The Effect of Three Agricultural Barriers on Migrating Anadromous Salmonid Juveniles in the Southern Portion of the Sacramento-San Joaquin River Delta

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The California Department of Water Resources installs temporary barriers in the southern portion of the Delta to maintain water levels for agricultural diversions (South Delta Agricultural Barriers: SDABs). The barriers could impede the outmigration of juvenile salmonids. In addition, the SDABs may provide refugia for ambush predators such as largemouth bass (*Micropterus salmoides*). During 2010 and 2011 acoustic telemetry and DIDSON imaging were employed to evaluate routing, survival, and predator abundance at the SDABs before, during and after barrier installation. Preliminary results showed that of those Chinook juveniles that entered the Old River in 2011, 98% selected the Old River Route and 2% selected the Middle River route for their migration through the south Delta. In 2011, the joint probability of route entrainment and survival from the "ORS" hydrophone array to the hydrophone array immediately upstream of Clifton Court Forebay's Radial Gates (Array: RGU) was 0.229 before-construction and 0.437 after-construction of the Old River at Tracy barrier. The "ORS" hydrophone array was located 0.5 km downstream of the Middle River-Old River divergence. In both 2010 and 2011, DIDSON imaging showed an increase in predator density through time. For example, the Middle River barrier in 2011 showed that predator density increased from 0.73 to 3.27 predators/1000 cubic meters from the before to after-construction phases. At the Old River at Tracy barrier density increased from 0.87 to 2.61 predators/1000 cubic meters. The DIDSON results suggested that the construction of these agricultural barriers created in-stream structure that could provide velocity refugia and/or increased predation attack success. Alternatively, predatory fishes might accumulate in these areas due to blockage of migratory routes. Ecosystem sustainability may be affected by these barriers because they alter the local density of predators, cause changes in survival and could cause indirect effects to outmigrating Chinook and steelhead.

Keywords: Chinook salmon, migration, fish barriers, survival modeling, predator density
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Combining Models of the Critical Streak Line and the Cross-Sectional Distribution of Juvenile Salmon to Predict Fish Routing at River Junctions

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Agent based models of juvenile salmon in the Delta are implemented within hydrodynamic models that vary from simple one-dimensional models to three-dimensional models. In one-dimensional models, an individual's location is modeled in the streamwise dimension. However, the hydrodynamic model provides no information about water velocities in the cross-stream or vertical dimension, which would be expected to influence the cross-stream location of fish. Yet the distribution of juvenile salmon across a channel's cross-section upstream of a river junction affects the proportion of fish that will enter one channel or the other. For example, fish located on one side of the critical streakline — the location in the channel cross-section that divides parcels of water entering one channel or the other — are more likely enter one channel than the other. By analyzing two-dimensional tracks of acoustic tagged juvenile salmon, we investigate how river flow and tides affect the cross-sectional distribution of juvenile salmon approaching the junction of the Sacramento River and Georgiana Slough. We then predict the probability of fish entering Georgiana Slough as the proportion of fish located to the Georgiana Slough side of the critical streakline. We found that the cross-section distribution of juvenile salmon is concentrated near center channel with fewer fish located near the shoreline. The critical streakline was nearly always to the Georgiana Slough side of the mean fish location in the cross section, leading to a lower probability of fish entering Georgiana Slough relative to the proportion of water entering Georgiana Slough. Our analysis provides a mechanistic understanding of why migrating juvenile salmon do not distribute among channels in direct proportionality to flow. Our framework also provides a simplified model for predicting migration routing in one-dimensional hydrodynamic models that do not inform the cross-stream location of inividuals.

Keywords: Juvenile salmon, hydrodynamic models, critical streakline, Georgiana Slough
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Vector and Optomotor Analyses Indicate that Adult and Juvenile Green Sturgeon Exhibit Rheotaxis

