Appendix G3

Evaluating Juvenile Chinook Salmon Entrainment Potential for Multiple Modified Fremont Weir Configurations: Application of Estimating Juvenile Winter-run and Springrun Chinook Salmon Entrainment onto the Yolo Bypass over a Notched Fremont Weir

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State of California
California Natural Resources Agency
Department of Water Resources

Yolo Bypass Salmonid Habitat Restoration and Fish Passage Project

Evaluating Juvenile Chinook Salmon Entrainment Potential for Multiple Modified Fremont Weir Configurations:

Application of *Estimating Juvenile Winter-run and Spring-run Chinook Salmon Entrainment onto the Yolo Bypass over a Notched Fremont Weir* (Acierto et al. 2014)

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Acronyms and Abbreviations

BDCP	Bay Delta Conservation Plan
CDEC	California Data Exchange Center
CDFW	California Department of Fish and Wildlife
CPUE	Catch per Unit Effort
CV	Central Valley
DWR	California Department of Water Resources
EIR/EIS	Environmental Impact Report/Environmental Impact Statement
JEET	Juvenile Entrainment Evaluation Tool
NAVD88	North American Vertical Datum of 1988
NCRO	California Department of Water Resources North Central Region Office
Reclamation	United States Bureau of Reclamation
RPA	Reasonable and Prudent Alternative
TUFLOW	2014 Yolo Bypass TUFLOW Hydrodynamic Model
USED	United States Engineering Datum
USGS	United States Geological Survey

1. Background

Juvenile Chinook Salmon (*Oncorhynchus tshawytscha)* that rear on the Yolo Bypass floodplain during periods of inundation experience enhanced growth and survival when compared to those that remain in the mainstem Sacramento River (Sommer et al. 2001). As a result, the floodplain-reared fish are expected to fare better in their marine environment (Claiborne et al. 2011). In addition to growth-related survival benefits, off-channel rearing provides emigrating salmon with alternate migratory routes and variable timing of ocean entry, further reducing its vulnerability to stressors such as predation and offshore ocean conditions (Schindler et al. 2010). It is likely that drawing more fish onto the Yolo Bypass floodplain would yield a direct increase in adult escapement, population resilience, and further contribute to the recovery of the species (Cramer Fish Sciences 2014). More fish could be drawn onto the Yolo Bypass by making modifications to the Fremont Weir, which is the primary source of inundation for the Yolo Bypass.

As part of the Yolo Bypass Salmonid Habitat Restoration and Fish Passage Project (California Department of Water Resources and the United States Bureau of Reclamation 2012), the California Department of Water Resources (DWR) and the United States Bureau of Reclamation (Reclamation) are working to increase inundation frequency, increase juvenile salmonid access to floodplain habitat, and improve fish passage in the Yolo Bypass. A gated structure (gated notch), or multiple gated structures in the Fremont Weir would allow flows to enter the Yolo Bypass and provide floodplain rearing habitat for juvenile salmonids while also providing upmigrating adult fish with a means of returning to the Sacramento River. This project would assist DWR and Reclamation with satisfying Reasonable and Prudent Alternative (RPA) Action I.6.1 (increased floodplain rearing habitat) and Action I.7 (improved fish passage) of the 2009 National Marine Fisheries Service's Biological Opinion and Conference Opinion on the Long-term Operations of the Central Valley Project and the State Water Project (Biological Opinion).

In 2014, the California Department of Fish and Wildlife (CDFW) developed an approach to evaluate the entrainment of juvenile Chinook Salmon onto the Yolo Bypass (Acierto et al. 2014). Specifically, Acierto et al. (2014) used historic flow data and Knights Landing rotary screw trap catch data of juvenile Chinook Salmon from 1997 to 2011 to compare existing conditions to a proposed notching of Fremont Weir. DWR has taken this approach with the same observed fish data, modified it to include additional hydrologic data, and organized it into a spreadsheet called the Juvenile Entrainment Evaluation Tool (JEET). The results from the JEET provide a means for comparing potential juvenile salmon entrainment for the proposed gated notch alternatives as part of the development of the Environmental Impact Report/Environmental Impact Statement (EIR/EIS) for the project.

