Implications of Using Mechanistic Versus Phenomenological Models of Juvenile Salmon Rearing and Migration In The Sacramento-San Joaquin Delta for Life Cycle Model Applications in Evaluating Biological Assessments

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Executive summary

The Winter Run Chinook Life Cycle Model (WRCLCM) was run for evaluating the Reinitiation of Consultation (ROCon) scenarios using the STARS model for predicting survival of smolts migrating through the Delta. It was found that the survival of migrating smolt was independent of the exports through the South Delta pumps because the STARS model does not use exports as an explanatory variable. For this reason, one alternative is to re-run the WRCLCM with the Newman model, in which the exports feature as a covariate. Additionally, the habitat capacity estimates in the Delta were not used in this analysis to weight the distribution of Delta-rearing fry. We discuss the rationale and implications of these choices and outline a future course of action when the ePTM does become available.

1. Introduction

The WRCLCM (Hendrix et al., 2014) involves the rearing and migration of fry in the Delta. This step has typically been performed using the distribution of fry in the Delta according to the relative carrying capacities in different parts of the Delta, and subsequently moving those fry through the system using the ePTM. However, for evaluating the ROCon Proposed Alternative (PA) and Current Operations Scenario (COS) scenarios, the Survival, Travel time and Routing Simulation (STARS) model of Perry et al. (2018) was used. This is because the ePTM is undergoing updates that will make it more biologically plausible, data-driven, and parsimonious.

2. **STARS model description**

The Delta STARS Model is an individual-based simulation model that predicts survival, travel time, and routing of juvenile salmon migrating through the Delta. The model's structure and parameters are based on a recent analysis (Perry et al. 2018) that relates individual survival, travel time, and routing of late-fall Chinook salmon to daily Sacramento River flows at Freeport and Delta Cross Channel (DCC) operations.

It is important to note that the STARS model is based on a set of relationships fitted to hatchery-origin late-fall Chinook salmon that migrated through the Delta between late November and mid-March over a five-year period (2007 - 2011). Therefore, model output should be thought of as a historical expectation. That is, the model provides predictions about survival based on what we know about a particular race that migrated through the Delta during a particular time of year under the environmental, operational, and physical characteristics of the Delta that occurred between 2007 and 2011.

Output from the model can be useful when used in conjunction with real time telemetry data to help understand what we might expect to occur based on what we have seen in the past. When real-time data and in-season observations deviate from the historical expectation, such deviations provide an important opportunity to learn about system dynamics.

2.1. ***Model simulations***

The STARS model simulates travel time, routing, and survival of individuals in a daily cohort as they migrate through eight unique reaches of the Delta (Figure 1). A daily cohort is defined as all fish that enter the Delta on a given day at Freeport. Because travel time, routing, and survival depends on river flow when an individual enters a given reach, overall survival of a daily cohort depends on the entire time series of daily flows during their migration time through the Delta. For example, two cohorts may enter the Delta at the same discharge, but their overall survival will differ if one cohort enters during an ascending hydrograph and another enters when it is descending.

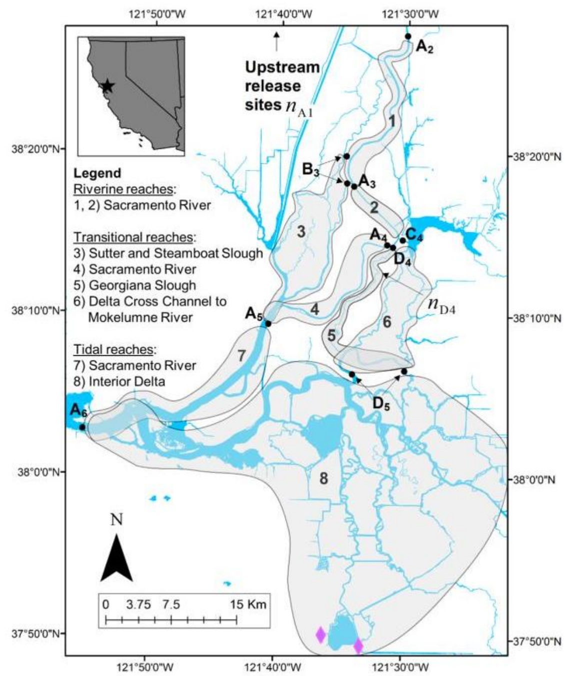

Figure 1. Reaches represented in the STARS model

2.2. *Model workflow*

The following pseudocode describes how travel time, survival, and routing are simulated given a daily time series of discharge and Delta Cross Channel gate operations:

1. Select parameter set i from the joint posterior parameter distribution (see Perry et al. 2018 for details).
2. Initiate the simulation with 1,000 fish at Freeport on day t.
3. Calculate survival in reach 1 given discharge on day t and parameter set i.
4. Draw individual travel times through reach 1 from a log-normal distribution where the mean of the distribution depends on parameter set i and discharge on day t. This yields a distribution of arrival times at the junction of Sutter and Steamboat Slough with the Sacramento River. Currently, if a fish's arrival time in a reach is later than the last date of available flow data, then the model assumes that flow remains constant based on the last date of available flow data. In the future, river flow forecasts would be incorporated so that the model provides more realistic real-time survival predictions.

5. Draw the route taken by each fish from a Bernoulli distribution where the probability of entering Sutter and Steamboat Slough is a function of discharge on the day each fish arrives at the junction.
6. Calculate the survival probability of each individual for the next reach downstream (Sacramento River or Sutter and Steamboat Sloughs) given the discharge on the day each fish entered the next reach.
7. Draw travel times for each individual for the next downstream reach given the discharge on the day each fish entered the reach.
8. For fish remaining in the Sacramento River, draw the route taken by fish at the junction of the Sacramento River with the DCC and Georgiana Slough from a multiple Bernoulli distribution where the probability of entering each route depends on the position of the DCC gates and discharge on the day each fish arrived at the junction.
9. Repeat steps 6 and 7 for all remaining reaches.
10. Repeat steps 2-9 for all days in the simulation.
11. Repeat 1-10 for all iterations of the joint posterior distribution.

