Attachment 11. Project Narrative

Project Title: A Next-generation Model of Juvenile Salmon Migration through the Sacramento-San Joaquin Delta

Applicant name: The Regents of the University of California, Santa Cruz

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Executive Summary/Abstract

The Institute of Marine Sciences at the University of California, Santa Cruz, is requesting funding over a period of three years to develop the next generation of models for understanding and forecasting juvenile salmon migration and survival through the Sacramento-San Joaquin River Delta. These new models will take advantage of the newest data and analytical methods to dramatically improve our ability to forecast salmon movement and survival through the Delta under a wide range of climatic and hydrologic conditions. The outcome of this research will be a simple, accurate, and robust tool for evaluating the impacts of future climate scenarios and management actions on California Central Valley salmon populations.

Introduction and Purpose

California depends on State and federal water projects, an elaborate system of reservoirs, flood control structures, water diversions, and canals, to manage its water scarcity problem. The Sacramento-San Joaquin Delta, and the large water diversion facilities therein, are central elements of the system that moves water from the relatively wet, low demand north to the dry, high demand south. Operation of the water projects alters the amount, quality, and circulation patterns of water in the Delta, and operations are constrained in part by measures meant to protect important native species such as Chinook salmon. Decades of research have shown that salmon survival is influenced strongly by freshwater inputs to the Delta, while the effects of water withdrawals on salmon survival are less clear (Newman and Brandes, 2010). More recent studies have shown that survival of salmon migrating through the Delta, especially in its interior and southern portions, is extremely low (Perry et al., 2016). California's co-equal goals of increasing water supply reliability and protecting the Delta ecosystem means finding ways to operate the water projects while improving survival of juvenile salmon that must migrate through the Delta. The only practical way to make progress on this wicked problem is through adaptive management, which requires quantitative models to predict the system response to management actions (Luoma et al., 2015).

Every year, juvenile Chinook salmon and steelhead (hereafter referred to as juvenile salmon) migrate to the Pacific Ocean from spawning grounds in the Sacramento and San Joaquin Rivers and their tributaries, passing through the Sacramento-San Joaquin Delta (hereafter, the Delta). While migrating through this system, fish move through diverse habitats, encounter predators, interact with highly dynamic flows, and are impacted by a multitude of human-made structures (Buchanan et al., 2013; Michel et al., 2013). There is scientific consensus (Medellín-Azuara et al., 2017) and agreement among policy makers (California Department of Fish and Wildlife (CDFW), 2012; California Proposition 1, 2014; California Natural Resources Agency, 2016) that integrated system-level models and ecosystem-level management are needed to effectively manage salmon populations and other key resources in the California Central Valley. To this end, the National Oceanographic and Atmospheric Administration (NOAA)'s National Marine Fisheries Service (NMFS) is developing simulation models to evaluate the potential effects of water project operations and habitat restoration on the dynamics of Chinook salmon populations in the Central Valley (Hendrix et al., 2014). These Life Cycle Models (LCMs) couple water planning models to biological models of Chinook salmon to predict how salmon populations will respond to different management actions, including changes to flow and export regimes, modification of water extraction facilities, and large-scale habitat restoration.

A crucial part of NMFS' LCMs is the ability to estimate survival of migrating juvenile salmon through the Sacramento-San Joaquin Delta under a wide variety of environmental conditions. The primary tool currently being used to do this is the NMFS Enhanced Particle Tracking Model (ePTM) – an agent based simulation model of juvenile salmon migration through the Delta, developed jointly by the Institute of Marine Sciences at the University of California at Santa Cruz (UCSC), NMFS, the United States Geological Survey (USGS), and the California Department of Water Resources (DWR) with funding from the Bureau of Reclamations (Jackson et al., in prep.; Sridharan et al., in prep.). Additionally, NMFS has short-term plans to incorporate ePTM into the Spring-run (Cordoleani, in prep.) and Fall-run LCMs, and long-term plans for linking the next-generation ePTM with a hydrodynamic and temperature model, the River Assessment for Forecasting Temperature model (Pike et al., 2013) and an agent-based model of spawning Salmon in the Sacramento River (Dudley, in rev.).

As computational models such as the ePTM begin to play increasingly important roles as decision-support tools in the integrated management of the Delta, three attributes of these models will be crucial. Firstly, models must be designed in such a way that new scientific data sources can be incorporated as they become available. Secondly, model predictions must be robust to the substantial season-to-season and year-to-year variation in biotic and abiotic conditions in the Delta. Finally, models and the data on which they rest must be peer reviewed and easily shareable with scientists and managers. There are several existing models of juvenile salmon migration dynamics in the Delta, each with unique scientific and management foci: statistical models such as the San Joaquin River Fall-Run Chinook salmon population model (Marston, 2005) and mark-recapture models (Perry et al., 2016), which are data analysis tools; a coarse-spatial and temporal resolution simulation model known as the Interactive Object-oriented Salmon (IOS) model (Zeug and Cavallo, 2014, Cavallo et al., 2011), which is designed to be a decision support tool; and fine-scale 3D individual based models including extensions to the UnTRIM-FISH Particle Tracking Model (PTM) (Gross et al., 2014), and rule-based automata models (Goodwin et al., 2014), which primarily address scientific questions. While 3D flow features are critical to salmon migration dynamics, an essential model requirement for species monitoring and management is that models are able to quickly assimilate new data and that they can be used to evaluate in-season scenarios quickly without the need for extensive computation (Burau et al., 2007; Perry et al., 2016). ***Thus, the challenge is to build a model of salmon outmigration through the delta that captures the salient processes affecting salmon movement and survival through the Delta, while retaining speed and interpretability. The structure and capabilities of the current ePTM, and the extensions proposed here will make the next-generation ePTM uniquely suited to meet this challenge.***

Project History / Need for CDFW Funds

The current generation ePTM is an agent-based model that simulates the movement and mortality of large numbers of individual juvenile Chinook salmon as they transit the Delta. The model is an extension of the PTM component of DWR's Delta Simulation Model II (DSM2), a model in which passive particles are moved through the channels within the Delta by advection and diffusion (Kimmerer and Nobriga 2008) using flows computed with DSM2's flow and water level solver – Hydro (Anderson and Mierzwa 2002; Figure 2). The ePTM extended DSM2-PTM by incorporating published information from past studies of fish navigation behavior (i.e., how fish swim in response to hydrologic conditions, time of day, channel junctions, etc.) into a ***navigation module***, and by incorporating a model of interactions between salmon and their predators into a ***predation module*** (Jackson et al., in prep; Sridharan et al., in prep). Simulated juvenile movements in the ePTM are due both to hydrodynamic forces exerted on the fish by flow, and also to active swimming behavior: simulated juveniles are able to hold position during different phases of the tide (Gibson, 2003; Liao, 2007), migrate toward the ocean, become confused about the oceanward direction when flow cues do not always correspond to the oceanward direction (e.g., Healey 1967; Davidsen et al., 2009), and swim during some parts of the diel cycle and not others (Chapman et al., 2013). When a simulated fish reaches a channel junction, it is routed with a probability proportional to the flow entering each channel. Interactions between salmon and their predators are captured using the "XT model" (Anderson et al. 2005), a mathematical model that describes encounters between juvenile salmon and predators as a random encounter process.

