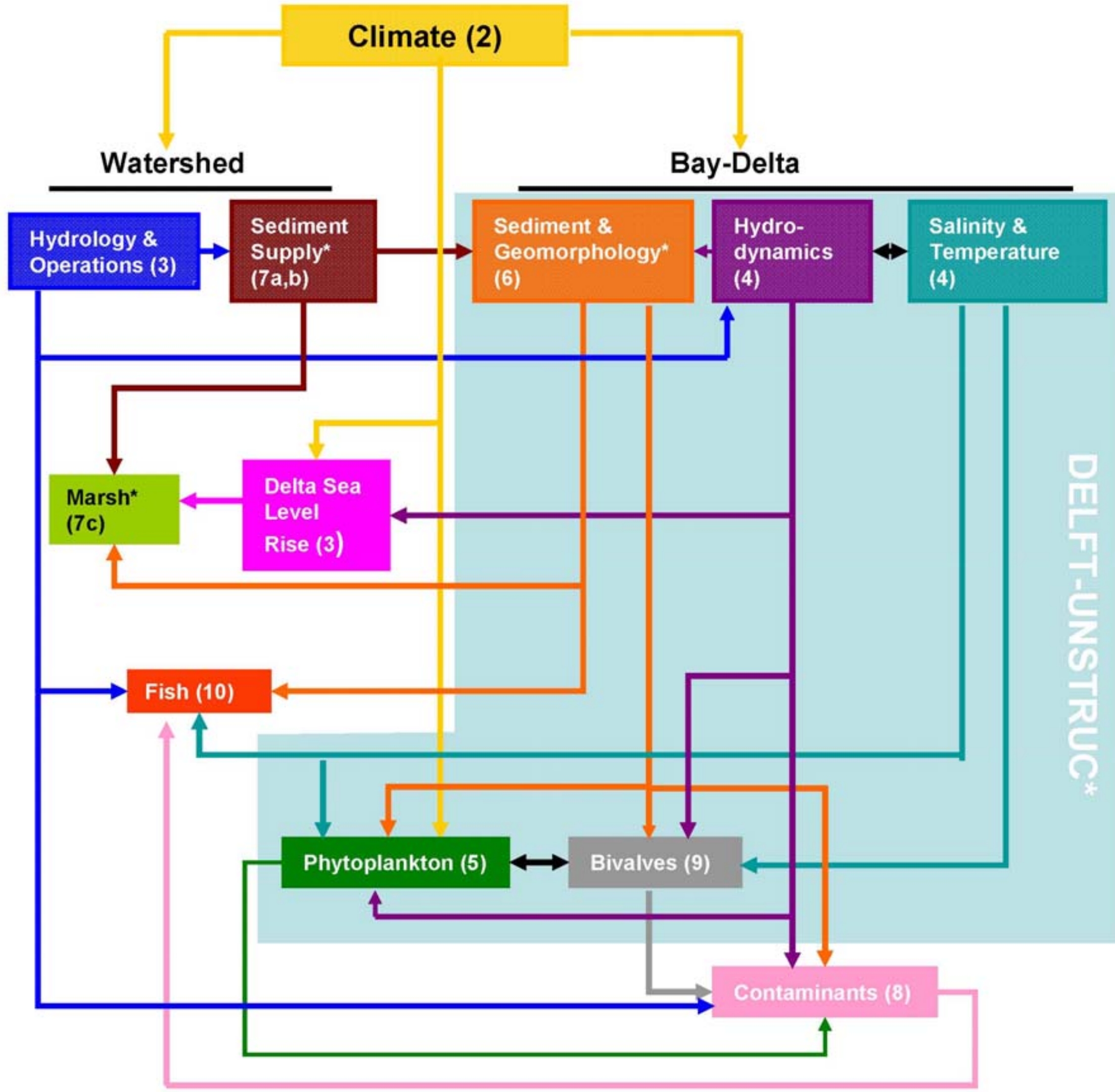

Fig. 1: Flow chart depicting underlying **conceptual model** of BDRW system components (boxes) and interconnections/ informational dependencies (arrows), as we propose to represent them in CASCaDE II. * represents new initiatives in CASCaDE II; all other components were developed or initiated in CASCaDE I and will be enhanced and extended in CASCaDE II. (Marsh accretion and watershed sediment supply are completely new. Sediment models for northern SF Bay were developed in CASCaDE I, but the Delta sediment/geomorphology model is new. Hydrodynamics, salinity, temperature, phytoplankton and bivalve modeling were performed/initiated in CASCaDE I, but the UNSTRUC framework for these is new in CASCaDE II.)

The overarching **conceptual model** guiding this project is that: (a) hydrologic and hydrodynamic processes in the BDRW system will be altered by changes in both external and internal forcings, and (b) system-level effects will include a cascading set of interconnected changes in Bay-Delta waterborne transports, sediment supplies and geomorphology, habitat and water quality, and distributions and abundance of native and alien species. These interconnections, as we propose to represent them in the CASCaDE II linked modeling framework, are presented in Fig. 1.

Because of the central role of surface water transport expressed in the above principles (and evidenced by the multiple hydrodynamic connections in Fig. 1), our proposal (and budget) places significant, strategic emphasis on the application of a new state-of-the-art hydrodynamic modeling foundation (Delft-UNSTRUC) for our assessments of the Delta ecosystem. In addition, one major new initiative in CASCaDE II relative to CASCaDE I is the application of a new Delta sediment model (sediment models were developed in CASCaDE I for San Pablo and Suisun Bays, but not for the Delta). Like hydrodynamics, Delta sediment dynamics directly influence several ecosystem components (see Fig. 1); thus, the application of a new sediment modeling capability represents another key emphasis in CASCaDE II, along with new watershed sediment analysis and modeling, which will provide critical boundary condition information for the Bay-Delta sediment model. These two major components, the new marsh accretion component (which will have implications for ecosystem processes well beyond this project), and the continued development and enhancement of existing components, are made fiscally feasible by the significant leveraging of DSP resources with USGS appropriated funds (see Budget Justification and Cost Sharing).

3. Approach and Scope of Work

Climate Modeling and Downscaling ② *Investigators* – Michael Dettinger, Dan Cayan (USGS/SIO)

Problem – A limited set of scenarios of projected global climate change-related effects, distributed in sufficient spatial and temporal detail to investigate implications on physical and biological systems in the San Francisco Bay, Sacramento and San Joaquin River Delta, and upstream watersheds is needed to provide insight into how these systems may respond to the changes.

Tools/Analysis – We will make a selection from among new GCM runs from the upcoming IPCC 5th Assessment Report, after evaluating their hindcast performance in simulating historical features that are germane to Bay/Delta regional climate. Two different downscaling methods will be employed: 1) a *statistical* approach, which is more efficient but provides less output variables and at lower resolution; 2) a *dynamical* approach, which is more computationally intensive but can provide more output variables than the statistical approach (including wind and cloud cover) and at higher resolution.

Using the statistical approach, a set of regional atmospheric variables will be extracted at daily resolution for the entire 20th and 21st centuries, including the meteorological forcings that are relevant to Bay/Delta hydrodynamics and ecosystems and the Bay/Delta watershed hydrology. A subset of this daily, 21st Century data, along with the associated model historical hindcast period, will be downscaled to 12 km horizontal resolution using a new hybrid Bias Corrected Constructed Analogues statistical technique [56]. Associated projections of hourly sea levels based on astronomical tides, GCM-driven storm surges, and ENSO forcings, along with secular sea-level rise estimated using a semi-empirical technique [65] will be developed, following [12].

The second (dynamical) downscaling approach will be applied to a set of wet and dry episodes during the middle and late 21st Century identified from the above suite of 21st Century model runs. This complementary form of downscaling using a regional dynamical atmospheric model (WRF or equivalent) will be performed to obtain hourly meteorological forcings, including surface-wind fields, over the Bay/Delta and watershed at 4km resolution. Although the regional dynamical model runs will not cover the entire period, because of the computational and data resources required, they will be chosen to include the multi-year development of a small set of historical and late 21st Century dry and wet sequences, in order to provide meteorological details of this evolution to the CASCaDE teams. The number of events selected will be limited to 6 in order to fit into available computation and data storage resources and be sufficiently investigated and managed by the other study teams. Historical simulations using this same regional climate model will be used to evaluate model performance (in comparison to observations) and to evaluate and diagnose changes introduced by the climate change simulations.