This technical memorandum provides a summary of the JEET development, as well as an analysis of the tool's results. This tool is one of several tools that will be used to evaluate the proposed gated notch alternatives, with each tool examining a specific set of parameters. Whereas this tool evaluates the entrainment potential of each alternative based on juvenile Chinook Salmon abundance and river flow, additional tools will be used to provide relative comparisons for other important performance metrics for each alternative. For example, The Juvenile Salmon Benefits Model (Hinkelman et al. 2017) includes hydraulic modeling (TUFLOW Classic) to quantify estimates of available habitat, growth, migration rate, and survival.

2. Target Species

The JEET includes an analysis of the potential entrainment of all Central Valley (CV) runs of juvenile Chinook Salmon based on data recorded at the Knights Landing rotary screw trap (Acierto et al. 2014). CV steelhead *O. mykiss* are not included in this analysis due to the limited availability of rotary screw trap catch data. Given the similarities in behavior and swimming capabilities amongst juvenile salmonids, it is assumed that steelhead would utilize a modified Fremont Weir in a manner similar to Chinook Salmon. The southern distinct population segment of North American Green Sturgeon *Acipenser medirostris* were not included in this analysis because the juvenile life stage of sturgeon is not a component of RPA Action I.6.1.

3. Modeled Scenarios

Six alternatives were developed for evaluation in the Yolo Bypass Salmonid Habitat Restoration and Fish Passage Project EIR/EIS. Existing conditions and each alternative were analyzed to compare differences in potential juvenile entrainment (Table 1). Under existing conditions, entrainment is assumed to occur when the Sacramento River stage exceeds the crest of the Fremont Weir at 32.0' (NAVD88, North American Vertical Datum of 1988)[1] at DWR's North Central Region Office's Surface Water Data Section (NCRO) gauging station located at the west end of the Fremont Weir (#A02170). The gated notch alternatives each allow Sacramento River water to enter the Yolo Bypass beginning at invert elevations ranging from 14.0' to 23.0' (station #A02170). Each alternative has a unique combination of gate and channel

[1] Although the Fremont Weir's crest elevation varies west to east, DWR's California Data Exchange Center (CDEC) documents the crest elevation as 32.0 ft (NAVD88) for station #A02170 (Fremont Weir west end). For modeling purposes and throughout this technical memo, all elevations are recorded in NAVD88.

design and invert elevation. The maximum flow rate for these alternatives ranges from 3,000 cfs to 12,000 cfs. Water years 1997 through 2011 were analyzed during the prescribed structural operational window of November 1 through March 15 (Alternative 4b functions identically to Alternative 4 with an earlier operational end date of March7).

Table 1. Description of alternatives included in the final Juvenile Entrainment Evaluation Tool analysis.

Alternative	Alignment	Gate Dimensions	Gate Invert Elevations	Description	Design Flow (cfs)
1	East	Gate 1: 18’ x 34’ Gates 2 & 3: 14’ x 27’	Gate 1: 14’ Gates 2 & 3: 18’	30’ bottom width, 30’ bench, no levee	6,000
2	Central	Gate 1: 17’ x 40’ Gates 2 & 3: 13’ x 27’	Gate 1: 14.8’ Gates 2 & 3: 18.8’	50’ bottom width, 30’ bench, no levee	6,000
3	West	Gate 1: 16’ x 40’ Gates 2 & 3: 12’ x 27’	Gate 1: 16.1’ Gates 2 & 3: 20.1’	60’ bottom width, 30’ bench, no levee	6,000
4[2]	West	Gate 1: 16’ x 40’ Gates 2 & 3: 12’ x 27’	Gate 1: 16.1’ Gates 2 & 3: 20.1’	60’ bottom width, 30’ bench, no levee, downstream water control structures	3,000
5	Central	27 Gates Intake A, B, & C: 10’ x 10’ Intake D: 10’ x 7’	Intake A: 14’ Intake B: 17’ Intake C: 20’ Intake D: 23’	Intake A & B: 80’ bottom width Intake C: 130’ bottom width Intake D: 142’ bottom width	3,400
6	West	Gates 1-5: 14’ x 40’	16.1’	200’ bottom width	12,000
Existing Conditions	--	--	--	Flow over existing weir	--

[2] Includes Alternative 4b, which is the same configuration as Alternative 4 with an earlier operational end date of March 7.