It is important to emphasize that, as in many computational models of migration, the behaviors simulated in the current generation ePTM are primarily based on the best available scientific information from literature, with a small proportion of the behaviors being based on direct behavioral studies undertaken by Chapman et al. (2013) of salmon in the Delta system. Due to data limitations in the past and the limitations of current analytical methods, the details of how juvenile salmon in the Delta swim as they migrate, how often and where they encounter predators, and how they interact with complex tidal and riverine flows are not well understood. However, ***several new datasets collected during studies conducted in the Delta by the DWR and by NMFS have the potential to shed substantial light on these poorly understood aspects of salmon migration. These datasets contain high-resolution, two-dimensional (2D) tracks of tagged smolts and smolt predators in several key regions of the Delta (Fig. 2, Fig. 3). These data contain the information needed to build a data-driven model of salmon migration through the Delta from the ground up. Funding from the CDFW would allow us to develop the novel analytical methods needed to estimate salmon migration behaviors and interactions between salmon and predators directly from these rich sources of behavioral data, and to use these data sources to build a robust model of salmon migration through the Delta system.*** Funding from CDFW will provide us with the personnel and resources we need to execute this project in the near term.

A broad suite of management decisions and scientific endeavors hinge on understanding salmon migration through the Delta, making the model we propose to develop both timely and of use to a broad audience. For example, survival of juvenile salmon through the Delta estimated using the ePTM is a core input into NMFS' Central Valley Winter-run Chinook salmon LCM (Hendrix et al., 2014), one of the primary tools that is currently being used to assess impacts of water use practices on this endangered run. However, there are still critical gaps in our understanding of fish movement and behavior within the Delta, and by not maximally leveraging existing data sources to build the most accurate juvenile salmon migration model possible, the LCM and other key management tools will be impacted. In addition, there are multiple direct applications of the proposed next generation ePTM as a decision support tool for water management within the Delta, such as operation of the Delta Cross Channel gate and the installation and removal of temporary salmon passage barriers.

Goals and Objectives

Our overall objective is to develop a next-generation version of the NMFS' ePTM that models juvenile salmon migration in a way that will accomplish the goals of speed, robustness and accessibility highlighted above. We will move well beyond existing computational models of salmon movement through the Delta by incorporating new behavioral data using novel analytical methods, and systematically building-in and evaluating model speed and robustness to diverse and changing environmental conditions. The development of this model will involve three specific tasks:

Task 1. Design navigation and predation modules of the next-generation ePTM based on new analysis of high-resolution 2D acoustic telemetry data. This will maximally leverage existing data sources to learn as much as possible about interactions between juvenile salmon and predators, and how salmon modify migration behavior in response to flows and other environmental variables.

Task 2. Reduce uncertainty in physical drivers of migration dynamics by improving the hydrodynamics module in the next-generation ePTM. We will accomplish this while retaining model simplicity by developing a hybrid 1D-3D model in which a 1D hydrodynamic driver is parameterized

using 3D modeling for critical geographic locations including key channel junctions, and flooded islands and wetlands.

Task 3. Evaluate and ensure the model's ability to robustly predict salmon fates across a wide range of environmental conditions while maximizing model simplicity.

Site Description

This study does not involve additional field research but instead uses existing data sources. These are described in "Approach and Statement of Work" below. Important geographic locations in the Delta that will be included in our model development are described in Figure 1.

Background and Conceptual Models

This proposal describes our plan to use what we have learned from the current generation ePTM to engineer a next-generation computational model that will provide both a research tool available to scientists and a decision support tool that managers can use to forecast the impacts of management actions and future climate scenarios on salmon outmigration through the Delta. A central theme of the work proposed here is to reduce model complexity where possible to make the next-generation ePTM easy to use and robust to changing hydrology, Delta habitat restoration, and changing water management practices. To this end, the proposed work focuses on integrating new data and building a next-generation hydrodynamic module, both of which will improve our ability to understand and forecast how fish will move through the system, and how human activity (e.g., water exports) and environmental variables will affect survival of migrating salmon to the ocean. We will build the next-generation ePTM following the tasks outlined above. Figure 2 illustrates the sub-components of these tasks and how they will be integrated to generate model predictions. In the first task, we will develop the navigation and predation modules of the next-generation ePTM in a data-driven fashion using information gleaned from analysis of fine-scale 2D acoustic telemetry datasets (Figure 2: swimming and predation). In the second task, we will develop a hybrid 1D-3D hydrodynamic model that integrates accurate 3D flow models of key junctions and open water bodies using the Semi-implicit Cross-scale Hydroscience Integrated System Model (SCHISM) with the existing DSM2 model of the Delta (Figure 2: Hydro and SCHISM modeling components). Finally, the improved hydrodynamics, fish behavior, and predation will be integrated into the ePTM, allowing us to simulate thousands of juvenile salmon migrating through the Delta system across a range of environmental conditions. In task three, we will systematically cross-validate model predictions to estimate model robustness.

Climate Change Adaptation

One of the primary goals of the proposed work is to develop a computational model that will allow for the prediction of the impacts of hydrologic scenarios on salmon migration through the Delta system. In the "Approach and Statement of Work" below, we describe how we will accomplish this in a way that will ensure that model predictions are robust to a wide range of environmental conditions. Although evaluating impacts of future climate scenarios is not a central goal of the proposed work, the modeling framework we will build is designed to be combined with environmental variables to evaluate the impact of climate on salmon migration success. This framework can be easily combined with other forecasting tools and used in the context of long-term management of salmon populations.

