# Technical Memorandum

December 28th 2023
From: Steven Zeug and Alex Constandache
Subject: Application of the Salmon Benefits Model (SBM) to a baseline condition and two conceptual scenarios for the Butte and Sutter basins.

**Background**

The Salmon Benefits Model (SBM) is a probabilistic simulation of juvenile Chinook salmon growth, movement, and survival in channel and floodplain habitats of the Sacramento River from the confluence with Moulton Weir to the Pacific Ocean. The model operates on a daily time step with juvenile salmon entering the model at the confluence of the Sacramento River and Moulton Weir. The temporal distribution of fish entering the model is determined by trap data collected upstream at Red Bluff Diversion Dam and adjusted for distance between Red Bluff and Moulton Weir using estimates of movement rate. Fish can move from the mainstem Sacramento River into the Butte Basin or Sutter Bypass at four locations including Moulton Weir, Colusa Weir, Tisdale Weir and Sacramento Slough. They may also remain in the Sacramento River throughout the rearing and migration period. During extreme high flow events (> 80,000 CFS at Bend Bridge), fish can also enter at three overflow relief weirs. However, given the low frequency of these extreme flow levels, entry at those relief weirs are not represented in the SBM. Fish grow, survive, and behave according to habitat specific rates (floodplain and channel). A full description of all model functions and data used to construct the model can be found below in the *Salmon Benefits Model Description* section below.

In the current effort, three hydrologic conditions (i.e., baseline and two river connection concepts) were considered for 5 different water years including 2003 (Above Normal), 2011 (Wet), 2013 (Dry), 2015 (Critical), and 2019 (Wet). For the baseline condition, hydrology and physical characteristics approximate the conditions that occurred in those years. For the two river connection concepts, an operable gate at Moulton Weir with an invert elevation of 61 feet begins spilling at a river discharge of 18,000 cfs and continues to spill up to the weir crest of 76 feet and a corresponding river discharge of 60,000 cfs. The first concept (Concept 1) assumes a maximum operable gate flow of 1,000 cfs as Sacramento River flows exceed 30,000 cfs and continue at this maximum rate up until weir overtopping. The second concept (Concept 2) assumes a maximum operable gate flow of 2,000 cfs as Sacramento River flows exceed 30,000 cfs and continue at this maximum rate up until weir overtopping. It should be noted that downstream flood control weirs at Colusa Weir and Tisdale Weir begin spilling at a river discharge of 35,000 cfs and 22,000 cfs, respectively, and the southern end of the Sutter Bypass at Sacramento Slough allows fish access to inundated habitat at all but the lowest river levels. For each condition, 1,000 iterations of the model were run to integrate variability in the statistical relationships that comprise the model.

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Three metrics were calculated to evaluate the effects of each scenario relative to the baseline. The first metric is the fraction of total juveniles entrained into the bypass at each of the four locations (Moulton Weir, Colusa Weir, Tisdale Weir and Sacramento Slough). Entrainment is calculated as a direct proportion of flow into the bypass and does not vary among different model iterations. The second metric is the size (fork length) of fish arriving at Chipps Island. This metric is calculated separately for fish entering the floodplain at each location and for fish that remain in the main channel. This metric is the result of multiple functions that include variation, and the metric is reported as an estimate and standard deviation. The third metric is the relative smolt-to-adult rate. This is calculated as the smolt-to adult rate for fish that enter the floodplain at each site relative to the smolt-to-adult rate for fish that remain in the main channel. A value > 1 indicates an advantage for fish entering the floodplain at that location. This metric is also reported as an estimate and standard deviation.

**Results**

***Fall/Spring Run Chinook Salmon***

*Entrainment*

There was considerable variation in entrainment of fall/spring run Chinook salmon among locations and water years. Across all years and location, the highest entrainment values under the baseline condition occurred at Colusa Weir (29%) and the lowest at Moulton Weir (< 0.5%). At Moulton Weir, the largest change among the concepts occurred in water year 2003 (Figure 1). Under the baseline, entrainment over Moulton Weir was estimated as 0.37%. This value increased to 3.2% under Concept 1 and 5.1% under Concept 2. In all other water years, increases in entrainment were more modest (≤ 2%).

***Figure 1****. Entrainment of juvenile fall/spring run Chinook salmon into the Butte and Sutter Basins at four locations under three hydrologic scenarios in 5 different water years.*

At Colusa Weir, there was a decrease in entrainment concomitant with the increased entrainment upstream at Moulton Weir. The largest decrease in Colusa Weir entrainment occurred in water year 2003. Under the baseline, entrainment was 29.4% and decreased to 26.7% (- 2.7%) under Concept 1 and 25.0% (- 4.4%) under Concept 2. In the remaining water years, reductions in Colusa Weir entrainment were more modest (≤ 1.6%). At Tisdale Weir and Sacramento Slough, changes in entrainment across Concepts were minor (< 1%).

*Size at Chipps Island*

The size of fall/spring run arriving at Chipps Island was variable among years for fish that were entrained at Moulton, Colusa and Tisdale Weirs (Figure 2). There was less variation in size for fish that entered the lower Sutter Bypass at Sacramento Slough or remained in the main channel Sacramento River (Figure 2). Across all locations, the size of fish arriving at Chipps Island was

greatest in 2019 and least in either 2013 or 2015 depending on exact location. When variability in the model relationships is considered (standard deviations), the patterns of differences among years was still supported; whereas, differences among concepts was less clear. For the baseline condition, fish that remained in the main channel achieved mean sizes at Chipps Island between 83.0 mm and 92.3 mm among years with high overlap when standard deviations are considered. In three years (2003, 2011, 2019) fish that entered the floodplain achieved greater sizes at Chipps Island (92 mm-138 mm)than those that remained in the river channel (85 mm – 92 mm) with the exception of fish that entered at Sacramento Slough in 2019. In 2013 and 2015 fish that entered the floodplain at Moulton, Colusa, and Tisdale Weirs achieved sizes at Chipps Island that were similar or lower to fish that remained in the river (Figure 2) This likely happened because floodplain inundation was brief and of low magnitude in these drier year types. Thus, few fish would have accessed the floodplain and their residence time was short. Fish that entered Sacramento Slough in 2013 and 2015 achieved greater size than those that remained in the main channel . Fish that enter from Sacramento Slough leave the floodplain once the weirs begin to spill. Thus, in years like 2013 and 2015 when weir spills are infrequent, fish that enter Sacramento Slough have more rearing opportunity.

There was less variation in fish size at Chipps Island among scenarios relative to years and when errors are considered, there was little differentiation among scenarios (Figure 2). The largest increase occurred for fish entering over Moulton Weir in 2015 when their size at Chipps Island increased by 13.2 mm under Concept 1 and 13.0 mm under Concept 2. In 2019 the size of fish that entered at Mouton Weir *decreased* by 7.1 mm under Concept 1 and 6.0 mm under Concept 2. At Colusa Weir increases in size were greatest in 2003 with values of 3.3 mm and 2.8 mm under Concept 1 and Concept 2, respectively. The largest decrease for fish entering at Colusa Weir occurred in 2015 under Concept 2 with a reduction of 8.6 mm. At Tisdale Weir, average size at Chipps Island increased under both Concepts in 2003 and Concept 1 in 2011. However, all increases were < 2 mm. In all other years and scenarios size of fish entering over Tisdale Weir declined with a maximum decline in 2019 with values of ~ 4 mm in each scenario. There was little variation in size at Chipps Island for fish that entered at Sacramento Slough with changes less than 1mm across all years and scenarios. Similarly, there were only minor changes in size at Chipps Island for fish that remained in the main channel of the Sacramento River.

To assess changes in size across the entire population for each Concept, a weighted average of fork length was calculated for each year. The size of fish arriving at Chipps Island for each rearing location (Moulton Weir, Colusa Weir, Tisdale Weir, Sacramento Slough, Sacramento River) was weighted by the proportion of juveniles that reared in each location. This analysis revealed that the size of fish arriving at Chipps Island varied substantially among years. Within the Baseline, size ranged from a low of 82.7 mm in 2013 to 108.8 in 2019. However, among scenarios, changes were modest with the largest increase under the Concept 2 condition in 2003 (+1.2 mm) and the largest decrease in 2019 under Concept 2 (-2.0 mm; Table 1).

**Table 1.** *Weighted average of fork lengths (mm) of juvenile fall/spring Chinook salmon arriving at Chipps Island. Weights were the proportion of juveniles using each rearing location.*

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| Condition/Water Year | 2003 | 2011 | 2013 | 2015 | 2019 |
|---|---|---|---|---|---|
| Baseline | 91.5 | 92.6 | 83.4 | 82.7 | 108.8 |
| Concept 1 | 92.6 | 92.6 | 83.0 | 82.3 | 106.7 |
| Concept 2 | 92.7 | 92.7 | 83.2 | 82.1 | 106.8 |
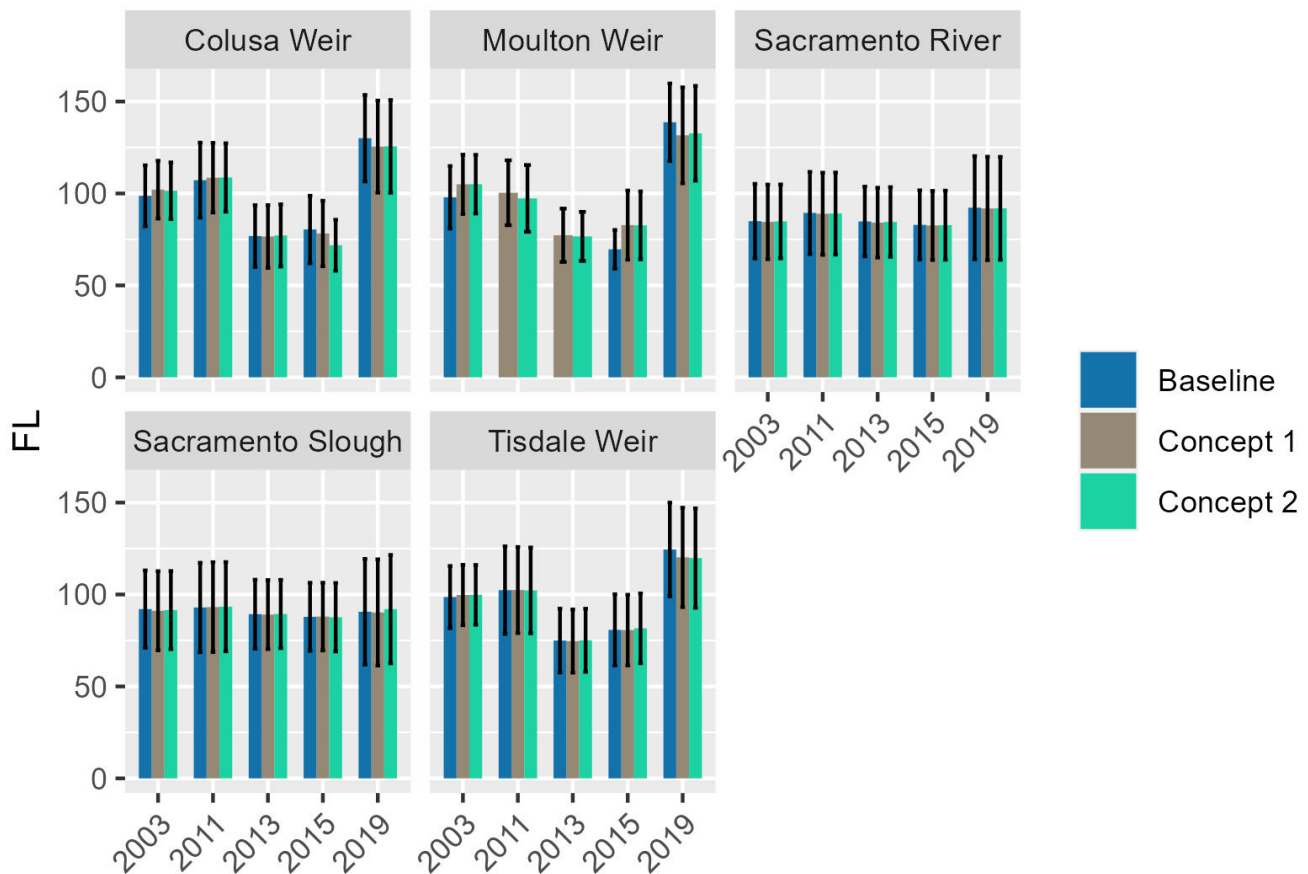


**Figure 2**. *Mean size (fork length) and standard deviations of juvenile fall/spring run Chinook salmon that arrive at Chipps Island after entering the floodplain at one of four locations or remaining in the main stem Sacramento River.*

*Relative smolt-to-adult rate (rSAR)*

The rSAR value for fall/spring run entering the floodplain varied across years and entry locations, although there was less variation among years for fish entering at Sacramento Slough relative to the other locations. (Figure 3). Even when considering model error (standard deviations), the

differences between 2019 and the two drier years (2013/2015) was clear for fish entering at the Moulton, Colusa and Tisdale Weirs.