Initially, three early project alternatives were modeled using TUFLOW Classic (Table 2). Those modeled results were used as inputs to the JEET, in addition to the Juvenile Salmon Benefits Model and an adult fish passage evaluation tool developed by DWR (California Department of Water Resources 2017a). The early JEET results indicated that increasing notch size was positively correlated with entraining greater quantities of fish onto the floodplain. These results are not surprising as the JEET is designed to examine the influence of flow and fish abundance on entrainment. Fish behavior, such as their cross-channel distribution under varying flows or their response to encountering physical structures, was deliberately omitted from this tool to avoid potentially confounding results as a result of introducing unknown or highly variable behavior (see Section 5. Key Assumptions and Limitations). However, because the gated structures rely on gate operations (a combination of open and closed gates) to limit inflow to 6,000 cfs, the adult fish passage evaluation tool showed that the maximum velocity criteria for adult fish passage (California Department of Water Resources 2017b) was exceeded at river stages well below the Fremont Weir crest, and thus adult fish passage was compromised (Table 3).

Table 2. Original project alternatives evaluated by the Juvenile Entrainment Evaluation Tool.

Alternative	Invert Elevation (NAVD88)	Bottom Width	Side Slope
Large Notch	14’	225’	3:1
Medium Notch	17.5’	225’	3:1
Small Notch	14’	20’	3:1
Existing Conditions	N/A (32.8’ @ crest of Fremont Weir)*	N/A	N/A

Table 3. Fisheries and Engineering Technical Team’s adult fish passage structural design criteria (California Department of Water Resources 2017b). These criteria represent the thresholds at which adult fish passage becomes compromised due to insufficient depth (avoidance behavior) or excessive water velocity.

Structure	Length	Depth Criterion	Velocity Criterion
Gate Structure / Short Channel Transitions	<60’	3’ Minimum	6 ft/sec Maximum
Downstream Channel	>60’	5’ Minimum	4 ft/sec Maximum

Note that the adult fish passage criteria defined in Table 3 was designed for both salmonids and sturgeon. Though salmonids are capable of passing structures that are significantly shallower or of higher velocity than listed in the criteria, the criteria are intended to account for the weakest performing target species (i.e. Green Sturgeon).

The project design team focused on optimizing adult fish passage by reducing velocities in the channel at the gate structure by adjusting the cross-sectional area of the channel to more closely match the downstream channel dimensions. Additionally, channel benches were added to some design alternatives so that when the velocity becomes too high in the main channel, depth and velocity criteria are met on the benches. As the stage rises in the passage channels and the main channel velocities approach the velocity threshold, flow spills out onto the benches providing a lower velocity option for fish to navigate. This design feature will presumably allow depth and velocity criteria to be met over a larger range of river stage and flow conditions. Three additional alternatives were developed incorporating a combination of benches, levees, and water control structures in an attempt to reduce the downstream inundation impact to local stakeholders.

4. Methods

4.1 Juvenile Entrainment Evaluation Tool Components

4.1.1 Fish Data Source

CDFW's Juvenile Salmon Emigration Monitoring Program operates two rotary screw traps in tandem in the Sacramento River at Knights Landing, roughly 5.5 river miles upstream from the Fremont Weir (38° 47' N, 121°, 41' W). CDFW generally operates these traps from October to June for each water year. The close proximity of the trap to the Fremont Weir makes this data source the best approximation for juvenile salmonid run timing at Fremont Weir. Acierto et al. (2014) evaluated the effects of providing increased access to floodplain habitat to Central Valley Chinook Salmon via a notch in the Fremont Weir. The study informed Central Valley and Delta projects related to the Yolo Bypass, including this project, the Sacramento River Flood Control Project, and the BDCP.

Acierto et al. (2014) used daily catch and trapping effort data to determine a daily catch per unit effort (CPUE) for Chinook Salmon. Run assignments were made based on the length-at-date criteria initially developed by Fisher (1992) and modified by Greene (1992) (Appendix A of del Rosario et al. 2013). CPUE was used instead of raw catch as a means of accounting for inconsistencies in trap operation and efficacy under varying flow conditions and debris load. CPUE accounts for the duration of trap operation and reduces the risk of over- or underestimating daily fish abundance.

Daily CPUE ($CPUE_i$) for each run was derived by:

$CPUE_i = C_i / (E_i/24)$, where C = daily catch, i = daily index, and E = effort (hours).