Required Inputs – From the upcoming IPCC 5th Assessment Report, a set of new 21st Century climate model (GCM) projections, along with 20th Century hindcasts (nominally 1950-1999), are expected to become available in the 2011-2012 time frame. Both medium and high greenhouse gas emissions scenarios will be included. These projections will be obtained from public sources or personal communications with the climate modeling groups. A subset (nominally 4 GCM simulations, based on 2 GCM's x 2 emissions scenarios) of the available climate model projections and historical runs, will be used by other tasks in this study. These 4 GCM simulations will be chosen to represent a plausible range of regional climate changes. Although many more scenarios could be produced with the statistical downscaling framework, the number of simulations employed is restricted because of the large effort required by the CASCaDE study teams to work through associated model investigations. The choice of the simulations will be informed by the climate scenarios and models included in the California climate change assessment, which is an ongoing study of the vulnerability and capability of adaptation to climate change in the State of California [e.g. 29,13].

Outputs/Deliverables – The statistical downscaling effort will produce daily precipitation and maximum and minimum temperatures (used directly by tasks ③④) at a 12 km grid over the Bay, Delta, and watershed for the 20th and 21st centuries, corresponding to the set of 4 climate model simulations adopted by the CASCaDE team (Y1). Hourly sea level projections (used directly by ④) will be developed for the location of the San Francisco tide gage for the 20th and 21st centuries for each of the 4 GCM simulations (Y2 or earlier if needed). A subset of 2-4 of the GCM simulations will be downscaled to hourly, 4 km resolution by the dynamical atmospheric model for selected 3-5 year wet and dry episodes; this output will include air temperatures, precipitation, humidity, cloud cover, and wind (used directly by ③④⑤;Y2-Y3) and may form the basis of baseline and future scenarios run by the more computationally intensive models in other tasks. Output timing will be coordinated with other tasks and adjusted as necessary. Data will be posted on the CASCaDE website for public use.

Watershed Modeling and Sea Level Rise ③ *Investigator* – Noah Knowles (USGS)

Problem – The atmospheric projections produced in ② must be translated into downstream hydrologic changes in order to produce a meaningful assessment of their ecological impacts. Also, the projections of water levels at the mouth of the estuary produced in ② must be propagated upstream to assess impacts throughout the estuary. These future scenarios of watershed outflows and sea level will form the physical context for in-Delta configuration changes to be studied in CASCaDE II. The data produced by this task will also be used to investigate how changing Delta inflow peaks would combine with higher sea levels to affect the potential for levee overtopping throughout the Delta.

Tools/Analyses – ***Watershed Modeling:*** A combination of models will be used to evaluate climate change impacts on stream flows and temperatures throughout the Sacramento-San Joaquin watershed. The Bay-Delta Watershed Model (BDWM) is a physically based model of hydrologic processes that generate streamflow. It operates at a daily time step with primary inputs of precipitation and air temperature, and simulates hydrologic variability throughout the watershed [42]. Under CASCaDE I, an operations component was coupled to BDWM— DWR's CALSIM II. Also, a reservoir- and stream-temperature model, driven with CALSIM outputs, was provided by the USBR and used to assess temperature changes under each scenario.

In CASCaDE II, these tools will be updated when newer models become available. Specifically, a new version of CALSIM is in development, and when it is released, the procedures developed in CASCaDE I will be updated to use that model. Also, USBR is updating their stream temperature model and this will be incorporated as it becomes available. Finally, as newer climate scenarios associated with the IPCC 5th Assessment Report become available and are downscaled by ②, they will be translated into managed hydrology (using BDWM, CALSIM, and the USBR model) for use by other tasks.

Modeling Water Levels: To translate hourly water levels at the Golden Gate Bridge to locations throughout the Bay-Delta, a combination of hydrodynamic models will be used. Seaward of the Delta, the TRIM-2D hydrodynamic model [15] will be used, as it is capable of accurately simulating water levels throughout the Bay and of performing, in a reasonable amount of time, the century-long simulations needed to address the effects of long-term climate change.

In the more hydrodynamically complex Delta, UNSTRUC and similar models capable of accurately simulating water levels are currently too computationally demanding to perform 100-year runs. Therefore, output from shorter UNSTRUC runs ④ will be analyzed to parameterize the relationship between stage at locations throughout the Delta, upstream inflow rates, and stage at the downstream confluence. Outputs from the watershed and TRIM-2D modeling efforts will then provide the corresponding inputs (upstream inflows and downstream water heights) for each 100-year scenario. When the resulting Delta stage estimates are combined with TRIM-2D output for the Bay, hourly water levels throughout the estuary for each 100-year scenario will be available for use in this and other tasks.

Finally, the resulting Delta water-level projections will be compared to levee heights extracted from 1-m Delta LIDAR data (produced by CA DWR) to assess the respective roles of climate-change-induced hydrologic changes and sea level rise in increasing levee overtopping risks throughout the Delta.

<u>*Required Inputs*</u> – This task will use the updated downscaled scenario time series from ②, including meteorological quantities and hourly water levels at SF. Also, simulated water levels throughout the Delta ④ will be used to develop statistical water-level models for the levee overtopping study.

<u>*Outputs/Deliverables*</u> –1) Monthly stream flow data (used by ④⑧⑩⑦a-b) for all scenarios (3 months after downscaled meteorology scenarios are available from ②. 2) Daily stream flow data (used by ④⑧⑩⑦a-b) for all scenarios (3 months after monthly stream flow data). 3) Stream temperature data (used by ④⑩) for all scenarios (3 months after daily stream flow data). 4) Bay-wide hourly water heights for all scenarios (3 months after Golden Gate water level projections are available from ①. 5) Delta-wide water heights (used by ⑦c) for all scenarios (3 months after Bay-wide hourly water heights). 6) Manuscript providing analysis of the respective roles of climate-change-induced hydrologic changes and sea level rise in increasing levee overtopping risks throughout the Delta (end Y3). 6) Bay-Delta Science Conference (BDSC) talk (2012). All data from this task will also be made publicly available.

Hydrodynamic Modeling (and Ecosystem Linkages) ④ *Investigators* — Lisa Lucas & Noah Knowles (USGS), Mick van der Wegen & Dano Roelvink (UNESCO-IHE), Post-doctoral Researcher (TBD)

<u>*Problem*</u> – The movement of water is a primary control on Delta water quality (e.g. salinity, water temperature, contaminants) and ecology (e.g. plankton accumulation), as well as the interactions between water quality and ecosystem components (e.g. the availability of phytoplankton as a food source to benthic bivalves, or the co-occurrence of favorable temperature and turbidity conditions for fish). These physical-water quality-ecological interactions are expected to evolve as a result of climate change via shifts in magnitude and timing of river inflows at the upstream boundaries, changes in sea level at the down stream boundary, and changes in atmospheric forcing (e.g. heating, wind) from above. In addition, future planned (e.g. water conveyance) and unplanned (e.g. earthquake induced levee failure) structural changes to the Delta have the potential to abruptly transform water movements and, consequently, water quality and ecosystem function. The large implications of hydrodynamics for management of ecosystem processes and water supply, therefore, require a high quality representation of Delta hydrodynamics and its water quality and ecosystem linkages.

<u>*Tools/Analysis*</u> – CASCaDE I applied multiple models to describe hydrodynamic processes separately in SF Bay and the Delta. By nature, both domains are strongly interconnected. Cascade II aims to provide more spatial and cross-disciplinary uniformity in the modeling strategy by applying a single model that describes flow patterns in the Bay-Delta system that will act as a basis for further water quality and ecological parameter assessment described in other tasks.