For fish entering the floodplain at Moulton Weir under baseline conditions, rSAR ranged from 0 in 2011 (entrainment 0.01%) and 2013 (no entry) to 3.70 in 2019 (Figure 3). Within years there were only small differences in rSAR among scenarios. The largest increases relative to the baseline occurred in 2011 and 2013. However, that is largely because there was no entrainment under the baseline in either year.  The rSAR values under Concept 1 and Concept 2 in 2013 were less than 1 indicating they were not as productive as fish that remained in the Sacramento River main channel. In 2019 rSAR for fish entering Moulton Weir declined by 0.80 and 0.53 under Concept 1 and Concept 2, respectively.
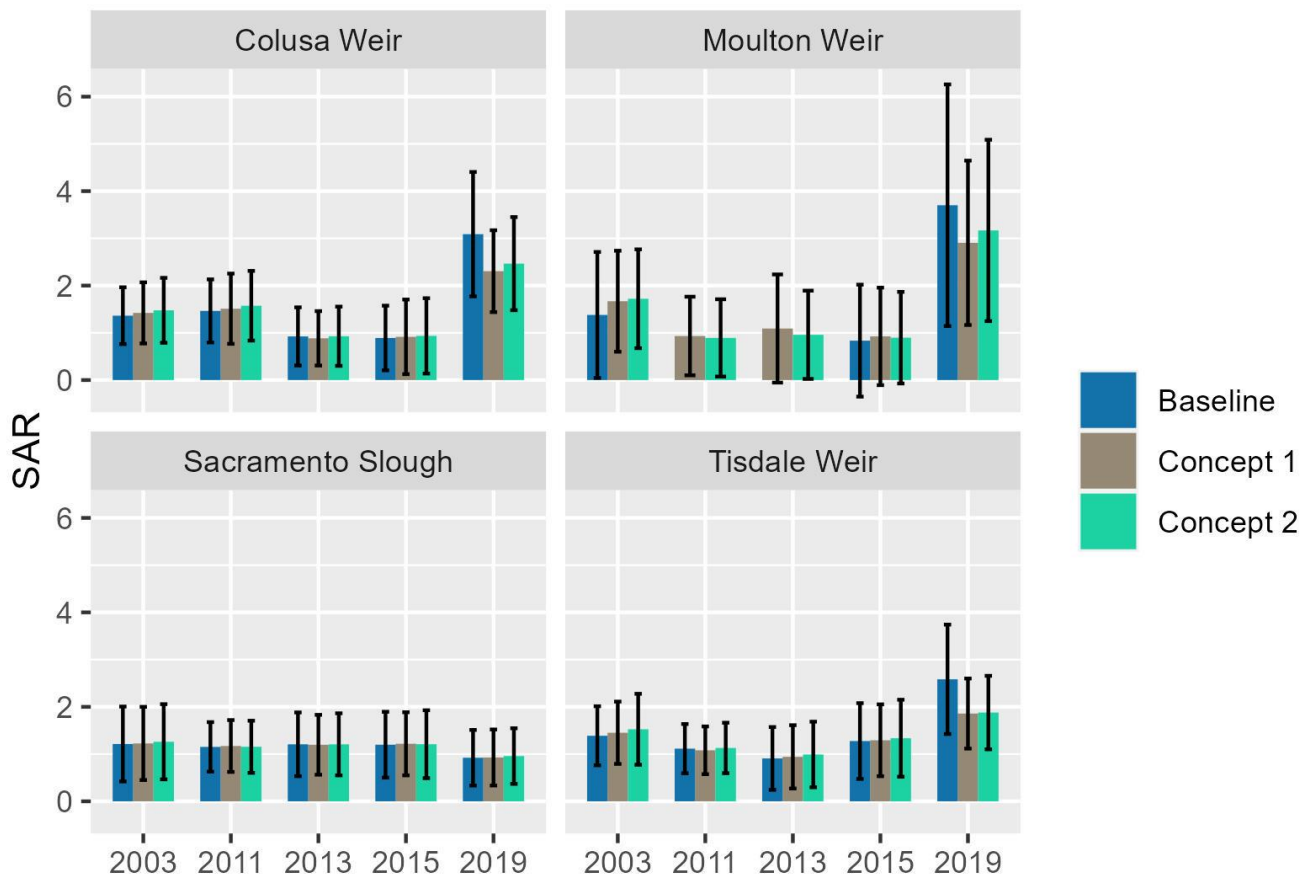


*Figure 3.* *Means and standard deviations of  relative smolt-to-adult rate for juvenile fall/spring run Chinook salmon entering the floodplain at four different locations.*

For fish entering Colusa Weir under the baseline, rSAR ranged from 0.89 in 2015 to 3.09 in 2019. Increases in rSAR across scenarios were modest with all values < 0.12. The largest decrease in rSAR occurred in 2019 when rSAR declined by 0.78 and 0.62 under Concept 1 and Concept 2, respectively. For fish entering over Tisdale Weir, rSAR was lowest in 2013 (0.91) and highest in 2019 (2.58). Across all scenarios, increases in rSAR were < 1.0 and the decreases in rSAR were highest in 2019 but still less than 1.0. Changes in rSAR at Sacramento Slough were minor with no changes higher or lower than 0.05.

To assess changes in rSAR across the entire population, a weighted average of rSAR was calculated for each year (Table 2). The rSAR for each location was weighted by the proportion of juveniles that reared in each location. This analysis indicated that rSAR increased most relative to the baseline in 2003 and this increase was small (0.07). In 2019, rSAR decreased relative to the base line with reductions of 0.35 under Concept 1 and 0.29 under Concept 2.

**Table 2.** *Weighted rSAR of juvenile fall/spring Chinook salmon arriving at Chipps Island. Weights were the proportion of juveniles using each rearing location.*

| Condition/Water Year | 2003 | 2011 | 2013 | 2015 | 2019 |
|---|---|---|---|---|---|
| Baseline | 1.18 | 1.06 | 0.99 | 1.02 | 1.89 |
| Concept 1 | 1.22 | 1.06 | 1.00 | 1.03 | 1.54 |
| Concept 2 | 1.25 | 1.07 | 1.00 | 1.03 | 1.60 |

### Winter run Chinook salmon

*Entrainment*

Similar to the fall/spring run results, there was considerable variation in entrainment of winter run Chinook salmon among locations and water years. Across all years and locations, the highest entrainment values under the baseline condition occurred at Colusa Weir during 2003 (23%) and lowest at Moulton Weir in 2011, when entrainment was 0%. At Moulton Weir, the largest change among the Concepts occurred in water year 2003 (Figure 4). Under the baseline, entrainment over Moulton Weir was estimated as 0.2%. This value increased to 1.7% under Concept 1 and 2.8% under Concept 2. In all other water years, increases in entrainment were more modest (≤ 2%).

At Colusa Weir, there was a decrease in entrainment concomitant with the increased entrainment upstream at Moulton Weir. The largest decrease in Colusa Weir entrainment occurred in water year 2003. Under the baseline, entrainment was 23.3% and decreased to 21.7% (- 1.6%) under Concept 1 and 20.7% (- 2.6%) under Concept 2. In the remaining water years, reductions in Colusa Weir entrainment were more modest (≤ 1.6%). At Tisdale Weir and Sacramento Slough, changes in entrainment across Concepts were minor (< 1%).

**Figure 4**. *Entrainment of juvenile winter run Chinook salmon into the Butte and Sutter Basins at four locations under three hydrologic scenarios in 5 different water years.*

*Size at Chipps Island*

The fork lengths of winter run arriving at Chipps Island were variable among years for fish that entered at Moulton, Colusa and Tisdale Weirs (Figure 5). There was less variation in size for fish that entered the lower Sutter Bypass at Sacramento Slough or remained in the main channel Sacramento River (Figure 5). For fish entering the floodplain at one of the three weirs, the size of fish arriving at Chipps Island was greatest in 2019 and least in either 2013 or 2015 depending on exact location. When variability in the model relationships is considered (standard deviations), the patterns of differences among years were still supported. For the baseline condition, fish that remained in the main channel achieved mean sizes at Chipps Island between ~ 93.2 mm and 98.0 mm among years with high overlap when standard deviations are considered. A similar range of sizes was observed for fish that entered the floodplain at Sacramento Slough (93.8 mm – 96.4 mm; Figure 5). In three years (2003, 2011, 2019) fish that entered the floodplain at one of the three

weirs achieved greater sizes at Chipps Island than those that remained in the river channel (102.8 mm – 152.0 mm).  In 2013 and 2015 fish that entered the floodplain at Moulton, Colusa, and Tisdale Weirs achieved sizes at Chipps Island that were similar or lower to fish that remained in the river or that entered the floodplain at Sacramento Slough (95.0mm – 97.63 mm).

There was less variation in winter run size at Chipps Island among scenarios relative to years, and when errors are considered, there was little differentiation among scenarios (Figure 5). The largest increases in size occurred in 2011 and 2013 because there was no entrainment under the baseline and entrainment did occur under both Concepts. Among years where there was entrainment under the baseline, the largest increase occurred for fish entering over Moulton Weir in 2003 when their size at Chipps Island increased by 6.4 mm under Concept 1 and 5.6 mm under Concept 2. In 2019 the size of fish that entered at Moulton weir *decreased* by 16.7 mm under Concept 1 and 16.5 mm under Concept 2. At Colusa Weir, the largest increases in size of winter run at Chipps Island were observed in 2003 (Concept 1 = 5.3 mm, Concept 2 = 5.7 mm). The largest decreases occurred in 2019 when size was reduced by 5.7 mm under Concept 1 and 6.2 mm under Concept 2.  In all other years, reductions in size were ≤ 2.5 mm.   In other years, both increases and decreases in size were observed but at lower magnitudes. At Tisdale Weir, average size of winter run at Chipps Island only increased in 2003 and under Alt 1 in 2015.  All of these increases were small (< 2 mm). Size declined in all other years with the largest magnitude in 2019 with declines of 4.6 mm and 3.9 mm under Concept 1 and Concept 2, respectively. There was little variation in size at Chipps Island for fish that entered Sacramento Slough with changes (increases and decreases) less than 2mm across all years and scenarios. Similarly, there were only minor changes in size at Chipps Island for fish that remained in the main channel of the Sacramento River.

