Enhanced Particle Tracking Model (ePTM):

Status of Model Development and Pilot Application during WY 2015
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1 ePTM Development

1.1 Introduction

The life cycle of anadromous fish such as Chinook salmon poses unique challenges for researchers, policymakers, managers, and the fish themselves. Spawning occurs in freshwater rearing habitats, while the majority of growth and maturation typically occurs in the ocean. Changes to the environment observed by migrating fish may alter their phenology and behavior in complex ways, with substantial implications for mortality, predation, and straying. Therefore, understanding the characteristics and consequences of migration is essential for effective management of these species. There is a strong need for tools to help predict the effects of changes in flow and other environmental factors on the survival of outmigrating juvenile Chinook salmon (smolts).

Smolts traversing the Sacramento-San Joaquin Delta in the Central Valley of California (hereafter, the Delta) confront a particularly challenging environment. The Delta, situated at the confluence of the Sacramento and San Joaquin Rivers, to the east of where these rivers empty into the Pacific Ocean through the San Francisco Bay, is a heavily engineered water conveyance system that was constructed for flood control and to deliver water for agricultural, municipal, and industrial use. It is also essential habitat for the winter-run and spring-run Chinook salmon (Oncorhynchus tshawytscha), an anadromous salmonid listed under the Endangered Species Act, including [NMFS, 2009]. The Delta consists of a complex network of rivers, streams, and sloughs that presents a very different environment from what these species experienced in their evolutionary pasts (Robinson et al. 2014). In addition, flow in the system has been drastically altered as a consequence of flood control measures, in-Delta consumptive uses, and exports from the Delta via Central Valley Project (CVP) and State Water Project (SWP) pumping facilities (Figure 1).

Due to the importance of this system to the economy of California and for conservation of the endangered Chinook salmon, a substantial amount of work has been done to identify and quantify the effects of various environmental and management factors on the survival of migrating smolts. A number of statistical methods have been applied to identify and quantify the effects of environmental covariates on survival using coded-wire tag data (Kjelson et al. 1989, Newman and Rice 2002), mark-recapture approaches (Perry et al. 2010, Perry et al. 2013), acoustic-tagging (Steel et al. 2013), and acoustic telemetry (Brandes and McLain 2000; Newman and Brandes 2010, Perry et al. 2010, Perry et al. 2012). While these statistical studies have provided much insight into the influence of various covariates on smolt survival, the complex channel network and tidally-driven, reversing flows that vary on hourly time scales, may limit our ability to extrapolate these relationships to novel conditions. A model that incorporates more mechanistic understandings of fish behavior and predation would complement these statistical models and enhance efforts to predict the consequences of anthropogenic and natural alterations of the Delta.
This report describes the development of an Individual-Based Modeling (IBM) and parameter inference framework for simulating the migration and survival of Chinook salmon smolts in the Delta. This model is an extension of the Delta Simulation Model II (DSM-2), a calibrated, validated, and widely-used hydrodynamic and water quality model developed by the California Department of Water Resources (DWR). DSM-2 includes a Particle Tracking Model (PTM) module that tracks the movement of passive, neutrally buoyant particles. The PTM has been extended to include more realistic smolt behaviors and predator-induced mortality, in order to provide a tool for testing hypotheses related to smolt migration behavior and predicting consequences of management actions and changes in environmental conditions.

Process-based models such as the IBM described herein present particular challenges related to parameterization, fitting to empirical data, and representing uncertainty. These inherent
difficulties are compounded by the computational expense involved in running a complex model such as this that simulates large numbers of individuals. The model formulation, calibration, and some example results that demonstrate the potential utility of this model as a management tool are discussed subsequently. An improved hydrodynamic rule for routing particles through junctions, and an improved parametric fitting to empirical data currently being implemented in the model are also detailed.

1.2 Role of ePTM

The IBM developed in this project is part of a larger stage-structured Life Cycle Model (LCM) of Chinook salmon (NMFS 2014). The various stages and states in the LCM define the migration of Chinook salmon through the Central California Valley to the Pacific Ocean and back to their spawning sites over their lifetimes, in which the floodplain and Delta smolt are modeled in the IBM (Figure 2 and Figure 3).

The IBM developed in this project would be useful in determining the impact of the planned water intake diversions in the North Delta due to the California Water Fix, and in directing habitat restoration efforts through the California Eco-Restore plans. This is because the IBM provides quick and reliable physically based relationships between stressor parameters and population measures in the Delta, and would thus be useful in modeling multiple hypothetical hydrological and water use scenarios. The results of these of sensitivity analyses, as well as simple physical models of habitat connectivity and interactions developed using the IBM results can inform management decisions on planned pumping operations, as well as siting habitat restoration projects.
Figure 2. Stages and states of Chinook salmon in the Life Cycle Model. The floodplain and Delta stages of smolts are modeled in the IBM. Red circle represents stages modeled in the IBM.
1.3 Model Formulation

The workflow of the IBM is outlined as (Jackson et al. 2015):

1. A one-dimensional hydrodynamic model (DSM-2) is run to obtain flow information for the Delta.
2. A PTM with $n$ behavior parameters incorporated is run for $k$ different value sets of the behavior parameters to produce certain metrics. This is called the Extended or Enhanced PTM (ePTM).
3. An $n$-dimensional function with $m$ hyperparameters (henceforth, the emulator) is fit to the metrics generated from the ePTM results, to generate an emulator $E_{ePTM}$.
4. The emulator is also fitted to the same metrics generated with acoustic-tag data, to generate an emulator $E_{DATA}$. 

Figure 3. Central Valley Chinook transition stages. Red trapezium indicates states modeled by IBM.
5. The $E_{\text{DATA}}$ hyperparameter set $M_{\text{DATA}}$ is compared with the $E_{\text{ePTM}}$ hyperparameter sets $M_{\text{ePTM},i}(i = 1, \ldots, k)$, and the hyperparameter set $M_{\text{ePTM},r}$ which maximizes the likelihood of $E_{\text{ePTM}}$ matching $E_{\text{DATA}}$ is chosen.
6. ePTM is run with the value set $r$ of the behavior parameters which corresponds to the hyperparameter set $M_{\text{ePTM},r}$.

DSM2 represents the Sacramento-San Joaquin Delta as a network of channels, joined by nodes, spanning from the mainstem Sacramento River near the city of Sacramento, CA, in the northeast; to the mainstem San Joaquin River near the city of Vernalis, CA, in the southeast; to the outlet of Suisun Bay in the west (Figure 4). DSM2 includes a one-dimensional hydrodynamics module (HYDRO) and a water quality model (QUAL), which simulate flows, velocities, water surface elevations, and transport of conservative and non-conservative water quality constituents.

![Figure 4. DSM-2 grid of the Delta. Legend: grey lines – one-dimensional channels, red dots – nodes, blue circles and lines – reservoirs and their connections, solid green arrows directed toward the grid – inflow boundary conditions, solid red arrows directed away from the grid – outflow boundary conditions, dashed green arrow – return flows, dashed red arrow – agricultural diversion flows.](image)

The PTM module of DSM2 is a quasi-three-dimensional model that runs using the outputs of the HYDRO module. HYDRO outputs are recorded at one hour intervals, while the PTM executes with a 15-minute time step. The cross-sectional areas at the ends of a channel and
the modeled flow rate in the channel are used to determine an average water velocity in the longitudinal direction at each end of the channel. Average velocities and cross-sectional areas at intermediate positions along the channel are interpolated linearly. The average longitudinal velocity at a given location is then translated into lateral and vertical velocity profiles using quartic and von Karman logarithmic functions, respectively (BDO 2002).

In the original DSM2 formulation, particles are modeled as neutrally buoyant and passively advected. A particle's velocity in the longitudinal direction is determined by the velocity at its three-dimensional location within this flow field (x, y, and z coordinates for the longitudinal, lateral, and vertical positions, respectively). The vertical and lateral velocity profiles result in longitudinal dispersion of particles. Particle movement in the vertical and lateral directions is simulated by random walks shaped by diffusivity functions that approximate empirical relationships (Miller 2002).

### 1.3.1 Fish behavior in ePTM

The ePTM incorporates active swimming and holding behaviors. When the fish are not holding position, their swimming speed is a user-specified constant, swimSpeed (Table 1). This swimming speed is added to the water velocity to obtain the net ground speed.

**Table 1. ePTM behavior parameters.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>swimSpeed</td>
<td>Active swimming speed (m/s)</td>
<td>Variable</td>
</tr>
<tr>
<td>holdThr</td>
<td>Upstream flow velocity (m/s)</td>
<td>Variable</td>
</tr>
<tr>
<td>constProbConfusion</td>
<td>Logistic regression constant (-)</td>
<td>Variable</td>
</tr>
<tr>
<td>slopeProbConfusion</td>
<td>Logistic regression slope (-)</td>
<td>-0.25</td>
</tr>
<tr>
<td>probAsses</td>
<td>Probability of assessment of downstream direction (Timestep$^{-1}$)</td>
<td>0.01</td>
</tr>
<tr>
<td>tideCountThr</td>
<td>Flow direction update frequency (cpd)</td>
<td>2</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Mean free path (Km)</td>
<td>Variable</td>
</tr>
<tr>
<td>$\omega$</td>
<td>Random movement speed (cm/s)</td>
<td>Variable</td>
</tr>
</tbody>
</table>

In addition to active swimming, the fish may hold position according to a phenomenon termed Selective Tidal-Stream Transport (STST; Gibson 2003). STST is a hypothesis for how fish may reduce energy expenditure while achieving average travel speeds greater than the average flow velocity in tidal regions. When the flow is downstream (towards the ocean), the fish allow themselves to be advected. On a flood tide, when the upstream flow exceeds some threshold, the fish hold position (station holding; Liao 2007), thereby limiting their advection back upstream and away from the ocean (Figure 5). In the ePTM, this is implemented via a user-specified upstream flow velocity, holdThr, below which the active swimming behavior is applied and above which the position of the fish is constant, i.e., ground speed is fixed at zero (Table 1).
In other words, the simulated fish neither with the flow, nor swim from their current location (at the cross-sectional position in the DSM-2 water body they are in) when the flow velocity is greater than holdThr.

Figure 5. Selective tidal-stream transport model.

An assumption of STST is that migrants are able to assess the downstream direction; without this ability, they would not know when to allow themselves to be advected and when to hold position. Although the exact combination of mechanisms that *O. tshawytscha* smolts use to orient themselves is unknown, it is likely that the direction of flow is used as a cue (MacKeown 1984, Smith 1985, Lucas et al. 2001, Braithwaite and Girvan 2003). Although flow is likely just one of a suite of cues that migrants use (McInerney 1964, Quinn and Brannon 1982, Hansen et al. 1987, Dittman and Quinn 1996, DeVries et al. 2004, Putman et al. 2013, Ueda 2014) the ePTM uses only flow as it is the cue most directly affected by water management decisions. Fish orientation is simulated using a model that includes both the average direction of flow in a given channel and some probability that the fish will accurately assess this net direction of flow and correctly orient themselves to the true downstream direction. The net direction of flow in a channel is determined by integrating the flow velocity over some user-specifiable number of tidal cycles, `tideCountThr` (Table 1). In the Delta, as the tides are semidiurnal in nature, using the value of `tideCountThr` of 2 would represent a 25 hour period. As abnormal river flow events typically do not last more than a few hours, a period of 25 hours is more than sufficient to determine the net flow direction in a channel. This phenomenological model allows capturing the hypothesized tendency of fish to migrate in the direction of net flow.