Community Support and Collaboration

The work we are proposing will be accomplished through a collaboration between scientists at UCSC and NMFS. Additionally, the next-generation ePTM will support the inter-agency LCM program described above by providing key inputs into fall, spring, and winter run LCMs. Finally, this work will take advantage of data produced through a collaborative acoustic telemetry project (NMFS and USGS) that is currently under review for funding through the Interagency Ecology Program.

Approach and Statement of Work

Task 1 ***Design navigation and predation modules of the next-generation ePTM based on new analysis of high-resolution 2D acoustic telemetry data.***

Two important, but poorly understood phenomena that are crucial parts of salmon migration through the Delta are navigation and salmon-predator interactions. Existing data from high-resolution acoustic tagging studies conducted in the Delta have the potential to provide rich information about both navigation and predation that could be used to improve model predictions. For example, the current generation ePTM assumes salmon enter channels at key junctions in the Delta with probabilities proportional to the flow entering each channel. More detailed analyses of behavioral data suggest that this is not likely the case (Perry et al. 2014). In principle, high-resolution 2D datasets provide a way to directly observe interactions between juvenile salmon and flow at these junctions and could be used to build a data-driven model of salmon routing in the Delta. However, limitations of existing data analysis methods have made it difficult to use these data to maximize what can be learned about how outmigrating juvenile salmon navigate the system, and what governs the rate and outcome of interactions between juvenile salmon and their predators. We will develop a suite of new analytical techniques and apply them to existing acoustic telemetry datasets to (i) determine how juvenile salmon outmigration behavior (e.g., holding and swimming) depends on physical variables such as freshwater flow, tides, time of day, and water temperature and salinity, and (ii) quantitatively characterize interactions between salmon and their predators. ***We will use these methods to design the navigation and predation modules (Figure 2) in the next-generation ePTM to reflect observed salmon navigation behavior and interactions between salmon and their predators.***

Data sources

Acoustic telemetry data from dense 2D arrays: Between 2009 and 2012, DWR studied salmon movement through the junction at the Head of Old River (HOR) on the San Joaquin River, with the goal of evaluating the efficacy of barriers in rerouting migrating juvenile salmon. The study design involved a 2D array of hydrophones at the junction between the San Joaquin River and Old River. The hydrophone array was designed to allow triangulation of 2D positions of acoustically tagged fish as they moved through the junction. This dataset contains detections of hundreds of juvenile salmon and their predators, often with a resolution of tens of seconds or less between detections (Figure 3). A similar dataset is available from a DWR study the junction between the Sacramento River and Georgiana Slough in 2011, 2012 and 2014. DWR has provided us with data from both the HOR studies and the Georgiana Slough Studies. Finally, the Pacific Northwest National Labs collaborated with NMFS to construct a hydrophone array on the Sacramento River at Freeport Diversion Dam in 2013, which produced 2D tracks for tagged Chinook smolts and their predators. We will use data from over one thousand tracked juvenile salmon collected at these three locations to extract fine-scale swimming behavior information. In addition to the 2D data, we will model local 3D flows using SCHISM (see detailed model description in Task 2 below) in these locations driven by the 2m and 10m Digital Elevation Model (DEM) bathymetry from DWR (Wang et al., 2011), and Acoustic Doppler Current Profiler (ADCP) velocity measurements made by the USGS in 2012.

Methodology

Measuring fish swimming behavior and hydrodynamic forcing by combining 3D hydrodynamics with dense hydrophone array data: We will develop a method for inferring fish swimming behavior from high-resolution tracks collected at HOR, Georgiana Slough, and Freeport. By analyzing the fine-scale juvenile movements and real-time navigational decisions juveniles make as they move through junctions, in conjunction with local hydrodynamics, we will refine understanding of how the physical environment influences the ultimate fate of outmigrating juvenile salmon. With the 2D acoustic data and the 3D flow models, we will extend a method known as "force matching" (Katz et al., 2011) to decompose observed movements of juveniles into two components: physical forces exerted on the juveniles by the flow, and volitional swimming behavior. In this approach, the fish's observed movements are assumed to be driven by a total effective "force," which causes the fish to accelerate, decelerate, and change direction (Hein et al., 2015). This total effective force can be decomposed into an environmental component, which represents the physical force exerted on the fish by the flow and environmental variables, and a behavioral component, which represents the fish's active swimming behavior. This force-based approach has been used successfully in the past to model fish movements in response to complex, high-dimensional stimuli (e.g., Katz et al., 2011). Because the modeled hydrodynamic forces and juvenile salmon trajectories are known, the "behavioral force" can be determined. After applying a machine learning filter to remove tracks of juvenile salmon that appear to have been consumed by predators (see below), we will calculate the effect of physical forcing on juvenile movement and infer the effective behavioral forces that characterize juvenile salmon swimming. We will use these measured quantities to build the navigation module in the next-generation ePTM (Figure 2). In particular, we will parameterize diel swimming behavior, responses to tidal forcing, responses to changes in salinity and turbidity, up-stream swimming, and responses to local flow structures using the behavioral rules measured directly from these detailed tracks of freely-swimming juvenile salmon. ***It is important to emphasize that this is a major departure from past computational models of fish movement (including the current generation ePTM), which typically parameterize fish navigation behaviors using models and hypotheses from the literature that have not been rigorously tested in the system being modeled.***

Infer predation rates and identify predation hotspots using tracks of freely swimming juvenile salmon and salmon predators: To determine when and where predation events occur, we will combine the data described in the previous section with detections from tagged predators at HOR, Georgiana Slough, and Freeport 2D hydrophone arrays. Identifying attacks and predation events from 2D tracking data is a challenging task: given a time series of detections from a tag that was originally implanted into a juvenile salmon, one must determine (i) if the tag transitioned from a movement pattern characteristic of a juvenile salmon to a movement pattern characteristic of a salmon predator, and (ii) if the tag did transition, when and where the predation event happened. This is known as a change point detection problem in time series analysis. In addition to detecting acoustically tagged juvenile salmon, all three 2D hydrophone arrays registered detections of acoustically tagged predators that were tagged and released as part of a number of predator studies conducted in the Delta. We propose to use deep learning (a machine learning technique based on artificial neural networks) of observed predator and salmon movement patterns to distinguish predator tracks from tracks of juvenile salmon (Krizhervsky et al., 2012; Wang et al., 2015; Goodfellow et al., 2016). In particular, we will use trajectories of tagged predators to develop a classifier that can determine whether a tagged juvenile salmon has been eaten by a predator or not. We will apply Recursive Neural Nets (RNNs) (Grossberg, 1988; Goodfellow et al., 2016) to map the trajectories of the juveniles and predators as functions of time. Then the time-series data obtained from RNNs will be used as input for unsupervised deep learning algorithms such as Self Organizing Maps (Kohonen, 2001), and manifold learning (Goldberg et al., 2008; Coifman and Lafon, 2006), which can classify sequences within a time-series as representing juvenile or predator movements. Finally, we will use change point detection analysis to determine when and where in a given salmon trajectory, predation occurred. This will allow us to determine whether there are predation hotspots within HOR, Georgiana Slough, and Freeport arrays, and how predation rate depends on time in the diel cycle, turbidity, salinity, tidal phase and fine-scale hydrologic features. ***We will use this information to build a new predation module that incorporates spatial and temporal variation in predation rates across the Delta, in a way that links predation to its underlying causes.***