To assess changes in size across the entire population of winter run, a weighted average of fork length was calculated for each year. The size of fish arriving at Chipps Island for each rearing location was weighted by the proportion of juveniles that reared in each location. This analysis revealed that the size of fish arriving at Chipps Island varied among years. Within the Baseline, size ranged from a low of 94.1 mm in 2015 to 101.8 in 2003. However, among scenarios, changes were modest with changes ≤ 1.9 mm (Table 3).

*Table 3. weighted average fork lengths for winter run arriving at Chipps Island in five water years. Fork lengths were weighted by the proportion of fish rearing entering the floodplain at four locations or remaining in the Sacramento River.*

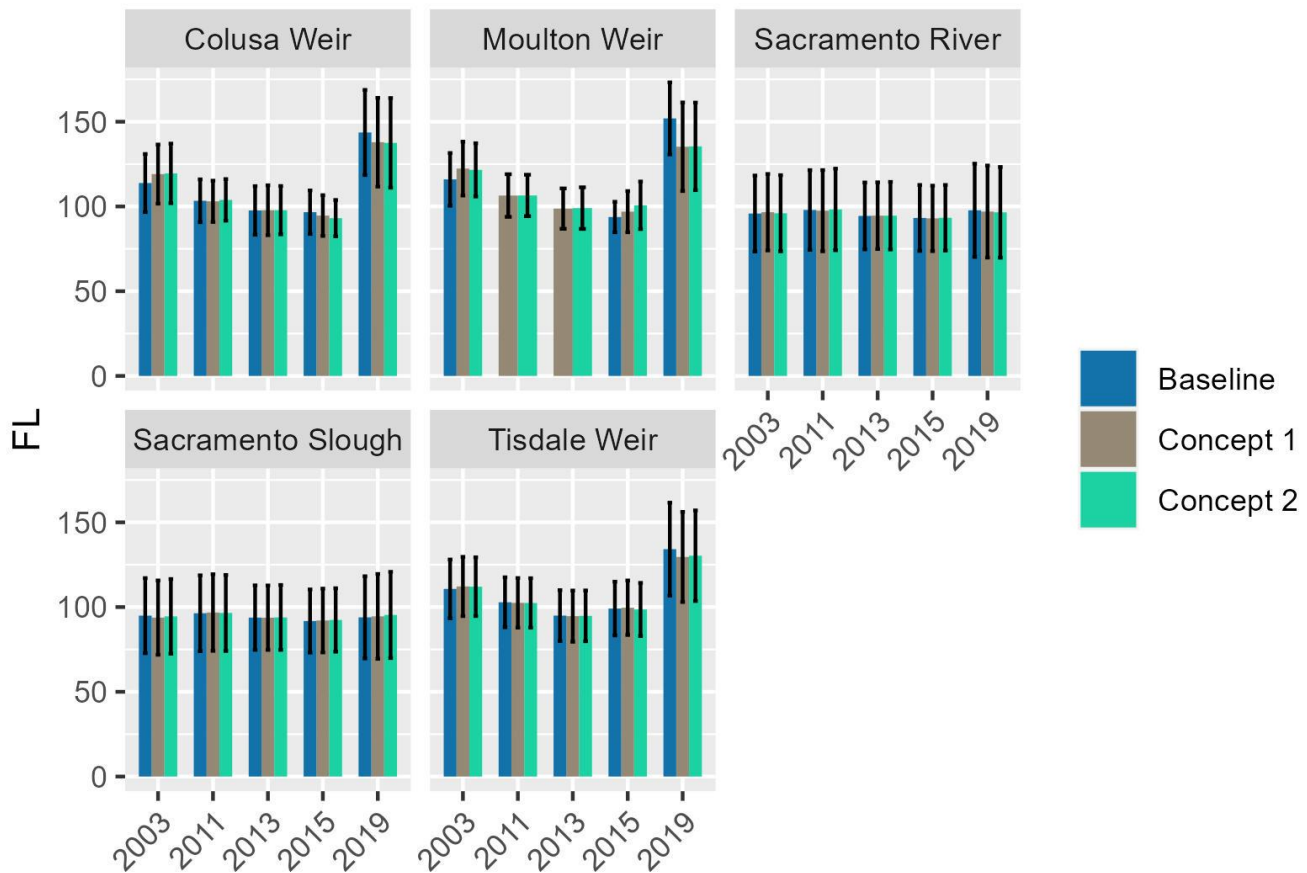| Conditions/Water Year | 2003 | 2011 | 2013 | 2015 | 2019 |
|---|---|---|---|---|---|
| Baseline | 101.8 | 98.6 | 95.0 | 94.1 | 101.3 |
| Concept 1 | 103.7 | 98.3 | 95.1 | 93.8 | 100.3 |
| Concept 2 | 103.5 | 98.9 | 95.1 | 93.9 | 100.0 |

**Figure 5**. *Means and standard deviations of fork lengths for winter run Chinook salmon arriving at Chipps Island after rearing in one of five locations.*

*Relative Smolt-To-Adult Ratios (rSAR)*

The rSAR value for winter run entering the floodplain varied across years and entry locations, although there was less variation among years for fish entering at Sacramento Slough relative to the other locations. (Figure 6). Even when considering model error (standard deviations), the differences between two wetter years (2019 and 2003) and the two drier years (2013/2015) was clear for fish entering at the Moulton, Colusa and Tisdale Weirs. Across all years and locations rSAR values were > 1.0 indicating that winter run that entered the floodplain had superior outcomes to fish that remained in the main channel. However, the magnitude of this floodplain advantage varied considerably among years and rearing locations.

For winter run entering the floodplain at Moulton Weir under baseline conditions, rSAR ranged from 0 in 2011 and 2013 (no entry) to 5.30 in 2019 (Figure 6). Among years where floodplain

entry at Moulton Weir was > 0, the lowest rSAR was 1.16 in 2015. For fish entering at Colusa Weir the range under the Baseline was 1.27 in 2015 to 4.25 in 2019.  The range for fish entering at Tisdale Weir was 1.26 in 2013 to 2.00 in 2019.  The range of values at Sacramento Slough was narrow ranging from 1.05 in 2011 to 1.09 in 2013.

Within years there were only small differences of rSAR among scenarios at each entry location. At Moulton Weir the largest increases relative to the baseline occurred in 2011 and 2013. However, that is largely because there was no entrainment under the baseline, but there was under the two Concepts.  In 2019, rSAR for fish entering Moulton Weir declined by 1.98 and 1.95 under Concepts 1 and Concepts 2, respectively.  For fish entering at Colusa Weir, the biggest changes occurred in 2019, when rSAR decreased by 1.98 and 1.95 under Concept 1 and Concept 2 respectively. In all other years, changes were < 1.0.

To assess changes in rSAR across the entire population, a weighted average of rSAR was calculated for each year (Table 4). The rSAR for each location was weighted by the proportion of juveniles that reared in each location. This analysis indicated that rSAR increased most relative to the baseline in 2003 and this increase was small (0.06). In 2019, rSAR decreased relative to the base line with reductions of 0.13 under Concept 1 and 0.12 under Concept 2.
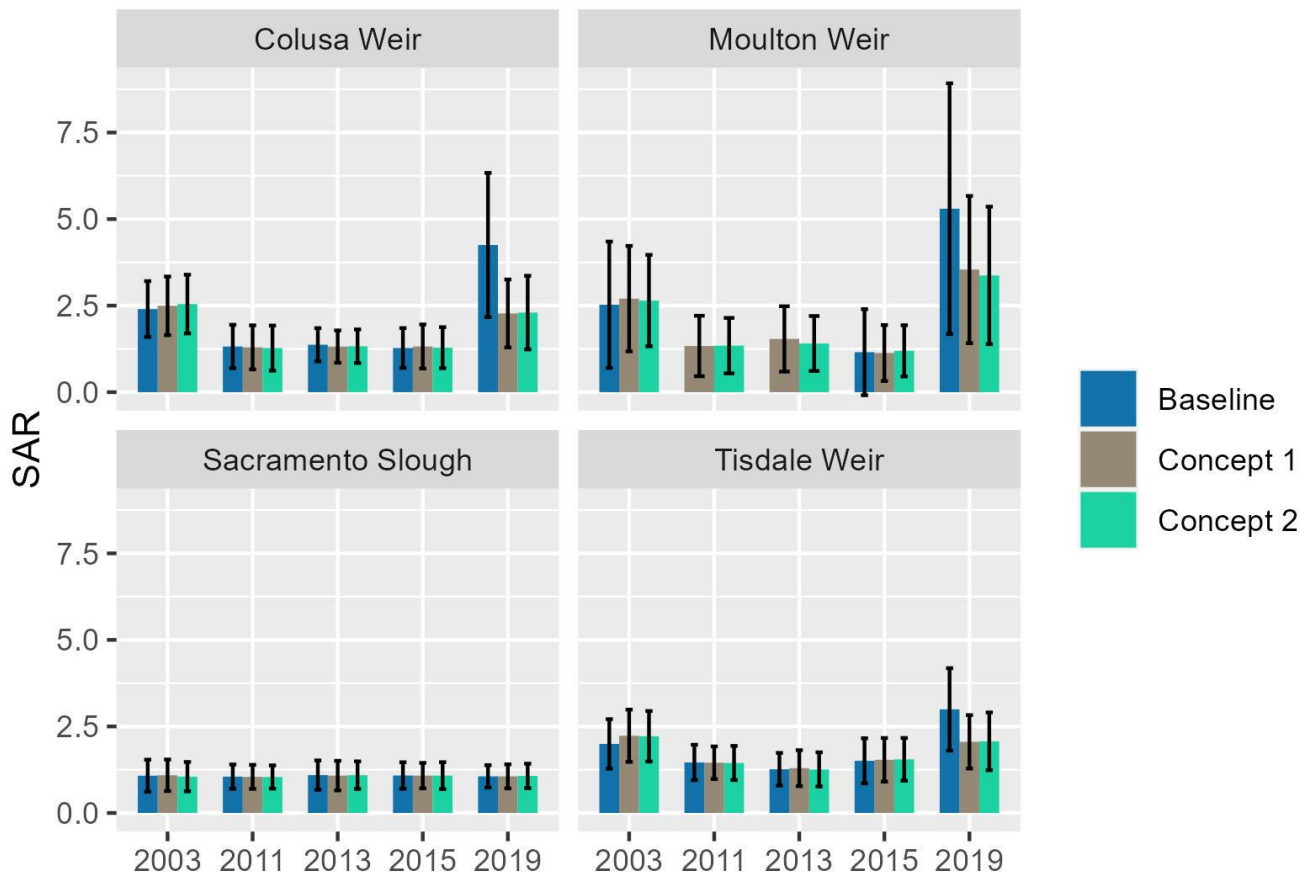
**Figure 6.** *Means and standard deviations of relative smolt-to-adult rate for juvenile fall/spring run Chinook salmon entering the floodplain at four different locations.*

**Table 4.** *Weighted rSAR of juvenile fall/spring Chinook salmon arriving at Chipps Island. Weights were the proportion of juveniles using each rearing location.*

| Condition/Water Year | 2003 | 2011 | 2013 | 2015 | 2019 |
|---|---|---|---|---|---|
| Baseline | 1.46 | 1.08 | 1.10 | 1.09 | 1.25 |
| Concept 1 | 1.51 | 1.07 | 1.10 | 1.10 | 1.12 |
| Concept 2 | 1.52 | 1.10 | 1.10 | 1.10 | 1.13 |

**Summary Remarks**

Analysis of the baseline and two concept conditions at Moulton Weir revealed that there were larger differences among water years than between scenarios within years. Entrainment at Moulton Weir was always low under the baseline for both runs analyzed (< 1%). Under the

concepts, entrainment only exceeded 5% in one year for one run and was frequently less than 2%. By comparison at Colusa Weir, where flow thresholds for overtopping are lower, entrainment approached 30% maximum under the baseline and was never less than 3.6%. Thus, the magnitude change in the number of fish that could access the floodplain habitat via Moulton Weir was not substantially increased. Additionally, entrainment at Colusa Weir and, to a lesser extent, Tisdale Weir, was reduced under the two concepts since more fish and flow were diverted over Moulton Weir which also attenuated effects of the operable gates.