It is likely that the assessment of the flow direction by the fish will be more accurate when the magnitude of the subtidal flow is large relative to the tidal flow. To capture this dependency, the signal-to-noise ratio, which is the absolute value of the average water velocity (the signal) divided by the standard deviation of the velocity (the noise) is computed. In riverine reaches, when the mean flow is downstream and tidal effects are minimal, this ratio will be large, and the fish will have a high probability of orienting in the downstream direction. In tidal regions, upstream flow during flood tides will be of the same order as downstream flow during ebb tides, and the signal-to-noise ratio will be small. In this case, fish will have a higher probability of confusing the flow direction and consequently holding when the flow is oceanward and allowing themselves to be advected when the flow is directed inland. The probability of a reversed orientation, is a logistic function of the signal-to-noise ratio that
saturates at a probability of 0.5 for low signal-to-noise ratios (the fish are no better than random at assessing the downstream direction) and at a probability of 0 for high signal-to-noise ratios (perfect accuracy). The shape of the logistic function is defined by two parameters: \textit{constProbConfusion}, which determines the location of the half-saturation point, and \textit{slopeProbConfusion}, which specifies the steepness of the function (Table 1 and Figure 6). Once a fish has made an assessment of the downstream direction, it will wait some period of time before revisiting the assessment again; this is modeled as a Bernoulli process, in which there is some probability, probAssess of re-evaluating the direction in any given time step (Table 1). The value of 0.01 is chosen to represent a very small likelihood that the simulated fish would reassess the prevailing flow direction within a flood or ebb phase of the tidal cycle, once it has already determined what the prevailing flow direction is. An increase in probAssess would result in the net decrease in advection with the flow and a decrease in the streamwise dispersion of the simulated fish due to the convolved effect of individual fish not experiencing the action of the ebb phase of the tides. Such high frequency tidal timescale reassessment by the fish is inconsistent with the STST model, and hence a larger values of probAssess are not investigated.

![Figure 6. Confusion model for fish. Top panel – signal-to-noise ratio, bottom panel – confusion parameters: red line – saturation point, green line – slope of logistic function.](image)

The particular route that each fish takes through the network of channels is determined by a series of routing decisions taken at junctions. When a fish reaches a node connected to two or more channels, the probability of the fish entering a given channel is determined by the fraction of the outflow from the node that is entering the channel. For example, if 70% of the water that is flowing away from the junction is entering a particular channel, the fish will have a probability of 0.7 of entering that channel.

1.3.2 Predation in ePTM

The DSM-2 PTM does not include mortality. The ePTM adds predator-induced mortality according to the XT model (Anderson et al. 2005). The probability of a fish surviving passage through a reach, $S$, is as follows:
\[ S = e^{-\left(\frac{1}{\lambda \sqrt{x^2 + \omega^2 t^2}}\right)} \] ... (1)

where \( x \) is the distance traveled and \( t \) is the travel time. The mean free path, \( \lambda \) is

\[ \lambda = \frac{1}{\rho \pi r^2} \] ... (2)

where \( \rho \) is the density of predators and \( r \) is the encounter distance. The term \( \omega \) is the random component of prey speed. The implementation of the XT model in the ePTM involves recording the \( x \) and \( t \) for the multiple channels that a fish traverses within a given time step. A survival probability for each of the time substeps that represent fish passage through a particular channel is then calculated using the different \( \lambda \) values in the different channels. The overall probability that the fish survives the time step is the product of the survival probabilities of the substeps, i.e.,

\[ S = \prod_{i=1}^{n} e^{-\left(\frac{1}{\lambda_i \sqrt{x_i^2 + \omega_i^2 t_i^2}}\right)} \] ... (3)

where \( n \) is the number of channels that the fish traversed during the time step, \( x_i \) is the distance traveled in channel \( i \), \( t_i \) is the time spent in channel \( i \), and \( \lambda_i \) and \( \omega_i \) are the channel-specific mortality parameters. In the ePTM, only the parameters \( \lambda_i \) and \( \omega_i \) are specified explicitly (Table 1).

### 1.3.3 Parameter inference

A multistate mark-recapture model framework coupled with acoustic telemetry data is employed to estimate parameter values for the ePTM. The mark-recapture model follows the framework of Perry et al. (2010), with the exception that the survival probabilities are outputs of the ePTM instead of estimates from the observations. In addition, the observed travel times of the tagged fish are modeled using Inverse Gaussian Reciprocal Normal (IGRN) distributions (Gurarie et al. 2009) and these are compared to the travel times predicted by the ePTM.

To account for the various sources of uncertainty, a Bayesian framework is utilized. This approach involves: (i) recording detection histories for each fish that was released in the acoustic telemetry studies, (ii) calculating travel time distributions for each cohort and reach, (iii) generating parameter values for the ePTM using a Markov chain Monte Carlo (MCMC) sampling routine, (iv) simulating the acoustic telemetry releases using the ePTM and the generated parameter values, (v) using the survival probabilities and travel time distribution parameters from the ePTM output to calculate the posterior probability of the ePTM having generated the observed capture histories and travel time distributions under the given set of parameter values, and (vi) repeating steps iii-v to generate posterior distributions for all ePTM parameters. Detailed descriptions of the components of this method are given below.

Generation of posterior distributions by MCMC sampling can require a large number of samples from the model of interest – in this case the ePTM. Running the ePTM directly for each sample of the MCMC would be impractical due to the computational requirements of spanning
the entire parameter space of behavior parameters. To overcome this computational burden, the ePTM output is emulated using the Gaussian Processes for Machine Learning (GPML) MATLAB toolbox (Rasmussen and Nickisch 2010). The GPML toolbox uses Bayesian supervised learning to generate emulators that provide a probabilistic mapping from ePTM inputs (behavior parameter values) to outputs, allowing for very rapid estimation of ePTM outputs for any arbitrary set of behavior parameter values. The emulators are defined by mean and covariance functions and their associated hyperparameters. The values of these hyperparameters are inferred from training data (outputs) collected at training points (inputs). A zero mean function and squared exponential covariance function are employed for the hyperparameters (Dancik et al. 2010).

A Gaussian Process (GP) defines a family of random functions that map from inputs to outputs. A draw from a GP is equivalent to drawing one of these functions with some probability and evaluating it at the specified input values. Functions that pass near to the training data are more likely to be drawn, i.e., their posterior probabilities are greater. This criterion is defined by the signal variance hyperparameter of the covariance function. The random functions also have a characteristic length scale, which is a second hyperparameter of the covariance function; this hyperparameter defines the stiffness of the functions, or how rapidly the output functions change for a given displacement in input space. Combined, these two criteria – that likely functions pass near to the training data and that they have a characteristic length scale – define probabilistic outputs that lie close to the training data when the parameter values are near the training points and that reflect increasing uncertainty as the input values move away from the training points. The output of the GP emulators is an expected value (mean) and a variance at the given input value. Training data for the emulators is generated using Latin hypercube sampling to generate 87000 training points in the five-dimensional parameter space.

The overall likelihood is comprised of a survival component and a travel time component. The survival component is calculated according to the matrix method for multi-stage mark-recapture models detailed in Fujiwara and Caswell (2002). The travel time component is calculated by numerically maximizing the IGRN log-likelihood function, which is based on the probability distribution function,

\[ h(t|x, \mu_v, \sigma_v, \sigma_w) = \frac{x}{\sqrt{2\pi(\sigma_v^2 + \sigma_w^2)^t}} e^{-\left[\frac{(x-\mu_v t)^2}{2(\sigma_v^2 + \sigma_w^2)^t}\right]} \]

where \( t \) is the travel time; \( x \) is the reach length, i.e., the distance traveled; \( \mu_v \) and \( \sigma_v \) are the mean and the variance of the velocities; and \( \sigma_w \) is the diffusion rate (Gurarie et al. 2009). Details of the MCMC formulation are beyond the scope of this report, and can be found in Dancik et al. (2010).

1.3.4 Model evaluation and comparison

We evaluated the fit of the models to the data using the conditional predictive ordinate (CPO) posterior predictive check, otherwise known as the leave-one-out cross-validation predictive density (Gelfrand, 1996). The CPO is an estimate of the model’s ability to predict out-
of-sample data. The predictive performance of the model for each observation $i$ can be estimated from MCMC output as follows:

$$CPO_i = \frac{1}{\sum_{t=1}^{T} p(y_i | \Theta_t)^{-1}} \ldots (5)$$

where $T$ is the number of MCMC samples and $p(y_i | \Theta_t)$ is the predictive density of the data $y_i$ given the model as parameterized in sample $t$, i.e., given $\Theta_t$.

Model comparison was performed using the Watanabe-Akaike information criterion (WAIC), also known as the widely-applicable information criterion (Gelman et al. 2013). In contrast with the more commonly used Deviance information criterion (DIC), which uses the posterior mean to estimate the predictive density, WAIC is a fully Bayesian estimate of out-of-sample predictive performance that uses the full posterior distribution. Similar to the method of calculating CPO, the Log Pointwise Predictive Density (LPPD) is computed as

$$\text{Computed LPPD} = \sum_{i=1}^{n} \log \left[ \frac{1}{T} \sum_{t=1}^{T} p(y_i | \Theta_t) \right] \ldots (6)$$

where $n$ is the total number of observations. To adjust for overfitting, one of two possible corrections for the effective number of parameters is then added:

$$\text{Computed pWAIC1} = 2 \sum_{i=1}^{n} \left\{ \log \left[ \frac{1}{T} \sum_{t=1}^{T} p(y_i | \Theta_t) \right] - \frac{1}{T} \sum_{t=1}^{T} \log [p(y_i | \Theta_t)] \right\} \ldots (7)$$

$$\text{Computed pWAIC2} = \sum_{i=1}^{n} V_{t=1}^{T} \log [p(y_i | \Theta_t)] \ldots (8)$$

where $V_{t=1}^{T}$ represents the sample variance, $V_{t=1}^{T} a_t = \frac{1}{T-1} \sum_{t=1}^{T} (a_t - \bar{a})^2$. Then,

$$\text{Computed WAIC} = 2(\text{Computed LPPD} - \text{Computed pWAIC}) \ldots (9)$$

### 1.4 Data and Methods

Field observations were obtained for fish travel times using both coded-wire tags, and acoustic telemetry. These datasets are used in the calibration and validation of the ePTM.