We will use a process-based numerical model, Delft-UNSTRUC, which is developed by the non-profit institution Deltares (Deltares is also the developer of the Delft3D modeling system (http://delftsoftware.wldelft.nl/) that was applied to San Pablo Bay in CASCaDE 1). Similar to Delft3D, UNSTRUC is a process-based numerical model that solves the shallow water equations, allows for 2D and 3D modeling approaches, computes variability in salinity and temperature, and includes formulations for sediment transport and morphodynamic development. In contrast to Delft3D, UNSTRUC employs a finite volume approach based on a flexible network, allowing for grid triangles, squares and pentagons. This new modeling approach is ideally suited for the combination of open waters and narrow channels found in the Sacramento-San Joaquin Delta.

In 2010, UNESCO-IHE and USGS began development of a Bay-Delta model based on UNSTRUC,

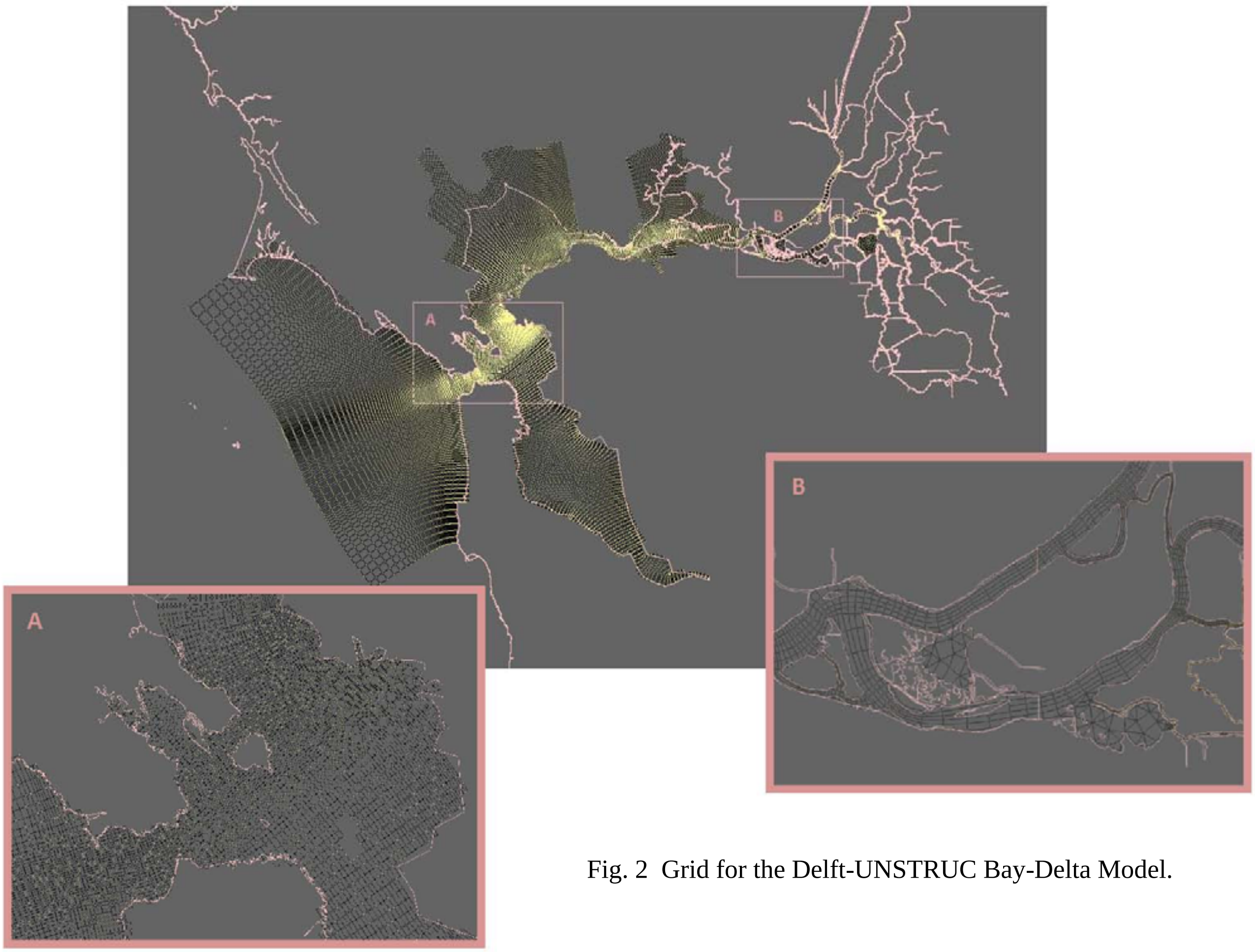

Fig. 2 Grid for the Delft-UNSTRUC Bay-Delta Model.

with a model domain extending from Point Reyes at the ocean, through the full SF Bay and Delta including the Yolo Bypass, and up to Sacramento and out to Mossdale (see Fig. 2). The basic Bay-Delta model is operational and water diversion structures (e.g. gates and barriers) are being added to better simulate existing conditions. Calibration and validation for water levels and salinity will be completed in the next half year and the full model ready for application to Delta studies by early 2011. The Bay-Delta model will be applied to evaluate ecosystem and geomorphic changes resulting from different scenarios of climate and structural change on the Bay-Delta System.

In the proposed study, the new model will be applied to investigate the Delta's response to scenarios of climate change, including upstream hydrologic changes, downstream sea level rise, and changes in local meteorological influences such as heating and wind stress (4 GCM scenarios will be examined, see

②). Additionally, we will examine the effects of structural change, including proposed new freshwater conveyance infrastructure and breached levee scenarios (at minimum we expect to explore 1 configuration each for the infrastructure and breached levee scenarios by project end).

The team listed above, with guidance from Cayan and Dettinger ②, will perform hydrodynamic model simulations of historical (baseline) and future (climate and structural change) scenarios. Because of the spatial and temporal detail captured by the model and its consequent computational requirements, we do not expect to be able to perform full 100-year simulations of Delta hydrodynamics commensurate with ② and ③. Instead, we plan to: 1) choose 2 representative historical years as "baseline" years (dry, wet), based on a combination of ranked river flow and hydrograph representativeness amongst the historical years, and 2) choose 2 future years (from flows projected in ③, representing wet and dry cases) with comparable flow rankings and hydrographs amongst the modeled future years). Historical "wet" and "dry" years will thus be comparable to future "wet" and "dry" years. Choosing specific years, as opposed to calculating "average" years as composites of many years, is necessary if the model is to be driven by episodically interconsistent boundary conditions (i.e. a stormy period that consistently affects river flows, sea level, and local meteorology, shown to be important by [13]). We see this approach as a starting point, and expect to adapt it as results progress. We plan to perform model runs with structural and climate change alone and in combination.

UNSTRUC will provide detailed flow field (and salinity and temperature) output in the Bay-Delta system. By application of the Delft WAQ/ECO software suite, UNSTRUC also offers a powerful tool to address water quality and ecological issues like phytoplankton and bivalve dynamics and their interactions. WAQ/ECO can be run "offline", applying saved UNSTRUC flow output to drive water quality and ecological simulations, increasing computational efficiency. Thus, UNSTRUC output becomes available to water quality and ecological research described in other tasks, forming a basis for standardization of scenario output results.

The team named above, with the collaboration and support of E. Elias and others at Deltares (funded through USGS cost-sharing), will model hydrodynamics, the variability of salt and water temperature, and link with ⑤ and ⑨ to develop the physical-water quality-ecology model linkages. The involvement of an environmental computing expert (Helly, UCSD) and computing resources at the UC San Diego Supercomputer Center (partial support requested herein) will facilitate the completion of multiple 1-year scenarios from the hydrodynamic and other coupled models.