Flows in the Sacramento River need to be relatively high prior to Moulton Weir overtopping (60,000 cfs). The two concepts begin to let flow through an operable gate in the weir when the river flow exceeds 18,000 cfs. Each operable gate achieve maximum flow of 1,000 or 2,000 cfs when the Sacramento River flow exceeds 30,000 cfs and continue at this maximum rate up until weir overtopping. This magnitude increase in flow through the operable gate under the two concepts is low relative to the magnitude that remains in the river. For example, the best information on entrainment indicates fish move into a junction in proportion to flow volume. The maximum increase in entrainment with a 1,000 cfs operable gate is 3.3% at a river flow of 30,000 cfs and reduces to 1.7% at 60,000 cfs. For a 2,000 cfs operable gate, the maximum increase in entrainment is 6.7% at a river flow of 30,000 cfs and reduces to 3.4% at 60,000 cfs. This relatively small increase in entertainment occurs infrequently because of the high flow magnitude needed to achieve maximum flow through the operable gates. Flow through the operable gates at those low levels could potentially have benefits for increasing flood magnitude and/or duration . However, fish must be present on the floodplain to benefit from those changes.

## Appendix 1: Salmon Benefits Model Description

## Modeling Approach

The primary goal of the Salmon Benefits Model (SBM) is to compare outcomes for juvenile Chinook Salmon rearing in floodplain and main channel habitats to inform restoration and operational decision making.  In this specific application, the SBM is being applied to floodplain rearing within habitats of the Butte Basin and Sutter Bypass to quantify how rearing habitat access and experience propagates to different life stages. The secondary goal of the SBM is to evaluate intuition and assumptions about the modeled system with available quantitative data and identify knowledge and data gaps that could refine understanding. The SBM is not intended to predict all possible trajectories of Chinook Salmon populations under different proposed scenarios or to predict specific outcomes. Instead, the SBM provides an experimental system built on quantitative data where consequences of various sets of assumptions can be rigorously examined and the range of outcomes for modeled Concepts can be compared (Peck 2004).

The SBM is a stochastic model where parameters of the model are used to define a distribution that is resampled each model day. Unlike a life cycle model, where progeny from one brood year influence outcomes of the next, the SBM takes a production model approach to simulation, where individual brood year-classes are tracked separately. The model simulates and tracks key stages of Chinook salmon life history, from the point of freshwater emigration (multiple access locations to the bypass) to returning adults and integrates the potential life stage-specific and cumulative impacts of restoration actions.

## Model Documentation

*Salmon sources and runs*

The Salmon Benefits Model  incorporates juvenile salmon migrating from three distinct sources: the Sacramento River, Feather River and Butte Creek.  Two runs are modeled separately in the Sacramento River, winter run and fall/spring run. Late-fall run Chinook salmon also occur in the Sacramento River.  However, this run primarily expresses a stream-type life history where juveniles spend their first summer in natal rearing habitat and then migrate directly to the ocean the following fall and winter as yearlings. They are much less likely to express rearing behavior relative to the other races of Chinook salmon and they were excluded from this analysis.  A single population of winter run spawns in the Sacramento River below Keswick Dam whereas spring run and fall run occur in multiple tributaries upstream of the Sutter Bypass.  In the Feather River and Butte Creek only fall/spring run are modeled.  Although both fall run and spring run occur in all three source rivers, juvenile data for the SBM comes from captures in rotary screw traps where run is assigned using the length-at-date model which cannot reliably separate fall and spring run juveniles due to overlap in spawn timing.

*Entry timing and size*

Timing of fish arrival at each junction and the size of fish at arrival was estimated using data from long-term juvenile salmonid monitoring programs that employed rotary screw traps in each of the three source rivers. For the Sacramento River, two monitoring locations were used, The United States Fish and Wildlife Service (USFWS) monitoring station at Red Bluff Diversion Dam and the California Department of fish and Wildlife (CDFW) monitoring station at Knights Landing. At the Red Bluff station, daily catch data was obtained for 11 years (2010-2020) and for Knights Landing, data for 15 years was obtained (1997-2012). For Butte Creek, capture data from a CDFW monitoring station between 1995 and 2015 was obtained. In the Feather River, data from 2009-2021 was obtained from a California Department of Water Resources monitoring station located in the high flow channel below the Thermalito Afterbay outlet.

For each location, daily catch was converted to a proportion of the yearly total to standardize among years. A smoothing function was then applied to characterize the proportion of the juveniles migrating on each day across all years. These daily values were then standardized so the sum of all daily values was equal to 1. This procedure was performed separately for winter run and fall/spring run at the two Sacramento River trap locations (Figure 1).
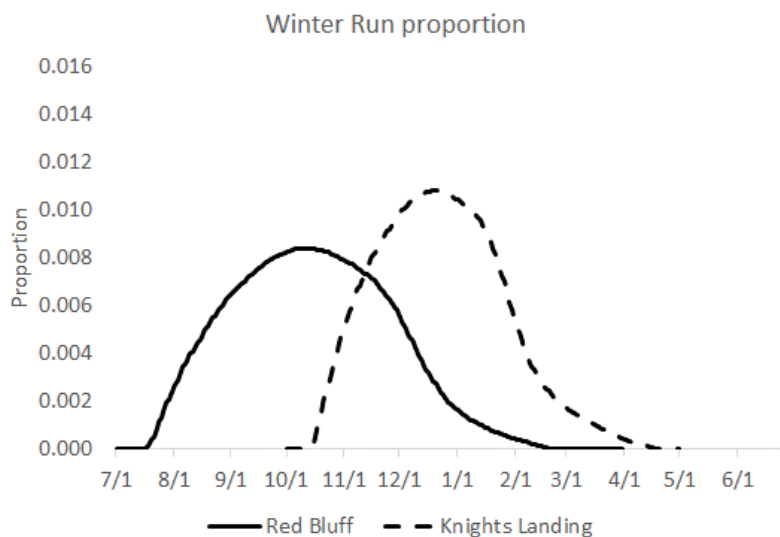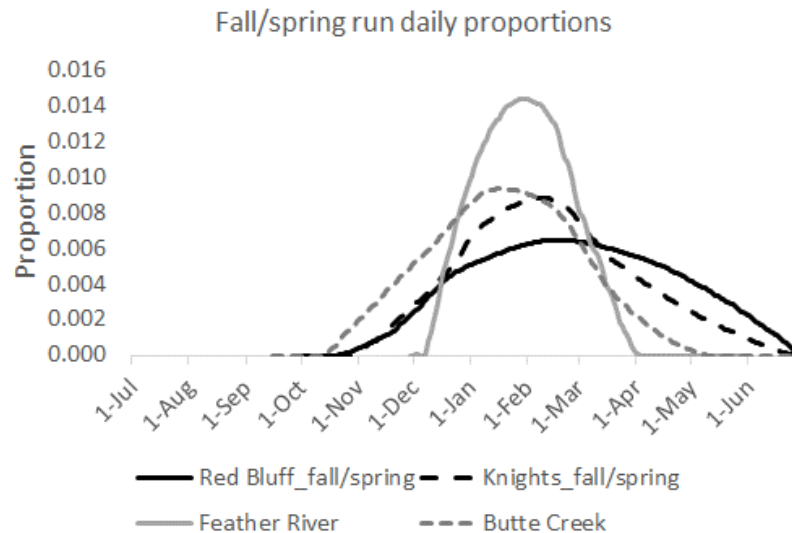
*Figure 1. Smoothed daily distributions of juvenile winter run (panel A) and fall/spring run (panel B) captured in two traps on the Sacramento River (Red Bluff and Knights Landing), the Feather River and Butte Creek.*

The timing of fish capture was adjusted to account for the time required to move between a trap location and each entrance to the Sutter Bypass. The calculation of movement rates between traps and floodplain entry locations is described below.

*Entrainment*

The potential for entrainment into the Butte Basin and Sutter Bypass is dependent on which of the three River fish are migrating in. For fish migrating in the Sacramento River, there are four locations where fish may enter the bypass. From upstream to downstream these locations are Moulton Weir, Colusa Weir, Tisdale Weir and Sacramento Slough. Fish migrating in the Feather River can enter the Sutter Bypass at Nelson Slough. All fish migrating from Butte Creek enter the north end of the Butte Basin and pass through the Sutter Bypass. At the three weirs on the Sacramento River and at Nelson Slough on the Feather River, fish enter the bypass in a 1:1 proportion with the volume of flow entering the bypass at that location. Movement of migrating juvenile Chinook Salmon into a distributary junction has been found to be strongly related to the proportion of water entering that junction (Cavallo et al. 2015, Perry et al. 2015). However, studies on route selection have only been performed on large (>100 mm) smolt-sized fish that are primarily exhibiting migration behavior. Fish entering the SBM domain are primarily fry exhibiting rearing behavior. How well the flow proportion-entrainment function represents fry behavior is unknown. Future studies are likely needed to address this uncertainty. Fish migrating in the Sacramento River can also enter the lower Sutter Bypass through Sacramento Slough as water levels rise in the Sacramento River mainstem. This occurs using a linear relationship where entrainment is zero at the lowest river stage and increases to a maximum of 20% of the fish passing by on a day. When any of the upstream weirs spill, fish stop moving into the bypass through Sacramento Slough as water begins to move out of the slough as the bypass drains.

*Entry timing and size*

The locations of fish capture in monitoring programs are not co-located with potential entry locations to the floodplain. To account for this discrepancy in spatial locations, the rate of migration was estimated. This was accomplished using juvenile winter run captured at two locations: Red Bluff and Knights Landing. Winter run were chosen for this analysis for two reasons. First, there is only a single population of winter run that spawns upstream of the Red Bluff traps so the source of fish is known. Fall and spring run spawn in multiple tributaries where variations in spawn timing can create additional uncertainty in migration rate. Second, the length-at-date criteria used to identify the race of salmon capture in monitoring programs is more accurate for winter run that have a unique spawn timing relative to fall and spring run that have overlapping spawn timing.

The daily capture distributions for winter run described above were converted to cumulative distributions at each trap location. The distance in river kilometers between the traps (250 km) was divided by the number of days elapsed between traps to estimate a migration rate(Figure 2). The specific migration rate for a fish on a given day is calculated by integrating a stochastic differential equation based on these rates.