Coded-wire tag data for multiple release locations across multiple water years between 1994 and 2007 was used. About 20,000 to 75,000 smolts were tagged and released at Discovery Park, Ryde, Sherman Island, Georgiana Slough, Isleton and Miller Park. These were recovered dead or alive at Chipps Island, CVP an SWP (Table 2).
Table 2. Coded-wire tag data.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Release location</th>
<th>Release date</th>
<th>Number released</th>
<th>Survival fraction to Chipps Island</th>
<th>Number recovered at CVP</th>
<th>Number recovered at SWP</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Discovery Park</td>
<td>1/16/2007</td>
<td>53,054</td>
<td>0.4</td>
<td>79</td>
<td>244</td>
</tr>
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<td>2</td>
<td>Ryde</td>
<td>1/18/2007</td>
<td>35,541</td>
<td>0.33</td>
<td>47</td>
<td>171</td>
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<tr>
<td>3</td>
<td>Ryde</td>
<td>12/9/2005</td>
<td>50,036</td>
<td>0.52</td>
<td>12</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>Sherman Island</td>
<td>12/12/2005</td>
<td>24,365</td>
<td>1.17*</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>Ryde</td>
<td>12/9/2004</td>
<td>49,515</td>
<td>0.6</td>
<td>0</td>
<td>0</td>
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<tr>
<td>6</td>
<td>Sherman Island</td>
<td>12/10/2004</td>
<td>24,148</td>
<td>0.65</td>
<td>0</td>
<td>0</td>
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<td>7</td>
<td>Ryde</td>
<td>12/6/2002</td>
<td>49,629</td>
<td>0.4</td>
<td>24</td>
<td>18</td>
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<td>8</td>
<td>Georgiana Slough</td>
<td>1/3/2002</td>
<td>77,053</td>
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<td>294</td>
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<td>11</td>
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<td>22</td>
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<td>12</td>
<td>Isleton</td>
<td>12/21/1999</td>
<td>49,089</td>
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<td>13</td>
<td>Georgiana Slough</td>
<td>12/1/1998</td>
<td>69,180</td>
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<td>16</td>
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<td>14</td>
<td>Ryde</td>
<td>12/2/1998</td>
<td>48,207</td>
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<td>Georgiana Slough</td>
<td>12/29/1998</td>
<td>68,492</td>
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<td>24</td>
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<td>17</td>
<td>Ryde</td>
<td>12/5/1997</td>
<td>46,756</td>
<td>0.67</td>
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<tr>
<td>18</td>
<td>Georgiana Slough</td>
<td>1/13/1998</td>
<td>66,893</td>
<td>0.26</td>
<td>24</td>
<td>0</td>
</tr>
<tr>
<td>19</td>
<td>Ryde</td>
<td>1/14/1998</td>
<td>49,059</td>
<td>0.94</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>20</td>
<td>Miller Park</td>
<td>12/2/1996</td>
<td>50,437</td>
<td>0.37</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td>21</td>
<td>Miller Park</td>
<td>1/14/1997</td>
<td>43,241</td>
<td>0.25</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>22</td>
<td>Ryde</td>
<td>1/11/1996</td>
<td>30,281</td>
<td>0.67</td>
<td>12</td>
<td>0</td>
</tr>
<tr>
<td>23</td>
<td>Isleton</td>
<td>12/5/1994</td>
<td>30,220</td>
<td>0.57</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td>24</td>
<td>Isleton</td>
<td>1/5/1995</td>
<td>31,557</td>
<td>0.39</td>
<td>48</td>
<td>183</td>
</tr>
</tbody>
</table>

*Possible incorrect value

1.4.1 Acoustic telemetry data

The capture history data were collected as described in Perry et al. (2013). Briefly, eight cohorts of late-fall run Chinook salmon smolts implanted with Vemco acoustic telemetry transmitters were released into the Sacramento River near Sacramento, CA between December 2006 and January 2009. In each migration year, one cohort was released in December and one was released in January. An array of telemetry stations were used to detect passage through 300 the mainstem Sacramento River, Steamboat Slough, Sutter Slough, Georgiana Slough, and the Delta Cross Channel (Figure 7).
1.4.2 Modeling methodology

The most general modeling methodology given the structure of the ePTM would involve treating all parameters as free and inferring reach-specific and release-specific values for each. This would entail up to eight parameters for each of the nine river reaches and five releases, for a total of 360 free parameters. The least complex model methodology that still retains fish movement and mortality would be the null model (which implies fixed values for all non-mortality parameters) with $\lambda$ and $\omega$ shared across all reaches and releases. In principle, any combination of fixed, free, shared, and independent parameters between these two extremes could be considered.
Through expert scientific judgment and in keeping with the goal of developing a modeling methodology that generalizes across time and space, a small subset of candidate modeling methodologies is identified. Since the purpose of this modeling methodology is to capture patterns that hold across release times, all candidate modeling methodologies share parameter values across releases, i.e., no parameters are release-specific. The parameter \( \omega \) is used to capture small-scale movement that is not modeled explicitly in the ePTM; this should be a constant factor across reaches and releases. The following parameters are fixed based on a priori design decisions: (i) tideCountThr is 2, i.e., the net direction of flow in a channel is calculated based on two tidal cycles, or roughly once every 25 hours, (ii) probAssess is 0.01 every time step of the model, which results in an expected time of approximately 24 hours between assessments of the downstream direction by an individual fish, and (iii) slopeProbConfusion is -0.25, which constrains the approximately linear portion of the logistic function to correspond to the range of signal-to-noise ratios across the Delta in a typical simulation run (Table 1).

A second goal of the parameter inference is to develop a calibration that could be extended to areas outside of the North Delta region where the acoustic telemetry data were collected. To achieve this, the reaches are divided into three categories: riverine, tidal, and transitional (Figure 8). For simulations outside of the North Delta, parameter estimates for these regions will be transferred to analogous regions of the Delta outside of the North Delta. River reaches outside of the North Delta are binned based on a combination of the median signal-to-noise ratio during calendar year 2007. Manual binning is performed to eliminate disjointed or inappropriate assignments. The initial signal-to-noise bins are:

\[
0 < \text{Tidal} \leq 0.1; \quad 0.1 < \text{Transitional} \leq 1; \quad \text{Riverine} > 1
\]

... (10)
With these constraints, three primary modeling methodologies and three comparison modeling methodologies are defined (Table 3). The simplest, modeling methodology A, assumes that swimSpeed, holdThr, constProbConfusion, and \( \lambda \) are shared across all reaches. Modeling methodology B assumes region-specific swimSpeed, holdThr, and \( \lambda \), but shared constProbConfusion. Modeling methodology C adds region-specific constProbConfusion. To assess the improvement in fit that could be achieved by knowledge of reach-specific predation intensity, modeling methodology D is developed for comparison with the modeling methodology with region-specific \( \lambda \) (modeling methodology B). Finally, for comparison to the extremes of model complexity that are possible under our constraints, modeling methodology E assumes reach-specific swimSpeed, holdThr, and \( \lambda \) and region-specific constProbConfusion; and modeling methodology F is the null model with reach-specific \( \lambda \).

### Table 3. Modeling methodologies tested.

<table>
<thead>
<tr>
<th>Modeling methodology</th>
<th>swimSpeed</th>
<th>holdThr</th>
<th>( \lambda )</th>
<th>( \omega )</th>
<th>constProbConfusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Shared</td>
<td>Shared</td>
<td>Shared</td>
<td>Shared</td>
<td>Shared</td>
</tr>
<tr>
<td>B</td>
<td>Region</td>
<td>Region</td>
<td>Region</td>
<td>Shared</td>
<td>Shared</td>
</tr>
<tr>
<td>C</td>
<td>Region</td>
<td>Region</td>
<td>Region</td>
<td>Shared</td>
<td>Region</td>
</tr>
<tr>
<td>D</td>
<td>Region</td>
<td>Region</td>
<td>Reach</td>
<td>Shared</td>
<td>Shared</td>
</tr>
<tr>
<td>E</td>
<td>Reach</td>
<td>Reach</td>
<td>Reach</td>
<td>Shared</td>
<td>Shared</td>
</tr>
<tr>
<td>F</td>
<td>Null</td>
<td>Null</td>
<td>Reach</td>
<td>Shared</td>
<td>Null</td>
</tr>
</tbody>
</table>

### 1.5 Behavior and Modeling Methodology Selection

A variety of behavior models are tested ranging from the null hypothesis of no swimming behavior, to the STST model (Table 4).

### Table 4. Behavior models tested.

<table>
<thead>
<tr>
<th>Behavior</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Null model: no behavior</td>
</tr>
<tr>
<td>2</td>
<td>Always swim towards ocean</td>
</tr>
<tr>
<td>3</td>
<td>Swim with downstream flow, drift with upstream flow</td>
</tr>
<tr>
<td>4</td>
<td>Swim with downstream flow, hold otherwise</td>
</tr>
<tr>
<td>5</td>
<td>Swim with falling tide, drift otherwise</td>
</tr>
<tr>
<td>6</td>
<td>Swim with falling tide, hold otherwise</td>
</tr>
<tr>
<td>7</td>
<td>Swim towards increasing salinity</td>
</tr>
<tr>
<td>8</td>
<td>Diurnal swimming: swim at specified time, hold otherwise</td>
</tr>
<tr>
<td>11</td>
<td>Selective tidal stream transport: swim downstream, probability of confusing</td>
</tr>
<tr>
<td></td>
<td>upstream for downstream</td>
</tr>
</tbody>
</table>

The likelihood of the fit of the ePTM results, \( \phi_1 \), to the data, \( \phi_2 \equiv \Phi_2(R, n, \mu, \sigma) \), which is assumed to be drawn form a normal distribution \( N(\mu, \sigma) \), is given by
\[-\log[L(\phi_1|\phi_2)] = \sum_{i=1}^{n} \left[ \log(w_i \sigma) + \frac{(O_i-P_i)^2}{2(w_i \sigma)^2} \right] \]  

... (11)

where \( R \) is the number of fish released, \( n \) is the number of fish recovered, and \( w_i \) are weights assigned to the variance due to sampling error.

The log likelihood of the fit of the ePTM results to the coded-wire tag data for various behavior models indicates that the STST model performance is the best available. This behavior pattern represents a good correlation between the model results and the field observations (Figure 8). Similarly, the log likelihood of the fit of the ePTM results to the acoustic telemetry data also indicates that the STST model performance is the best available (Table 5). Hence, this behavior pattern is selected. The posterior distributions for the five estimated parameters and the five modeling methodologies, A to E are shown in Figure 10, Figure 11, Figure 12, and Figure 13. F being the null hypotheses, is not shown.

![Figure 9. Comparison of ePTM results and coded-wire tag data.](image)

<table>
<thead>
<tr>
<th>Behavior</th>
<th>Log likelihood</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-1617</td>
</tr>
<tr>
<td>5</td>
<td>-1327</td>
</tr>
<tr>
<td>11</td>
<td>-801</td>
</tr>
</tbody>
</table>
Figure 10. `swimSpeed` for different modeling methodologies A-E. Vertical lines are the median values in each reach. Shaded areas are the 95% confidence intervals.
Figure 11. holdThr for different modeling methodologies A-E. Vertical lines are the median values in each reach. Shaded areas are the 95% confidence intervals.
Figure 12. constProbConfusion for different modeling methodologies A-E. Vertical lines are the median values in each reach. Shaded areas are the 95% confidence intervals.
To compare the survival estimated by the ePTM to that generated by direct estimates of survival, the median posterior survivals estimates for each reach and each release are plotted versus the estimates that were obtained by Perry et al. (Figure 14). Figure 15 shows an overview comparison of the travel time distributions predicted by the ePTM to the observed travel time distributions.
Figure 14. Survival posteriors vs. mark-recapture estimates. RMSD: root mean squared deviation (smaller is better); color codes indicate reach colors specified in Figure 7.
Figure 15. Two-sample Kolmogorov-Smirnov statistic for the travel time distributions. ePTM IGRN CDF-empirical IGRN CDF. Positive numbers – ePTM predicts faster arrival times than the observed data. Horizontal lines are medians across releases for each reach. The overall median of the absolute value of the Kolmogorov-Smirnov statistic is shown in the inset.

The Cumulative Distribution Functions (CDFs) of the IGRN distributions fit to the estimated and observed travel times are compared using the Kolmogorov-Smirnov statistic, which is a nonparametric comparison of the shape and location of two CDFs based on the maximum distance between them in the direction of the ordinate axis. The CPO and WAIC for the full likelihood are shown in Figure 16. The CPO and WAIC for survival and travel time are shown in Figure 17, to assess the contributions of the separate components of the likelihood. In
both Figures 16 and 17, lower values of WAIC and corresponding higher values of the CPO indicate better modeling methodology performance. Thus, the null modeling methodology, F always performs poorly. In most release scenarios, the different modeling methodologies produce comparable results. It is hypothesized that in such scenarios, the tagged fish and simulated fish traveled along similar paths along the Sacramento River. Release scenarios 7 and 8 likely indicate situations in which the tagged fish and simulated fish traveled along more complex paths through the Delta, and hence, modeling methodologies with greater spatial complexity produce better results during these release scenarios.