For the juvenile entrainment analysis, $CPUE_i$ were acquired from Appendix A of Roberts et al. (2013), which is the white paper version of Acierto et al. (2014). $CPUE_i$ was further converted to determine the daily proportion of a given years' total CPUE that was in the river (P_i) at Knights Landing by run (see Section 4.2 for detailed conversion steps). P_i is an estimate of what proportion of the total population of a given run was present in the Sacramento River at Knights Landing on a given day.

$$\mathbf{P_i = CPUE_i / \sum CPUE_i}$$

This daily proportion (P_i) was applied to the total annual observed $CPUE_i$ sum to derive the estimated daily number of fish in-river (for added detail on this application, refer to Section 4.2). Mortality was not estimated for the stretch of river from the Knights Landing rotary screw traps to the Fremont Weir. As a result, P_i at Knights Landing is assumed to equal P_i at Fremont Weir for this evaluation.

4.1.2 Flow Data Source

The proportion of Sacramento River flow diverted into the Yolo Bypass was used to estimate the number of fish likely to enter the Yolo Bypass. To remain consistent with the 1997 through 2011 range of available CDFW fish catch data (Roberts et al., 2013), the same 15-year period of Sacramento River daily stage height was used (provided by NCRO).[3] When there was no flow over the Fremont Weir, this proportion was determined by dividing the flows through the proposed channel by the flows in the Sacramento River.

For flow over the Fremont Weir, the flow portion was calculated based upon the combined Sacramento River and Sutter Bypass flows.

Flows onto the Yolo Bypass were modeled using TUFLOW Classic. The TUFLOW model is designed to provide discharges at a number of locations in the vicinity of Fremont Weir confluence area. Model inflows include the Sacramento River below the Knights Landing Outfall Gates, Sutter Bypass, Feather River, and the Natomas Cross Canal. These flows are balanced by the outflows, which include Fremont Weir overtopping, Sacramento River at Verona, and all project-related channel discharges. For consistency, the flows in the Sacramento River and Sutter Bypass were calculated by subtracting all of the other flows into the confluence area from the flows leaving the confluence area.

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[3] Fremont Weir mean daily stage height data were obtained from NCRO in the United States Engineering Datum (USED). Stages were converted from USED to the NAVD88 by subtracting 1.45 feet (Fremont Weir west end gauge only). Note: this conversion is site specific and should not be applied to other gauges.

Flow gauge data was used to the extent available. When actual flow data was not available, flows were estimated using computer/spreadsheet models, estimation techniques, or information from previous studies. California Department of Water Resources (2017c) provides a detailed overview of flow data sources, node locations, flow equations, and TUFLOW model development.

Based upon the discussion above, when there is no flow over the Fremont Weir, the proportion of flow diverted onto the Yolo Bypass is based upon the following equation:

FP = (NOTCH) / (NOTCH + VON - FEA - SUT - NCC)

Where:

FP = Flow proportion

NOTCH = Discharge through the proposed weir “notch” and channel

VON = Discharge in the Sacramento River at Verona

FEA = Discharge in the Feather River

SUT = Discharge in the Sutter Bypass (including Sutter Slough)

NCC = Discharge in the Natomas Cross Canal

During Fremont Weir overtopping, Sacramento River discharge over the Fremont Weir (FRE) was added to both the numerator and the denominator, and the Sutter Bypass discharge was removed from the denominator making the flow proportion based upon the combined Sacramento River flow and the flow in the Sutter Bypass. The proportion of flow (FP) entering the Yolo Bypass during an overtopping event was estimated by modifying the original equation used by Acierto et al. (2014), to exclude flows from the Feather River Basin. The inclusion of flows from the Feather River and the Natomas Cross Canal during overtopping conditions resulted in artificially high total flows being input into the river just upstream of Fremont Weir (the denominator), which would bias the result towards lower estimates for entrainment. Thus, the equation was modified to exclude flows from the Feather River and the Natomas Cross Canal to become:

FP = (NOTCH + FRE) / (NOTCH + FRE + VON – FEA – NCC)

Where:

FRE = Fremont Weir discharge

A detailed synopsis of the TUFLOW modeling effort, including a description of flow inputs and locations, can be found in the Yolo Bypass Salmonid Habitat Restoration and Fish Passage Hydrodynamic Modeling Draft Report (California Department of Water Resources 2017c).