The migration rates calculated above were then used to estimate the day when juvenile winter run and fall/spring run Chinook salmon would arrive at each potential entry location (Figure 3).
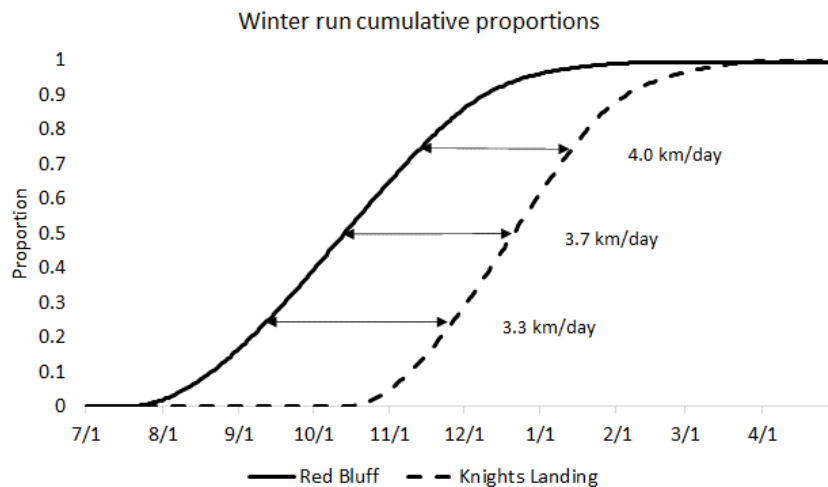


*Figure 2. Cumulative distribution of juvenile winter run captured at the Red Bluff diversion Dam and Knights Landing screw traps. Horizontal lines are the points where 25%, 50% and 75% of fish are captured at each location.*
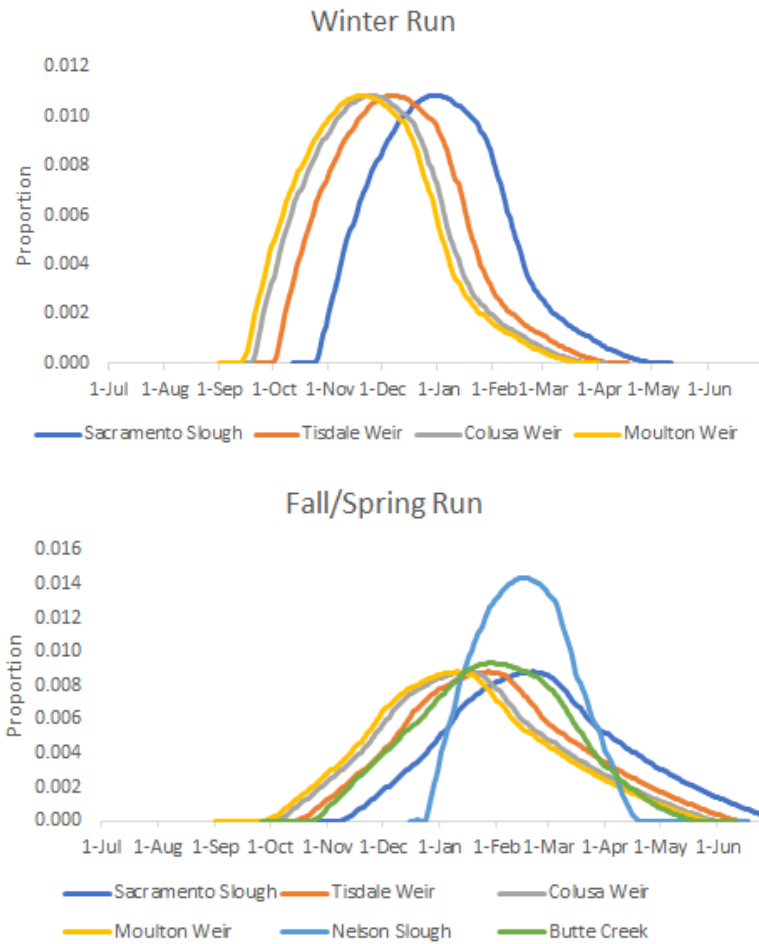
*Figure 3. Approximate distributions at each entry location to the floodplain for winter run (top panel and fall/spring run (bottom panel).*

The size of juvenile Chinook salmon was estimated from the same screw trap data used to estimate timing. The size of fish from each run captured on each day of the year was averaged over the same years of data and a smoothing function was applied. On each day in the model, the mean and standard deviation of size for that day is used to inform a normal distribution from which the daily value is sampled.
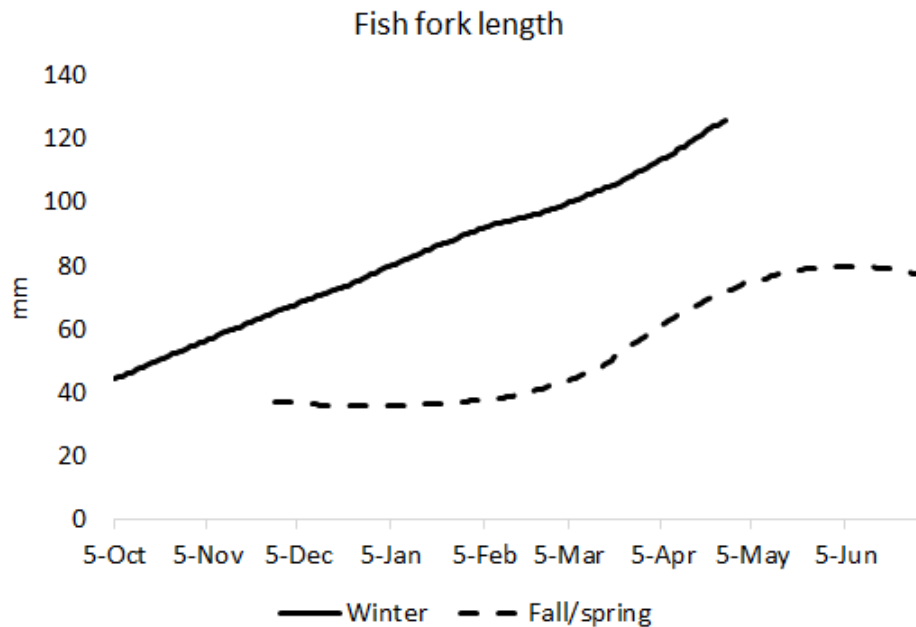
Figure 4. Mean size-at-date for winter run and fall/spring run captured in the Knights Landing screw trap. Each point has an associated standard deviation that is used to define a normal distribution that is resampled each day.

*Behavior*

When a cohort of juvenile Chinook salmon arrives at a junction between a river channel and entrance to the floodplain, the proportion that engages in rearing behavior is a function of the average FL of the cohort. We chose a logistic function for the shape of the relationship

$$y = d + \frac{a - d}{1 + \left(\frac{x}{c}\right)^b}$$

where $a$ is the minimum value, $b$ controls curve steepness, $c$ is the inflection point, and $d$ is the maximum value with default parameter values in the SBM of 0, 15, 80, and 1, respectively. The proportion rearing and the cohort abundance are used to draw the number of individuals rearing from a binomial distribution.

On each day, fish may switch from rearing to migrating behavior as a function of their fork length on that day and water temperature. First, the probability $p\_T$ of temperature induced transition is computed, using a sigmoid function. Then the size induced transition probability $p\_S$ is computed with the Yolo formula. The ultimate transition probability is $p = (1 - p\_T) * p\_S + p\_T$ and each fish is switched on a particular day with this probability. A fish cannot switch from migrating to rearing (except at Sac Slough).

*Rearing*

The duration of rearing on the floodplain is a function of flood duration. We digitized points in Figure 3 of Takata et al. (2017) and fit a negative binomial regression model.  A cohort that is rearing on the floodplain draws a residence time from a negative binomial distribution based on the flood duration on the day that the cohort begins rearing.

For rearing fish that remain in the Sacramento River, rearing duration is determined by movement rates and fork length.  Rearing fish move at a rate of 3.7 km/day which was calculated based on the travel time of winter run between Red Bluff and Knights Landing described above. Fish continue to grow each day and the probability of switching to migrating behavior increases each day as fork length increases as described above in the section on behavior. In the Delta, rearing duration is a function of Sacramento River flow and salmon FL at Freeport. We used data from coded-wire tag releases of juvenile fall-run Chinook Salmon at Elkhorn, Ryde, and Rio Vista that were recaptured at Chipps Island reported in the USFWS Chipps Island Survival Table (https://www.fws.gov/lodi/juvenile_fish_monitoring_program/jfmp_index.htm). We calculated days at large (proxy for residence time) as the difference between the last recovery date and the first release date. We fitted a negative binomial regression model with days at large as a function of the average FL in a release group and Sacramento River flow at Freeport on the day of release. All cohorts draw a Delta residence time from a negative binomial distribution based on average fork length and Sacramento River flow at Freeport. For cohorts on the Sacramento River route, Delta entry is the model entry date. On the YB route, Delta entry is the model entry date for non-rearing cohorts and the model entry date plus rearing time for rearing cohorts. For all cohorts, the transit time is subtracted from the Delta residence time to determine the Delta rearing time. Rearing duration for both the YB and Delta is truncated on the first day that temperatures exceed a threshold value (default = 22 ºC).

*Growth*

Growth of fish on the floodplain and in the Sacramento River and Delta is based on release and recapture of coded wire tagged juvenile Chinook salmon.  Floodplain growth rates were estimated using data collected in Butte Creek and the Sutter Bypass by the California Department of Fish and Wildlife between 1996 and 2004.  In this effort, CDFW collected wild Chinook salmon fry and parr in screw traps located in Butte Creek and implanted them with coded wire tags.  These fish were later recaptured in a screw trap located within the Sutter Bypass.  Growth rates in the Sacramento River were estimated using data collected by the California Department of Water Resources. The CDWR study used coded wire tagged parr (mean fork length 56.3 mm) obtained from the Feather River Fish Hatchery and released between 1998 and 2009.  These fish were released in the Sacramento River near the Interstate 5 crossing and recaptured in trawls and seine surveys downstream in the river and Delta.

For both data sources, daily growth was estimated as.
$$G = \frac{S_c - S_r}{D}$$

Where $G$ is daily growth rate (mm•day$^{-1}$), $S_r$ is the mean size of a release group, and $S_c$ is the size of a recaptured individual from the release group. Only fish that had been at large longer than 14 days were used for growth estimation. Since the size at release is the mean for a group, recaptures below 14 days at large could result in negative growth rates because of variations in the size of fish within the group and the short time available for growth. In Sutter Bypass growth was estimated to be 0.61 mm•day$^{-1}$ (SD, 0.17) and in the Sacramento River the estimate was 0.48 mm•day$^{-1}$ (SD, 0.20). In the model growth is calculated according to a stochastic differential equation that is integrated over time based on the rates described above.

*Survival*

Juvenile Chinook salmon that are assigned rearing behavior experience a daily survival rate of 0.99. A model with survival as a function of time is known as an exposure model (Anderson et al. 2005) because the probability of survival is inversely related to time spent rearing (exposure to predators or other mortality sources). For fish rearing on the floodplain, exposure time is determined by the flood duration. In the Sacramento River and Delta the length of expose is based on the movement rate for rearing fish described above. Thus, in the SBM, there is a trade-off between increased growth on the floodplain with the additional mortality incurred during rearing. The growth-survival trade-off is reflected in the probability of returning as an adult because ocean survival is modeled as a function of fork length at ocean entry (described below). Floodplain rearing reduces the probability that a juvenile fish reaches the ocean, but the increased size from floodplain rearing increases the probability of surviving during ocean residence. Given the floodplain growth rate and the ocean survival relationship used in the model, and ignoring survival during active migration, the minimum daily rearing survival value to make rearing worthwhile (i.e., growth benefit outweighs rearing mortality) is approximately 0.99. This rearing survival value is not based on empirical data. However, in the Effects Analysis for the Yolo SBM, we explore the implications of lower rearing survival on the conclusions drawn from the SBM.

*Migration*

For fish that are assigned migration behavior, survival and movement rates are based on acoustic tagging studies. In the Sacramento River upstream of Fremont Weir, survival and movement rates were estimated using data from Zeug et al. (2020). The river was divided into two reaches based on the placement of acoustic receivers in the study area; from Moulton Weir to Tisdale, and from Tisdale to Sacramento Slough. The mean survival estimates and error was used to inform an normal distribution that was resampled each day. Survival through the first reach was 50.1% (95% CI, 45.0% to 56.8%) and 31.0% (95% CI 24.4% to 38.3%) in the second reach. Migration rate in each reach was also implemented as a normal distribution that is resampled each day. In the first reach migration rate is 56.6 km•day$^{-1}$ (SD, 14.4 km•day$^{-1}$), and 50.5 km•day$^{-1}$ (SD, 13.0 km•day$^{-1}$) in the second reach.