**Figure 16.** log(CPO) of the complete likelihood (survival and travel time). Higher numbers indicate a superior predictive performance. Lower WAIC values indicate better predictive performance.
From the RMSD (Figure 14), CPO and WAIC (Figure 16 and Figure 17) estimates, it is apparent that the modeling methodologies D and E provide the best fit to the observed data, and hence the best performance. Moreover, the performance of D and E are comparable. Hence, the modeling approach D is selected as the best tradeoff between performance and model complexity.

1.6 Implementation

The IBM is implemented through the interaction of several computer languages:

1. DSM-2 HYDRO: Fortran
2. ePTM: Java
3. MCMC calibration: Matlab
4. Initialization, Pre- and postprocessing: Python 2.7
5. Datasets and timeseries: Excel and .csv files

1.7 Applications

The ePTM based IBM has several potential applications in ecological management and is particularly powerful in alternate scenario studies. It can be used for long term planning studies, as well as short term operational decision making. Two examples it is currently being calibrated for are discussed subsequently.

Figure 17. log(CPO) of (a) survival and (b) travel time. Higher numbers indicate a superior predictive performance. Lower WAIC values indicate better predictive performance.
1.7.1 Long term planning

The ePTM calibrated for existing Delta operations from 1980 to 2010 is being deployed to study the potential ramifications of water management changes to the transport and fate of Chinook salmon smolt and changes in its habitat availability and quality. This is done by releasing 100 simulated fish per timestep at one location in the Sacramento River, one location in the Yolo Bypass floodplain, and 402 locations in the Delta, and estimating their survival probabilities to Chipps Island over a period of 4-5 months every water year (Figure 18). When coupled with survival estimates for each release location, the modeled survival probabilities provide estimates of the habitat quality and availability in the Delta. This coupling is achieved by a weighted resampling of the modeled total survival probability distributions for all releases with weights assigned to each release location based on the survival estimates of each location. Such a resampled result is shown as an example in Figure 19.

Figure 18. Release locations for long term planning study.
The ePTM is also being used to analyze the impacts of the California Water Fix by modeling simulated fish with the same model calibrations as that for the existing Delta water use operations on a new DSM-2 grid containing the proposed intake pipelines and Forebay in the upper Sacramento River (Figure 20). These scenarios, known as the No Action Alternative (NAA), and the Planned Action (PA) represent, respectively, no change to the existing water use operations, and implementing the intakes (BDCP 2013).

Efforts are currently underway to achieve the transition of the ePTM to the new proposed operations DSM-2 grid, and run the ePTM from water years 1920 to 2003. These hydrological scenarios represent what impact the proposed intake operations are likely to have on existing water use patterns in the Delta (for recent years after 1973, the last year a new water regulation structure was constructed on the Sacramento River), and what impact they are likely to have in an ecological restoration context through the California Eco-restore (for years earlier than 1973, representing a shift of the Delta hydrology towards less managed conditions).

The ePTM can also be extended to include the NAA and PA scenarios in a climate change context by varying the tidal stage at Martinez and inflows in the Sacramento and San Joaquin Rivers in the output of DSM-2 Hydro.
1.7.2 Short Term Operations

The ePTM can also be used as a short term decision-making tool with model runs for periods of 4-5 months at most. As it is capable of running several hundred thousand particles very quickly in its current configuration, it can be used to study the impact of in-delta gate operations and hydrological events on the fate of simulated fish. Operation rules can be defined and tested for a range of possible outcomes, and the most rules producing the most desirable outcomes can be refined and simplified. The ePTM results can also be used to develop metrics for fish transport and fate, such as the Potential Entrainment Index (Nam 2008).
When simulating tidally driver flows, poorly resolved boundary conditions and coarse spatial and temporal resolution can cause significant compounding of the numerical stencil scale timestep and gridsize dependent errors (Fringer et al. 2006). Therefore, tidal simulations must be performed with timestep sizes that at least do not result in the aliasing of the semi-diurnal tidal constituents. This requires that the timestep size be limited to the order of a few minutes at most. In the case of DSM-2, it can result in incorrect representation of the tidal constituents, resulting in erroneous predictions of simulated fish fates in tidally influenced areas or channels with strong tidal phasing between connected water bodies such as Three Mile Slough and the confluence of the Sacramento and San Joaquin Rivers at Antioch (Sridharan 2015). It is to be noted that in the short term studies with ePTM, the Hydro timestep size of 1 hour, and the ePTM timestep size of 15 minutes are not sufficient to resolve the effects of tides in the Delta. The errors due to the coarse temporal resolution are absorbed into the emulator, thereby producing potentially erroneous behavior parameter values, and the computational penalty for finer timestep sizes is minimal in DSM-2 Hydro and ePTM. It is recommended that shorter timesteps on the order of 5 minutes for Hydro and 100s for ePTM be adopted (Sridharan 2015).

1.8 Improvements

The Kolmogorov-Smirnov statistic indicates that the ePTM consistently predicts faster fish arrival times to Chipps Island. Three reasons for this are: (i) the GP fit assumes constant bulk hydrodynamic conditions, while the Delta produces spatially and temporally variable hydrodynamics, (ii) even the reach specific fish behavior may be too simplistic to account for observed spatial and temporal behavioral patterns, which introduce multimodalities in the temporal distributions of metrics used in the calibrations, and (iii) the junction routing model is too simplistic to account for observed hydrodynamic routing. These issues are addressed through the improvements underway.

1.8.1 Multinomial emulation

In order to address multimodalities in the timeseries of observed metrics, a multinomial function fit to the ePTM results and acoustic telemetry data – rather than the GP – is a more accurate operation. Consider (Perry, p.c.):

\[ y_1, \ldots, y_k \sim \text{Multinomial}(N, \pi_1, \ldots, \pi_k) \]  \quad \ldots (12)

where \( y_k \) is the sample count for category \( k \), \( \pi_k \) is the probability of occurrence of category \( k \),

\[ N = \sum_{k=1}^{k} y_k \]  is the total number of multinomial sample outcomes, and \( \pi_k = 1 - \sum_{k=1}^{k-1} \pi_k \).

The distribution can be represented as a series of independent conditional binomial distributions:
\[ y_1 \sim \text{Binomial}(N, p_1) \]
\[ y_2 | y_1 \sim \text{Binomial}(N - y_1, p_2) \]
\[ y_3 | y_1, y_2 \sim \text{Binomial}(N - y_1 - y_2, p_3) \]
\[ \vdots \]
\[ y_k | y_1, ..., y_{k-1} \sim \text{Binomial}(N - \sum_{j=1}^{k-1} y_j, p_k) \text{ for } k = 1, ..., K - 1 \]
\[ y_K = \text{Binomial}(N - \sum_{j=1}^{K-1} y_j, p_K) = 1 \]

Here, \( p_1 \) is the probability of observing category 1 and \( 1 - p_1 \) is the probability that the outcome was any of the other categories 2 through \( K \). Now, conditional on observing \( y_1 \), the probability that \( y_2 \) occurs is \( p_2 \) and \( 1 - p_2 \) is the probability of observing categories 3 through \( K \). The conditional binomial distributions for the remaining sample counts follow the same logic. The conditional binomial cell probabilities are related to the multinomial cell probabilities as follows:

\[
p_1 = \frac{\pi_1}{1 - \pi_1} \\
p_2 = \frac{\pi_2}{\sum_{k=2}^{K} \pi_k} = \frac{\pi_2}{1 - \pi_1} \\
p_3 = \frac{\pi_3}{1 - \pi_1 - \pi_1} \\
\vdots \\
p_k = \frac{\pi_k}{1 - \sum_{j=1}^{k-1} \pi_j} \text{ for } k = 1, ..., K - 1
\]

The logistic function of the maximum likelihood estimators for the \( p_k \)s – which is simply the logistic function of the following proportions – is emulated:

\[
\text{logit}(\hat{p}_1) = \log \left( \frac{y_1}{N} \right)
\]
\[
\text{logit}(\hat{p}_2) = \log \left( \frac{y_2}{N - y_1} \right)
\]
\[
\text{logit}(\hat{p}_3) = \log \left( \frac{y_3}{N - y_1 - y_2} \right)
\]
\[ \vdots \]
\[
\text{logit}(\hat{p}_k) = \log \left( \frac{y_k}{N - \sum_{j=1}^{k-1} y_j} \right) \text{ for } k = 1, ..., K - 1
\]

where \( \text{logit}(x) = \ln(x/(1-x)) \). The transformation back to the \( \pi_k \)s are achieved within the MCMC.

### 1.8.2 Streamline following junction rule

Several two- and three-dimensional numerical studies have been conducted which detail the propagation of tidal and non-tidal flows through channel junctions (Debnath and Chatterjee 1978, Brown and Arellano 1980, Hill and Souza 2006, Rhoads and Sukhodolov 2008, Wang et al. 2009, Buschman et al. 2010, Tippins and Mueller 2010). They also deal with the transport of
scalars such as sediments through junctions (De Serres et al. 1999, Dargahi 2004, Frings and Kleinhaus 2008). These studies have been validated with laboratory experiments (Pittaluga et al. 2003, Ramamurthy et al. 2007, Thomas et al. 2011) and field studies in the Delta (Lacy 2000, Burau 2005, Perry and Skalski 2008, Cavallo et al. 2013, Brandes 2014, Burau 2014, Cavallo 2014, Perry 2014, Gleichauf et al. 2014), and indicate that scalars sometimes follow streamlines through junctions. Hence, the flow based routing rule used in DSM-2 PTM will be updated with a more sophisticated junction rule from the PTM STARWalker (Sridharan 2015).

A streamline following rule is implemented as follows (Figure 21): first, the junction is modeled as a polygon with small reaches of the connecting channels included. The flows into or out of each channel are imposed as the two-dimensional steady state horizontal streamfunction with Neumann boundary conditions on the section of the channels upstream to the nodes and as Dirichlet conditions on the channel banks. The polygon along with the boundary conditions is then conformally mapped onto a unit circle where the Laplace equation for the streamfunction is solved using the MATLAB toolbox developed by Driscoll (1994). The solution is then transformed back onto the original polygon on a triangular grid (Driscoll and Vavasis 1996).

This process is applied for a junction with three, four or five channels with various channel widths and orientations for unique flow scenarios. The streamlines that delineate where a particle would be advected are then identified for each scenario. The corresponding part of the cross-section in the original channel where the particle is determined where it will move to. By inverting the flows into each channel, and by using a combination of rotation and mirroring of the unique scenarios, all possible flow combinations can be obtained. These scenarios are then imposed as rules in a lookup table in the STARWalker to determine where a particle will move to at the junction.

Only the topology of flows and the relative widths of the connecting channels and magnitudes of flows affect the rule for the junction in each scenario. The orientation of the connecting channels or their depths do not matter, as this is a two-dimensional approximation of the junction only (Kacimov 2000, Ramamurthy et al. 2007; Figure 22). Secondly, while there are many possible flow scenarios, some are inadmissible due to physical constraints. Such scenarios will have branch cuts in the delineating streamlines and are not considered.