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The spatial and temporal dynamics of water flows can profoundly affect the movements of fish. Moving in opposition to a current increases the energetic cost of transport since the animal has to exert an added effort to compensate for the opposing movements of the water mass in which it is swimming. Alternatively, currents may facilitate an individual's movement and decrease energetic costs. Given such costs and benefits, fish would be expected to have evolved means to both detect currents and use them when possible to move efficiently, thus minimizing energy output. Species thus have evolved a behavioral capability termed rheotaxis, the ability to detect flowing water, and in some cases derive the direction of flow and move either in its direction (positive) or its reverse direction (negative). Adult green sturgeon forage near the bottom in the presence of negligible currents in the San Francisco Estuary, but ascend in the water column and migrate during strong flows. They perceive the direction of flow, and move upriver or downriver actively swimming in the direction the current is flowing. Vector analysis was applied to tracking and current data to demonstrate that the direction of sturgeon swimming is non-random and statistically similar to the direction the current flow. Experiments were carried out on juvenile green sturgeon in a flow chamber with a moving background above and below the subject. While the presence of flow was an excellent predictor of proportion of time spent positively rheotactic, the presence of visual stimuli was not. We recommend that similar field and experimental studies be carried out on juvenile salmonids to improve the ability to predict their rates of movement through the estuary in variable flows.

Keywords: Sturgeon, flows, rheotaxis, vector analysis
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Are All Who Wander Lost? Evaluating the Mechanistic Potential for Altered Juvenile Salmonid Routing and Navigation in a Hydrodynamically Complex and Modified Tidal Estuary

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Anadromous fishes have evolved to migrate through complex environments to survive and exploit available resources (food and habitat). In simple river-estuary systems, juvenile salmonids migrating to the ocean may require no navigation beyond "going with the flow" until saline waters are reached. However, for juvenile salmonids migrating and rearing in tidal channels of an inverted estuary (such as the Delta) or traversing large open waters such as San Francisco Bay (or the Pacific Ocean), navigation by hydrodynamic, chemical, or geomagnetic cues are likely to be important. Field studies, modeling exercises, and management decisions related to juvenile passage through the Delta can benefit from a clear understanding of these navigation cues and their likely importance to salmonid rearing and migration. Utilizing model simulation results and other data sources, we will provide an overview of how migration cues suggested by the scientific literature functioned in a natural Delta and how they have changed in response to physical changes and water project operations in the modern Delta. From this foundation, we will propose hypotheses for how water project operations may influence juvenile salmonid navigation in the Delta, examine conclusions supported by available data, recommend areas where additional investigation is needed, and discuss implications for models of juvenile salmonid migration through the Delta.

Keywords: salmon, navigation, hydrodynamics, routing, rearing, behavior, evolution
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Using an Individual-Based Model to Explore How Routing, Predation, and Export Salvage Can Influence Through-Delta Survival for Juvenile Salmonids Originating from the San Joaquin River Basin

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Tagging studies show poor through-Delta survival for juvenile salmonids in the South Delta; management actions that can improve survival for these fish are urgently needed. Early coded-wire tag studies suggested survival was best for fish remaining in the mainstem San Joaquin River, but recent acoustic telemetry studies have not confirmed this earlier finding. We developed an individual-based model of juvenile salmonid passage through the Delta (called the IB-DPM) that incorporates routing based on hydrodynamics, salvage based on exports, and survival based on the XT model, which includes both distance traveled and exposure time. We used the IB-DPM to conduct simulation experiments that involved varying South Delta exports and varying the in-river survival of juvenile salmonids through key migratory routes in the South Delta. We found that when in-river survival rates are high, natural migration through the San Joaquin River provides the best outcomes. Conversely, we found that when in-river survival is low, migrating fish have higher through-Delta survival when entrained, salvaged, and trucked because salvage and trucking incurs less mortality than migrating in river through a (presumed) gauntlet of predators. We also found that overall survival to Chipps Island was higher for total exports (CVP + SWP) of 5,000 cfs than exports of 1,500 cfs over a large range of survival values because increasing exports increases the probability that fish will be salvaged, particularly at the CVP facility, which has much lower pre-screen mortality (0.15) than the SWP facility (0.85). Given poor habitat and high predation mortality in the South Delta, these findings suggest placement of the HORB blocks access to what can be the highest survival route for juvenile salmonids originating from the San Joaquin River basin.