From Fremont Weir downstream, survival was estimated with a Bayesian implementation of a Cormack-Jolly-Seber model (adapted from Kery and Schaub 2012) based on empirical survival studies conducted of comparable reaches within the two migratory systems (Johnston, *unpublished data*, Perry, *unpublished data*, Table 1). The survival values were converted to survival per kilometer ($S_{km}$) as follows:

$$S_{km} = S^{\left(\frac{1}{reach\ length}\right)}$$

**Table 1.** Survival estimates for reaches available from empirical studies of acoustically-tagged late-fall run juvenile Chinook salmon emigrating in 2012, 2013, and 2016.

| Year | Migration Route | Reach | Distance (km) | Survival Estimate | Survival Per Kilometer |
|------|----------------|-------|---------------|-------------------|------------------------|
| 2012 | Sacramento River | Knights Landing – Above Freeport | 46.3 | 0.720 | 0.9929 |
| 2012 | Sacramento River | Above Freeport – Chipps Island | 106.2 | 0.615 | 0.9954 |
| 2013 | Sacramento River | Knights Landing – Below Freeport | 74.1 | 0.508 | 0.9909 |
| 2013 | Sacramento River | Below Freeport – Chipps Island | 78.3 | 0.453 | 0.9899 |
| 2016 | Sacramento River | Verona – Freeport | 52.8 | 0.958 | 0.9992 |
| 2016 | Sacramento River | Freeport – Chipps Island | 80.8 | 0.737 | 0.9962 |
| 2012 | Yolo Bypass | Hwy I-5 – Chipps | 90.1 | 0.470 | 0.9897 |
| 2013 | Yolo Bypass | Hwy I-5 – Chipps | 90.1 | 0.180 | 0.9795 |
| 2016 | Yolo Bypass | Hwy I-5 – Chipps | 90.1 | 0.551 | 0.9933 |

The estimates of survival per kilometer (Table 1) from the three years of empirical data were then applied to the modeled water years according to similarity in the Fremont stage time series for those years. Applying migration survival on a per kilometer basis is known as a gauntlet model (Anderson et al. 2005) because migrating fish need to move through a gauntlet of predators to reach the ocean and cannot reduce their predation risk by migrating at a faster rate. Thus, migration rate does not affect migrating survival in the SBM.

Migration rates downstream of Fremont Weir were calculated from available empirical data from the modeled routes (Table 2). Migration rate data were available for hatchery, late-fall run juvenile Chinook salmon emigrating through the Sacramento River and the Yolo Canal Complex in three years: 2012, 2013, and 2016 (Johnston, *unpublished data*, Perry, *unpublished data*). Empirical data on movement rate for these years encompass water discharge – that is, the

observed movement rates reflect the speed of fish emigrating in the corresponding flow for those three years. Mean movement rates from the three years of empirical data were then applied to the modeled water years according to similarity in the Fremont stage time series for those years.

**Table 2.** Mean migration rates (km•day$^{-1}$) in the two migratory routes of the SBM, calculated from acoustically-tagged emigrating late-fall run juvenile Chinook salmon.

| Year | Sacramento River | Canal Complex |
|------|------------------|---------------|
| 2012 | 17.4 | 10.7 |
| 2013 | 11.4 | 7.5 |
| 2016 | 60.5 | 21.4 |

*Ocean Survival*

In the SBM, survival from ocean entry to return at age 3 is modeled as a function of fork length at ocean entry because fish size is positively correlated with ocean survival in salmonids (Ward et al. 1989, McGurk 1996). We were provided a dataset (Will Satterthwaite, *unpublished data*) of juvenile Chinook salmon releases and recoveries that were the basis of Satterthwaite et al. (2014). The dataset contains release weight, but not fork length. Thus, the first step was to convert weights to fork lengths. We used catch of fall-run Chinook salmon at the Knights Landing RST from 2000-2012 (Figure 6) to develop the following relationship.

$$L = 48W^{0.3}$$ 
(Eq. 7)

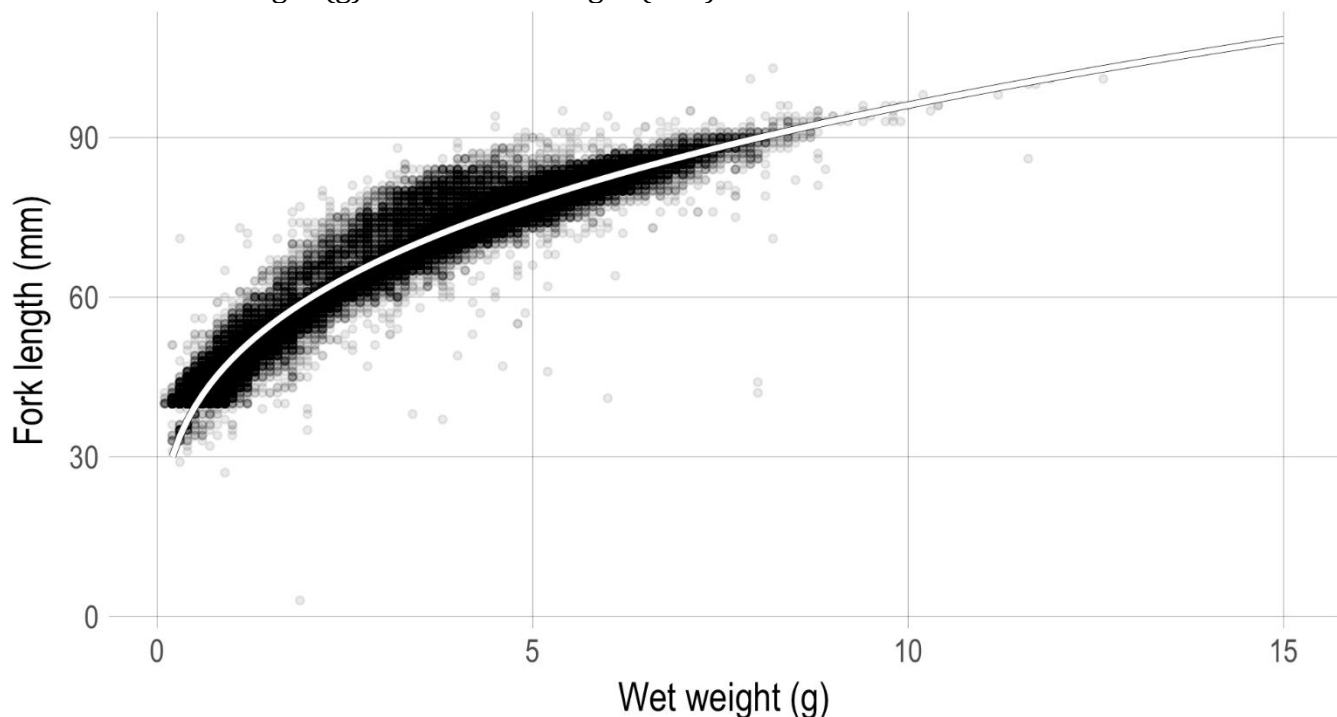where $W$ is wet weight (g) and $L$ is fork length (mm).

**Figure 1.** Fork length and wet weight of fall-run Chinook salmon caught at the Knights Landing Rotary Screw Trap from 2000-2012. Circles are observed values and white line is fitted relationship.

Satterthwaite et al. (2014) focused on how release timing in the San Francisco Bay affected ocean survival of fall-run Chinook salmon. They made several decisions about how to filter the dataset to better address their focus on release timing. For our analysis, we excluded fewer records because we wanted a larger size range for fitting a relationship between size at ocean entry and ocean survival. Similar to Satterthwaite et al. (2014), only age-3 recoveries were considered when estimating ocean survival because prior to being caught at age 3, the predominant source of mortality is from natural causes, and recoveries of age 2 and age 4 fish are comparatively rare. We also excluded data from releases in 2006 and 2007 because the fishery was closed in 2008 and 2009, which precluded age-3 recoveries. We fitted a generalized linear model with a quasi-binomial error distribution and a logit link to predict survival, $S$, at age 3 from fish fork length, $L$, at release (Figure 7):

$$S = \text{logit}^{-1}(-7.385 + 0.025L) \tag{Eq. 8}$$
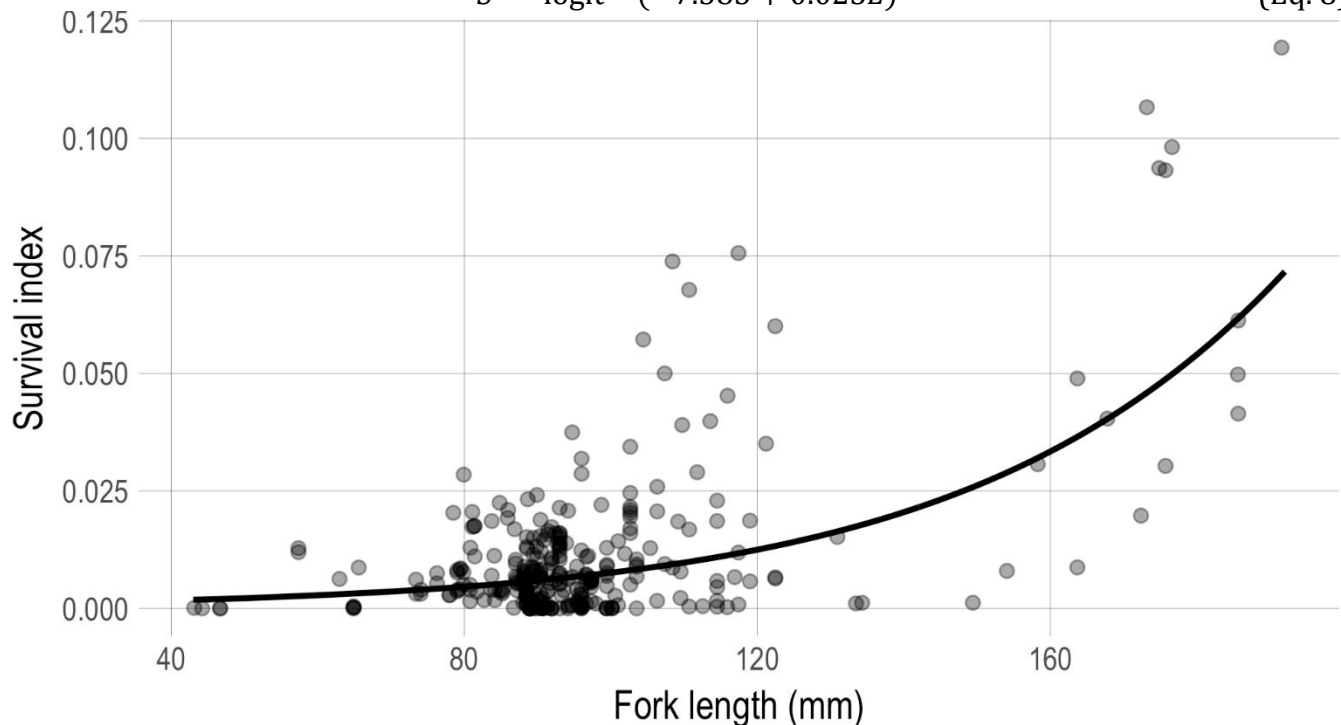


**Figure 2.** Age 3 survival index versus fish fork length at release for hatchery fall-run juvenile Chinook salmon released in the San Francisco Bay, 1978-2011. Circles are observed values and line is fitted relationship, which is used in the Salmon Benefits Model.

In the SBM, ocean survival involves two ocean year types: (1) all cohorts draw an ocean survival value from the same distribution or (2) ocean survival increases with increasing fork length at estuary entry (detailed above). The type of ocean year is randomly determined by drawing from a uniform distribution. If the drawn value is less than the specified ocean year type probability, which defaults to one, then ocean survival is based on the fork length relationship.