This simulation yields a posterior distribution of reach-specific survival probabilities, reach-specific travel times, and routing histories for a cohort of 1,000 individuals entering the Delta at Freeport on each day of the daily time series.

2.3. *Model extension to Yolo Bypass*

To account for survival in Yolo Bypass, which begins just downstream of the Freemont Weir, near the mouth of the Feather River, the Bayesian survival model on which STARS is based has been refit using the same data set as used in Perry et al. (2018) to estimate survival and travel time relationships for the Sacramento River between the mouth of the Feather River and Freeport. This slight modification has no effect on the other parameters in the model reported by Perry et al. (2018). Below are figures showing the new survival and travel time relationships for this reach (Figure 2) and how they influence the overall travel time and survival relationship relative to those reported in Perry et al. (2018) [Figure 2].

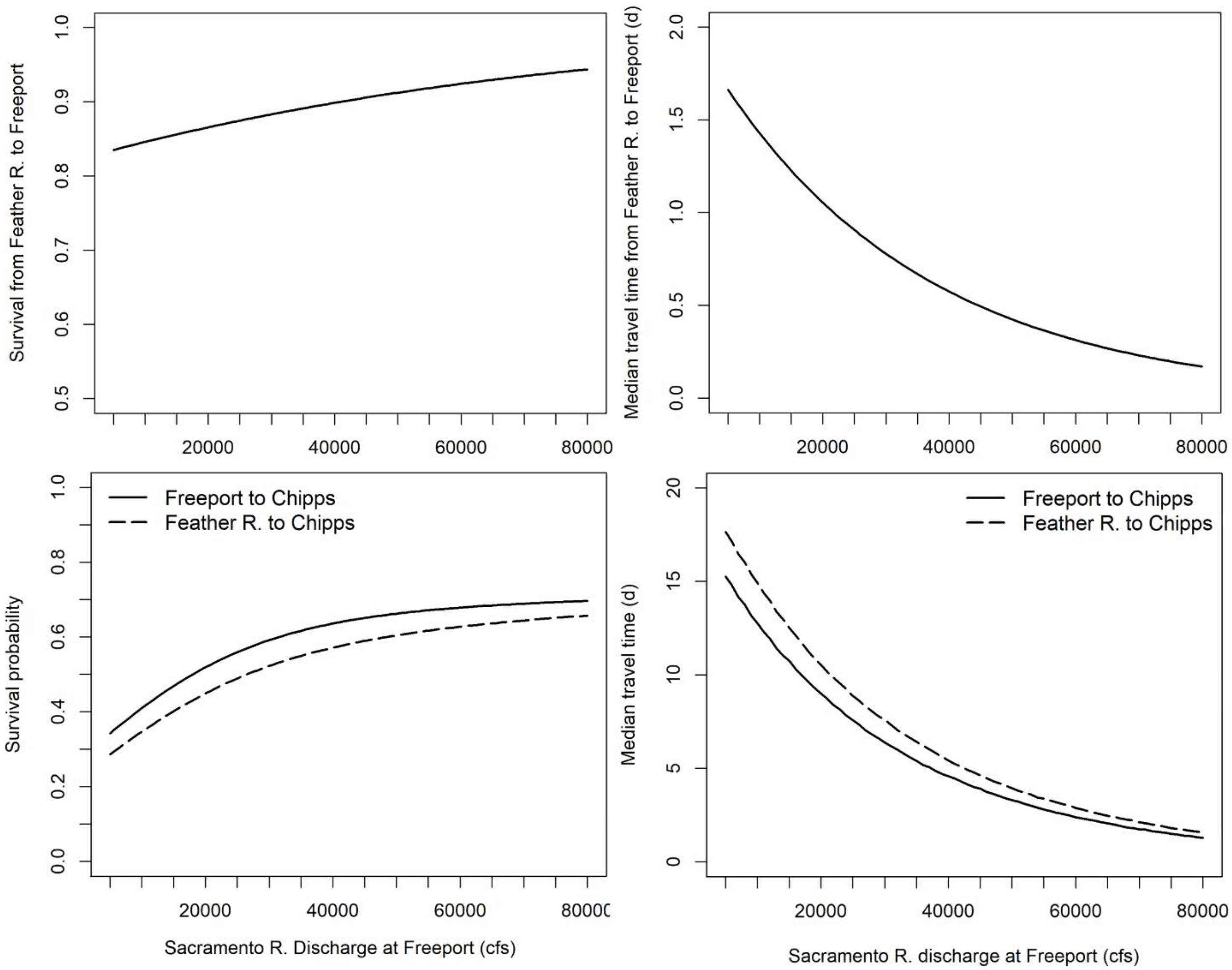

Figure 2. STARS model applied to Yolo Bypass. The top plots show the survival and travel time as a function of Sacramento River flow for the reach between the Feather River and Freeport. The bottom plots show the same quantities between the Feather River and Chipps Island.

3. Rationale for not using the habitat capacity to redistribute Delta-rearing fry with the STARS model

STARS is a statistical model that simulates the movement of salmon through different reaches of the Delta and estimates their survival probability from the beginning of each reach to Chipps Island (Perry et al., 2018). Typically, the survival through the Delta in individual based models such as the ePTM or STARS is modeled and then weighted by the distribution of individual simulated fry in different regions within the Delta. For the ePTM, these are DSM2 nodes. For STARS, they are the reaches in the model. Owing to the lack of reliable data with which to build the habitat capacity estimation model in the ROCon scenarios, any result that includes the habitat-based redistribution will likely involve large uncertainty. This is borne our in a comparative analysis of the survival of migrating smolt based on three different distribution methods of Delta-rearing fry. Note that in these comparisons, the survivals in the historic years between 1980 and 2010, as well as the habitat capacities estimated in those years were used. The habitat-based distribution of fry was hence not carried out in these runs.