Keywords: individual-based, agent-based, model, salmonid, exports, predation, XT model, gauntlet, exposure
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Hydrological Landmarks, Hydrodynamic Transport, Final Destinations and Travel Times of Commuter Salmon in an Urban Estuary

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The population of the endangered Chinook Salmon depends on physical stressors in their early-life habitat in California's Central Valley rivers; altered hydrology, water use, and predation as they transit through the Sacramento-San Joaquin Delta (henceforth, the Delta) and San Francisco Bay; and physical and biological processes in the coastal ocean. Of these, the Delta is where targeted management action can have the most impact. It is also the most contentious setting in terms of multipurpose water use, varied interest groups and legislation. A mechanistic understanding of fate is crucial to informing best management practices. In this study a novel particle tracking model with accurate hydrodynamics and well-reasoned behavior hypotheses has been developed and used to simulate the movement and fate of Chinook Salmon smolts as they swim towards the ocean via the Delta. The effects of (i) flow, (ii) water diversion and gate operations, (iii) predation, and (iv) hydraulics induced habitat quality manifest themselves on the ultimate fates of simulated smolt and the time to those fates. Spatial correlations with fate occur due to the combination of these four stressors, such as entrainment by water diversions occurring within the zone of influence of the pumping projects and increased escapement due to better habitat. Temporal dynamics of the fates are explained by the dominant travel pathways of Salmon through the Delta and the system scale hydrodynamic transport and mixing mechanisms along these pathways. A comparison of simulated smolt with simulated tracer particles decomposes the fish biology from the hydrodynamics, and also addresses three key questions: (i) what data gaps need addressing in fish monitoring and modeling, (ii) can environmental parameters be used as surrogates for fish surveys in data-poor situations, and (iii) can the hydrodynamics help us infer the fate of other species in the Delta and in other estuarine systems.

Keywords: Particle Tracking, Salmon, transport and mixing, Spatial and temporal fate
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ELAM (Evaluating Likely Animal Movement) at Georgiana Slough: Leveraging 52 Data Sets Over 17 Years toward Representing Fish in Any 2-D/3-D Hydrodynamic and Water Quality Model

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Understanding key fish behavior phenomena, such as the repeated observation that fish change their response to unchanging hydraulics, is key to reducing infrastructure design iterations. I analyzed fish movement behavior across 52 data sets representing 17 years of observation when hydraulics was concurrently measured. Results support observations dating back to the 1950s, and earlier, regarding the importance of water acceleration and inertial stimuli in fish movement. Findings also support the notion that fish, like other animals, evaluate the world in relative terms. I leverage this prior work to understand the potential for guiding fish in critical Bay-Delta areas such as Georgiana Slough. Water acceleration can "shape" individual trajectories of downstream migrating fish based on four behaviors: *B*{1} fish moves as a correlated random walk biased in the direction of water flow; *B*{2} fish swims toward faster water when water acceleration changes (increases) by sufficient magnitude; *B*{3} fish swims upstream when water acceleration changes (increases) by a larger magnitude; *B*{4} fish swims towards its acclimatized depth if pressure (depth) changes by sufficient magnitude. Key to evaluating likely animal movement (ELAM) in a 2-D or 3-D hydrodynamic and water quality model are (i) very few tunable parameters, (ii) realism in describing behavior switching, and (iii) computationally efficient optimization appropriate for the parameters of the behavior algorithm and the spatial statistics used. Computer simulations can then elucidate behavior combinations, *B*, that satisfactorily reproduce measured fish patterns. At Georgiana Slough, fish behavior is important. Particles, with no behavior, released at the same times and positions as real fish observations enter the slough in greater numbers than remain in the Sacramento River for two time periods we have evaluated so far: 1-7 January 2009 (53.6% Georgiana versus 46.4% Sacramento) and 16-22 January 2009 (55.8% Georgiana versus 43.5% Sacramento; 0.7% exit upstream).

Keywords: Individual based model, fish passage, ecohydraulics, fish navigation, fish movement
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Examining Hypothesized Delta Smelt Environmental Cues and Swimming Behaviors using an Agent-Based Model