To validate this rule, mixing at a confluence of two rivers is performed by releasing 10,000 neutrally buoyant particles uniformly across the cross-section in one channel and none in the second channel. Both these channels merge into a third channel. Each channel is 100m wide and 10m deep; the source channels are 1km long and the downstream channel is 20km long. The mean velocity in each source channel is 0.5m/s and that in the third channel is 1m/s and the timestep size is 10s. The two streams mix completely at the confluence under the randomizing condition, thereby producing a uniform cross-sectional concentration in the third channel. Under the streamline following condition, the time required for mixing once in the third channel agrees with the theoretical result \( \sim 0.3 \frac{W^2}{\varepsilon_H} = 10,000s \) (Fischer et al. 1979; Figure 23).
Figure 21. Workflow for following streamlines at a junction: polygon of the junction $\rightarrow$ flow boundary conditions $\rightarrow$ conformal map of the junction $\rightarrow$ grid for solution of streamfunction $\rightarrow$ streamfunction at the junction.
Figure 22. Streamfunction and delineating streamlines for different channel orientations for three channel junctions. Here, flow topology and relative widths of channels are held constant. The values of the streamfunction are shown in the colorbar in Figure 21.

Figure 23. STARWalker validation: Mixing at the confluence of two rivers.

It is evident that even with severe restrictions such as the one-dimensional flow and pseudo-three-dimensional PTM model, the use of a limited number of super-particles released at
relatively small spatial and temporal frequencies and the consequent possibility of spatial and temporal aliasing and the lack of any biological behavior except mortality impost during postprocessing, the streamline following junction rule does reasonably well in predicting the general characteristics of the expected Delta smelt salvage with passively-behaving particles (Figure 24).

![Diagram](image.png)

**Figure 24.** Comparison of the streamline following junction rule implemented in STARWalker and the flow based routing rule implemented in DSM-2 PTM (J-PTM here) based model results to Delta Smelt salvage at CVP. In comparison, the UNTRIM-FISH PTM model of Gross et al. (2010) produced a Model Skill Score (MSS) of 0.6 for passive particles for the same period in 1999 (see Figure 5-14 in Gross et al. 2010)

### 1.9 Timeline of Proposed Work

The ongoing development of ePTM entails significant coding and calibration efforts. The following timeline is proposed:

2. Implementation of streamline junction rule: September – December, 2015
3. Adapting ePTM for California Water-Fix runs: September, 2015
4. Running ePTM for alternative action scenarios: September – October, 2015
1.10 Conclusions

The ePTM incorporates Salmon smolt behavior, mortality and predation in order to more realistically simulate Chinook salmon smolt passage through the Delta than a PTM that models neutrally buoyant particles. Multiple behavior patterns have been investigated and it has been found that the STST swimming model best represents real smolt behavior. The behavior parameters are allowed to vary spatially in the model to simulate – with as much verisimilitude as possible – the changing swimming behavior of smolts and predation patterns in the Delta. This variability is on a regional spatial scale, i.e., riverine, transitional and tidal for swimming, and on a reach length scale for predation. This is because smolt are expected to be governed by environmental variables such as temperature, salinity and ecosystem markers which are likely to change at the regional level, while predator abundance and feeding patterns are likely to satisfy more urgent needs and vary on smaller spatial scales.

The calibration of the ePTM behavior parameters has been performed rigorously using both coded wire tag and acoustic tag mark-recapture data. The field observations have been incorporated into the calibration through a Bayesian inference framework that infers the travel time, survival probability and transition probability in each reach along possible travel paths from the arrival times at various monitoring stations. A novel calibration process utilizing the MCMC approach has been devised to span the parameter space of the behavior parameters and select the ranges of parameter values that maximize the likelihood of the metrics of travel time distributions and survival probabilities estimated from the ePTM results matching those estimated from the field observations.

The validation of the ePTM has indicated modalities in the travel time distributions that it is not able to replicate. Moreover, the ePTM incorporates errors due to the flow based routing of particles through the junctions of the Delta into the behavior parameters and hence ascribes values of the behavior parameters to the modeled smolt that may not be realistic. Hence, future calibrations would include the more complex and realistic streamline following rule at junctions. The more robust multinomial emulation will also be incorporated to better predict behavior parameter ranges and include greater spatial variability in behavior patterns.

The model has currently been calibrated only for winter-run Chinook salmon in the North Delta. The extension the calibration to the rest of the Delta will be undertaken subsequently by adopting the same behavior parameter values in different regions of the North Delta to the analogous regions in the other parts of the Delta as well. The pilot application is using the ePTM in the early stages of the on-going calibration effort. Although the pilot study shows promising results, we are working on improvements to the ePTM model as well as the calibration.
2 Pilot Application in WY 2015

2.1 Background for WY 2015 Application

As part of the Interagency 2015 Drought Strategy\(^1\), the pilot application of the ePTM was considered as an additional tool “to inform real time OMR limits and in consideration of any request for flexibility in OMR flow management.” In consideration of previous requests for flexibility and drought contingency planning the regular PTM module of DSM-2 has been used to infer the advection of fish through the delta based on proposed hydrologic conditions. There have been a number of efforts to enhance the PTM to reduce uncertainty in the conclusions based those PTM results, including this effort by the SWFSC. The goal of the trial use of the ePTM as described in the Interagency 2015 Drought Strategy was to provide periodic output that could inform DOSS and the RTDOT in real-time decision making between March 1 and May 31, 2015. In response to TUC Petitions from Reclamation and DWR in January and February 2015, NMFS decided to accelerate the development and use of the ePTM, among other tools and sources of real-time fish distribution, by DOSS and RTDOT. However, since the ePTM was still under development and technical documentation through Water Year 2015, NMFS did not use the ePTM as the basis for decisions regarding flexibility in Delta operations. Instead, the preliminary use of ePTM was merely explored to determine the manner in which it might be used in the future as a consideration for decision making. The application of the ePTM during Water Year 2015 was considered a “dry run” of the process, and as a means to begin to understand aspects of the model while in its preliminary stage. In addition, several webinars were held for stakeholders in order to share the stage of model development more widely. For a general, non-technical overview of ePTM, refer to Appendix A.

2.2 Examples of WY 2015 Application

During Water Year 2015, the preliminary use of the ePTM was explored with two scenarios: the first was for February OMR flexibility, and the second for water project operation flexibility from April to September. The summarized results for ePTM scenarios described below were discussed during DOSS meetings, however given the preliminary stage of the ePTM development, DOSS did not outline conclusions nor provide advice based on the pilot application of the ePTM.

2.2.1 Example 1: February OMR flexibility

The first scenario was in response to the February 9, 2015 TUC Petition\(^2\) requesting flexibility in OMR flow of 6,250 cfs on a 5-day running average. The DSM-2 simulations that were performed and evaluated for the baseline and proposed OMR flexibility operational scenarios are shown in Table 6. This application of the ePTM occurred after the requested dates for OMR flexibility as a post-hoc analysis.

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One thousand eParticles were inserted over 24 hours at each insertion point on the first day of the model simulation period of interest: February 11, 2015 until March 2, 2015. While the hydrology in the baseline and proposed action scenarios differed mainly during a 5-day period from February 12, 2015 to February 16, 2015 (see highlighted rows in Table 6), eParticles were tracked within the simulation for an additional two weeks after the export/OMR action ended (until March 2, 2015). This extended particle-tracking period allowed time for eParticles to reach some “fate”, e.g. the export facilities or Chipps Island. The three eParticle insertion points were: (1) Sacramento River at Sherwood Harbor (representing salmonids entering the north Delta); (2) Middle River at Railroad Cut (representing salmonids in the south Delta); and (3) San Joaquin River at the mouth of Old River (representing salmonids in the central Delta) (refer to Appendix B, map on p. B-9). Sacramento River winter-run Chinook salmon are the listed juvenile salmonid most likely to be in the Delta during mid-February, so the insertion points were selected to assess impacts to that run (though note that the ePTM model does not have a winter-run-specific calibration). Since winter-run Chinook do not have a population in the San Joaquin basin, no insertion point at Mossdale was included. By inserting a number of these eParticles at select Delta locations into a simulation of forecasted hydrology, the ePTM can provide information on predicted route selection and fate of eParticles to inform management about various hydrodynamic effects of operations on salmonid movement. The current "behavior" function is based on a preliminary calibration to late-fall-run Chinook movement data in the north Delta.

---

3 Insertion Point-- refers to a location where the eParticles are inserted into the model. The insertion location can change based on monitoring information and so as to reflect the current understanding of species distribution.
Table 6. DSM-2 input for scenarios evaluated in February TUC Petition. Highlight added to show the difference between the “Baseline” scenario and “Proposed Action” scenario of OMR flexibility.

<table>
<thead>
<tr>
<th>Date</th>
<th>Freeport Flow (cfs)</th>
<th>Vernalis Flow (cfs)</th>
<th>Baseline Outflow (cfs)</th>
<th>Combined Exports (cfs)</th>
<th>OMR</th>
<th>Proposed Action Outflow (cfs)</th>
<th>Combined Exports (cfs)</th>
<th>OMR</th>
</tr>
</thead>
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<tr>
<td>6-Feb</td>
<td>9,543</td>
<td>890</td>
<td>7,219</td>
<td>2,575</td>
<td>~200</td>
<td>7,219</td>
<td>2,575</td>
<td>~200</td>
</tr>
<tr>
<td>7-Feb</td>
<td>10,640</td>
<td>870</td>
<td>11,238</td>
<td>4,075</td>
<td>-3,500</td>
<td>11,238</td>
<td>4,075</td>
<td>-3,500</td>
</tr>
<tr>
<td>8-Feb</td>
<td>22,738</td>
<td>940</td>
<td>14,421</td>
<td>5,175</td>
<td>-4,500</td>
<td>14,421</td>
<td>5,175</td>
<td>-4,500</td>
</tr>
<tr>
<td>9-Feb</td>
<td>48,840</td>
<td>1,230</td>
<td>33,223</td>
<td>5,775</td>
<td>-5,000</td>
<td>33,223</td>
<td>5,775</td>
<td>-5,000</td>
</tr>
<tr>
<td>10-Feb</td>
<td>54,900</td>
<td>2,590</td>
<td>62,620</td>
<td>6,000</td>
<td>-5,000</td>
<td>62,620</td>
<td>6,000</td>
<td>-5,000</td>
</tr>
<tr>
<td>11-Feb</td>
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<td>65,480</td>
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<td>-5,000</td>
<td>65,480</td>
<td>6,500</td>
<td>-5,000</td>
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<td>52,944</td>
<td>7,900</td>
<td>-6,250</td>
</tr>
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<td>46,900</td>
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<td>45,980</td>
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<td>-5,000</td>
<td>44,630</td>
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<td>43,900</td>
<td>2,100</td>
<td>42,560</td>
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<td>41,135</td>
<td>7,825</td>
<td>-6,250</td>
</tr>
<tr>
<td>16-Feb</td>
<td>40,900</td>
<td>2,000</td>
<td>39,360</td>
<td>6,400</td>
<td>-5,000</td>
<td>37,960</td>
<td>7,800</td>
<td>-6,250</td>
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<tr>
<td>17-Feb</td>
<td>37,900</td>
<td>1,900</td>
<td>36,310</td>
<td>6,300</td>
<td>-5,000</td>
<td>36,310</td>
<td>6,300</td>
<td>-5,000</td>
</tr>
<tr>
<td>18-Feb</td>
<td>34,900</td>
<td>1,800</td>
<td>33,210</td>
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<td>-5,000</td>
<td>33,210</td>
<td>6,300</td>
<td>-5,000</td>
</tr>
<tr>
<td>19-Feb</td>
<td>31,900</td>
<td>1,700</td>
<td>30,110</td>
<td>6,300</td>
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<td>30,110</td>
<td>6,300</td>
<td>-5,000</td>
</tr>
<tr>
<td>20-Feb</td>
<td>28,900</td>
<td>1,600</td>
<td>27,035</td>
<td>6,275</td>
<td>-5,000</td>
<td>27,035</td>
<td>6,275</td>
<td>-5,000</td>
</tr>
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<td>21-Feb</td>
<td>25,900</td>
<td>1,500</td>
<td>24,035</td>
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<td>-5,000</td>
<td>24,035</td>
<td>6,175</td>
<td>-5,000</td>
</tr>
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<td>1,400</td>
<td>20,885</td>
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<td>20,885</td>
<td>6,175</td>
<td>-5,000</td>
</tr>
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<td>5,975</td>
<td>-5,000</td>
<td>19,985</td>
<td>5,975</td>
<td>-5,000</td>
</tr>
<tr>
<td>24-Feb</td>
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<td>1,200</td>
<td>19,985</td>
<td>5,975</td>
<td>-5,000</td>
<td>19,985</td>
<td>5,975</td>
<td>-5,000</td>
</tr>
<tr>
<td>25-Feb</td>
<td>24,900</td>
<td>1,100</td>
<td>19,785</td>
<td>5,775</td>
<td>-5,000</td>
<td>19,785</td>
<td>5,775</td>
<td>-5,000</td>
</tr>
<tr>
<td>26-Feb</td>
<td>24,900</td>
<td>1,000</td>
<td>19,885</td>
<td>5,775</td>
<td>-5,000</td>
<td>19,885</td>
<td>5,775</td>
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</tr>
<tr>
<td>27-Feb</td>
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<td>900</td>
<td>19,785</td>
<td>5,775</td>
<td>-5,000</td>
<td>19,685</td>
<td>5,775</td>
<td>-5,000</td>
</tr>
<tr>
<td>28-Feb</td>
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<td>800</td>
<td>19,685</td>
<td>5,775</td>
<td>-5,000</td>
<td>19,685</td>
<td>5,775</td>
<td>-5,000</td>
</tr>
</tbody>
</table>