Required Inputs – Bathymetry throughout the Bay-Delta is required (and currently being refined under other funding), as well as LIDAR data of islands for computations on potential impact of levee breaching (CA DWR). Flow and temperature boundary conditions will be provided by ③ for future scenarios; existing measurements (IEP, BDAT, DAYFLOW databases) will provide boundary conditions and calibration/validation data for historical conditions. Ocean sea level forcing and meteorological data will be provided by ②. Data gathering has begun. Guidance on conveyance and flooded island scenarios will be sought from the DSP, UC Davis Delta Solutions Group, USGS Earthquake Hazards Group, and others.

Outputs/Deliverables – Hydrodynamic parameters will drive SS and geomorphological computations ⑥. Temporally and spatially variable velocity, stage, salinity, and temperature (with suspended sediment concentration SSC ⑥) will be stored and available to drive offline water quality and ecological simulations (⑤⑨) for the baseline, climate, and configurational change scenarios. Seasonal evolution of salinity distributions will be used to assess the potential shifts in estuarine versus freshwater clam colonization ⑨. Assessments of salinity and temperature (with SSC ⑥) will be used in projections for fish populations ⑩. Residence times in key regions will be made available to ⑧ for contaminant modeling. Hydrodynamic model output will be used to evaluate changes in levee overtopping risk ③. Order of runs will be staged relative to availability of inputs from other tasks. We expect:

baseline/historical runs (Y1), configuration scenario runs (Y2), climate scenario runs (Y2-Y3). One manuscript documenting this work will be in preparation by end Y3. BDSC presentation (2012).

Phytoplankton Dynamics ⑤ *Investigators* – Lisa Lucas (USGS), Wim Kimmerer (SFSU)

Problem – Phytoplankton biomass (PB) represents the dominant food supply to the pelagic foodweb supporting the Delta's upper trophic levels such as fish [74,61], and depends on the relative rates of algal growth, loss (e.g. to consumers), and transport [50]. In turn, many other ecosystem components (e.g. primary consumers ⑨ and contaminant dynamics ⑧) are influenced by phytoplankton growth and standing stock. We propose to address the questions: 1) How are Delta PB and primary productivity (PP) directly and indirectly linked to water quality, hydrodynamic transport, and secondary producers? 2) How will these relationships shift with changes in climate and Delta physical configuration? 3) How can we improve on existing approaches for linking physical models with biological models?

Tools/Analysis –The customized Delta phytoplankton model will link to ④ and ⑥ via the Delft WAQ/ECO modules. Phytoplankton computations will be performed "offline", using saved hydrodynamics and SSC. The spatial domain for this model will be Suisun Bay and the Delta, implementing seaward hydrodynamic boundary conditions derived from full Bay-Delta runs. Parlaying approaches developed during CASCaDE I and other previous CALFED funded efforts (see Fig. 3), the phytoplankton model includes light-dependent algal net growth and loss to zooplankton and bivalve grazing [48]. Water column irradiance depends on photosynthetically active radiation (PAR) at the water surface and on turbidity. Calculation of hydrodynamics, turbidity and phytoplankton "under one modeling roof" will significantly improve on our previous approach of specifying static turbidity maps from spatially coarse sampling. Light attenuation will be derived dynamically from 1) SSC fields calculated at refined spatial and temporal resolution consistent with those of the phytoplankton calculations, and also 2) a dynamic self-shading component proportional to PB. Although the possible effects of nutrient form (ammonium) on the Delta phytoplankton community is an area of active exploration, necessary parameters for modeling such relationships are still needed [58]; thus, nutrient effects on growth will not be modeled because nutrient limitation is extremely rare in the Delta [38,39]. Modeling of cyanobacteria blooms, an increasingly important issue in the Delta, is beyond the scope of this project; however, we hope that the proposed work and continued observations by others in the Delta will form a basis on which to eventually build that component.

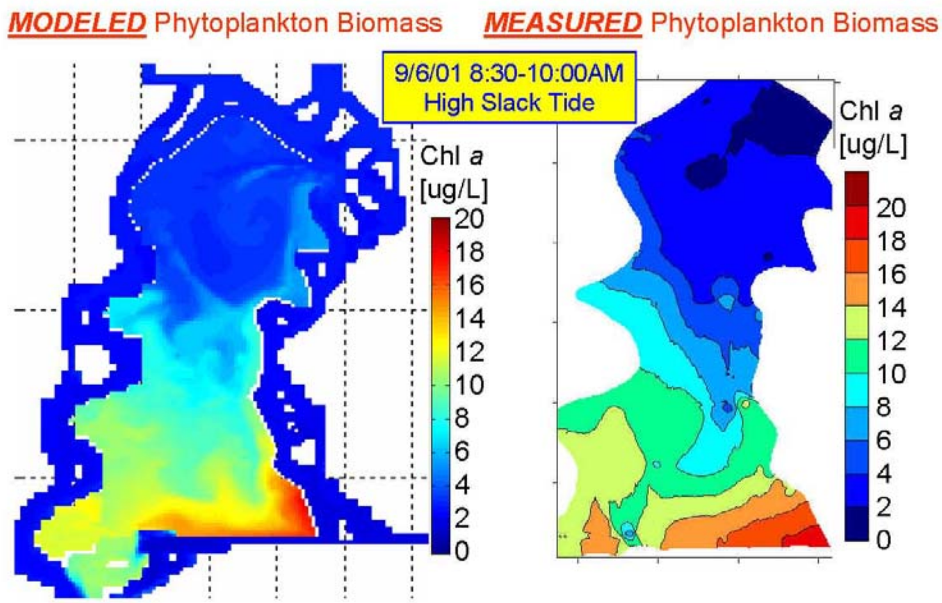

Fig. 3. Regional 3D model of phytoplankton (as chl *a*), TRIM3D hydrodynamics, and water temperature in a Delta flooded island (Mildred Island), driven by measured grazing, turbidity, meteorology, tides [left], and measured chl *a* for the same time period [right]. (Lucas & Thompson (USGS), Baek & Stacey (UCB), unpub. data)

Because 1) algal standing stock depends on removal rate by benthic grazers [49,47], 2) benthic biomass and thus grazing depends on food availability, and 3) the necessary data now exist, we will couple a dynamic benthic grazer model ⑨ to the phytoplankton model for a 2-way linkage. Kimmerer (SFSU) will lead the calculation of zooplankton grazing rates, which depend on, e.g., species, temperature, and food concentration. We lack data on functional responses of feeding to food, so we propose to estimate grazing rates from growth and reproductive rates, which are related to feeding by the relatively well-constrained gross growth efficiency [44]. Reproductive and growth rates of copepods have been determined in several studies [e.g., 41, 32, and ongoing work]. Biomass estimates will be made from IEP monitoring data on abundance and individual masses by species and life stage.

Required Inputs – Surface PAR will be derived from solar radiation provided by ②. Turbidity will be provided by ⑥. Velocities, and water temperatures for zooplankton grazing and algal growth rate comparisons, will come from ④. ⑨ will provide dynamic values of benthic grazing rate. Because several models will sequentially produce output used in this task we anticipate: 1) structural change scenarios to be run prior to climate change scenarios; 2) focusing on a subset of climate scenarios for which ③④⑥⑦ suggest significant changes from baseline. Depending on the timing of completion of runs by ⑥, we anticipate possibly using preliminary results and guidance from ⑥⑦ to establish bounds on turbidity for climate scenarios. Future boundary conditions for phytoplankton will be based on historic relationships between chlorophyll, flow, season, and year type [e.g. 39]. IEP-EMP and USGS data will be used for validation.

Outputs/Deliverables – Model runs are expected to be 3-6 months in duration. For the selected scenarios, changes in PB and PP magnitude and distribution, and Delta PB mass balance will be assessed. Calculations of PB will dynamically drive the bivalve model ⑨, and will be available to ⑧ and ⑩. Expected schedule of deliverables: 1) linkage of phytoplankton model with UNSTRUC (Y1); 2) verification and validation for baseline/historic runs with imposed benthic grazing rates and turbidity (Y1-Y2); 3) linking with ⑨ and ⑥ (Y2-Y3); 4) selected future scenarios runs (Y3); BDSC presentation (2012); manuscript in preparation (end Y3).