3.1. *Distribution according to routing probabilities*

The STARS model assumes that fry rearing in the Delta enter a reach with a probability of entering that reach three months prior to the actual simulation of smolts for that month. We do not include the River reach, S_0 in this analysis. Under this assumption, the weighted average monthly survival, S_Δ^i, in a month i is

$$S_\Delta^i = \frac{S_1^i + \left(1-\psi_{SS}^{i-3}\right)S_2^i + \psi_{SS}^{i-3}S_3^i + \psi_{Sac}^{i-3}S_4^i + \psi_{Geo}^{i-3}S_5^i + \psi_{DCC}^{i-3}S_5^i + \left(\psi_{Sac}^{i-3} + \psi_{SS}^{i-3}\right)S_7^i + \left(\psi_{Geo}^{i-3} + \psi_{DCC}^{i-3}\right)S_8^i}{2\left(1+\psi_{Sac}^{i-3} + \psi_{Geo}^{i-3} + \psi_{DCC}^{i-3}\right) + \psi_{SS}^{i-3}} \quad \ldots (1)$$

where S_j^i is the survival from the beginning of reach j to Chipps Island of smolts that have arrived at that reach as fry three months ago with probability P_j^{i-3} from the previous reach and reared there. For example, for reach 2, $P_2^{i-3} = \left(1 - \psi_{SS}^{i-3}\right)$, while for reach 7, $P_7^{i-3} = \left(\psi_{Sac}^{i-3} + \psi_{SS}^{i-3}\right)$. ψ_j^{i-3}s are the total probabilities of arriving at reach j. The routing probabilities are estimated in the STARS model.

The assumption in (1) is that the fry are distributed in each reach according to their probability of getting there.

3.2. *Distribution according to the hypothesis of the ideal free distribution*

In ePTM post-processing, we assume that smolt that have been released from each DSM2 node and subsequently simulated, are in fact distributed according to the carrying capacities associated with those nodes. This is known as a the hypothesis of ideal free distribution (Shepard and Litvak, 2004). Summing over nodes per reach, an equivalent STARS result is

$$S_\Delta^i = \frac{\sum_{j=1}^{8} K_j^i S_j^i}{\sum_{j=1}^{8} K_j^i}; \qquad \ldots (2)$$
$$K_j^i = \sum_{m=1}^{8} k_m \left(\sum_{n=1}^{n_j} A_{mn}^i\right)$$

where, k_m is the carrying capacity per unit area for a class m habitat, and in reach j in month i, K_j^i is the carrying capacity, A_{mn}^i is the area of class m habitat available at node n, and n_j is the number of nodes within that reach.

3.3.***Distribution according to habitat colonization***

In this hybrid formulation, we account for fry entering various reaches with different probabilities three months prior to their maturation to smolt, as well as the probability of the colonization of these reaches based on the relative carrying capacities of the reaches. The rationale is that since the system is rarely carrying capacity limited, it is unreasonable to expect that fry will occupy regions of poor habitat within the interior Delta purely according to the ideal free distribution. We refer to the schematic shown in Figure 3.

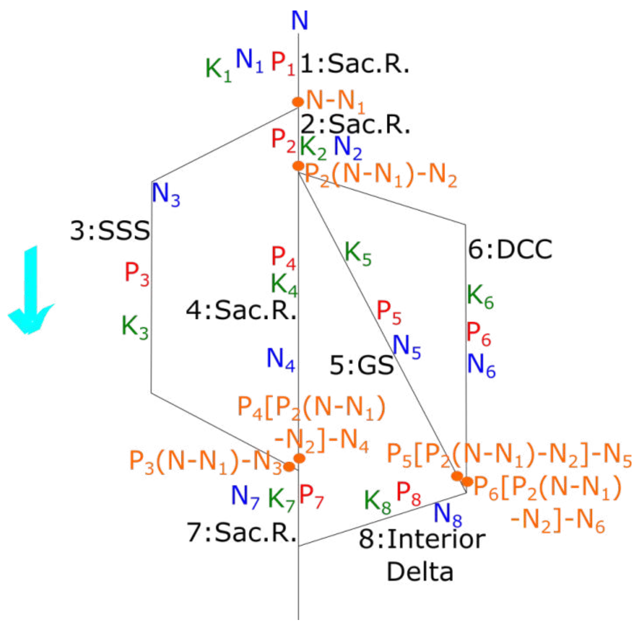

Figure 3. The reaches of the STARS model. Black text indicates the reach and the STARS reach code (refer to Figure 1). The blue arrow indicates the direction of the mean river flow. Text indicates the carrying capacity of each reach estimated from (2) [green], the probability of entering each reach from the previous reach (red), the number of fry that arrive into the system and decide to rear in each reach (blue), and the number of fry left to enter the subsequent downstream reach after the colonization of the upstream reach is completed (orange). The orange circles indicate the end of each upstream reach.

From the definition of the STARS model framework, we have

$$\begin{aligned}
\psi_{Sac} &= (1-\psi_{SS})P_4 \\
\psi_{Geo} &= (1-\psi_{SS})P_5 \\
\psi_{DCC} &= (1-\psi_{SS})(1-P_4-P_5) \\
\psi_7 &= \psi_{SS}+\psi_{Sac} = \psi_{SS}(1-P_4)+P_4 \\
\psi_8 &= \psi_{Geo}+\psi_{DCC} = (1-\psi_{SS})(1-P_4)
\end{aligned} \quad \ldots (3)$$

which gives

$$
\begin{aligned}
P_1 &= 1\\
P_2 &= 1 - \psi_{SS}\\
P_3 &= \psi_{SS}\\
P_4 &= \frac{\psi_{Sac}}{1-\psi_{SS}}\\
P_5 &= \frac{\psi_{Geo}}{1-\psi_{SS}}\\
P_6 &= \frac{1-\psi_{SS}-\psi_{Sac}-\psi_{Geo}}{1-\psi_{SS}}\\
P_7 &= \psi_{SS} + \psi_{Sac}\\
P_8 &= \psi_{Geo} + \psi_{DCC}
\end{aligned} \quad \ldots (4)
$$

Now, as fry enter each reach, we assume that they can only choose between the reach they have entered and the downstream reaches they have access to. With this assumption, the distribution based on the carrying capacities becomes

$$
\begin{aligned}
w_1 &= \frac{K_1^i}{\sum_{j=1}^{8} K_j^i}\\
w_2 &= \frac{K_2^i}{\sum_{j=2}^{8} K_j^i}\\
w_3 &= \frac{K_3^i}{\sum_{j=2}^{8} K_j^i}\\
w_4 &= \frac{K_4^i}{\sum_{j=4}^{8} K_j^i}\\
w_5 &= \frac{K_5^i}{\sum_{j=4}^{8} K_j^i}\\
w_6 &= \frac{K_6^i}{\sum_{j=4}^{8} K_j^i}\\
w_7 &= \frac{K_7^i}{K_1^i+K_2^i+K_3^i+K_4^i+K_7^i}\\
w_8 &= \frac{K_8^i}{K_1^i+K_2^i+K_5^i+K_6^i+K_8^i}
\end{aligned} \quad \ldots (5)
$$

Note that we assume that the colonization happens over the three-month period, and that the final distribution of smolts beginning their migration is based on the carrying capacities in the month of maturation. This is a simplifying assumption.