## Model Assumptions and Limitations

Due to limited data available for several CV Chinook salmon life stages, traditional statistical models become difficult to apply when attempting to predict outcomes of future management actions (Williams 2006). Unlike predictive models, simulation models can be useful for organizing existing knowledge and identifying gaps in understanding, even if the model predictions are imprecise (Williams 2006).  Simulation models should be thought of as experimental systems or aids that are distinct from the "real world" in which the consequences of various sets of assumptions can be examined (Peck 2004). However, model usefulness is measured by how well it captures the interactions of the most important factors and leaves out unimportant ones (Ford 1999), thereby limiting model complexity and simplifying interpretation of results.  More complex models can be too dataset-specific and have poor predictive ability, mainly due to estimation error, while simpler models can be too general and incorporate error due to system oversimplification (Astrup et al. 2008). Therefore, we attempted to model the benefits floodplain rearing for Chinook salmon with a level of complexity that captures the key factors thought to influence fish survival and size, while limiting the inclusion of factors that have low utility for evaluating project effects, or that are unsupported by existing scientific knowledge.

*Data Availability*

Simulation models depend upon available data to inform model relationships, resulting in a complexity level that matches the depth of knowledge known about a subject (Astrup et al. 2008). When local data is limited, model relationships can often be informed by populations outside the study region, laboratory studies in controlled experimental settings, or artificially raised (hatchery) surrogates. For example, many of our model relationships rely on data from hatchery fish. This is because most experimental studies are of hatchery-origin fish, conducted under the assumption that outcomes and behavior are at least similar between fish of different natal origins, races and animal husbandry. In the SBM we used data from multiple sources including natural and hatchery origin fish from multiple races.  We assume that all runs move, grow, and survive according to the same rules.

*Entrainment*

Models for how juvenile Chinook salmon are distributed in the channel and throughout the water column at floodplain-channel junctions are currently unavailable. Therefore, at three weirs (Moulton, Colusa, Tisdale) on the Sacramento River we assumed that juvenile Chinook salmon are equally distributed across the channel and throughout the water column and enter the junctions in proportion to the flow entering the bypass. Similar dispersion assumptions have been used to estimate juvenile salmon entrainment at junctions in the tidal Delta (Cavallo et al. 2015, Perry et al. 2015). At Sacramento Slough, water backs up into the Sutter Bypass as stage height increases in the Sacramento River.  Thus, there is not a "flow split" similar to what occurs at the flood control weirs. At this location fish enter Sacramento Slough according to a logistic function with a maximum entrainment of 20%. Once any of the weirs start spilling, fish no longer enter this

location as flow is now direct out of Sacramento Slough as the bypass drains. The empirical data that do exist to inform salmon routing at junctions has been collected using hatchery-origin smolts that were actively migrating through the tidal Delta. Here we are making inferences about fry and parr sized fish that are engaging in rearing behavior, or switching between rearing and migrating, in a non-tidal lowland reach. It is unknown if data collected on smolts is transferable to the conditions modeled in the SBM. Additionally, the morphology of each junction may affect the entrainment relationship, but we treat each junction the same within the SBM. If more information becomes available to inform more sophisticated relationships between flow and juvenile salmon entrainment, or if different entrainment alternatives are examined in the future, model functionality can be changed to evaluate alternative mechanisms of entrainment.

*Growth*

In this application of the SBM, growth is estimated from release and recovery of coded wire tagged juveniles. The fish used for "floodplain" growth were natural origin fry sampled in Butte Creek and then recaptured in the borrow canals within Sutter Bypass. The fish used for the "river" were Feather River Hatchery fish released at the Elkhorn Boat Ramp on the Sacramento River and recaptured in the Delta. These releases were not paired among the same years but were collected over overlapping but distinct time periods. Thus, we are assuming that natural and hatchery origin fish feed, grow, move, and survive in a similar way. Once the CWT fish are released, it cannot be determined what habitat the fish actually reared in. For the Butte Creek releases, fish may have stayed in the main channel of Butte Creek or reared in floodplain habitat. Fish released in the main channel may have also reared in tidal marsh within the Delta. Additionally, we apply the estimated growth rates without regard to space and time. This assumes that growth rates do not change in space and time or with fish size.

*Movement*

Juvenile salmon movement in the riverine and floodplain portions of the model is greatly simplified and limited by data availability. Modeled fish in the Sacramento River move with a one dimensional random walk with drift. The drift rate and the variance of the daily steps are dependent on the current reach the fish is in, and the current behavior of the fish (rearing vs. migrating), which are themselves random variables that may change from day to day. Migratory behavior in juvenile salmonids is a complex process related to growth, hormonal development, and environmental parameters, all of which may influence habitat use and movement throughout the emigration period (Iwata 1995). While juveniles may shift between rearing and actively migrating during the emigration process (Hoar 1953; Iwata 1995), the mechanisms that inform these complex movements are not well understood or easily modeled. Therefore, we instead modeled the average downstream movement of juvenile Chinook Salmon based on simple movement rates. A simplified model was then applied for juveniles rearing on the floodplain. Data is not available to inform model rules for how fish should move across the floodplain in two dimensions, nor is data available to inform simulation of high-resolution behavior and habitat selection on floodplains.

*Survival*

We assumed that rearing survival in both the floodplain and river operates under an exposure model where time spent rearing reduces overall survival. Other factors that may influence survival include behavior (e.g., habitat selection, activity level) and physical attributes of the individual fish (e.g., size). We also assumed that rearing survival is the same throughout the migration season, across Chinook salmon runs and years, and within both the river and floodplain. Within the floodplain, survival increases with flood magnitude. This was done under the assumption that predator and prey contact rates are inversely proportional to water volume. These survival components of the model can be updated as more data becomes available.

We assumed that migrating juvenile Chinook salmon survive according to a gauntlet model. Survival might be better represented by a survival model that incorporates both distance and time traveled (i.e., XT model; Anderson et al. 2005), but mechanisms underlying the XT model are not yet well understood in the model universe. We also assumed that mortality was evenly applied within individual reaches. We assumed that survival estimates from studies of large, hatchery, fall and late-fall run Chinook salmon conducted in a limited number of years apply to wild fish of other runs and sizes in all other years. We also assumed that migrating survival is constant throughout the migration season.

*Ocean survival*

Studies have shown that juvenile Chinook salmon survival in the ocean can vary due to many factors including entry timing, physical ocean conditions, trophic dynamics, and size or condition of fish upon entry (Wells et al. 2012, Satterthwaite et al. 2014, Woodson 2014). However, because we wanted to incorporate a growth-survival trade-off for floodplain rearing in the model, we only incorporated the effect of fish size on ocean survival. The constraint of hatchery release data is that release size is often confounded with release timing. Thus, we may be overestimating the benefit of large size on ocean survival. We are also assuming that the ocean survival relationship, which is based on data from hatchery fall-run Chinook salmon, applies to wild origin fish of all runs.

*Model output*

Multiple metrics can be produced from SBM output, however; three metrics that are particularly useful are the relative smolt-to-adult rate (rSAR), the size of juvenile salmon exiting the Delta at Chipps Island, and location-specific entrainment rates.

The rSAR compares the number the number of adults that return to spawn for every juvenile that rears on the floodplain relative to the same value for juveniles that remain in the main channel. Thus, it is a multiplier for spawner abundance that describes the incremental benefit of rearing on the floodplain in units of adult spawners. This value is calculated for each location where fish can

enter the Sutter and Yolo Bypasses to quantify location specific benefits that arise from variation in exposure to floodplain rearing time.

The size of fish exiting the Delta at Chipps Island describes the total growth benefits realized by fish rearing on the floodplain vs those that remain in the main channel.  Size has a direct effect on survival of fish migrating through the lower Sacramento River and Delta and in the ocean. Similar to the rSAR metric, size at Chipps Island is calculated for each location where fish enter floodplain habitat.

Entrainment rate at each location integrates the distribution of migrating fish in time with life history stage,  migration rate and year-specific hydrology to describe the proportion of fish expected to access floodplain habitat.

Sensitivity analysis

A sensitivity analysis was performed on the SBM to understand how parameter uncertainty influences two model outputs; the size of fish arriving at Chipps Island, and the relative smolt-to-adult rate. Here we performed a global sensitivity analysis where all parameters are varied simultaneously. This strategy is superior to one-at-a-time methods where one parameter is allowed to vary while all others are held constant.  This is because with global methods, the model runs the same way it is intended for scenario evaluation. We ran 1000 iterations of the model and then calculated Sobol' sensitivity indices (and confidence intervals) for both outputs (Fork Length at Chipps and rSAR) at each entry location and for both runs of salmon. Sobol' indices have two components, a main effect that measures how the variance in a parameter directly influences variance in the output, and a total effect that incorporates first-order interactions among model parameters. Index values with confidence intervals that did not overlap zero were considered significant. Negative values are also interpreted as non-significant effects .

For Fall/Spring run, the strength of Sobol' indices for both main and total effects on relative smolt-to-adult rate (rSAR) depended most on the location of floodplain entry (Figure 3).  For main effects, Sobol' indices for all parameters were close to zero for all floodplain entry locations except for Nelson Slough on the Feather River. At that location the mean Sobol' index values was higher but never exceeded .3 and the confidence intervals overlapped with zero.  Total effect index values increased slightly for Nelson Slough and also increased for Sacramento Slough and some parameters for Sacramento Slough became significant. For all other entry locations index values remained near zero (Figure 3).  The higher index values for Nelson Slough likely reflect the rarity with which there is a connection to the floodplain at this location.  For Sacramento Slough, the entry function has links with multiple hydrologic parameters and these interactions likely account for the higher index values at this location when first order interactions are considered (total effect index).

Main effect index values for winter run were near zero for all entry locations except for Sacramento Slough.  At that location, entry timing and size-at-date were both significant direct

effects on size at Chipps. When first order interactions were considered (total effect indices), all parameters had significant Sobol' Index values for Sacramento Slough. Additionally, at Moulton Weir, entry timing had a significant effect though the index value was relatively low (~0.10).
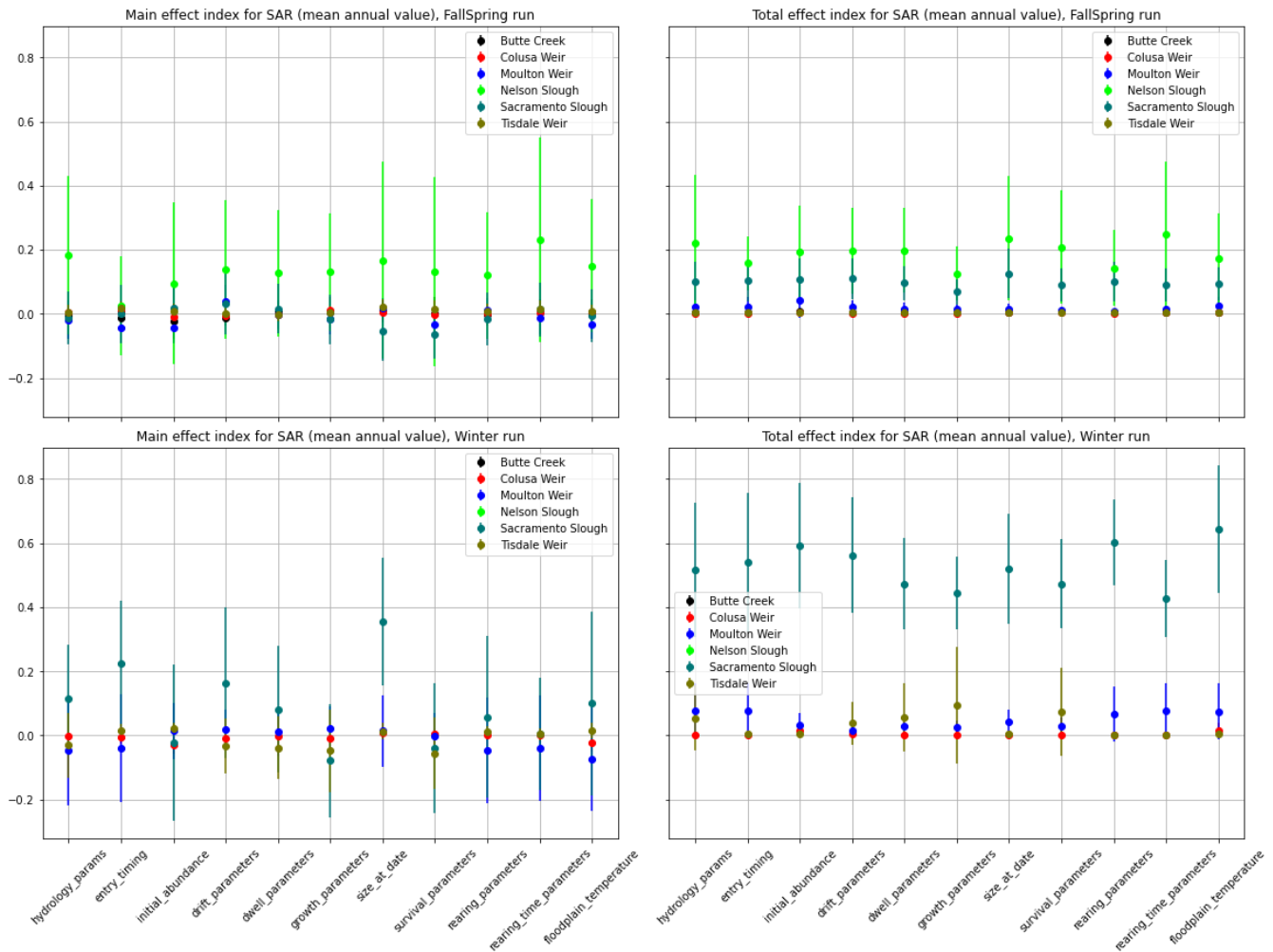