Turbidity and Geomorphology ⑥ *Investigators* – Bruce Jaffe (USGS), Mick van der Wegen & Dano Roelvink (UNESCO-IHE)

Problem —The future Bay-Delta system may undergo considerable change due to sea level rise, changing river flows, levee breaches, flooding, different water management strategies and wetland restoration projects. Future conditions (e.g. increased tidal prism) may change the sediment budget, resulting in altered turbidity levels and related ecological effects (e.g. on phytoplankton, fish) throughout the Bay-Delta system. Although there is a qualitative understanding of many of the sediment processes of the Delta [70], it is difficult to quantify the effects of changing conditions. Therefore there is a need for a model to quantitatively assess impacts of possible future scenarios on the Bay-Delta system, in particular the sediment related characteristics such as turbidity and morphology. The objectives of this task are to: 1) use a model to better understand SS processes in the Bay-Delta; 2) assess how SS dynamics may change under future scenarios; and 3) explore implications for Delta geomorphology (due to the paucity of available validation data for the Delta and the need to first focus on characterizing and understanding the dominant sediment transport processes, this last objective will have the least emphasis and will be treated as preliminary).

Tools/Analysis – We will use a process-based numerical model, Delft-UNSTRUC, as described in ④. In UNSTRUC, the predicted flow fields will be coupled to sediment transport formulae so that model results can be analyzed in terms of sediment transports and related turbidity levels in the Delta. Analysis will focus on the Delta, but will include the Bay when necessary (e.g., propagation of water level and salinity from the ocean to the Delta). Climate and structural change scenarios described in ② and ④ above will be run with the sediment model. The modeled sediment transport patterns in the Delta will be analyzed to increase understanding of sediment input, throughput and settlement/erosion in the Delta. UNSTRUC has an open source character so links can be made efficiently to other (e.g. phytoplankton) models used within the CASCaDE II framework via the Delft WAQ/ECO modules. The team named above, with Wright (⑦b), Dastgheib (UNESCO-IHE), Elias (funded through USGS cost-sharing), and a Ph.D. student and M.S. student (both funded through USGS cost-sharing) will perform this work.

Required Inputs – In addition to data needed in ④, required inputs are SSC in the Bay-Delta for calibration/validation (USGS). SS boundary conditions will be provided by ⑦a-b. Data gathering has begun. Projected wind will be provided for selected periods by the dynamical downscaling effort in ②.

Outputs/Deliverables – Expected schedule: Output will include a calibrated model that describes yearly sediment budgets for the Bay-Delta system based on the current situation (Y1-Y2). Although the focus is on the Delta, assessments will be made of changing turbidity levels throughout the Bay-Delta under different scenarios of configurational (Y2) and climate change (Y3). Spatial and temporal variations in turbidity will be used as inputs for ⑤⑧⑨⑩ and ⑦c. One manuscript documenting this work will be in preparation by end Y3.

Sediment Supply and Marsh Sustainability ⑦ a-c *Investigators* – Scott Wright, David Schoellhamer, Judy Drexler, Lorrie Flint, Tara Morgan-King (USGS)

Problem (Sediment Supply, 7a-b) – One of the lessons from CASCaDE I is that future turbidity and geomorphic change in the estuary depend on sediment supply [30] from the watersheds. We simulated two scenarios of sediment supply: constant and decreasing, because we did not know if sediment supply will continue to decrease or remain constant. Turbidity, geomorphic change, and wetland sustainability all depend on assumed sediment supply. A complete conceptual model of Delta sedimentation was developed by [70]. The conceptual model contains submodels for sediment supply from rivers, regional transport from rivers to the Delta and between the Delta and Bay, and local within-Delta sedimentation.

Sediment supply from the Sacramento River, the primary source of sediment to the Delta, decreased by one-half during the second half of the 20th century [87]. Diminishment of the hydraulic mining pulse of sediment, sediment trapping behind reservoirs, deposition in flood bypasses, and armoring of river channels all are likely contributors [28,73,87]. The effect of sediment trapping behind reservoirs, including channel degradation and decreased sediment load, can appear downstream decades after reservoir construction [63]. The amount of sediment that accumulated behind dams of the Central Valley is greater than the decrease in supply, indicating that channels downstream from dams were eroding [87]. Cross sections at USGS gaging stations confirm that channels were eroding [26,37,71]. Large erosion occurred in water year 1997 and from 1997-2005 the channels were stable.

The decrease in sediment supply from the Sacramento River was accompanied by a decrease in Delta turbidity [38]. Also, SSC in SF Bay was 36% less in the 2000s compared to the 1990s [69]. Turbidity in the Delta is a key habitat variable for phytoplankton and some fish species of concern. Turbidity limits light availability and primary production [38]. Delta smelt larvae feeding sharply decreases when turbidity is less than 18 NTU [6]. Turbidity in the Delta is closely related to SSC in the tributary rivers.

The objectives of ⑦a-b are to a) analyze existing data to assess whether sediment supply has been continuing to decrease or whether a new post-dam equilibrium has been established, and b) develop a predictive model of sediment supply from the Sacramento River for projecting future sediment supply under various climate scenarios.

7a: Trend in Sediment supply from the Central Valley to the Delta (Schoellhamer, Morgan-King)

Tools/analysis –We will 1) analyze Freeport SSC and flow data 2002–present and compare to [87] to determine whether sediment supply is now stationary or decreasing, 2) analyze cross sections at USGS gages below the lowest dams to estimate erosion rates from the 1990s to the present [37] and compare these with flow records to determine if the channels are stabilizing, and 3) analyze bed material size changes through time.

Required inputs – This task requires existing information on sediment transport and channel cross-sections below dams.

Outputs/Deliverables – This analysis will show whether sediment supply is continuing to decrease due to human impacts in the watersheds (expected end Y2). These results will be used by ⑥⑩ and ⑦c. This task will also produce a BDSC presentation (2012) and a draft manuscript by end Y3.

7b: Projecting future sediment supply from the Sacramento River (Wright, Flint)

Tools/analysis – We will develop a rainfall-and-sediment runoff model (HSPF) for the Sacramento River watershed below the major dams. While climate change could affect sediment flow through the reservoirs, this is likely a second order effect compared to effects on supply from below the dams. Future climate boundary conditions will be developed for the four climate scenarios and downscaled to sub-daily for application of the HSPF model. The model will be calibrated using existing sediment transport data from gages throughout the watershed (an extensive database exists), deposition rates within the major bypasses, and datasets assembled for ⑦a. The primary test of the model calibration will be reproduction of the declining trend in sediment supply over the past 50 years. For other rivers that supply sediment to the Delta (San Joaquin, Cosumnes, Mokelumne) we will use the general results from the detailed model of the Sacramento watershed along with existing sediment transport data to make simplified empirical estimates of future sediment loads. This approach is being used because the Sacramento accounts for approximately 80% of the sediment supply to the Delta.

Required inputs – This task requires reservoir outflows (from ③) for the future climate scenarios, meteorological data such as precipitation and air temperature (from ②), and watershed information such as soils, vegetation, channels, geomorphology (e.g. NRCS SSURGO, California GAP analysis, aerial photos). Sediment transport data from USGS gages are also required for calibration.

Outputs/Deliverables – This model will provide assessments of future sediment supply for the four climate scenarios. These results will be used by ⑥⑩ and ⑦c. Expected schedule of deliverables: summary of existing data (end Y1), preliminary calibrated model (Y2), calibrated/validated model and future climate results (early Y3), documentation in preparation (end Y3), BDSC presentation (2012).

7c: Delta Marsh Sustainability Under Future Scenarios of Sea-Level Rise (Drexler, Swanson)

Problem – New data are available for addressing the question of marsh sustainability in the Delta under future sea-level rise scenarios. The CALFED-funded REPEAT (Rates and Evolution of PEat Accretion through Time) project has yielded vertical accretion histories (between 6000 years BP to~250 yr BP) for marshes in the Delta [25]. Currently, as part of a separate USGS project, Swanson, Drexler, and Schoellhamer are adapting a model [11] to predict future vertical accretion rates in the SF Estuary. This model, the Wetland Accretion Rate Model for Ecosystem Resilience (WARMER), will improve on the current Callaway accretion model by incorporating a mechanistic model for sediment accretion and including functions for above and belowground organic production.