After algebraic manipulation, in which we estimate that of N fry that enter the system, for the j^{th} reach, there is a probability of entry of N_j remaining fish into that reach from the upstream reach (the orange numbers in Figure 3) of P_j^{i-3} and a probability of colonization given by w_j, the fraction of fish, and hence the weights ascribed to the survival from each reach due to the arrival of fry three months earlier, and their colonization of the reaches is given by

$$
\begin{aligned}
rcw_1 &= w_1 \\
rcw_2 &= (1-w_1)w_2(1-\psi_{SS}) \\
rcw_3 &= (1-w_1)w_2\psi_{SS} \\
rcw_4 &= (1-w_1)(1-w_2)w_4\psi_{Sac} \\
rcw_5 &= (1-w_1)(1-w_2)w_5\psi_{Geo} \\
rcw_6 &= (1-w_1)(1-w_2)w_6(1-\psi_{SS}-\psi_{Sac}-\psi_{Geo}) \\
rcw_7 &= (1-w_1)w_7[(1-w_3)\psi_{SS}+(1-w_2)(1-w_4)\psi_{Sac}] \\
rcw_8 &= (1-w_1)(1-w_2)w_8[(1-w_5)\psi_{Geo}+(1-w_6)(1-\psi_{SS}-\psi_{Sac}-\psi_{Geo})]
\end{aligned}
\quad \ldots (6)
$$

The overall survival is then given by

$$S_{\Delta}^{i} = \frac{\sum_{j=1}^{8} rcw_j S_j^i}{\sum_{j=1}^{8} rcw_j} \quad \ldots (7)$$

3.4.***Comparison of survivals among the three approaches***

We plot the three timeseries of survival in Figure 4. In Figures 5 and 6, the survivals from the different formulations are compared. In these plots, S_all_RW, S_all_CW and S_all_RCW respectively indicate the overall survival with the STARS formulation, the ePTM formulation and the hybrid formulation. Since in the STARS model, the interior Delta is disproportionately large compared with the other reaches, we also report the results after ignoring this reach in Figures 7 to 9. In all these figures, we report the survival estimated from December to May of 1980 to 2010.

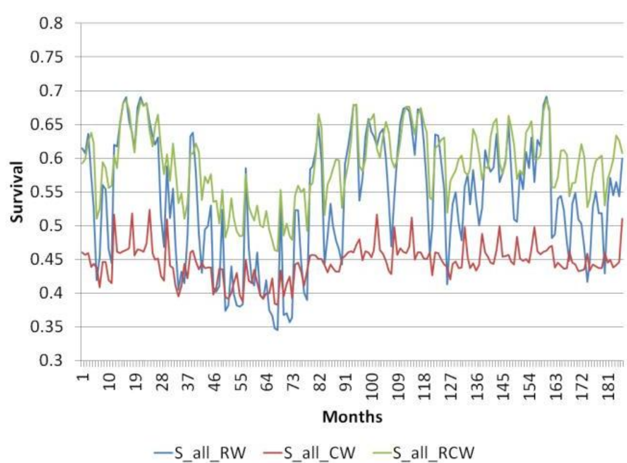

Figure 4. Timeseries of survival estimated by different methods.

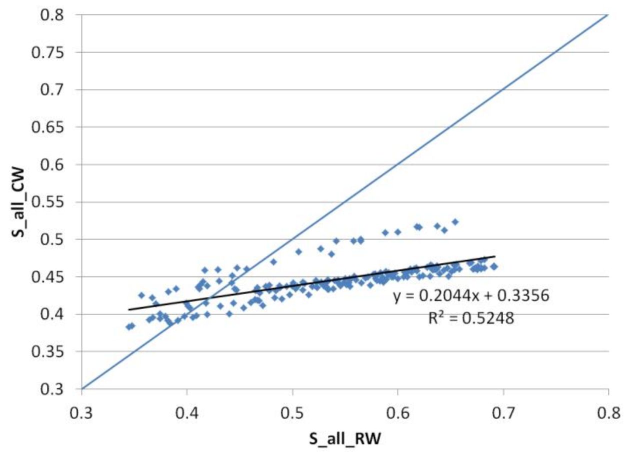

Figure 5. Comparison of STARS vs ePTM equivalent formulation. Black line and equation indicate the OLS fit. The 1:1 line is indicated in blue.

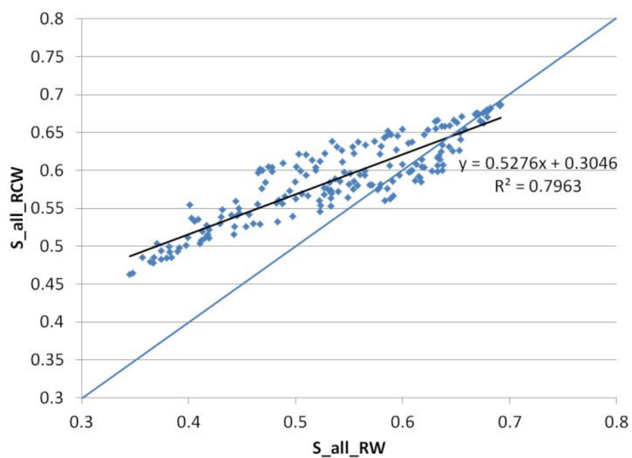

Figure 6. Comparison of STARS vs hybrid formulation. Black line and equation indicate the OLS fit. The 1:1 line is indicated in blue.