For each insertion point, per scenario (either the Proposed Action or Baseline) the output of the model run was an excel spreadsheet with one thousand rows (one row per eParticle) and several columns. There were a total of six excel spreadsheets for the February ePTM runs. The results were summarized using cumulative histograms that focused on the proportions of eParticles that ended up at the SWP, CVP, Chipps Island, or Martinez by the end of the model run (Appendix B). In addition, the proportions of eParticles that “died” at the SWP, CVP, or any other waterbody combined were summarized via cumulative histograms as well (Appendix B). All figures were produced using the R Statistical Software (R Core Team 2015).  

2.2.2 Example 2: April through May Water Project Operations Flexibility

The second ePTM scenario was in response to the March 24, 2015, TUC Petition requesting modifications to several flow and water quality compliance points, and DCC gate

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operation flexibility, from April to May 2015. The DSM-2 model parameters that were performed and evaluated for three operational management scenarios are shown in Error! Reference source not found..

Table 7. DSM-2 Model input for scenarios evaluated in the biological review. DSM-2 run name is listed parenthetically for each scenario.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>NDOI April</th>
<th>NDOI May</th>
<th>Freeport flow (cfs)</th>
<th>Vernalis flow (cfs)</th>
<th>Combined Exports (cfs)</th>
<th>DCC Status</th>
</tr>
</thead>
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<tr>
<td>Baseline (Hydrology 1)</td>
<td>7,100</td>
<td>7,100</td>
<td>(VNS + export)</td>
<td>710 + 3100 cfs (4/1 - 5/1)</td>
<td>1,500</td>
<td>Closed</td>
</tr>
<tr>
<td>Project Description – DCC Gate Closed (Hydrology 2)</td>
<td>4,000</td>
<td>4,000</td>
<td>(Lower VNS + export)</td>
<td>300 + App. 2e flow (4/1 - 5/1)</td>
<td>1,500</td>
<td>Closed</td>
</tr>
<tr>
<td>Project Description -- DCC Gate Open (Hydrology 2')</td>
<td>4,000</td>
<td>4,000</td>
<td>(Lower VNS + export)</td>
<td>300 + App. 2e flow (4/1 - 5/1)</td>
<td>1,500</td>
<td>Open for 2 months</td>
</tr>
</tbody>
</table>

One thousand eParticles were inserted over 24 hours at each insertion point on the first day of the model simulation period of interest: April 2, 2015 until June 2, 2015. In this application, the simulation period was two months because the major changes in proposed operations occurred during April and May. The particle simulation was not extended into June both because water temperatures in the Delta were expected to be unsuitable for salmonid migration by June, and eParticles inserted on April 2 would likely have reached their fate well before June 2, leaving nothing to track. This last point highlights a limitation of a single insertion time – if the duration of the alternate operations scenarios exceeds the residence time of the eParticles, the results are only informative about the operations that occur while the eParticles are in residence in the Delta. On the other hand, interpreting the cumulative fate in a simulation with multiple insertion times per insertion point has challenges as well. The three eParticle insertion points were: (1) Sacramento River at Sherwood Harbor (representing Sacramento basin salmonids entering the north Delta); (2) Middle River at Railroad Cut (representing salmonids from either the Sacramento or San Joaquin basin in the south Delta); and (3) San Joaquin River at Mossdale (representing salmonids from the San Joaquin basin entering the south Delta). A variety of listed juvenile salmonids are expected to be present in the Delta during April and May: winter-run Chinook salmon (likely uncommon after mid-April), spring-run Chinook young-of-year, and Central Valley steelhead. Because Central Valley steelhead are present in both the Sacramento and San Joaquin basins, we included a Mossdale insertion point to represent Delta entry from the San Joaquin basin. To limit our scenarios, we dropped the “Central Delta” insertion point at the mouth of Old River. For each insertion point, per hydrology scenario (either 1, 2, or 2-prime) the output of the model run was again an excel spreadsheet with one thousand rows and several columns. There were a total of nine excel spreadsheets for these runs. The summarized results (cumulative histograms and tables) focused on the proportions of eParticles that ended up at the SWP and CVP (combined), Jersey Point, Prisoners Point, Chippis Island, or Martinez (Appendix C). The proportions of eParticles that
“died” at the SWP and CVP, any other waterbody combined, or remained “In system” were also summarized (Appendix C).

Additionally, the results of the ePTM scenarios runs for the March 24, 2015 TUC Petition were compared with “Null” PTM results, or enhanced Particles with no behavior component (Appendix C). The ePTM run in “null” mode mimics the standard PTM in DSM-2 (PTM), such that particles move passively and do not experience mortality. Summary figures were produced in either R Statistical Software or Microsoft Excel. Directional trends from the ePTM results were similar to those observed in the PTM results. For example, both ePTM and PTM runs showed a relative increase in the proportion of particles reaching the CVP and SWP during the Project Description hydrology when compared to the baseline hydrology. Likewise, both the ePTM and PTM results showed a decrease in the proportion of particles passing Chipps Island (exiting the Delta) by the end of the simulation model period of interest for the Project Description hydrology. However, there were also substantial differences in the results of the ePTM and PTM model runs. In particular, the eParticles traveled farther distances in a shorter time and therefore displayed a different spatial distribution pattern by the end of the model runs.

Spatial summaries of the percentage of eParticles that “died” per waterbody per scenario and insertion point were also explored and briefly discussed during DOSS meetings (Appendix D). Potential interpretations of spatial summaries as a tool for future decision-making, should note that behavioral parameters were calibrated based on region-scale travel times and survivals. So, while eParticles do experience very local hydrology, eParticles use region-scale rules to respond to that hydrology. This tool provides a foundation for future hydrodynamic and telemetric studies, and will require further calibration with observation in distinct reaches if accurate simulation at smaller spatial scales is desired. In order to get accurate population-level patterns, the ePTM implements certain hypotheses about how eParticles might be behaving and further studies are needed (see section 1.8) to make these more accurate. While the behavior of an individual eParticle may not be modeled exactly (i.e. some individual eParticles may appear to “swim upstream” of their respective insertion point), the pilot demonstration of the ePTM does show differences in the proportion of eParticles dying and surviving to different location in the Delta. The differences between modeled runs with distinct operational patterns are small compared to the differences of these runs results with null PTM results. These results suggest the model does a fair job of capturing aggregate patterns (refer to Appendix D). The ePTM provides a robust foundation for further hydrodynamic and telemetric investigations in the Bay-Delta. These studies should provide results for (1) more accurately parameterizing particle behavior and (2) determining if a 1-D model is sufficient to characterize multimodal and secondary circulation flows, which are also hypothesized to influence fish behavior. Spatial summaries were also produced using the R Statistical Software.

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6 In System—refers to the proportion of particles that did not reach a terminal fate and did not “expire” by the end of the model run.
3 References


20. Driscoll T., *Schwarz-Christoffel toolbox user’s guide – version 2.3*, University of Delaware, 1994


45. NMFS, *Biological opinion on the long-term Central Valley Project and State Water Project operations criteria and plan*, Report, 2009


Appendix A: NMFS ePTM FAQ Sheet, February 2015

- **How is the enhanced Particle Tracking Model (ePTM) different than the standard PTM module of DSM2?**

  The standard PTM module relies solely on passive advection or movement of particles according to the hydrodynamics of the system. The ePTM adds elements of fish behavior, such as swimming and holding, to the particle transport; these behavioral elements are governed by abiotic conditions and particle response to them. The ePTM also includes predator-induced mortality (see next FAQ).

- **Is predation included?**

  Yes. The ePTM uses the “XT Model” of Anderson *et al.* (2005) which characterizes predation-related survival as a function of distance and time travelled by the particle, predator density, predator reaction distance, and a random movement component.

- **What species does the ePTM represent?**

  To date, the ePTM has been calibrated to behavior of late-fall run Chinook salmon smolts outmigrating through the northern Delta. Though not yet calibrated for additional species and runs, or central or southern Delta regions, the ePTM is expected to be an improvement upon the standard PTM for comparing changes in salmonid distribution patterns and fates under alternate operational and hydrologic scenarios.

- **What data were used to calibrate the ePTM?**

  The calibration has relied on mark-recapture data from acoustic telemetry studies of late fall-run Chinook salmon smolts that were released into the Sacramento River in December and January of 2006 through 2009. The results provide information on fish traveling through the mainstem Sacramento River, Steamboat Slough, Sutter Slough, Georgiana Sough, and the Mokelumne River via the Delta Cross Channel. This is used to infer survival probabilities in each reach and the probability of routing.

- **Why isn’t the ePTM calibrated to south Delta data?**

  Initial efforts have focused on the north Delta because there is a rich source of acoustic telemetry data to use in the calibration. Calibrating the ePTM to south Delta data is a time-intensive effort that likely would not have been completed in time for a spring 2015 pilot application. Considering this, NMFS decided to advance the initial calibration rather than pause that and shift resources to a south Delta calibration effort at this time.

- **What dictates particle “behavior”?**
The particle behavior is based on the direction and velocity of flow, the variation (standard deviation) of water velocity, stage, and the geographic location of the fish.

- **Does behavior change based on location (e.g., upriver vs. Bay)?**

  Yes. The current version has region-specific parameters; riverine, transitional, and tidal areas have different values for the parameters that characterize behavior and mortality probabilities for those regions. This allows a “shift” from one “behavior” to another as the particle travels through the system. This could be switched to reach-specific behavior, depending on results of model calibration.

- **Will the particles have the same behavior in the same conditions?**

  On average, particles within a region (i.e., riverine, transitional, and tidal) will behave similarly, since the same parameters would apply given the abiotic conditions. However, some behavioral elements, such as swimming speed, differ between riverine, transitional, and tidal regions, so particle response to similar hydrologic conditions may be region-specific. The ePTM also includes multiple sources of stochasticity that influence the fates of individual particles under a given set of conditions. For example, probability distributions that are functions of current conditions are used to model mortality, route selection at junctions, and an individual’s assessment of which direction is ”downstream.”