Task 2. ***Reduce uncertainty in physical drivers of migration dynamics by improving the hydrodynamics module in the next-generation ePTM.***

We will re-design the hydrodynamics module in the next-generation ePTM, incorporating more sophisticated hydrodynamics to capture key processes that influence salmon migration and survival that cannot be captured with the current generation ePTM (Figure 2). Currently, several hydrodynamic models of varying complexity exist for the Delta. The most popular decision support tools are DSM2 (Anderson and Mierzwa, 2002) and the Resource Management Associates 2D Bay-Delta Model (Sankaranarayanan and McCay, 2003). These models solve the shallow-water equations and model the decoupled water quality parameters such as temperature, salinity and turbidity. More sophisticated models include 3D models which solve fully coupled hydrodynamics and water quality such as UnTRIM-3D (MacWilliams et al., 2007) and SUNTANS (Chua and Fringer, 2011), and de-coupled models such as DELFT3D (Van der Wegen, 2011). A new open-source, extensively documented and well-supported finite element based model of the Delta, Bay-Delta SCHISM (Zhang et al., 2016), is an attractive alternative. We have the technical expertise and active collaborations with the DWR to optimally utilize this model as part of the next-generation ePTM.

The Bay-Delta system is typically modeled either as a fully 1D, 2D or 3D system. In this proposal, the novel application of SCHISM coupled with DSM2 will result in a hybrid 1D-3D model, allowing us to benefit from the accuracy of a sophisticated model at critical locations while retaining the speed and versatility of the 1D model at the system scale. While flows in the Delta will be represented by DSM2-Hydro, fine-scale processes in key river junctions and open-water bodies will be represented using SCHISM (Figure 2). Improving representation of particle trajectories at channel junctions and within open-water bodies in the Delta has been shown to improve predictions of the movements and fates of Delta Smelt, a species with less complex swimming behavior than that of salmon (Figure 4) (Gross et al., 2010; Sridharan et al., in rev.). Improving the underlying hydrodynamic model would greatly enhance our ability to accurately model salmon movement as well (MacWilliams et al., 2016). In addition, channel bends have been shown to influence migration route selection at key junctions such as HOR and Sutter and Steamboat Sloughs (Perry et al., 2014). Capturing the distribution of water column velocities in these bends near junctions will be crucial to inform routing predictions, but cannot be done within the current ePTM framework. ***We will improve the underlying hydrodynamics in the next-generation ePTM, using SCHISM to capture more detailed flows in two types of locations that are not represented well in the current generation ePTM: (i) channel junctions, which influence routing, and (ii) open water bodies (e.g., flooded islands in the interior Delta), where juvenile salmon may spend substantial amounts of time during outmigration.***

Data sources

The key junctions involved in transport and mixing within the Delta are: the Sacramento River and the Sutter and Steamboat Sloughs; the mainstem Sacramento River and Georgiana Slough and the Delta Cross Channel; the Three Mile Slough and Antioch complex; Mossdale; HOR; Georgiana Slough and the mainstem San Joaquin River; and the San Joaquin and Old and Middle Rivers (Figure 1) (Cavallo et al., 2011; Perry et al., 2014; Sridharan, 2015). Perry et al. (2014) collected data on the cross-sectional distributions of juveniles migrating through these junctions during different flow conditions, which will be useful in parameterizing routing. Further, open water bodies such as the flooded islands including Frank's Tract and Mildred Island and Clifton Court Forebay are important in biotic and abiotic exchange within the Delta (Monsen et al., 2007). We will utilize the 10m and 2m DEMs developed by DWR to model all of the aforementioned locations using SCHISM.

Methodology

We will accomplish 1D modeling using DSM2. However, we propose to parameterize the movement rules of simulated salmon through key junctions in the Delta where critical migration route selection choices have to be made (Perry et al., 2010; Cavallo et al., 2015) using SCHISM. Owing to the complexities of the 3D flow mechanisms within open water bodies, we will also use SCHISM to parameterize residence times and mixing mechanisms in these regions.

The current ePTM only represents channel junctions with a flow-weighted routing model. Open water bodies such as flooded islands, wetlands and the Clifton Court Forebay are not represented, and river bends are not parameterized accurately. While the junction model in Sridharan et al. (in rev.) allowed particles to move into downstream channels depending on which streamlines they were in, real junctions in the Delta often experience more complex hydrodynamics which includes mixing across streamlines due to turbulence, dead zones, recirculation zones, flow separation and secondary currents, and tide phase-dependent reordering of streamlines (Gleichauf et al., 2014). To ensure that we can accurately model how fish interact with flows in these regions, we will incorporate a junction model modified from Sridharan et al (in rev.). In this model, we will identify the location of the bifurcating streamline – the streamline that partitions the flow into the downstream channels (sometimes referred to as "critical streakline"; Perry et al., 2014) – from SCHISM at each time step, and allow simulated juveniles to remain on their side of this streamline with a probability determined from our analysis of 2D junctions described in Task 1. Flooded islands and open-water bodies were represented as instantaneously well-mixed reactors in Sridharan et al. (in rev.). We will extend this representation in the ePTM to include the effects of other open-water processes with a set of parameters that include a dead zone volume and short circuit pathways, by fitting classic models of reservoir dynamics (Danckwerts, 1953) to the modeled residence times in these water bodies obtained from passive particle tracking within SCHISM.

Task 3. ***Evaluate and ensure model's ability to robustly capture key physical and biological drivers while maximizing model simplicity.***

We propose to systematically measure model robustness, and to provide model predictions and measures of model performance in a format that will make the next-generation ePTM more accessible and easier to use. We will do this by (i) evaluating model robustness using a comprehensive cross-validation framework that uses out-of-sample predictions of travel times, routing, and survival from acoustic telemetry and coded wire tagging data, and (ii) making modeling results available in a form that is appropriate for use as a decision support tool, including providing estimates of prediction-specific model uncertainty measured through cross-validation.