Figure 3. Results of the global sensitivity analysis of the SBM for the output "relative smolt-to-adult rate". Sobol' Indices were calculated for each parameter and entry location. Main effect indices measure the direct relationship between an parameter and output (rSAR) and total effect indices also consider first order interactions among parameters.

Sobol' index values for fork length at Chipps Island followed a similar pattern as above (Figure 4). For fall/spring run, main effect index values were near zero for all parameters and entry locations. When first order interactions are considered (total effect indices), almost all parameters became significant for Nelson Slough whereas values for all other locations remained near zero. Nelson Slough is rarely connected to the floodplain and this infrequent activation is likely the reason for the sensitivity of parameters at that location. For winter run, main effect indices were near zero

for all parameters and locations.  When first order interactions are considered (total effect indices) values for Sacramento Slough increased but never exceeded ~0.1 and confidence intervals still overlapped with zero.
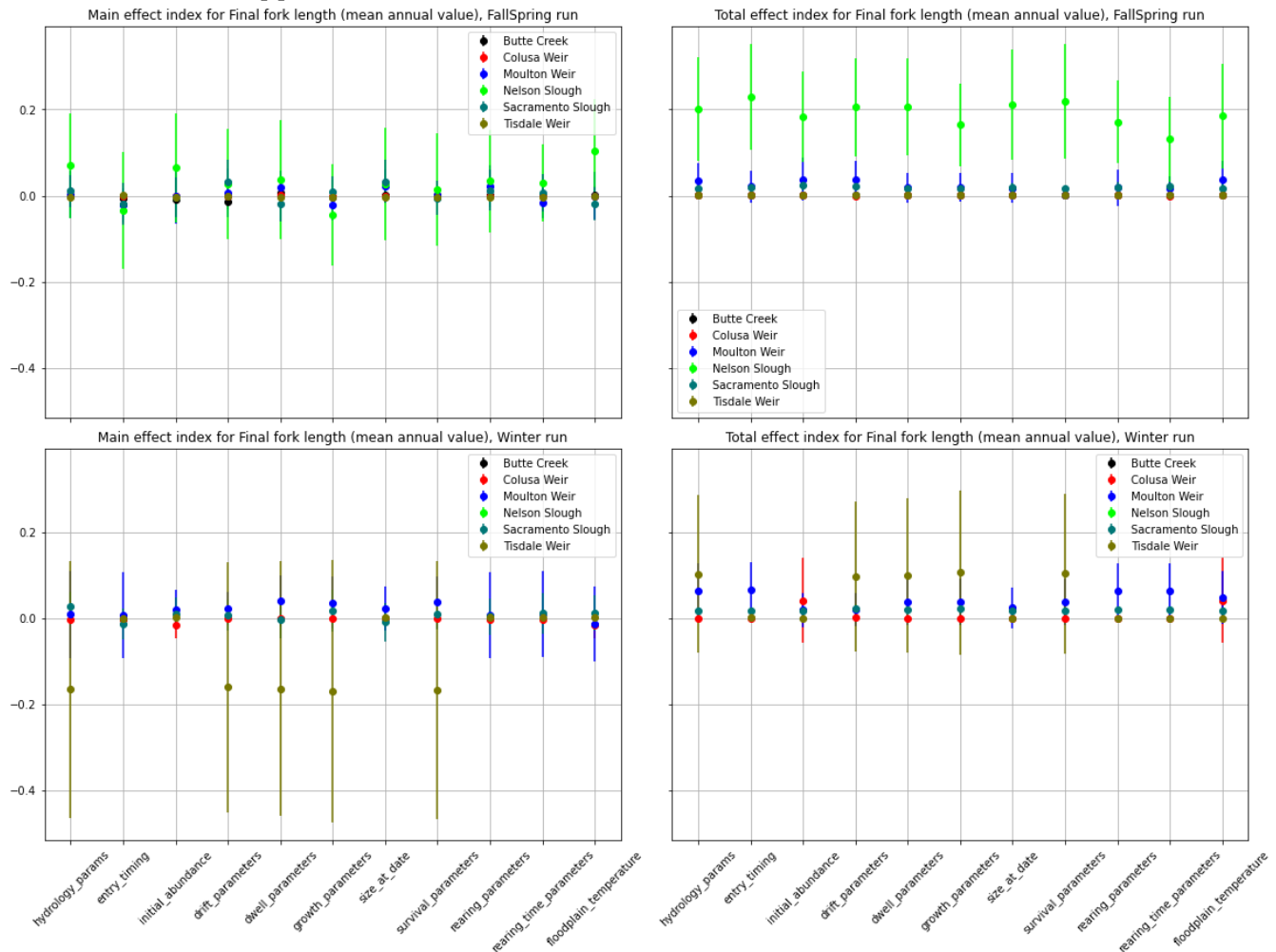


Figure 4. Results of the global sensitivity analysis of the SBM for the output "fork length at Chipps Island". Sobol' Indices were calculated for each parameter and entry location. Main effect indices measure the direct relationship between a parameter and output (fork length) and total effect indices also consider first order interactions among parameters.

When viewed together, this sensitivity analysis indicates that the SBM outputs "fork length at Chipps" and "rSAR" are relatively insensitive to the parameters examined for fish entering over Moulton, Colusa, and Tisdale Wiers.  The greatest sensitivity of either output to model parameters occurred for fish that entered Nelson Slough and Sacramento Slough. Nelson Slough is connected very infrequently which may account for the greater sensitivity relative to other locations. At Sacramento Slough, sensitivity of outputs was greatest when first order interactions were considered. The function for fish entry into Sacramento Slough includes river stage and is terminated with weir spill. Thus, the increase in magnitude of sensitivity when interactions are considered makes sense.

Although model outputs were generally insensitive to variance in model parameters, this analysis can not determine if the model structure is correct or that all the right parameters are included. Continued research, revision and integration of new data will continue to improve the SBM.

## Literature Cited

Anderson, J.J., E. Gurarie, and R.W. Zabel. 2005. Mean free-path length theory of predator-prey interactions: Application to juvenile salmon migration. Ecological Modelling 186:196-211.

Astrup, R., K.D. Coates, E. Hall. 2008. Finding the appropriate level of complexity for a simulation model: An example with a forest growth model. Forest Ecology and Management 256:1659-1665.

Cavallo, B., P. Gaskill, J Melgo, S.C. Zeug 2015. Predicting juvenile Chinook Salmon routing in riverine and tidal channels of a freshwater estuary. Environmental Biology of Fishes 98:1571-1582.

Ford, A. 1999. Modeling the Environment: An Introduction to System Dynamics Models of Environmental Systems. Island Press, Washington, D.C.

Hoar, W. S. 1953. Control and timing of fish migration. Biological Reviews 28: 437-452.

Iwata, M. 1995. Downstream migratory behavior of salmonids and its relationship with cortisol and thyroid hormones: a review. Aquaculture 135:131-139.

Johnston, M. Yolo Bypass acoustic telemetry studies of juvenile salmon (2012-213). Unpublished data.

Kery, M. and M. Schaub. 2012. Bayesian population analysis using WinBUGS: A hierarchical approach. Academic Press, San Diego, California.

McGurk, M.D. 1996. Allometry of marine mortality of Pacific salmon. Fisheries Bulletin 94:77–88

Peck, S.L. 2004. Simulation as experiment: a philosophical reassessment for biological modeling. Trends in Ecology and Evolution 19:530-534.

Perry, R.W., P.L. Brandes, J.R. Burau, P.Y. Sandstrom, J.R. Skalski. 2015. Effect of tides, river flow, and gate operations on entrainment of juvenile salmon into the interior Sacramento-San Joaquin Delta. Transactions of the American Fisheries Society 144:445-455.

Satterthwaite, W. H., S. M. Carlson, S. D. Allen-Moran, S. Vincenzi, S. J. Bograd, and B. K. Wells. 2014. Match-mismatch dynamics and the relationship between ocean-entry timing and relative ocean recoveries of Central Valley fall run Chinook salmon. Marine Ecology Progress Series 511:237:248.

Satterthwaite, W.H. Coded-wire tag data from bay releases and ocean recoveries (1978-2011). Unpublished data.

Takata, L., T.R. Sommer, J.L. Conrad, and B.M. Schreider. 2017. Rearing and migration of juvenile Chinook salmon (*Oncorhynchus tshawytscha*) in a large river floodplain. Environmental Biology of Fishes. https://doi.org/10.1007/s10641-017-0631-0

Ward, B.R., P.A. Slaney, A.R. Facchin, R.W. Land. 1989. Size- biased survival in steelhead trout (Oncorhynchus mykiss): back-calculated lengths from adults' scales compared to migrating smolts at the Keogh River, British Columbia. Canadian Journal of Fisheries and Aquatic Sciences 46:1853–1858.

Wells, B.K., J.A. Santora, J.C. Field, R.B. MacFarlane, B.B. Marinovic, W.J. Sydeman. 2012. Population dynamics of Chinook salmon *Oncorhynchus tshawytscha* relative to prey availability in the central California coastal region. Marine Ecology Progress Series 457:125-137.

Williams, J. G. 2006. Central Valley salmon: A perspective on Chinook and Steelhead in the Central Valley of California.  San Francisco Estuary and Watershed Science, 4(3). jmie_sfews_10982. Retrieved from: https://escholarship.org/uc/item/21v9x1t7

Woodson, L.E., B.K. Wells, P.K. Weber. R.B. MacFarlane, G.E. Whitman. R.C. Johnson. 2013. Size, growth, and origin-dependent mortality of juvenile Chinook salmon *Oncorhynchus tshawytscha* during early ocean residence. Marine Ecology Progress Series 487:163-175.

Zeug, S.C., Null, R., Brodsky, A., Johnston, M., Ammann, A.J. 2020. Effect of release timing on apparent survival of juvenile fall run Chinook salmon from Coleman National Fish Hatchery. Environmental Biology of Fishes 103:411-423.