Spatial Analysis of Juvenile Chinook Salmon Entrainment in Tidally Forced Junctions

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Data from the 2001 and 2003 Delta Cross Channel studies, the 2006 Clarksburg Bend Study, and the 2011 and 2012 Georgiana Slough Non-Physical Barrier (GSBNP) studies show that acoustically tagged juvenile Chinook salmon are not uniformly distributed in these river junctions and river bends. Thus, juvenile salmon are not uniformly distributed throughout a river's cross section approaching a junction, and therefore entrainment probabilities cannot be calculated based on flow data alone. As a result, understanding entrainment rates in these junctions requires an understanding of both the water-velocity patterns and spatial distribution of juvenile salmon within the junction area.

We analyzed large numbers of multidimensional tracks from acoustically tagged juvenile salmon migrating through critical junctions in the Delta using aggregate spatial statistics. In order to understand the processes influencing the spatial distribution of these fish, we aggregated fish tracks into groups that were exposed to a range of similar covariate values. We used the critical streakline and flow ratio metrics discussed in earlier talks to collapse the complexities of the two-dimensional velocity fields in the junctions into time series of critical streakline locations which we used to sort fish into groups that traveled through the junctions under similar velocity conditions. Empirical two-dimensional probability distribution functions (PDFs) were calculated for each of these covariate groups, and statistics calculated from these PDFs were used to gain insights into the mechanisms affecting juvenile salmon entrainment in Delta junctions.

Keywords: fish swimming in moving water
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Using Acoustic Telemetry to Assess the Effect of a Floating Fish Guidance Structure on Entrainment of Juvenile Salmon into Georgiana Slough

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The interior of the Sacramento-San Joaquin River Delta is a location of high mortality for out-migrating ESA listed juvenile salmonids, relative to alternative migration routes. Reducing the probability of entrainment into the Interior Delta from the Sacramento River via Georgiana Slough is therefore one action that can increase juvenile salmonid survival. In 2011 and 2012, a non-physical barrier comprised of intermittent light, a bubble curtain, and modulated sound was placed at the entrance of Georgiana Slough. This non-physical barrier reduced the proportion of juvenile salmon entering Georgiana Slough from 22.3% to 7.7%. However, the largest reduction in entrainment probability (up to 40 percentage points) occurred near the critical streakline which defined the streamwise division of flow vectors entering Georgiana Slough and the Sacramento River. These insights led us to hypothesize that a relatively small shift in the cross-sectional distribution of fish towards the Sacramento River side of the critical streakline could considerably reduce the probability of fish being entrained into Georgiana Slough. To test this hypothesis, a 350 ft long, shallow-draft (5-10 feet deep) floating boom (the "floating fish guidance structure" or FFGS), intended to guide fish away from the Georgiana Slough side of the river channel, was installed upstream of the entrance to Georgiana Slough during the spring of 2014. Nearly 5,000 acoustic tagged late fall Chinook salmon were released into the Sacramento River near Sacramento to evaluate the effect of the FFGS on entrainment of fish into Georgiana Slough. The analysis is currently incomplete, but the presentation will include the effects of the FFGS treatment (FFGS deployed or not deployed) and other factors (e.g., river discharge and location of the critical streakline) on the probability of entrainment into Georgiana Slough.

Keywords: acoustic telemetry, fish protection, behavior, migration routing, juvenile salmon
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Diel Activity Patterns of Juvenile Late-Fall Chinook Salmon with Implications for Operation of the Delta Cross Channel

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Identifying mechanisms affecting fish distribution associated with water withdrawals can provide a basis for management actions to improve juvenile salmon survival. Under the rationale that fish distribute in proportion to the discharge that enters a migration route, the Delta Cross Channel (DCC) has been prescriptively closed for most of the out-migration season to reduce juvenile salmon entrainment and subsequent mortality within the interior Sacramento-San Joaquin River Delta. Recent observations indicate the fraction of fish entering a route can be in disproportion to the amount of flow allocated to the route. To further investigate this, we implanted acoustic transmitters into 2,983 juvenile Chinook salmon and released them upstream of the DCC to evaluate arrival timing and entrainment into the DCC. Nighttime arrival and entrainment into the DCC were modeled using logistic regression with covariates for flow, the change in flow, and water temperature. Although the proportion of the diel period having negative flows was most important to fish arrival, river flow and water temperature were also important drivers of nighttime arrival probabilities at the DCC, whereas river flow and the change in flow were the more important drivers of entrainment probabilities. Application of the model to observed conditions suggests nighttime closure of the DCC may reduce fish entrainment into the DCC (as much as 68%) during the winter migration period. Opening the gates only during the day would allow water to be diverted to the pumping stations and closing the gates at night could minimize entrainment into the interior delta.