- **What do fish do at junctions?**

  While the current calibration of the ePTM maintains the standard PTM method of routing particles in direct proportion to flow, future calibrations may introduce more complex routing functions such as non-linear flow relationships or combined width- and flow-based routing.

- **Has the ePTM been applied previously?**

  No. This is the initial application of the ePTM to inform management and operations decisions.

- **Is there an example of ePTM output with actual data?**

  At the moment, only raw output data are available. NMFS/DOSS are working to generate some standard output summaries and plots.

- **What interpretations or conclusions is the current version of ePTM best suited to inform?**

  This is still being determined. Because the model is in relatively early development stages, it is not clear which operational modifications it could best inform. This pilot application will help to determine the model’s strengths and limitations.
Appendix B: ePTM results (2/23/15) for OMR flex request

Disclaimer:

These results have been summarized as part of a pilot application of the enhanced Particle Tracking Model (ePTM), which is still under development. The novel “behavior” assigned to passive particles in the ePTM is an attempt to provide a better fit between the PTM predictions and empirical data on fish movement through the Sacramento San Joaquin Delta. The current “behavior” function is based on a preliminary calibration to late-fall-run Chinook movement data in the north Delta; the documentation for which is also still being developed.

Glossary:

**Insertion location:** refers to a location where the particles are inserted into the model. The insertion location can change based on monitoring information and so as to reflect the current understanding of species distribution.

**Scenario:** refers to the hydrologic conditions as described in the DSM2 output file which are used as the basis of conditions in the ePTM.

**Fate:** refers to a particular location at a given time in the model. Some fates are “terminal,” meaning once a particle reaches a terminal fate they are removed from the model (i.e. CVP, SWP or exiting the Delta)

**Exit:** refers to the geographic limit of the model. In the case of the Delta and DSM2, exit refers to those particles that have passed Martinez.

**Other Mortality:** refers to the proportion of particles that expire during the model run but do not reach a terminal fate (this is a new element of “behavior” added to the ePTM based on reach specific mortality).

**In System:** refers to proportion of particles that did not reach a terminal fate and did not expire by the end of the model run.

Model parameters:

The model parameters follow the hydrologic conditions described in Table 1 that was provided with Reclamation’s request letter. Three separate insertion locations were used for the ePTM runs of the baseline and the proposed action scenarios during which 1000 particles were “inserted” into the model on February 11. Each model was then run until March 2 (19 days after insertion).
Table 1: DSM2 Model input for scenarios evaluated in biological reviews.

<table>
<thead>
<tr>
<th>Date</th>
<th>Freeport Flow (cfs)</th>
<th>Vernal Flow (cfs)</th>
<th>Baseline</th>
<th>Proposed Action</th>
<th>Baseline</th>
<th>Proposed Action</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Outflow</td>
<td>Combined Exports</td>
<td>CMR</td>
<td>Outflow</td>
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<td>39,200</td>
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<td>-5,000</td>
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<tr>
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<td>6,000</td>
<td>-5,000</td>
<td>36,300</td>
</tr>
<tr>
<td>23 Feb</td>
<td>34,900</td>
<td>1,600</td>
<td>33,210</td>
<td>6,000</td>
<td>-5,000</td>
<td>33,210</td>
</tr>
<tr>
<td>25 Feb</td>
<td>31,900</td>
<td>1,700</td>
<td>30,110</td>
<td>6,000</td>
<td>-5,000</td>
<td>30,110</td>
</tr>
<tr>
<td>27 Feb</td>
<td>28,900</td>
<td>1,600</td>
<td>27,035</td>
<td>6,275</td>
<td>-5,000</td>
<td>27,035</td>
</tr>
<tr>
<td>29 Feb</td>
<td>25,900</td>
<td>1,500</td>
<td>24,035</td>
<td>6,175</td>
<td>-5,000</td>
<td>24,035</td>
</tr>
</tbody>
</table>

Particle Fate:

Table 1a: Sacramento particle fate as a proportion of 1000 particle “release.” Baseline and Proposed Action scenarios, Feb 11, 2015 – March 2, 2015, (19 Days) Insertion: Sherwood Harbor (DSM2 node 332)

<table>
<thead>
<tr>
<th>Sacramento Start</th>
<th>CVP</th>
<th>SWP</th>
<th>CVP &amp; SWP</th>
<th>Exit</th>
<th>Other Mort</th>
<th>In system</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>0.20%</td>
<td>0.50%</td>
<td>0.70%</td>
<td>40.00%</td>
<td>56.20%</td>
<td>3.10%</td>
<td>100.00%</td>
</tr>
<tr>
<td>Proposed Action</td>
<td>0.20%</td>
<td>0.80%</td>
<td>1.00%</td>
<td>40.60%</td>
<td>55.60%</td>
<td>2.80%</td>
<td>100.00%</td>
</tr>
</tbody>
</table>

Table 1b: Central Delta particle fate as a proportion of 1000 particle “release.” Baseline and Proposed Action scenarios, Feb 11, 2015 – March 2, 2015, (19 Days) Insertion: Mouth of Old River (DSM2 node 39, DJFMP “Prisoner’s Point” station #815)

<table>
<thead>
<tr>
<th>Central Delta Start</th>
<th>CVP</th>
<th>SWP</th>
<th>CVP &amp; SWP</th>
<th>Exit</th>
<th>Other Mort</th>
<th>In system</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>2.30%</td>
<td>9.50%</td>
<td>11.80%</td>
<td>37.40%</td>
<td>39.70%</td>
<td>11.10%</td>
<td>100.00%</td>
</tr>
<tr>
<td>Proposed Action</td>
<td>1.90%</td>
<td>12.10%</td>
<td>14.00%</td>
<td>34.10%</td>
<td>39.50%</td>
<td>12.40%</td>
<td>100.00%</td>
</tr>
</tbody>
</table>

Table 1c: South Delta particle fate as a proportion of 1000 particle “release.” Baseline and Proposed Action scenarios, Feb 11, 2015 – March 2, 2015, (19 Days) Insertion: Middle River at Woodward Island (DSM2 node 121, SWFSC real time receiver location)

<table>
<thead>
<tr>
<th>South Delta Start</th>
<th>CVP</th>
<th>SWP</th>
<th>CVP &amp; SWP</th>
<th>Exit</th>
<th>Other Mort</th>
<th>In system</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>7.60%</td>
<td>37.20%</td>
<td>44.80%</td>
<td>3.00%</td>
<td>23.40%</td>
<td>28.80%</td>
<td>100.00%</td>
</tr>
<tr>
<td>Proposed Action</td>
<td>6.90%</td>
<td>41.30%</td>
<td>48.20%</td>
<td>2.50%</td>
<td>22.40%</td>
<td>26.40%</td>
<td>100.00%</td>
</tr>
</tbody>
</table>
Appendix C: NMFS ePTM results (3/23/15) for TUCP April – May

Model developed by: National Marine Fisheries Service’ Southwest Fisheries Science Center (SWFSC)
DSM2 Hydro provided by: California Department of Water Resources (DWR)
Model run and summarized by: NMFS California Central Valley Area Office (CCVAO)

Disclaimer:
These results have been summarized as part of a pilot application of the enhanced Particle Tracking Model (ePTM), which is still under development. The novel “behavior” assigned to passive particles in the ePTM is an attempt to provide a better fit between the PTM predictions and empirical data on fish movement through the Sacramento San Joaquin Delta. The current “behavior” function is based on a preliminary calibration to late-fall-run Chinook movement data in the north Delta; the documentation for which is also still being developed.

Glossary:
**Insertion location:** refers to a location where the particles are inserted into the model. The insertion location can change based on monitoring information and so as to reflect the current understanding of species distribution.

**Scenario:** refers to the hydrologic conditions as described in the DSM2 output file which are used as the basis of conditions in the ePTM.

**Fate:** refers to a particular location at a given time in the model. Some fates are “terminal,” meaning once a particle reaches a terminal fate they are removed from the model (i.e. CVP, SWP or exiting the Delta)

**Exit:** refers to the geographic limit of the model. In the case of the Delta and DSM2, exit refers to those particles that have passed Martinez.

**Other Mortality:** refers to the proportion of particles that expire during the model run but do not reach a terminal fate (this is a new element of “behavior” added to the ePTM based on reach specific mortality).

**In System:** refers to proportion of particles that did not reach a terminal fate and did not expire by the end of the model run.

Model parameters:
The model parameters follow the hydrologic conditions described in Table 1 that was provided with Reclamation’s Biological Review. Three separate insertion locations were used for the ePTM runs of the Baseline, the Project Description (DCC gate closed), and Project Description (DCC gate open) scenarios during which 1000 particles were “inserted” into the model on April 1. Each model was then run until June 2 (60 days after insertion).
Table 1. DSM2 Model input for scenarios evaluated in the biological review. DSM2 run name is listed parenthetically for each scenario.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>NDOI</th>
<th>Freeport flow (cfs)</th>
<th>Vernalis flow (cfs)</th>
<th>Combined Exports (cfs)</th>
<th>DCC Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline (Hydrology 1)</td>
<td>7.100</td>
<td>7,100 - (VNS + export)</td>
<td>710 - 3,100 cfs (4/1 - 5/1)</td>
<td>1,500</td>
<td>Closed</td>
</tr>
<tr>
<td>Project Description – DCC Gate Closed (Hydrology 2)</td>
<td>4,000</td>
<td>4,000 - (Lower VNS + export)</td>
<td>300 - App. 2e flow (4/1 - 5/1)</td>
<td>1,500</td>
<td>Closed</td>
</tr>
<tr>
<td>Project Description – DCC Gate Open (Hydrology 2')</td>
<td>4,000</td>
<td>4,000 - (Lower VNS + export)</td>
<td>300 - App. 2e flow (4/1 - 5/1)</td>
<td>1,500</td>
<td>Open for 2 months</td>
</tr>
</tbody>
</table>

Particle Fate:
Table 1a: Sacramento particle fate as a proportion of 1000 particle “release.” Baseline, Project Description (DCC gate closed), and Project Description (DCC gate open) scenarios, April 1, 2015 – June 2, 2015, (60 Days) Insertion: Sherwood Harbor (DSM2 node 332)

<table>
<thead>
<tr>
<th>Sacramento Insert.</th>
<th>Jersey Point Passage</th>
<th>Prisoners Point Passage</th>
<th>Chipp's Island</th>
<th>CVP &amp; SWP</th>
<th>Exit</th>
<th>Other Mort.</th>
<th>In system</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline (Hydro 1)</td>
<td>8.70%</td>
<td>1.10%</td>
<td>36.40%</td>
<td>0.00%</td>
<td>37.00%</td>
<td>62.90%</td>
<td>0.10%</td>
<td>100.00%</td>
</tr>
<tr>
<td>PD (Hydro 2)</td>
<td>6.30%</td>
<td>5.20%</td>
<td>33.80%</td>
<td>0.30%</td>
<td>35.60%</td>
<td>63.70%</td>
<td>0.40%</td>
<td>100.00%</td>
</tr>
<tr>
<td>PD (Hydro 2')</td>
<td>9.20%</td>
<td>3.50%</td>
<td>33.20%</td>
<td>0.20%</td>
<td>36.50%</td>
<td>63.10%</td>
<td>0.20%</td>
<td>100.00%</td>
</tr>
</tbody>
</table>

Proportion of particles arriving from Sacramento (Sherwood Harbor) insertion location, (4/1/15 - 6/2/15)

1 The TUCP identifies proposed modification of the average monthly flow during the Vernals 31-day pulse flow period to be no less than 710 cfs.
Table 1b: Central/South Delta particle fate as a proportion of 1000 particle “release.” Baseline, Project Description (DCC gate closed), and Project Description (DCC gate open) scenarios, April 1, 2015 – June 2, 2015. (60 Days) Insertion: Middle River at Railroad Cut (DSM2 node 121, SWFSC real time receiver location)