In this project, we aim to further improve WARMER by using sea-level rise estimates provided by ③ [see also 43]. In addition, we plan to use data ⑦b to estimate future SSC for winter and spring/summer, to help constrain the range of future mineral deposition in Delta marshes. The main objective of this project is to determine whether Delta marshes are capable of vertically accreting at rates that will guarantee their sustainability through time or whether some are destined to be “drowned” under predicted rates of sea-level rise.

Tools/Analysis – We will run WARMER with sea-level rise estimates and mineral deposition estimates tailored to the upper reaches of the SF Estuary in order to determine the vertical accretion rates that are needed for Delta marshes to remain sustainable through time. We will compare these rates to the vertical accretion rates measured in the REPEAT study and by Reed [66] to determine how different sea-level rise scenarios affect marsh sustainability.

We will also collect 1-m peat cores in marshes that were part of the REPEAT study in order to determine vertical accretion rates over the past ~100 years. Peat cores will be analyzed for bulk density, % organic carbon, ^{210}Pb, and ^{137}Cs. These analyses will permit an understanding of the organic vs. inorganic content of the peat, age determination of the peat layers, and determination of yearly vertical accretion rates. Recent accretion rates will be compared to WARMER estimates to see if they are adequate for Delta marshes to remain sustainable under scenarios of future sea-level rise.

Required inputs – Existing and new peat core data, sea-level rise estimates from ③, and data from ⑦b to estimate future SSC for winter and spring/summer. Approximately 1 month of field work and additional laboratory work.

Outputs/Deliverables –This project will provide the first region-specific estimates of the overall sustainability of Delta marshes under future rates of sea-level rise (by end Y3), a BDSC presentation (2012), and a manuscript in preparation (by end Y3).

Contaminant biodynamics ⑧ *Investigators* – Robin Stewart, Sam Luoma (USGS)

Problem – Contaminants such as Se have the potential to impede restoration of key fish species and the food webs that support them. The fate and impacts of contaminants in the SF Bay-Delta depends on a number of interlinked processes including: 1) physical transport; 2) biogeochemical transformation/degredation/biotransformation; 3) uptake into phytoplankton and/or partitioning onto particles, and; 3) physiological uptake and elimination by higher organisms. Biodynamic models have been developed for Se that have helped evaluate these processes and identify those that are most influential in controlling bioaccumulation in organisms in general [54,2,77,72]. Yet, efforts to extend these models into dynamic estuarine environments are ongoing. For the SF Bay and Delta, identification of Se sources (local estuarine vs. riverine inputs) and key processes modulating uptake into the food web base has been confounded by limited bioaccumulation data in resident species and their food across a range of hydrodynamic and estuarine conditions [46]. Further, sufficiently detailed computational models (hydrodynamic, sediment and phytoplankton) for quantifying complex estuarine processes at spatial and temporal scales relevant to Se biogeochemical cycling/bioaccumulation have not be available until now.

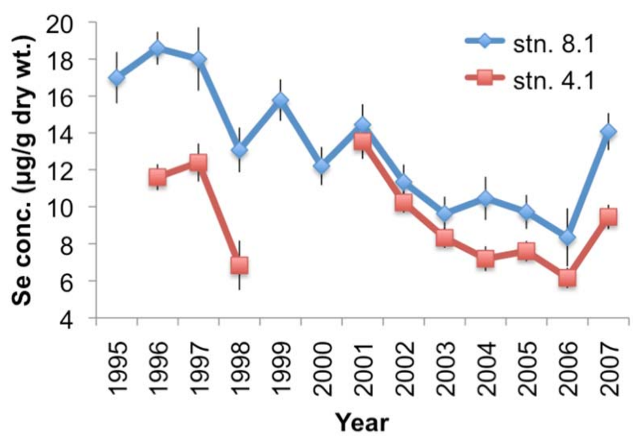

Fig. 4. Selenium concentrations in *Corbula amurensis* from 1995 through 2007 at stations 8.1 (Carquinez Strait) and 4.1 (confluence of Sacramento and San Joaquin Rivers).

This study component proposes to address the questions: 1) How does Se bioaccumulation in the invasive clam *Corbula amurensis* (*CA*) vary with hydrologic conditions (as characterized by source water contributions (Sacramento vs. San Joaquin River) and residence time)? Does residence time alter the relative contribution of internal vs. external sources of Se accumulated by clams in Suisun Bay? 2) How do SS and phytoplankton dynamics influence variability of Se bioaccumulation in *CA* in northern SF Bay? 3) How will these relationships influence the fate and bioaccumulation of Se in *CA* and its predators (e.g., white sturgeon, Sacramento splittail, diving ducks) with changes in climate and Delta physical configuration? 4) How can we improve on existing approaches for linking physical models with biological models?

Tools/Analyses – As part of CASCaDE I and ongoing USGS funded studies, we now have Se data in *CA* spanning 14 years (1995 – 2010) that include both dry and wet conditions and changes in water operations (Fig. 4). Using historical dissolved Se concentrations for both Bay and riverine end-members

[19,20] and Delft-UNSTRUC output, we will: 1) compute relative source (internal vs. external) contributions to dissolved Se at Carquinez Strait and the Confluence (Se time series stations) during the summer and fall of a wet year and dry year; 2) alter riverine loadings to reflect changes in operations and estimate relative source contributions to dissolved Se at the same stations. Dissolved Se will then be used to estimate particulate Se concentrations [3,2] that will be incorporated in the biodynamic Se model [45,53,64,68,76] to estimate changes in *CA* Se concentrations for summer-fall (growth rates for *C. amurensis* provided by ⑨). Based on output from ⑤ and ⑥ suspended sediment and phytoplankton models we will then alter the composition of suspended particulate material (inorganic vs. phytoplankton vs. detritus) and Se assimilation efficiency [68] to quantify changes in clam Se concentrations. Model simulations will then be compared to the historical Se dataset to help identify and verify critical processes driving change in Se bioavailability through time. Lastly, we will use a) output from ④ for scenarios of climate and Delta configuration change to estimate dissolved Se, and b) the biodynamic model to estimate fall Se concentrations in *CA*. Using a range of trophic transfer factors for white sturgeon, Sacramento splittial and a diving duck [64], and salinity-driven distributions of invasive clams (*CA*, *C. fluminea*) we will estimate Se concentrations in clam-predators in the Bay- Delta and their potential risk for Se toxicity ⑩ (based on toxicity thresholds established for surrogate species).

Required Inputs – This component requires: residence times and source water contributions at Carquinez Strait and the confluence from ④; site specific growth rates for *CA* from ⑨; computed SSC from ⑥; phytoplankton biomass from ⑤; and regional distributions of invasive clams from ⑨.

Outputs/Deliverables – An improved approach integrating estuarine processes (hydrodynamics, SS, and phytoplankton) and biodynamic uptake of Se to evaluate the potential fate and impacts of Se under selected climate and Delta configuration scenarios (depends on availability of inputs, by end Y3). BDSC presentation (2012), and manuscript in preparation (by end Y3).

Food Web Effects of Invasive Bivalves– *Corbula*, *Corbicula*, and *Dreissena spp.* ⑨

Investigators – Janet Thompson, Francis Parchaso (USGS)

Problem – We have shown that grazing by the invasive bivalves *Corbula amurensis* (*CA*) and *Corbicula fluminea* (*CF*) can limit net growth of primary producers in the Bay-Delta system [1,49,47,79,51]. These bivalves have the potential to limit restoration success by outcompeting native zooplankton, shrimp, and larval fish for food [40], and by increasing the trophic transfer of contaminants in the system [76,46]. We learned in CASCaDE I [80,81] that these bivalves could increase their prominence in the food web as follows: (1) Populations of both species are food limited and thus an increase in quality phytoplankton biomass will likely increase the biomass of the bivalve populations. (2) Because juveniles are the dominant *CF* age class in most of the Delta, and because growth is fastest in smaller clams, an increase in food will likely lead to a dramatic increase in biomass and hence grazing rate, which may lead to subsequent food reductions. (3) Because *CA* and *CF* have overlapping distributions, both species can rapidly spread with changing water quality conditions. (4) Increased water temperatures, projected in CASCaDE I, will extend *CF*'s reproductive season in the system.