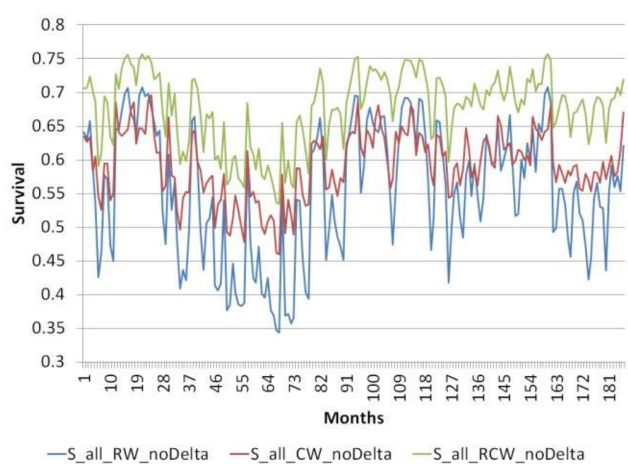

Figure 7. Timeseries of survival estimated by different methods after neglecting the interior Delta.

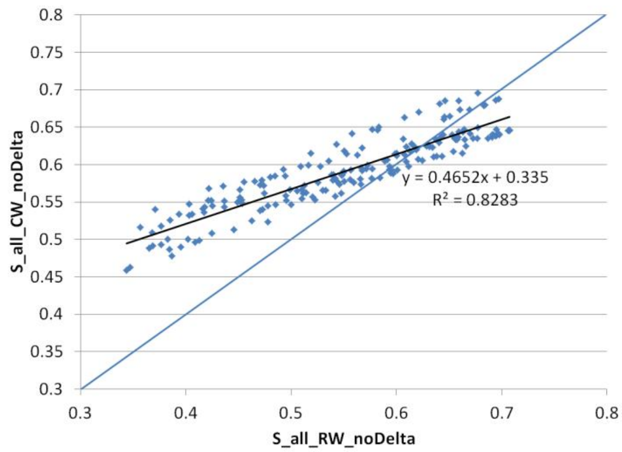

Figure 8. Comparison of STARS vs ePTM equivalent formulation after neglecting the interior Delta. Black line and equation indicate the OLS fit. The 1:1 line is indicated in blue.

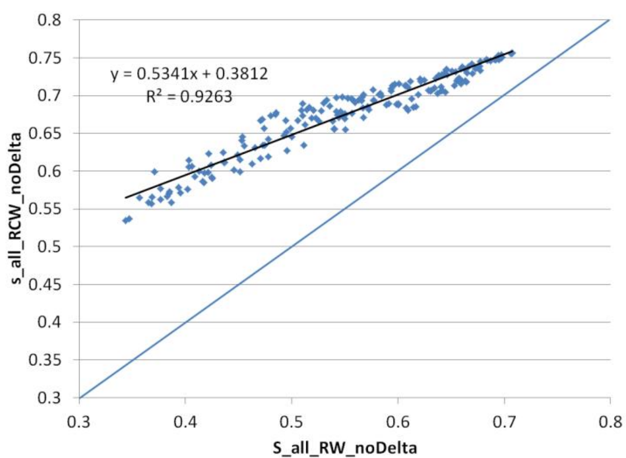

Figure 9. Comparison of STARS vs hybrid formulation after neglecting the interior Delta. Black line and equation indicate the OLS fit. The 1:1 line is indicated in blue.

3.5. *Discussion*

When the interior Delta is included in the analysis, the inclusion of habitat capacity lowers the overall survival, while the inclusion of both habitat capacity and routing probability increases survival compared with the STARS formulation. When the interior Delta is excluded, the survival increases in both cases from the STARS formulation, but the hybrid formulation produces the highest survival. The explanation for this behavior is that the good habitat is largely in the Sacramento River and the North-Delta Sloughs. So, excluding the interior Delta raises survival overall in a model that includes habitat capacity compared with a model that does not.

The hybrid model produces increased overall survival due to the interaction of the higher probability of remaining in the mainstem Sacramento River or entering the Sutter and Steamboat Sloughs in STARS, and the better habitat there.

Given the uncertainty in generating the habitat capacity estimates, as well as the phenomenological differences between the results in the three formulations, it seems that the wisest course of action at this juncture would be to avoid introducing this uncertainty. Therefore, fry are not distributed according to habitat capacity, and only the formulation based on routing probabilities is used.

4. The role of exports on survival of migrating smolt

The USBR biological assessment (USBR, 2019) with the DSM2 model involved only minor differences in the Sacramento River inflows and almost no difference in the operations of the Delta Cross Channel between the COS and PA scenarios (Figure 10). However, the exports were different between the two scenarios (Figure 10), and so were the hydrologic regimes of the Delta (Figures 11-16).

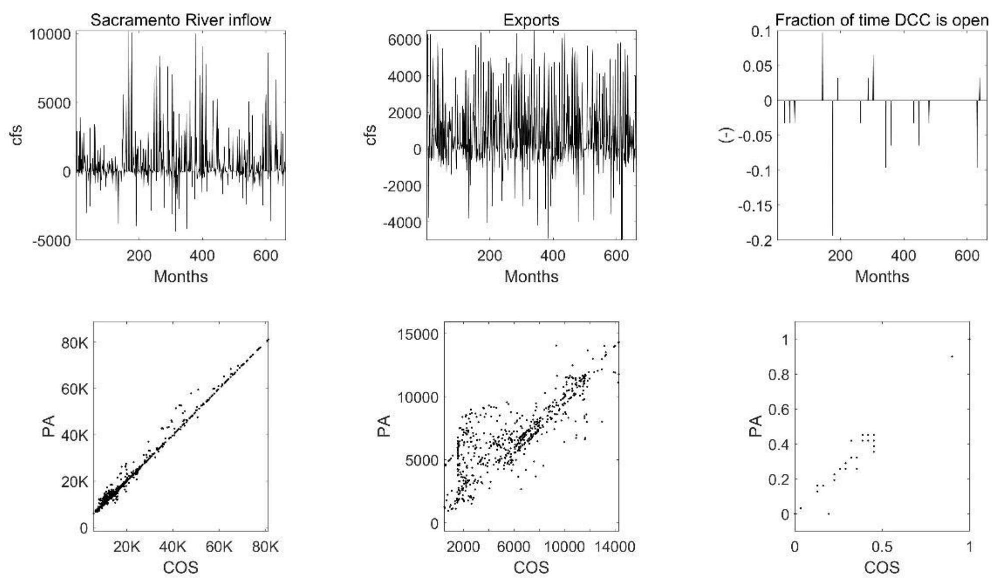

Figure 10. Comparison of the COS and PA scenarios between January and June. Top plots are timeseries and bottom plots are scatter plots. All variables fall tightly on the 1:1 line, except some high exports in the PA scenario.