<table>
<thead>
<tr>
<th>Middle River Inset</th>
<th>Jersey Point Passage</th>
<th>Prisoners Point Passage</th>
<th>Chipp’s Island</th>
<th>CVP &amp; SWP</th>
<th>Exit</th>
<th>Other Mort.</th>
<th>In system</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline (Hydro 1)</td>
<td>21.90%</td>
<td>14.90%</td>
<td>20.00%</td>
<td>20.10%</td>
<td>19.60%</td>
<td>59.30%</td>
<td>1.00%</td>
<td>100.00%</td>
</tr>
<tr>
<td>PD (Hydro 2)</td>
<td>13.30%</td>
<td>15.20%</td>
<td>11.30%</td>
<td>32.10%</td>
<td>10.50%</td>
<td>56.60%</td>
<td>0.80%</td>
<td>100.00%</td>
</tr>
<tr>
<td>PD (Hydro 2’)</td>
<td>15.10%</td>
<td>15.50%</td>
<td>12.00%</td>
<td>31.70%</td>
<td>11.50%</td>
<td>56.00%</td>
<td>0.80%</td>
<td>100.00%</td>
</tr>
</tbody>
</table>

Table 1c: San Joaquin particle fate as a proportion of 1000 particle “release.” Baseline, Project Description (DCC gate closed), and Project Description (DCC gate open) scenarios, April 1, 2015 – June 2, 2015. (60 Days) Insertion: Mossdale Crossing (DSM2 node 6)

<table>
<thead>
<tr>
<th>Sacramento Insert.</th>
<th>Jersey Point Passage</th>
<th>Prisoners Point Passage</th>
<th>Chipp’s Island</th>
<th>CVP &amp; SWP</th>
<th>Exit</th>
<th>Other Mort.</th>
<th>In system</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline (Hydro 1)</td>
<td>23.20%</td>
<td>24.10%</td>
<td>22.10%</td>
<td>14.00%</td>
<td>21.30%</td>
<td>64.70%</td>
<td>0.00%</td>
<td>100.00%</td>
</tr>
<tr>
<td>PD (Hydro 2)</td>
<td>10.50%</td>
<td>17.50%</td>
<td>8.10%</td>
<td>18.00%</td>
<td>7.50%</td>
<td>74.00%</td>
<td>0.50%</td>
<td>100.00%</td>
</tr>
<tr>
<td>PD (Hydro 2’)</td>
<td>10.80%</td>
<td>18.60%</td>
<td>8.80%</td>
<td>20.80%</td>
<td>9.00%</td>
<td>69.80%</td>
<td>0.40%</td>
<td>100.00%</td>
</tr>
</tbody>
</table>
Proportion of particles arriving from Mossdale insertion location,
(4/1/15 - 6/2/15)

- Baseline (Hydro 1)
- PD Hydro 2
- PD Hydro 2' (DCC open)
Insertion = Sacramento R. at Sac, Fate = Chipps
With Behavior

Insertion = Sacramento R. at Sac, Fate = Chipps
No Behavior
Insertion= Sacramento R. at Sac, Fate= Martinez
With Behavior

Insertion= Sacramento R. at Sac, Fate= Martinez
No Behavior
Insertion= Middle River at Railroad Cut, Node=Jersey Pt.  
With Behavior

Cumulative Percentage of enhanced Particles

Days after enhanced particle insertion (Apr 1 - May 31, 2015)

Insertion= Middle River at Railroad Cut, Node=Jersey Pt.  
No Behavior

Cumulative Percentage of enhanced Particles

Days after enhanced particle insertion (Apr 1 - May 31, 2015)
Insertion= Middle River at Railroad Cut, Node=Prisoner's Pt.
With Behavior

Insertion= Middle River at Railroad Cut, Node=Prisoner's Pt.
No Behavior
Insertion: San Joaquin River at Mossdale, Fate=SWP & CVP
With Behavior

Cumulative Percentage of enhanced Particles

Days after enhanced particle insertion (Apr 1 - May 31, 2015)

Insertion: San Joaquin River at Mossdale, Fate=SWP & CVP
No Behavior

Cumulative Percentage of enhanced Particles

Days after enhanced particle insertion (Apr 1 - May 31, 2015)
Insertion= San Joaquin River at Mossadale, Fate=Martinez
With Behavior

Insertion= San Joaquin River at Mossadale, Fate=Martinez
No Behavior
“Null” PTM results (3/23/15) for TUCP April - September

For comparison with ePTM results – NO behavior and NO mortality.

Glossary:

Insertion location: refers to a location where the particles are inserted into the model. The insertion location can change based on monitoring information and so as to reflect the current understanding of species distribution.

Scenario: refers to the hydrologic conditions as described in the DSM2 output file which are used as the basis of conditions in the PTM.

Fate: refers to a particular location at a given time in the model. Some fates are “terminal,” meaning once a particle reaches a terminal fate they are removed from the model (i.e. CVP, SWP or exiting the Delta)

Exit: refers to the geographic limit of the model. In the case of the Delta and DSM2, exit refers to those particles that have passed Martinez.

Other Mortality: Not applicable in the “null” PTM runs.

In system: refers to proportion of particles that did not reach a terminal fate and did not expire by the end of the model run.

Model parameters:

The model parameters follow the hydrologic conditions described in Table 1 that was provided with Reclamation’s Biological Review. Three separate insertion locations were used for the PTM runs of the Baseline, the Project Description (DCC gate closed), and Project Description (DCC gate open) scenarios during which 1000 particles were “inserted” into the model on April 1. Each model was then run until June 2 (60 days after insertion).

Table 1. DSM2 Model input for scenarios evaluated in the biological review. DSM2 run name is listed parenthetically for each scenario.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>NDOI</th>
<th>Freeroute flow (cfs)</th>
<th>Vernals flow (cfs)</th>
<th>Combined Exports (cfs)</th>
<th>DCC Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline (Hydrology 1)</td>
<td>7.100</td>
<td>7.100- (VNS +export)</td>
<td>710-3100 cfs (4/1-5/1)</td>
<td>1,500</td>
<td>Closed</td>
</tr>
<tr>
<td>Project Description – DCC Gate Closed (Hydrology 2)</td>
<td>4.000</td>
<td>4,000- (Lower VNS +export)</td>
<td>300+ App. 2c flow (4/1-5/1)</td>
<td>1,500</td>
<td>Closed</td>
</tr>
<tr>
<td>Project Description -- DCC Gate Open (Hydrology 2)</td>
<td>4.000</td>
<td>4,000- (Lower VNS +export)</td>
<td>300+ App. 2c flow (4/1-5/1)</td>
<td>1,500</td>
<td>Open for 2 months</td>
</tr>
</tbody>
</table>

1 The TUCP identifies proposed modification of the average monthly flow during the Vernals 31-day pulse flow period to be no less than 710 cfs.
Particle Fate:

Table 1a: Sacramento particle fate as a proportion of 1000 particle “release.” Baseline, Project Description (DCC gate closed), and Project Description (DCC gate open) scenarios, April 1, 2015 – June 2, 2015, (60 Days) Insertion: Sherwood Harbor (DSM2 node 332)

<table>
<thead>
<tr>
<th>Sacramento Start</th>
<th>Jersey Point</th>
<th>Prisoners Point</th>
<th>Chipp's</th>
<th>CVP &amp; SWP</th>
<th>Exit</th>
<th>Other Mort</th>
<th>In system</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline (Hydro 1)</td>
<td>61.00%</td>
<td>50.80%</td>
<td>32.40%</td>
<td>0.40%</td>
<td>41.90%</td>
<td>0.00%</td>
<td>57.70%</td>
<td>100.00%</td>
</tr>
<tr>
<td>PD Hydro 2</td>
<td>57.80%</td>
<td>68.90%</td>
<td>22.10%</td>
<td>1.50%</td>
<td>22.80%</td>
<td>0.00%</td>
<td>75.70%</td>
<td>100.00%</td>
</tr>
<tr>
<td>PD Hydro 2' (DCC open)</td>
<td>56.20%</td>
<td>57.90%</td>
<td>17.60%</td>
<td>0.80%</td>
<td>19.20%</td>
<td>0.00%</td>
<td>80.00%</td>
<td>100.00%</td>
</tr>
</tbody>
</table>

Proportion of particles arriving from Sacramento (Sherwood Harbor) insertion location, (4/1/15 - 6/2/15)

Table 1b: Central/South Delta particle fate as a proportion of 1000 particle “release.” Baseline, Project Description (DCC gate closed), and Project Description (DCC gate open) scenarios, April 1, 2015 – June 2, 2015, (60 Days) Insertion: Middle River at Railroad Cut (DSM2 node 121, SWFSC real time receiver location)

<table>
<thead>
<tr>
<th>Middle River</th>
<th>Jersey Point</th>
<th>Prisoners Point</th>
<th>Chipp's</th>
<th>CVP &amp; SWP</th>
<th>Exit</th>
<th>Other Mort</th>
<th>In system</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline (Hydro 1)</td>
<td>3.70%</td>
<td>2.80%</td>
<td>1.80%</td>
<td>81.20%</td>
<td>1.60%</td>
<td>0.00%</td>
<td>17.20%</td>
<td>100.00%</td>
</tr>
<tr>
<td>PD Hydro 2</td>
<td>1.80%</td>
<td>1.90%</td>
<td>0.30%</td>
<td>82.70%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>17.30%</td>
<td>100.00%</td>
</tr>
<tr>
<td>PD Hydro 2' (DCC open)</td>
<td>2.00%</td>
<td>2.50%</td>
<td>0.30%</td>
<td>84.00%</td>
<td>0.20%</td>
<td>0.00%</td>
<td>15.80%</td>
<td>100.00%</td>
</tr>
</tbody>
</table>
Proportion of particles arriving from Middle River insertion location, (4/1/15 - 6/2/15)

Table 1c: San Joaquin particle fate as a proportion of 1000 particle “release.” Baseline, Project Description (DCC gate closed), and Project Description (DCC gate open) scenarios, April 1, 2015 – June 2, 2015, (60 Days) Insertion: Mossdale Crossing (DSM2 node 6)

<table>
<thead>
<tr>
<th>Mossdale</th>
<th>Jersey Point</th>
<th>Prisoners Point</th>
<th>Chipp's</th>
<th>CVP &amp; SWP</th>
<th>Exit</th>
<th>Other Mort</th>
<th>In system</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline (Hydro 1)</td>
<td>23.80%</td>
<td>36.40%</td>
<td>7.30%</td>
<td>21.80%</td>
<td>5.70%</td>
<td>0.00%</td>
<td>72.50%</td>
<td>100.00%</td>
</tr>
<tr>
<td>PD Hydro 2</td>
<td>2.00%</td>
<td>3.10%</td>
<td>0.20%</td>
<td>33.10%</td>
<td>0.10%</td>
<td>0.00%</td>
<td>66.80%</td>
<td>100.00%</td>
</tr>
<tr>
<td>PD Hydro 2' (DCC open)</td>
<td>3.70%</td>
<td>5.80%</td>
<td>1.00%</td>
<td>31.10%</td>
<td>0.30%</td>
<td>0.00%</td>
<td>68.60%</td>
<td>100.00%</td>
</tr>
</tbody>
</table>

Proportion of particles arriving from Mossdale insertion location, (4/1/15 - 6/2/15)
Appendix D: Spatial summaries of ePTM results for percentage of eParticles that “died” per waterbody for TUCP April-May