Keywords: Day and night salmon movement, water conveyance, and salmon entrainment
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Individual Based Modeling of Juvenile Chinook Salmon

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Movement of juvenile chinook salmon in the north Delta has been investigated by the USGS using acoustic tagged salmon and high resolution hydrodynamic data. Observed salmon movement in the winter of 2008 were strongly influenced by both salmon behavior and hydrodynamics. Due to limited spatial coverage of the hydrodynamic data, the specific behaviors which result in the observed paths through the north Delta cannot be determined from the data alone. In order to better understand and quantify salmon behaviors and thereby improve the ability to predict salmon movement through the Delta, three-dimensional modeling tools have been developed and applied. These tools include a high resolution three-dimensional hydrodynamic model, a three-dimensional particle tracking model and an individual based model that specifies salmon behavior.

The UnTRIM Bay-Delta model was refined in the North Delta to a cross-channel resolution of approximately 5 m and along channel resolution between 5 and 10 m along the Sacramento River between Georgiana Slough and the Clarksburg Bend and downstream of the Sacramento River junctions with Georgiana Slough, the Delta Cross Channel, Steamboat Slough and Sutter Slough. The resulting model was validated using ADCP velocity transects to evaluate prediction of streamwise and cross-stream velocity. The model predicted similar secondary circulation structure to the observations throughout the tidal cycle but typically predicted smaller cross-channel velocity amplitude than calculated from the ADCP observations.

Particle tracking was performed using these hydrodynamics for both passive particles and particles with specified swimming behaviors. We evaluated hypothesized holding behaviors and outmigration behaviors by comparing the distribution of modeled particle transit times for alternative simple behavior scenarios to the observed distribution of travel times for acoustically tagged salmon throughout the North Delta.

Keywords: Individual based model, particle tracking model, hydrodynamic model, chinook salmon
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Evaluation of a Hypothesis for How Water Flow Pattern Shapes Fish Trajectories near Infrastructure

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Decades of empirical studies have identified many factors that affect the relationship between fish movement and water flow, yet applying quantitative knowledge across multiple locations regarding how infrastructure modifies the outcome of naturally evolved behavior, and at a scale that management can use, remains a challenge. Stochastic processes may dominate the moment-to-moment decisions of animals, and individuals may change their behavior response to a fixed stimulus over time. Near infrastructure, studies cannot measure all the external (e.g., hydrodynamic, water quality, social) and internal (e.g., bioenergetic, cognitive) factors across the range of spatiotemporal scales that may influence fish behavior. Recognizing these constraints, we relate fish behavior to factors that management most directly influences, namely the quantity and structure of water flow, and focus at a scale resolution where future environmental pattern might be forecast. Using a hypothesis for how fish might hydraulically navigate flow field obstacles in natural free-flowing rivers, we reproduce the observed 3-D movement trajectories and distribution patterns of juvenile Pacific salmon across 47 flow fields assembled from multiple data sources over 14 years near seven dams. We explain fish movement in terms of a behavioral response to experienced water acceleration and velocity near infrastructure. To describe behavior dynamically, where response can change with context, we use a simple individual-based model coupled to a multi-dimensional hydrodynamic model. With a limited evolutionary history for navigating engineered infrastructure, such as dams, fish behavior should reflect their response evolved in natural rivers. As such, we surmise that our hypothesis is applicable to fish outside the context of dams, in natural settings and near other forms of infrastructure in the Bay-Delta system such as fish diversion devices (booms and non-physical barriers) and passage structures as well as have implications for habitat design.