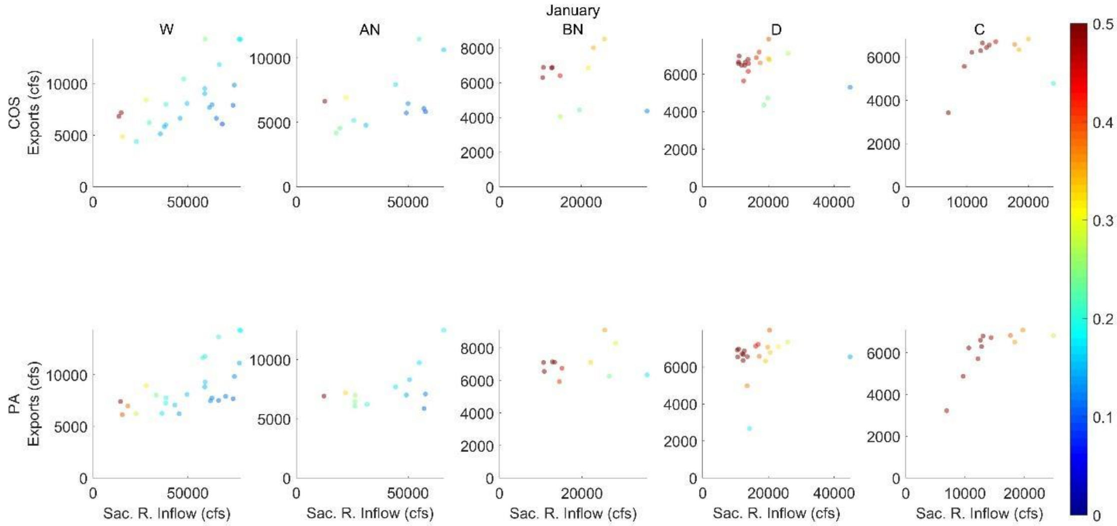

Figure 11. State-space of Delta hydrology in different water year types in the month of January. The points have been color coded by export to inflow ratio. Closed circles indicate that the Delta Cross Channel was fully closed in that month, while open circles indicate that it was partially open. The state-space does not change appreciably between the two scenarios.

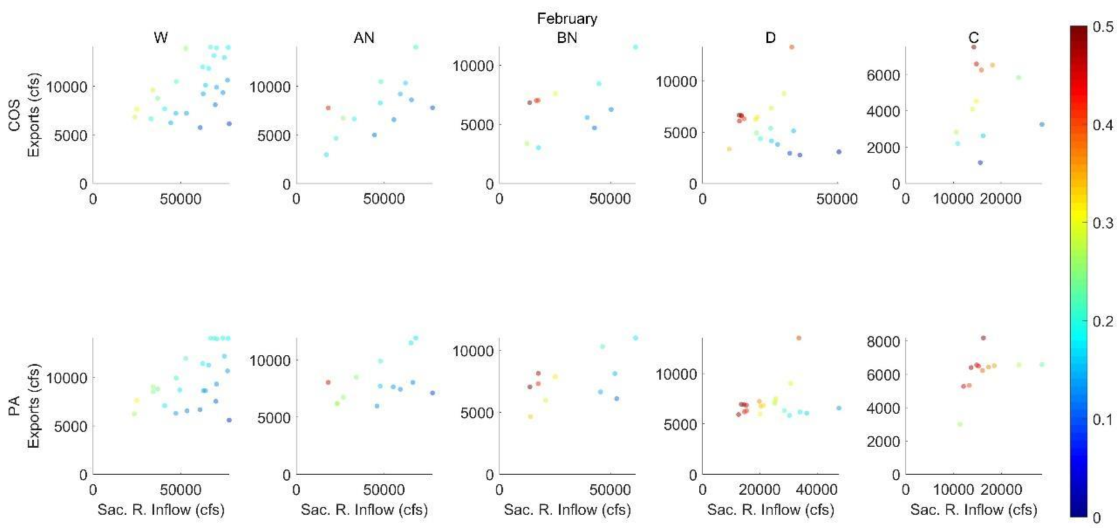

Figure 12. State-space of Delta hydrology in different water year types in the month of February. The points have been color coded by export to inflow ratio. Closed circles indicate that the Delta Cross Channel was fully closed in that month, while open circles indicate that it was partially open. The state-space changes appreciably between the two scenarios only in the dry and critical water years, with exports increasing in the PA scenario relative to COS.