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Understanding the cues and mechanisms of delta smelt migration smelt in the Sacramento-San Joaquin Delta would enable improved management of resources during the rapid seasonal changes in fish distribution. Migratory cues may be related to decreasing salinity and/or increasing turbidity as flows increase after winter rains. Catch history indicates these small fish move upstream rapidly, at 1.8-6.3 km/day, requiring some version of tidal surfing behavior to avoid unrealistic energy expenditure. We developed several simple behaviors including swimming along depth, salinity or turbidity gradients, rheotaxis, and lateral or cross-stream taxis for use in agent-based modeling frameworks. Behaviors were triggered by absolutes or gradients of water quality, current speed, depth, distance to shore, and flood or ebb tidal status. Behaviors and associated triggers were combined into simple behaviors sets using delta-smelt swimming speeds, with the goal of examining the efficacy of turbidity seeking, lateral tidal migration strategies, and rheotaxis both independently and in combination with other likely behaviors. These behavior sets were applied to particle tracking routines using both depth-averaged (RMA2) and 3-dimensional (UnTRIM) calibrated hydrodynamic models that include sediment-transport-derived turbidity and salinity. Results showed that tidal migration that involved swimming along depth gradients (i.e. swim shallower during ebb) retained particles at higher flows compared to tidal migration with respect to current speed (i.e. swim to lower velocity water during ebb). In general, following turbidity gradients results in lower particle retention and less upstream movement than depth or speed based cues. During high flows, simulated delta smelt have difficulty moving upstream in the Sacramento. Currently, the hydrodynamic models do not resolve velocity very near to the shore, yet migrating fish may take advantage of these low velocity refugia during strong ebb flows. Higher resolution modeling of critical migration corridors may be necessary to examine fish behavior in high-flow scenarios.

Keywords: delta model, particle tracking, hydrodynamic, delta smelt behavior, fish, Sacramento
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Using Gaussian Process Models to Fit an Enhanced Particle Tracking Model to Acoustic Telemetry Data of Juvenile Salmon

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Particle tracking models embedded within hydrodynamics models provide a means for understanding how passive particles are transported in a complex hydrodynamic environment such as the Sacramento-San Joaquin River Delta. Recent efforts have focused on adding behaviors to particles to simulate how juvenile salmon negotiate the complex channel structure and tidal environment of the Delta. Modeling fine-scale hydrodynamics coupled with fish behaviors can provide a better understanding of patterns in migration timing, routing, and survival. However, methods for estimating values of behavioral parameters in stochastic particle tracking models are lacking. Here we present techniques for estimating behavioral parameters in an enhanced particle tracking model (ePTM) employed in the DSM2 (Delta Simulation Model 2) hydrodynamic model by fitting the ePTM to acoustic telemetry data. First, we used Gaussian process models (i.e., Kriging) to map specific values of behavioral parameters (e.g., swimming velocity) to ePTM outputs that can be evaluated against the telemetry data (e.g., reach-specific travel times). The Gaussian process model allowed us to predict the outputs of the ePTM at any input value of the behavioral parameters without having to actually run the ePTM, which is computationally prohibitive. Next, we estimated behavioral parameters by fitting the ePTM outputs, as predicted by the Gaussian process model, to telemetry data on juvenile late-fall Chinook salmon collected from 2007-2010. The fitting was implemented in a Bayesian framework using Markov Chain Monte Carlo techniques, which allowed us to incorporate multiple sources of uncertainty such as stochasticity of the ePTM, error from the Gaussian process model, and inherent sampling error associated with the telemetry data. Our methods provide a general framework for fitting complex agent based models to empirical data, providing not only estimates of behavioral parameters, but also estimates of uncertainty.

Keywords: particle tracking model, juvenile salmon, DSM2, hydrodynamic model
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Particle Swarm Optimization Techniques for Estimating Juvenile Salmon Behavioral Parameters in an Enhanced Particle Tracking Model

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The Sacramento-San Joaquin Delta (hereafter Delta) is an intensively managed network of interconnected channels that juvenile salmon must negotiate. Tools that can predict the effect of changing flows on fish movement and survival through the Delta are becoming increasingly important as ecosystem-level impacts such as climate change and water exports increase. Enhanced particle tracking models that incorporate simulated fish behavior within a hydrologic model of the Delta can provide these predictions. Accurately modelling fish behavior within this context, however, presents numerous challenges. Optimizing behavioral movement parameters to fit simulations to empirical data necessitates iteratively generating simulation results, a process which can require intensive computing resources. Furthermore, the simulations contain a stochastic component, which causes results to vary even when using the same set of behavioral inputs, thus complicating efforts to fit the simulation results to data.

Our analysis focuses on a novel method for estimating the behavioral parameters of an enhanced particle tracking model (ePTM) by fitting the model to empirical field data. We utilize a simulated maximum likelihood approach within the context of a particle swarm optimization routine to fit the DSM2 ePTM to travel times of acoustically tagged juvenile salmonids in the north Delta. We expect the calibrated ePTM to become a valuable tool for managers seeking to understand and predict how changes to Delta hydrology will affect juvenile salmonid behavior and survival.

Keywords: particle tracking model, behavioral parameter estimation, particle swarm optimization
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