Data sources

Since 2011, NMFS has performed acoustic tagging studies of Chinook salmon released into the Sacramento River and its tributaries. Tagged salmon are detected at hydrophones throughout a large-scale array that extends from the upper Sacramento River to the Golden Gate Bridge. Detections at each hydrophone array provide a way of estimating salmon survival and routing (e.g., Perry et al., 2015). In addition to acoustic telemetry data, the Regional Mark Processing Center hosts databases of coded wire tagging programs undertaken by DWR and CDFW since the 1970s. These data contain coded wire tagged hatchery and wild Chinook salmon releases within the Delta, Fall Midwater and Spring Kodiak surveys, as well as rotary screw trap and beach seine data on destructively sampled juvenile salmon. Using a catch per unit effort conversion, the juveniles that are collected and scaled up to population level numbers that would have been detected at the monitoring stations. Data from coded wire tagging studies could provide an additional source of information for testing the predictions of the next-generation ePTM using a wider range of fork-lengths (~50-200mm length). However, using coded wire-tagging data presents some unique analytical challenges. Perhaps the most important of these is that it is not possible to use coded wire tags to record individual juvenile migration histories, and records are seldom available at all survey locations due to changing sampling locations between years. To deal with these challenges, we propose to implement a Baum-Welch Hidden Markov Model (HMM) optimization algorithm (Welch, 2003), which will allow us to estimate the most likely migration routes of recovered coded wire tagged salmon, along with survival statistics along these routes. This will allow us to use the coded wire tagging data to test model predictions using an additional data source that has wider spatial coverage and over several decades compared to the much more recent acoustic telemetry arrays. ***This will not only provide another***

data source we can use to evaluate model robustness, it will also greatly extend the utility of coded wire tagging in salmon ecology science.

Methodology

Comprehensive cross-validation of model predictions: ***To ensure that survival and movement predictions of the next-generation ePTM are robust to a wide range of hydrologic conditions, we will perform a systematic cross-validation of model predictions, modifying the details of navigation, predation, and hydrodynamic modules to achieve robust predictions on out-of-sample data.*** To do this, we will focus on key statistics that are of interest to Delta scientists and managers: (i) yearly travel times through the Delta (Sacramento to Chipps Island/Benicia/Golden Gate), (ii) yearly survival through the Delta, (iii) yearly reach-specific travel times, (iv) yearly reach-specific survival, and (v) all of the above (i-iv) on a monthly basis. We will use data from the NMFS acoustic tagging program to calculate these statistics using Cormack-Jolly-Seber survival and travel time models (e.g., Perry et al., 2010; Buchanan et al., 2013), as well as using output from the coded wire tagging analyses described above. We will then systematically investigate the ability of the ePTM to reproduce these statistics (see Figure 5 for an example) by calibrating and testing the model in three different ways. First, we will calibrate the model using data selected randomly from all months in the acoustic detection dataset. We will then test the model on months that were not included in the model calibration dataset. Second, to evaluate how robust the model is to variation among water year types (e.g., wet versus dry), we will calibrate the model using years belonging to one water year type (evaluated by discharge levels in the Sacramento and San Joaquin Rivers) and test model predictions against the other water year types. Finally, to evaluate how robust model predictions are to seasonal variation in salmon movement and survival, we will calibrate the model using only data from early season migrants and test model predictions against data from salmon that outmigrated later in the season. We will then reverse this protocol, calibrating using late season migrants and predicting early season migrants. Taken together, these cross-validation steps will allow us to provide estimates of model robustness for different kinds of predictions that may be desired when the model is used as a decision support tool.

Figures

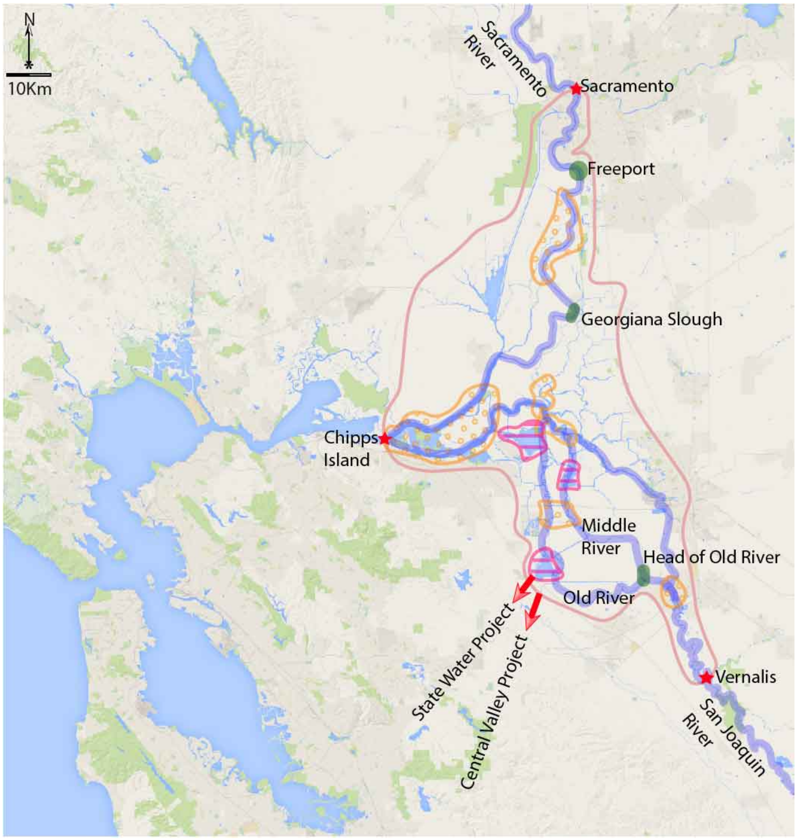

Figure 1. **Major Delta waterways and key hydrologic features to be included in the next-generation ePTM.** Red boundary indicates the region of the Delta that is the domain of the ePTM. Green shaded regions on the Sacramento and San Joaquin Rivers are locations of 2D acoustic telemetry studies (Head of Old River, Georgiana Slough, and Freeport) where 3D hydrodynamic modeling will be performed with SCHISM (Zhang et al., 2016). Yellow patches and pink hatched regions respectively show important channel junctions and open water bodies that will also be modeled with SCHISM to more accurately capture complex hydrodynamics.