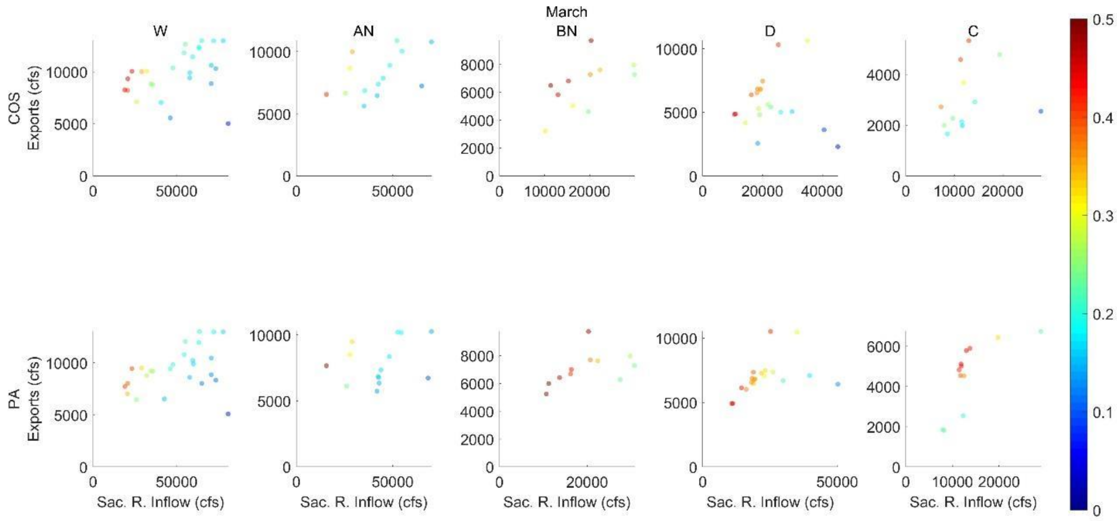

Figure 13. State-space of Delta hydrology in different water year types in the month of March. The points have been color coded by export to inflow ratio. Closed circles indicate that the Delta Cross Channel was fully closed in that month, while open circles indicate that it was partially open. The state-space changes appreciably between the two scenarios only in the dry and critical water years, with exports increasing in the PA scenario relative to COS.

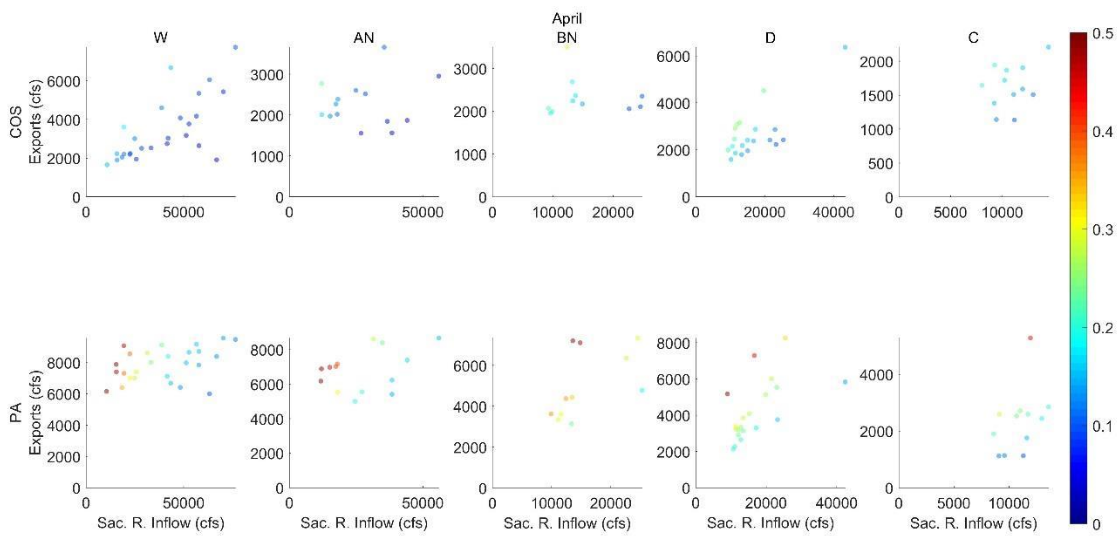

Figure 14. State-space of Delta hydrology in different water year types in the month of April. The points have been color coded by export to inflow ratio. Closed circles indicate that the Delta Cross Channel was fully closed in that month, while open circles indicate that it was partially open. The state-space changes appreciably between the two in all water year types, with exports increasing in the PA scenario relative to COS.

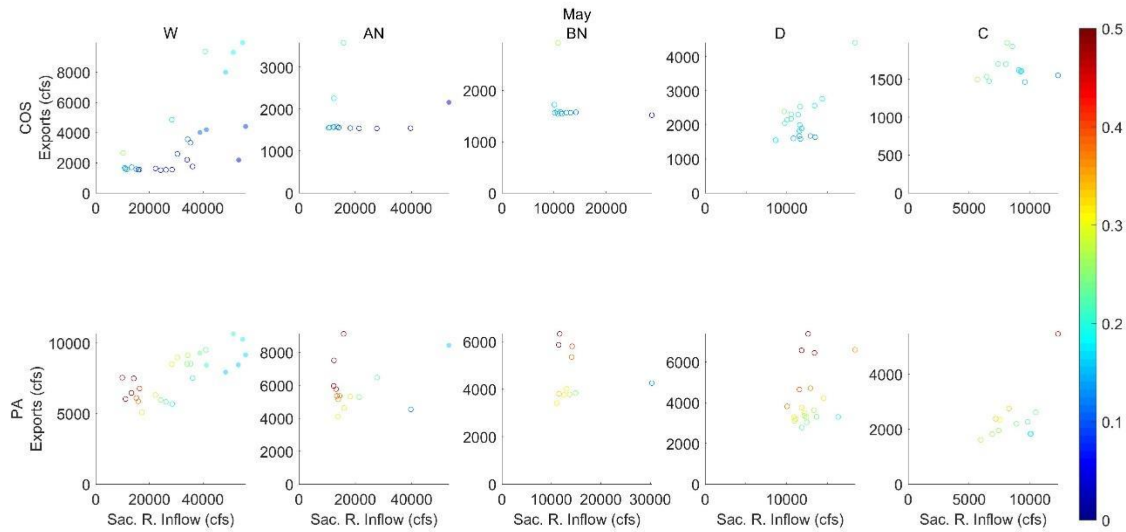

Figure 15. State-space of Delta hydrology in different water year types in the month of May. The points have been color coded by export to inflow ratio. Closed circles indicate that the Delta Cross Channel was fully closed in that month, while open circles indicate that it was partially open. The state-space changes appreciably between the two in all water year types, with exports increasing in the PA scenario relative to COS.