Dreissena polymorpha (Zebra Mussel, *DP*) and *Dreissena bugensis* (Quagga Mussel, *DB*) are not yet in the Estuary although they are present in a nearby reservoir (San Justo) and in southern California. (http://www.des.water.ca.gov/zmwatch/calif_distribution/index.cfm). Because these filter feeding species have the potential to place additional stress on the food web [59,5] and to accumulate contaminants [67], we will consider these species in CASCaDE II.

The physical Delta will be altered with climate change, new infrastructure, and new flooded islands. Bivalves will respond to the corresponding changes in salinity distribution, turbidity, temperature, and residence time. The bivalves will both alter and respond to the quantity of phytoplankton; thus motivating the dynamic feedback between bivalves and phytoplankton in the models.

Tools/Analyses –UNSTRUC will dynamically link to the phytoplankton and bivalve population models via the Delft-WAQ/ECO modules. Population parameters derived in CASCaDE I will be used in the bivalve model to assess changes in the distribution, biomass, and food consumption of *CF* and *CA* for each scenario analyzed in ⑤. We will examine the potential for *DB* and *DP* effects on phytoplankton biomass by imposing literature-based grazing rates within areas where salinity is not limiting.

The Biomass Based Stage-Structured Model (BBSSM) for a Bivalve Grazer [85,22,23] allows us to model biomass change in several age classes for multiple species. The model was designed to look at populations with known year class-specific growth rates, mortality rates, pumping rates, assimilation rates, reproductive seasonality, and respiration rates. Growth rates and mortality rates were determined in CASCaDE I and the remaining parameters have been published for *CA* and *CF* as reported in [80,81]. Grazing rates will be estimated as described in [49,79].

Life history parameters for *DP* and *DB* are unknown for this system although early reports from Lake Mead (http://www.lakemeadsymposium.org/program_c.htm) show *DP*'s physiological tolerances to be much broader than in the Great Lakes [59]. We will examine data from similar latitudes and temperatures and derive a series of parameters that will be available for our immediate use (i.e. grazing rates) and for future/immediate use should either or both species invade.

Error analysis will include resampling the parameter distributions and validating the model against our 20 year time series data for *CA* and *CF*. A comparison of projected and actual biomass and distribution of the bivalves will be used to establish an overall error of the coupled models. Simulations will be run for the same periods as done in the phytoplankton model

Required Inputs – Bivalve distribution initial conditions and evolution require water temperature, salinity, and habitat evolution (e.g. depth) based on physical changes to the Delta ④. Initial conditions will assume population structure and species distributions consistent with today's distributions.

Outputs/Deliverables –(1) BBSSM calibrated offline with imposed phytoplankton biomass (before hydrodynamic runs are available) (Y2). (2) Distribution, biomass (with year class separation), and grazing rate for *CA*, *CF* based on habitat type, salinity and temperature in Suisun Bay and Delta for selected scenarios (Y3). (3) Compilation of *DP*, *DB* datasets and parameters (Y1); projected distribution and grazing rates from literature (Y3); these will be posted on the CASCaDE website as they become available. (4) 2-BDSC presentations (2012).

Native and Alien Fishes ⑩ *Investigators* – Larry Brown, Marissa Bauer (USGS)

Problem – As summarized in ②-⑨ above, climate change in combination with changes in physical configuration of the Delta will likely cause a variety of changes in hydrodynamics, physical processes, and primary productivity. These processes are important to understand for their own sake; however, present policy and management interest includes ecosystem health as a co-equal goal with water supply reliability. In practice, interest has focused on the status of native fishes, particularly threatened and endangered species [75] that are protected by federal and state legislation. Recent efforts have focused on declines in pelagic fishes, specifically, delta smelt, longfin smelt, age-0 striped bass, and threadfin shad [75,7] and much has been learned about the biology and habitat requirements of these species [e.g., 27,62,82]. However, many other fishes, including alien species, also occupy the Delta and may be having direct or indirect effects on species of concern [9,75,7]. There is evidence for multiple causes for declines of pelagic fishes, including alien fishes, alien clams, changes in chlorophyll-a, and a variety of physical factors, such as water clarity, water temperature, salinity, and water exports [55]. Therefore, it is important that the results of CASCaDE II be interpreted in the context of possible effects on both native and alien fish populations.

Tools/Analysis – We do not propose a particular modeling strategy for this task. As noted in this PSP, many uncertainties remain about the basic biology of many native species. This is a lesson we learned in CASCaDE I. There is sufficient biological and physiological data to make strong inferences about some species but for other species inferences are very uncertain. As in CASCaDE I, our approach will be to interpret the outputs from the other CASCaDE II tasks in the context of native fish biology on a species by species basis (e.g. Fig. 5). Where possible we will collaborate with other researchers with existing models or specialized knowledge of specific species. For example, an individually-based model for delta smelt is being developed (Drs. Wim Kimmerer, SFSU, Kenneth Rose, LSU, and William Bennett, UCD), and an individually-based model for striped bass has been developed (Dr. Frank Loge, UCD). Dr. Bill Bennett, a delta fishes expert, collaborated with us on CASCaDE 1.

Required Inputs – We do not require specific inputs. We will interpret whatever information is generated by ②-⑨. At a minimum, we expect to receive data on salinity, water temperature, and turbidity. These variables are known to have important effects on species of concern [27,62].

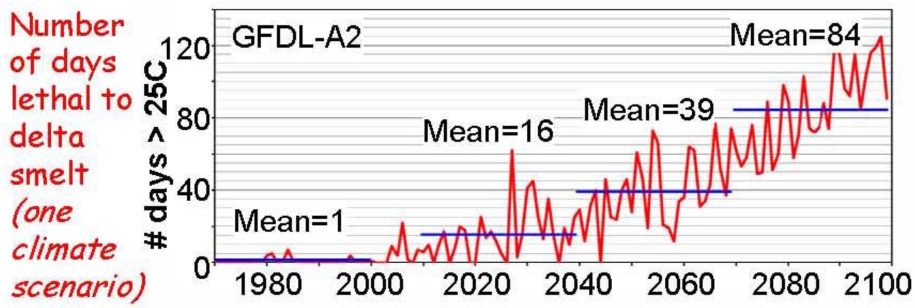

Fig. 5. (L. Brown USGS, Unpubl. data, CASCaDE I results) Number of days per year projected to be lethal to delta smelt. Projections of daily mean water temperature near Rio Vista were obtained using a statistical model [87] of Delta water temperature forced by downscaled air temperature from global climate models (one model-scenario shown here). Rio Vista is near or within areas of important delta smelt habitat. The critical thermal maximum for is 25.4 C for delta smelt acclimated to 17 C [79]. Water temperatures above around 25 C are considered lethal [8]. The “historical” baseline was obtained by hindcasting water temperatures using the model [87] and historical input data.

Outputs/Deliverables – Our outputs will be interpretations of outputs from other tasks (completed Y3). A BDSC presentation (2012) and draft manuscript (end Y3) will be produced.