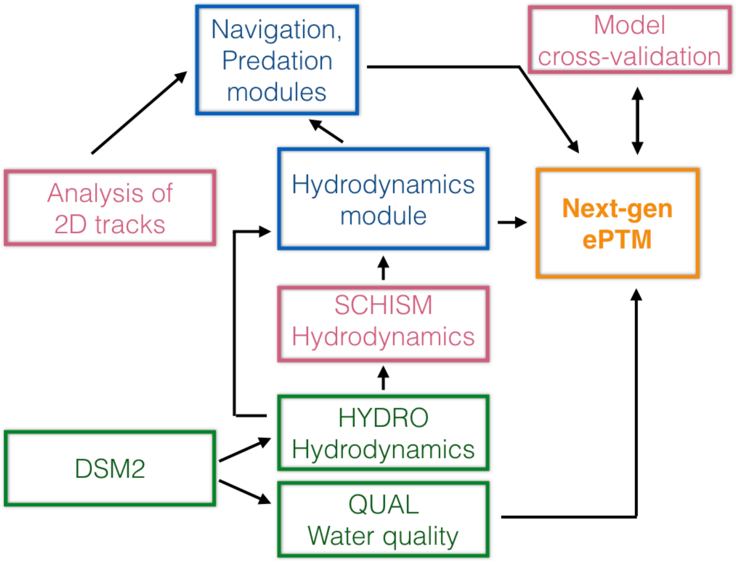

Figure 2. Workflow of proposed next-generation ePTM modeling framework. Driving physical models (green), new analyses and model components (red), ePTM modules (blue).

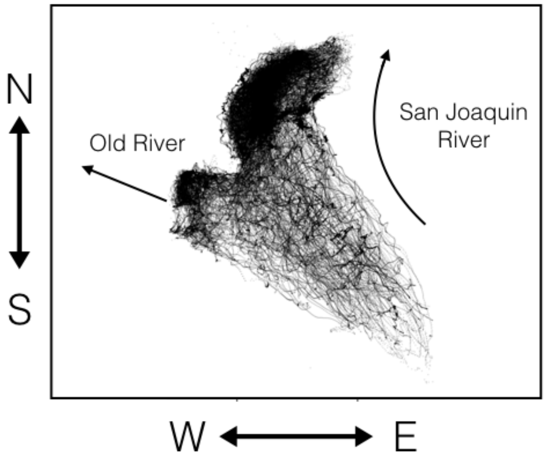

Figure 3. Two-dimensional tracks of acoustically tagged Chinook salmon smolts passing through the junction at the Head of Old River and the San Joaquin River. Each black dot is a detection of an acoustic tag implanted in a smolt. Tracks collected from 232 fish are shown (over 400,000 individual detections). By using a force matching method (Katz et al., 2011) to analyze tracks alongside ADCP data and three-dimensional hydrodynamic modeling, we will build ***navigation and predation modules*** in a data-driven way. Data were provided by California Department of Water Resources.

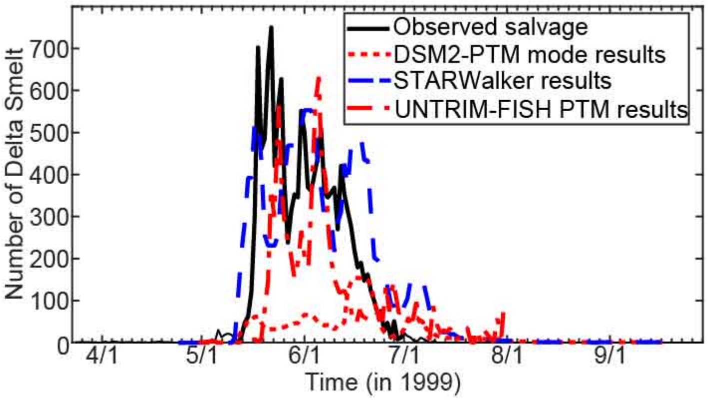

Figure 4. Effect of improved hydrodynamics on predicting take of Delta Smelt at the Central Valley Project fish screens: DSM2-PTM (red dotted line) is a 1D model does not include hydrodynamic junction routing, open-water, river bend, and exchange flow dynamics. This model performs poorly (contrast model predictions in red dotted line to observed salvage in solid black line). STARWalker is a 1D model that includes simplified representation of hydrodynamic junction routing and open-water processes and performs well (blue dashed line more closely matches solid black). UNTRIM-FISH PTM is a full 3D hydrodynamic model that out-performs both 1D models, suggesting that features of the 3D flow improve model predictive power.

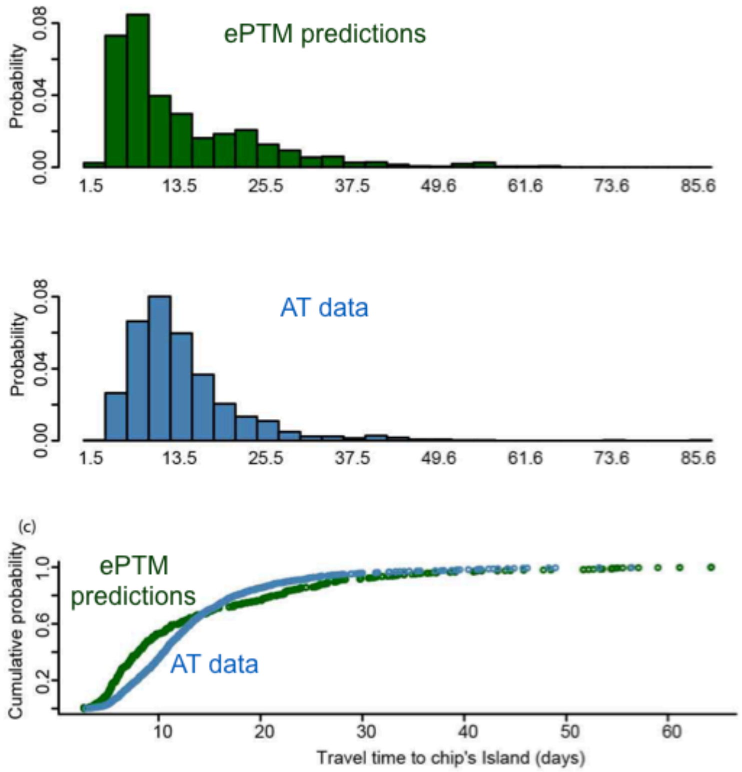

Figure 5. Schematic showing a hypothetical comparison between ePTM predictions (green) for travel time distribution and travel time data from acoustic tagging (blue). Cumulative distribution functions provide a way of summarizing arrival time data. These and other model predictions will be compared to out-of-sample data to provide a measure of model robustness.