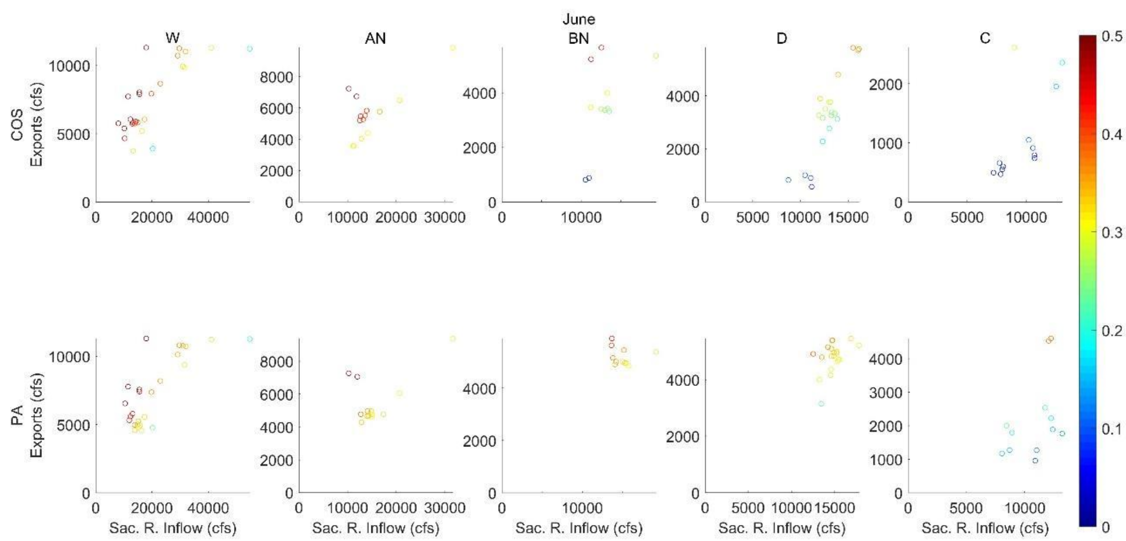

Figure 16. State-space of Delta hydrology in different water year types in the month of Junw. The points have been color coded by export to inflow ratio. Closed circles indicate that the Delta Cross Channel was fully closed in that month, while open circles indicate that it was partially open. The state-space changes appreciably between the two in all water year types, with exports increasing in the PA scenario relative to COS.

4.1. *The importance of exports on survival*

As a result of the design choices of the biological assessment, and because the STARS model does not explicitly incorporate the effect of the exports on survival, we found that there was no perceptible difference in survivals between the two scenarios. However, previous simulations with the older version of the ePTM have shown that in periods of high export to inflow ratios, the extent of the flow entrainment and consequently simulated smolt entrainment into the pumps is increased (Figure 17).

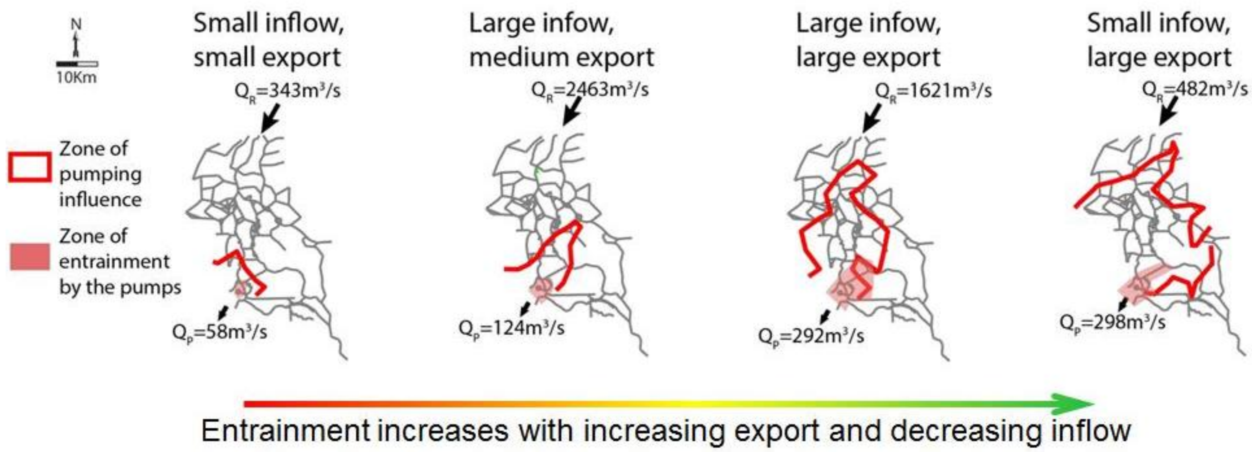

Figure 17. The zones of pumping influence and entrainment by the pumps. In these simulations in four different three-month periods, the zone of pumping influence is defined as the spatial extent from the pumps where the flow in the DSM2 channels is at least correlated with the flow through the pumps by 90%. The zone of entrainment is estimated as the spatial extent from which at least 90% of all simulated smolt uniformly released in all DSM2 nodes are entrained into the pumps. The entrainment into the pumps increases, and hence the survival of smolts decreases with increasing exports and decreasing inflow. In all the panels, the DSM2 grid of the Central and South Delta are indicated.

4.2. *Discussion*

It is apparent from Figure 17 that the zone of influence and zone of entrainment is restricted largely to the South Delta. Thus, it may be possible that the exports do not influence Winter run Chinook survival after all. But this is not a certainty, and cannot be assumed as such.

This is the reason why it has been decided to use the Newman model, which includes exports explicitly (Newman, 2003).

5. **Incorporating habitat capacity and survival with ePTM**

A principal disadvantage of phenomenological models such as the Newman model or the STARS model is that the effects of routing and explanatory variables such as exports cannot be incorporated mechanistically. This is where a well constructed process-based model such as the ePTM is more powerful.

When the new iteration of the ePTM is ready, the arrival of Delta-rearing fry at various locations within the Delta will be modeled using the ePTM as passive particles three months prior to the actual migration of matured smolt. These particles will be seeded in the Sacramento River at the upstream end of the DSM2 grid, and will end their movement at different DSM2 nodes according to a stopping criterion based on the maximum carrying capacity of that node. In this manner, both the routing probability, as well as preferential colonization of areas can be easily incorporated.

Subsequently, the ePTM will be again used to simulate the migration of matured Delta-rearing smolt through the system three months later.

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