4. Feasibility

There are several reasons for which we believe this ambitious program is feasible. First, the proposed study is a natural extension of research performed by the project team over the past 5-30 years. The PI team includes subject matter experts who have spent their careers performing field, laboratory, theoretical, and modeling studies in the Bay-Delta which forms the basis of the proposed modeling studies. During CASCaDE I, we learned first hand of the challenges involved in linking multiple modeling approaches that span and resolve disparate spatial and temporal scales. Now we move forward with strategies for facing those challenges. Specifically, we propose to use a single modeling framework (Delft-UNSTRUC and its WAQ/ECO modules) to provide the single “roof” under which the majority of modeled Bay-Delta processes will be computed (hydrodynamics, sediment, geomorphology, salinity, temperature, phytoplankton, bivalves). This single model housing will greatly expedite R&D, preparation of model inputs, co-analysis of outputs, etc. A hydrodynamic model domain reaching from the ocean to the edge of the watershed will simplify specification of seaward boundary conditions. UNSTRUC is currently under development and being configured specifically for the Bay-Delta. Required Bay-Delta data sets are currently being gathered and refined. 3D hydrodynamics and salinity and 2D SS are expected to be calibrated and validated for the Delta by early 2011; 3D SS will be calibrated and validated in the months following. Funding for skilled and knowledgeable subcontractors in strategic positions (e.g. supporting hydrodynamic and sediment modeling) further speaks to feasibility (see “Qualifications” for more description). Approaches and relevant datasets for modeling ecological components and contaminants have been developed through the course of CASCaDE I. An impressive slate of Bay-Delta scientists will serve as advisors to this project: James Cloern (USGS, phytoplankton ecology), Peter Moyle (UC Davis, fish biology), Steve Lindley (NOAA, landscape and fish ecology), Anke Müeller-Solger (IEP Lead Scientist, zooplankton ecology), Jon Burau (USGS, hydrodynamics). This advisory team will periodically attend PI meetings and consult as needed with the PI's. Knowles and Lucas will serve as co-administrators and scientific co-coordinators of the project. As in CASCaDE I, we expect 3-4 (in-person, video-conference) meetings per year of all investigators for defining research strategies, coordinating model inputs, outputs, and timelines, sharing and interpreting output, and planning publications and presentations. Because the majority of this team has worked together for >10 years, we have established productive working relationships and efficient methods of operation.

Finally, this project is feasible because it proposes to leverage resources from the Delta Science Program with USGS appropriated funds. The total project cost is $4.2M, of which approximately $2.7M will be provided by the USGS Hydrologic Research and Development and Priority Ecosystem Science (PES) Programs. The USGS San Francisco Bay-Delta program (including CASCaDE I) has been supported by these funds since 1995. Subject to the availability of appropriations, Federal Matching Funds ($22,550) for Task 7b will also be provided if the proposal is selected and DSC enters into an agreement with the USGS California Water Science Center.

5. Relevance to the Delta Science Program

Relevance to this PSP — **This proposal most directly addresses Topic 3** (Coupled Hydrologic and Ecosystem models). Through: • linking models/analyses of climate, hydrology, sea level rise, hydrodynamics, sediment transport, geomorphology, salinity, temperature, phytoplankton (including primary productivity and mass balance analyses), bivalves, marsh accretion, contaminant biodynamics, and fish • applying those models to assess ecosystem effects of new water conveyance infrastructure and planned or unplanned levee breaches in conjunction with climate change • the PI's years of SF Bay-Delta research and previous development, contribution to, and publication of conceptual (including DRERIP) and numerical models that form the foundation of the proposed work • existence or current development of the proposed modeling components • analysis of modeled turbidity, temperature, and salinity distributions for said scenarios vis a vis requirements for specific fish and bivalve species • the previous, current, and proposed analysis of decades of collected data for deriving functional relationships within the CASCaDE models, and to configure, calibrate and validate them,
this proposal will address these Topic 3 needs: • coupling of hydrodynamic, sediment, water quality, and ecosystem models to inform management planning and operations • building on existing conceptual and quantitative models • applying models for assessing potential outcomes of water management alternatives • linking models that provide information on discharge, water velocities, flow paths, water quality, residence time, and inundation patterns with ecosystem models that simulate key ecosystem attributes such as primary and secondary production, habitat responses to inundation, fish behavior, growth, and mortality • ecosystem modeling focused on food webs,
…and related Topic 3 questions: #1 (re: linkages between Delta hydrodynamics, water quality, primary and secondary production, and food web dynamics); #3 (re: distribution of habitat requirements for aquatic organisms under different flow regimes, alternative conveyance and climate change scenarios); #4 (re: the effect of altered flow regimes, conveyance modifications, and sea level rise predictions on losses of organisms. This study also addresses **Topic 2** (Food Webs…) and the identified need to assess climate change effects on water quality parameters that may affect aquatic food webs. In particular, question #4 under this topic (re: critically important drivers of food webs) will be addressed. **Topic 4** (…Decision Support…) will also be supported by this study, through 1) continued development of simple indicators of ecosystem response to climate change begun in CASCaDE I and useable by resource managers to encapsulate species thresholds and ecosystem turning points (e.g. Fig. 5); 2) a

connection with the previously funded DeltaEFT (Ecological Flows Tool, ESSA Technologies and the Nature Conservancy). We have jointly identified ways that CASCaDE can provide inputs and insights to this decision support tool. D. Marmorek (ESSA President, see attached letter of support) has agreed to attend periodic CASCaDE team meetings to help us identify new ways in which CASCaDE outputs can be made relevant to this and other decision making models for the Delta. This project is highly responsive to the **DSP's priorities** on the need for **interdisciplinary projects**, **analysis/integration/ synthesis of existing information**, **collaborative proposals** (*scientists from 4 USGS offices, 3 universities, and 1 non-profit*), and significant **cost sharing** *(see "Cost sharing" attachment*).

Relevance to DSP Issues Outside this PSP — With foci on water flow and quality as well as on ecosystem function, the proposed study is aimed at developing model-based tools and understanding and producing objective, science based results that will support the DSC in both of its co-equal goals. The tools and results developed will be relevant to the State of California in its planning and consideration of the effects of water management and conveyance alternatives, restoration, and planned and unplanned levee breaches on water quality, native and alien species, and ecosystem function. The suite of models, once developed and validated, will be applicable for running many more scenarios than are planned for this 3-year project. For example, the models could be used to explore the question of whether more variable Delta salinities could effectively limit exotic species [60]. The modeling framework could also be used to explore whether increased numbers of dendritic channels could increase primary productivity (as presented by C. Enright [DWR] and J. Burau [USGS]).

6. Qualifications

Many scientists on the CASCaDE team have spent all or most of their careers studying the SF Bay-Delta system, its watershed, and California climate. Most were participants in CASCaDE I and other previous modeling projects and have a deep background in relevant Bay-Delta field and laboratory studies on which their modeling approaches are based. This team has a history of presenting and publishing results. Their publication records speak to their experience and productivity in their respective fields. Collectively, these scientists have first-authored >100 peer-reviewed publications relevant to the Bay-Delta-Watershed and California climate, along with numerous more co-authored and in their respective disciplines directly relevant to the project tasks. Several members of the team have served in advisory roles for CALFED and other resource management entities, and thus bring to the team knowledge of policy and management interests and concerns. Subcontractors were strategically chosen to participate in this study for several reasons. UNESCO-IHE (Van der Wegen, Roelvink, Dastgheib) and Deltares (Elias) subcontractors are 1) experts in the processes and modeling of hydrodynamics, sediment dynamics, and geomorphology; 2) experts in the use and adaptation of Delft models; and 3) eager to integrate their models of physical processes with ecological models. In collaboration with USGS staff, this team is already developing/configuring UNSTRUC for the Bay-Delta. Van der Wegen and Roelvink were productive team members on CASCaDE I. Kimmerer (SFSU), an expert on Bay-Delta zooplankton ecology and intimately knowledgeable of available zooplankton data for the Delta, will strengthen this aspect of the phytoplankton model. We are allocating resources for critical technical support, including training/assistance from Deltares for facilitating the UNSTRUC hydrodynamic linkage with water quality and ecology modules. We have also chosen Helly (UCSD) because of his expertise in environmental supercomputing, geospatial analysis, and prior experience with Delft models; he will assist us in porting/optimizing our code for running at the San Diego Supercomputing Center and maintaining an up-to-date basemap of the region. Knowles and Lucas will serve as co-administrators and scientific co-coordinators of the project.

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