Schedule & Deliverables

Task No.	Task Title	Deliverables and Key Project Milestones	Estimated Completion Dates
1	Project Management and Administration	1.1 Quarterly Progress Reports	1.1 Due within thirty (30) days following each quarterly month for the duration of the agreement.
		1.2 Quarterly Invoices	1.2 Due within thirty (30) days following each month (or) quarterly month (or) semi-annual.
		1.3 Executed Subcontracts	1.3 Due with Quarterly Progress Reports
		1.4 Project Data	1.4 All data due with Final Report
		1.5 Draft Final Report	1.5 Due sixty (60) days prior to end of grant term
		1.6 Final Report	1.6 Due at least thirty (30) days prior to end of grant term
		1.7 Project Close-Out Report	1.7 May 1, 2021
		1.8 Final Invoice	1.8 May 1, 2021
2	Peer review	2.1 present data analysis at scientific meetings	2.1 Dec 31, 2019
		2.2 present model predictions and modeling results at scientific meetings	2.2 May 1, 2021
		2.3 prepare and submit a manuscript detailing analysis of 2D datasets	2.3 Jun 1, 2020
		2.4 prepare and submit a manuscript detailing model structure and results	2.4 May 1, 2021
3	Data sharing and access	3.1 Develop online platform for reporting and visualizing model predictions	3.1 May 1, 2021
		3.2 Final version of ePTM code posted on public Github repository	3.1 May 1, 2021

Feasibility

The collaborative team we have assembled is well prepared to execute the work proposed here. Dr. Peter Raimondi (UCSC) has extensive experience studying ecological interactions in marine and aquatic systems, with a particular emphasis on interactions between ecology and hydrodynamics. Dr. Steven Lindley and Dr. Eric Danner (NOAA, NMFS) helped develop the current generation ePTM and have significant experience modeling interactions between salmonids, environmental variables, and predators. Dr. Andrew Hein (NOAA, NMFS) has developed new techniques to model sensory biophysics and movement behavior of wild animals, alongside statistical methods to learn behavioral rules from data. In addition to having the technical expertise to carry out the proposed work, the Institute of Marine Sciences (PI Raimondi, director) at UCSC and the NMFS Southwest Fisheries Science Center (Co-I Lindley, director) have a history of successful collaboration on projects that are directly relevant to public policy in California. UCSC and NMFS jointly developed the Central Valley Chinook Winter Run Life Cycle Model (WRLCM), which was funded by USBR, and has been used extensively to evaluate how federal and state water project management actions affect Central Valley Chinook salmon populations. Most recently, this model was used in the Endangered Species Act Section 7(a)(2) Biological Opinion for the California WaterFix Project in Central Valley, California. Importantly, UCSC and NMFS have worked together to established strong relationships with stakeholders within the Central Valley, including state and federal water contractors, fisheries managers, and local water districts through a series of workshops and presentations we have given on the WRLCM, the current generation ePTM, and associated models.

Justification of personnel supported by Prop 1 Funding: In addition to the team of researchers who will serve as Principal and the co-investigators mentioned above, we are requesting funding to support additional personnel who will be crucial to the success of the proposed work. We will support Co-investigator, Dr. Vamsi Sridharan (UCSC) as a hydrodynamics project scientist through this funding. Dr. Sridharan is a hydrodynamics expert who was one of the primary developers of the previous version of the ePTM and has also developed detailed models of channel junctions in the Delta. Dr. Sridharan's involvement in this project will allow us to begin developing the hydrologic components of the next-generation ePTM immediately at the start of the funding period. We will support Dr. Natnael Hamda (UCSC) as a project scientist as part of this proposal. Dr. Hamda (UCSC) is a machine learning expert who has been developing tools for automatic behavior classification and behavioral change point detection. The methods that Dr. Hamda is pioneering will be crucial in the new data analyses we propose in Tasks 1 and 3. In addition to these two project scientists, we will hire a biophysical modeler and a fluid dynamicist as postdoctoral scholars. These scholars will add additional expertise to our team. For the fluid dynamics postdoctoral scholar, we will seek a scientist with expertise in computational fluid dynamics modeling who can help to provide the hydrodynamic information that will be required for the "force matching" analysis in Task 1, and to help construct the 1D-3D hydrodynamics module proposed in Task 2. For the biophysical modeling postdoctoral scholar, we will recruit a scientist who can combine the hydrodynamic output produced by the fluid dynamics postdoc with analysis of the 2D telemetry data to engineer the navigation module described in Task 1. This scientist will also perform the comprehensive cross-validation proposed in Task 3. Additionally, we are requesting funding for a programming specialist, who will carry out three duties that are central to all three Tasks in the proposed work: (1) translate research-phase model code into high-performance code (e.g., via conversion to c++ or the like) that will reduce run times making computation tractable, (2) execute next-generation ePTM model runs on a dedicated ePTM computational server and manage this server, and (3) translate raw model output and model code into a form that can be easily accessed and used by managers, scientists, and other stakeholders (see "Data Management and Access" below). Finally, we are requesting part-time support for Anne Criss (UCSC), deputy director of the UCSC - NOAA Fisheries collaborative program. In addition to administering the collaborative program within the UCSC Institute of Marine Sciences, she has extensive experience as the project manager for the Central Valley Chinook Lifecycle Model (CVC-LCM). In this role she helped build and sustain a multiagency and multi-partner collaborative research project that met deliverables as well as managed external relations with other agency collaborators and facilitated outreach to stakeholders and other interested parties. She brings over 20 years experience managing successful high-level science and policy collaborative programs and managing education and outreach programs.

Data Management and Access

Although the work proposed here does not involve collecting additional field data, one of our primary goals is to provide model output that can be used to support management decisions and future scientific studies. To this end, we will use the model output generated through the cross-validation procedure described above to build a library of model predictions over a wide range of environmental conditions. This will include estimates of model robustness for different seasons and hydrologic conditions developed through our cross-validation procedure. To make these model outputs most useful, we will provide predicted juvenile salmon travel times and outmigration survival under different conditions in a format that is easy to query. Additionally, we will develop an interface for next-generation ePTM simulated juvenile salmon tracks and hydrodynamic information within Google Earth. We will make both statistics and visualizations available to stakeholders through an online platform, for example California Environmental Data Exchange Network (CEDEN), bay-delta live (BDL), Calfish.org, or NOAA's ERDDAP data server.