Keywords: fish movement behavior, hydraulic pattern, individual based model, ecohydraulics
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Juvenile Salmon Response to Levee Repair on the Sacramento River

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California Department of Water Resources (DWR) and the United States Army Corps of Engineers (USACE) are engaged in levee repair focused on preventing levee erosion and flooding. The repairs also include features to improve the fish habitat including shallow water benches and instream woody material. However, there remains uncertainty about how fish respond to these features. In addition, questions regarding which enhancement provides the most benefit to fish also remain. To address these questions, we investigated fish movement using acoustic tags at rivermile 85.6. Approximately 200 detailed 2D fish movement tracks were collected in the vicinity of the repair site in 2010 and in 2011. We also collected detailed bathymetric and hydraulic data and developed a 2D computational fluid dynamics (CFD) model of the levee repair site. We then developed a fish movement model using the Eulerian-Lagrangian-Agent Method (ELAM) and used the fish movement data from the 2D acoustic tag tracks for calibration of modeled fish movement. The fish movement model matched observed travel times and spatial distribution accurately. The fish movement data and subsequent modeling suggest that juvenile salmon respond to local hydraulic features produced by the levee repair by moving away from the habitat enhancement. These results are counter to the goal of the increasing juvenile salmon residence at the repair sites. Before fish arrive in the Bay-Delta they must move through hundreds of miles of river where levees impact the habitat. It is important that habitat be available for all life stages of juvenile salmon as migration to the Bay Delta happens. Our results suggest that the environmental features incorporated into levee design are not working as intended. Given the prevalence of levees on the Sacramento system it is important that we consider how learn how to better improve conditions for migrating and rearing salmonids.

Keywords: levee repair, salmon, hydraulics, fish movement models, telemetry
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Ecohydraulic Design and Post-Project Appraisal of Salmonid Spawning and Rearing Habitat Enhancement Projects on the Lower American River

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The lower American River is a local treasure running through the highly urbanized region of Sacramento and its neighboring communities. Hydrologic regulation of the river by upstream dams, the corresponding blockage of sediment supply to the river downstream and blockage of fish passage to the historically available habitat upstream have resulted in deleterious consequences to populations of Chinook salmon and steelhead trout that depend on the American River Watershed for both spawning and rearing. In the last six years, concerted efforts by agencies including the U.S. Bureau of Reclamation, U.S. Fish & Wildlife Service, California Department of Fish and Wildlife, NOAA Fisheries, Sacramento County Parks and the Sacramento Water Forum have resulted in several habitat enhancement projects in the lower American River. These projects have focused on the creation and enhancement of spawning and juvenile rearing habitat through gravel augmentation and side channel enhancement or creation. The projects are designed using ecohydraulic principles to provide the desired hydraulic conditions at flows that typically occur during the spawning periods for the two species. This approach relies upon two-dimensional hydraulic modeling combined with species specific habitat suitability criteria that were developed using observations made in the lower American River. The potential for mobility of the placed gravel is also considered during the design process. Following implementation, physical monitoring has tracked the evolution of sites through time and documented the hydraulic conditions present following construction. Utilization of the sites for spawning has been rigorously documented. Post-project appraisals indicate that the ecohydraulic design approach is working, with ~80% of the redds that have been documented in the sites occurring in areas predicted to be highly suitable with the hydraulic-habitat suitability modeling approach. Furthermore, river wide redd surveys have shown that a majority of the redds are occurring in the enhanced sites.

Keywords: gravel augmentation, steelhead, Chinook salmon, enhancement, design, spawning, side channel
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Using Agent-Based Models to Gain Insight into the Influence of Behavior, Predation and Water Project Operations on Fates of Migrating Chinook Salmon Smolts

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Problem statement: Migration of anadromous salmonids from freshwater spawning and rearing grounds to the ocean is a key stage in their life cycle. We seek to understand the behavior of migrating Chinook salmon smolts in the Sacramento-San Joaquin Delta in order to predict the effects of changing inflows and outflows on their migration routes, survival, and ultimate fates, both at an individual and population level.

Approach: We began with the California Department of Water Resources' Delta Simulation Model II (DSM2), which includes a spatially-explicit, individual-based particle tracking model with passive, neutrally-buoyant particles. We extended DSM2 to include active swimming and more complex route selection behaviors, and included mortality based on travel distance and time. Model calibration and selection were performed using coded-wire tag and acoustic telemetry data. Smolt fates were simulated for a variety of smolt release locations, historical flow scenarios, and alternative behavioral hypotheses.