A second research product is the next-generation ePTM source code itself. This code will be open source and distributed by means of the GitHub open source version control system and repository. The license will be a common open source license (Berkeley/MIT/Apache/Creative Commons). During the first 2.5 years of the project the source code will be marked as pre-alpha level of development and inappropriate for use. In the third year of the project, versions of the code suitable for use by scientists, managers, and other stakeholders will be versioned and tagged within the version control system.

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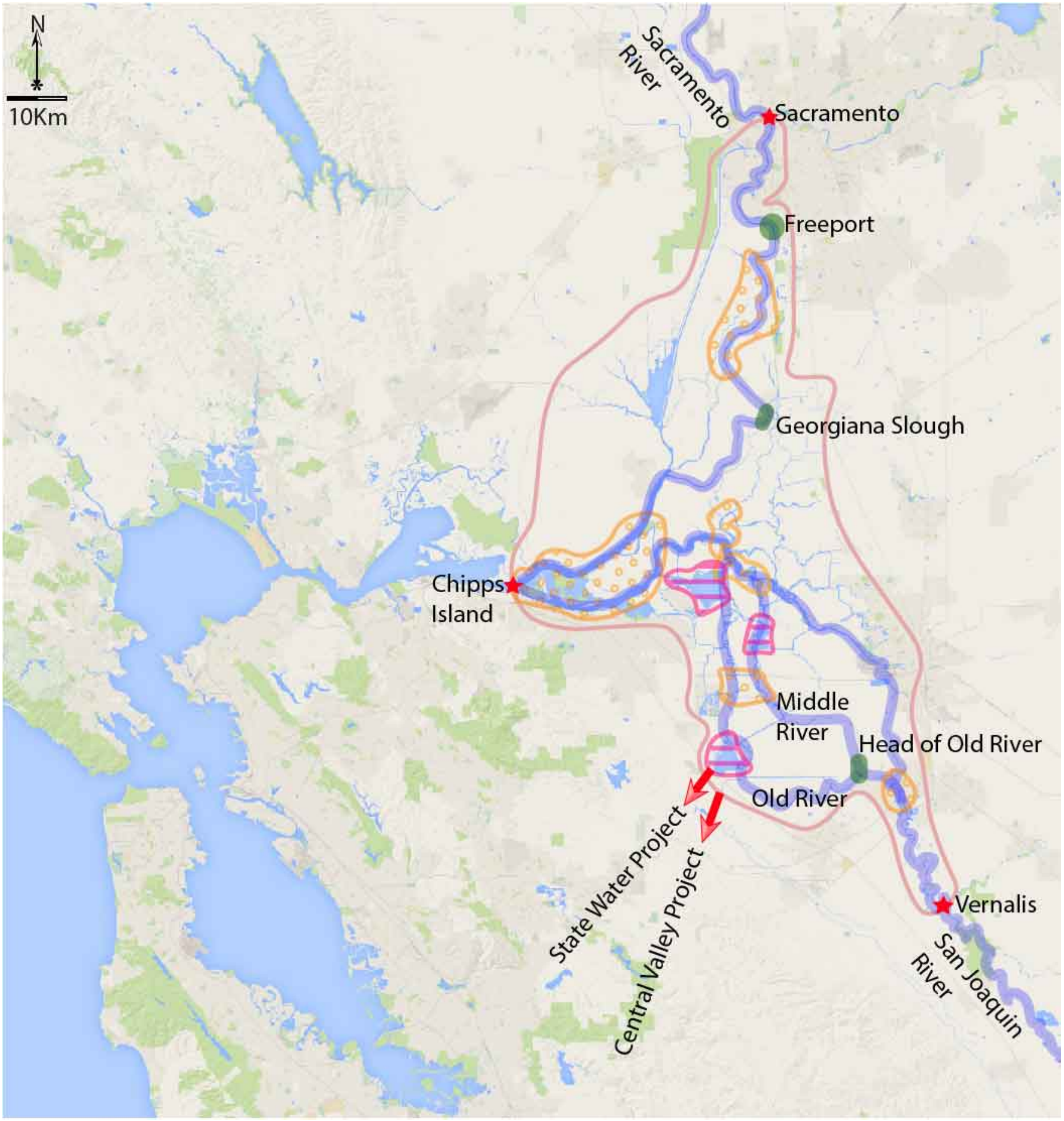
Project Conservation Targets

Project Conservation Targets: Ecosystem Categories	CDFW Prop 1 Project Acreage / length	Overall Project Acreage /length (Note: include here additional areas for which you are not requesting CDFW Prop 1 funding)
Total Project Acreage	**0**	**0**
Total number of non-contiguous sites	0	0
Fluvial / Riparian Ecosystems		
Riparian and Riparian Wetlands: Riparian Forest, Riparian scrub/shrub, Willow thicket, shaded riverine aquatic, open water, and floodplain (*acres*)	0	0
Stream or River (*length in miles*)	0	0
Lake or Pond		
Open water, emergent wetland (*acres*)	0	0
Non-Tidal Wetland Ecosystems		
Perennial Non-tidal Wetland (*acres*)	0	0
Seasonal Wetland: vernal pools, alkali wetlands, wet meadows, mountain meadows (*acres*)	0	0
Managed Wetland (*acres*)	0	0
Tidal Wetland Ecosystems		
Tidal Emergent Wetland, Tidal Perennial Aquatic, tidal marsh, tidal channels, mudflats, shallow intertidal or subtidal, flooded island, open water, Channel margin habitat, and Tidal/upland transition zone (*acres*)	0	0
Upland Ecosystems		
Forest or woodland (*acres*)	0	0
Grassland (*acres*)	0	0
Others ecosystems (*acres*)		
Wildlife friendly agriculture (*acres*)	0	0
☒ Not applicable. If not applicable, check box and provide justification below: This is a wholly modelling project. We therefore do not propose to perform any physical conservation tasks within the ecosystem.		



Overall study region, major Delta waterways, and key hydrologic features to be included in the proposed modeling work. Red boundary indicates the region of the Delta that is the modeling domain. Green shaded regions on the Sacramento and San Joaquin Rivers are locations of 2D acoustic telemetry studies (Head of Old River, Georgiana Slough, and Freeport) where 3D hydrodynamic modeling will be performed. Yellow patches and pink hatched regions respectively show important channel junctions and open water bodies that will also be in 3D to more accurately capture complex hydrodynamics. See Project Narrative for a detailed description of regions and modeling.