Results: Behavior and mortality dramatically affect the fates of particles – in particular, the fraction of smolts entrained in the Central Valley Project and State Water Project export facilities is strongly influenced by migration behavior. The behavioral hypothesis most concordant with the data included active swimming in the downstream direction; selective tidal-stream transport; and a probability of individual smolts incorrectly assessing the downstream direction, with this probability based on the relative strengths of the net flow and the tidal amplitude in a given channel. In accordance with observations, travel times through the Delta were shorter, and mortality much reduced, compared to the null model.

Conclusions/Relevance: Our preliminary results underscore the importance of understanding the behavioral processes underlying observed patterns of smolt migration and fate. A mechanistic understanding of this key life stage will be an essential component in predicting the consequences of water management, conservation actions, and climate change for endangered salmonid populations.

Keywords: Agent-based modeling, Chinook salmon smolts, migration, behavior, mortality
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Visualizing Juvenile Salmonid Behavior, Mortality, and Salvage in the Delta: Practical Application of an Individual-Based Model

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Managers and biologists are expected to manage water project operations and take other actions that can contribute to recovery or, minimally, provide protection for sensitive fish species. In addition, Delta researchers need a means to quantitatively assess the possible fates of tagged fish between points of detection or recovery. We have developed an individual-based model of juvenile salmonid passage through the Delta (the Individual Based Delta Passage Model or IB-DPM) which provides a "sand box'' wherein biologists and managers can explore how different assumptions about juvenile salmonid behavior, predation, and their respective interactions with hydrodynamic conditions may influence the proportion of fish surviving to Chipps Island or arriving at export facilities. The IB-DPM represents a simplified network of Delta channels that include primary migratory routes for juvenile salmonids entering from both the Sacramento and San Joaquin Rivers. The routes represented in the IB-DPM include 196 DSM2 channels, 15 channel junctions, and 2 physical barriers (DCC and HORB). Hydrodynamic inputs to the IB-DPM are based on DSM2 HYDRO simulations of either historic conditions or hypothetical boundary conditions. The historic simulations allow for calibration of the model with data from fish tagging studies and the hypothetical conditions allow for virtual experiments on the effects of proposed water operations on juvenile salmon passage through the Delta. In this talk, we will outline the key biological assumptions of the IB-DPM, demonstrate the user-friendly interface of the model, and illustrate the challenges associated with model calibration based on coded-wire tag and acoustic telemetry studies. The IB-DPM provides an example of a powerful, yet relatively simple individual-based modeling approach that can be broadly applied to enhance understanding and effective management of complex ecological issues.

Keywords: individual-based model, salmonid, migration, salvage, inflow, exports
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A Reevaluation of the Relationships Between X2, the Low Salinity Zone, and Fish Habitat Utilization

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The UnTRIM Bay-Delta model is a three-dimensional hydrodynamic and salinity model of the San Francisco Estuary, which extends from the Pacific Ocean through the entire Sacramento-San Joaquin Delta. The UnTRIM Bay-Delta model has been used in studies of San Francisco Bay and the Sacramento-San Joaquin Delta for California DWR, USBR, USGS, USEPA, and the US Army Corps of Engineers. The UnTRIM Bay-Delta characterizes the areal and volumetric extent of estuarine habitat in the Low Salinity Zone (LSZ) over a range of historic conditions, and has been used to develop maps of Low Salinity Zone extent for a range of X2 values.

This analysis extends the LSZ extent analysis to cover a 34 year period spanning from 1980 through 2013 to evaluate how the size and position of the LSZ has changed over much longer timescales than have previously been explored. In addition, this study re-evaluates the effect of the commonly made assumptions about the low end of the salinity range which have been used in this type of analysis (either 0.5 or 1.0 psu) on the resulting non-monotonic relationship between X2 and the LSZ. A new approach for characterizing the LSZ is proposed which is shown to be more consistent with both the utilization of fish habitat in low salinity ranges based on fish survey data and with the X2-abundance relationships which generally exhibit monotonic trends of increasing abundance with decreasing X2.

Keywords: Low Salinity Zone, X2, Delta smelt, Physical Habitat
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