4.2 Approach

Daily flow splits (proportion of flow diverted from the Sacramento River onto the Yolo Bypass) for each alternative were developed (see Section 4.1.2) and coupled with the daily fish presence data derived from Acierto et al. (2014) (see Section 4.1.1). Acierto et al. (2014) used $CPUE_i$ to estimate the daily proportion of each run passing Fremont Weir (fish data came from Knights Landing located 5.5 river miles upstream, and a 100% survival estimate was applied). This was applied to the total annual observed $CPUE_i$ sum of each run to determine the daily estimated number of fish in the proximity of Fremont Weir for each day (Table 4):

Daily # of Fish in River = P_i * Annual $CPUE_i$ Sum

Once the daily number of fish in the vicinity of the weir was determined, entrainment onto the Bypass was estimated using a proportion of flow entrainment hypothesis (Table 5). This hypothesis assumes that fish are distributed in a 1:1 ratio with flow across the Sacramento River at Fremont Weir, and therefore the proportion of flow diverted onto the Bypass is equal to the proportion of the population that is entrained on a given day (See Figure 1 for complete conversion process). For example, if 1,000 juvenile winter-run Chinook Salmon are present on a day in which 30% of the flow is drawn onto the Yolo Bypass, then 300 winter-run are entrained onto the Yolo Bypass. This analysis was limited to dates that fell within the proposed project operational window of November 1 – March 15, with the exception of Alternative 4b, which has an operational window of November 1 – March 7.

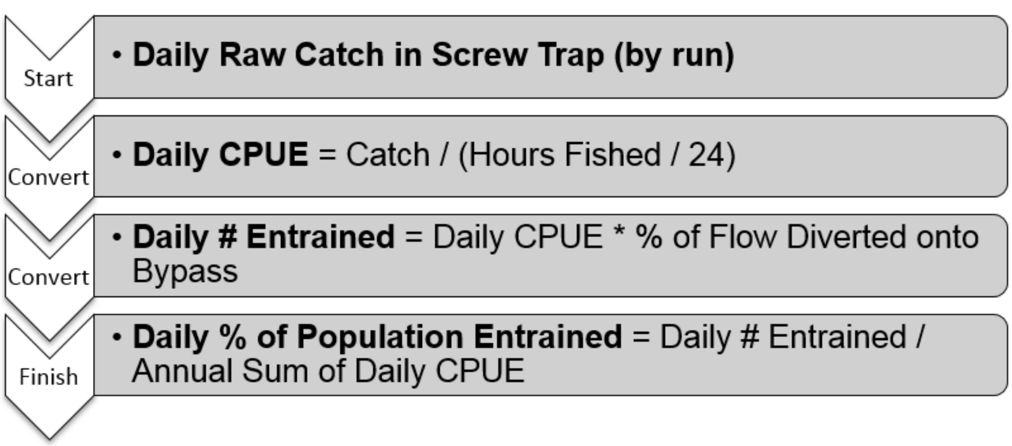

Figure 1. Flow chart of daily screw trap catch data conversion process.

Table 4. Example calculation of the estimated daily number of juvenile Chinook Salmon in the Sacramento River at Fremont Weir (by run).

Date	Stage (ft. - NAVD 88)	Annual Sum Fall-Run CPUE	Annual Sum Spring-Run CPUE	Annual Sum Winter-Run CPUE	Annual Sum Late Fall-Run CPUE	Fall-Run CPUE (%)	Daily CPUE Fall-Run	Spring-Run CPUE (%)	Daily CPUE Spring-Run	Winter -Run CPUE (%)	Daily CPUE Winter-Run	Late Fall-Run CPUE (%)	Daily CPUE Late Fall-Run
12/8/1996	20.96	24,089	1,139	162	78	0.00	1	0.15	2	1.77	3	6.62	5
12/9/1996	21.08	24,089	1,139	162	78	0.06	16	0.94	11	2.70	4	4.37	3
12/10/1996	24.14	24,089	1,139	162	78	0.04	11	1.27	15	2.77	5	2.56	2
12/11/1996	28.12	24,089	1,139	162	78	0.44	106	12.91	147	7.47	12	11.00	9
12/12/1996	30.49	24,089	1,139	162	78	1.18	285	13.92	159	5.35	9	2.93	2
12/13/1996	33.14	24,089	1,139	162	78	1.07	259	11.46	131	3.13	5	4.55	4
12/14/1996	33.82	24,089	1,139	162	78	0.38	91	7.24	82	2.34	4	2.08	2
12/15/1996	33.77	24,089	1,139	162	78	0.67	161	11.08	126	2.04	3	3.71	3

Table 5. Example calculation of the daily proportion of the total annual juvenile Chinook Salmon population entrained onto the Yolo Bypass with a modified notch in place (by run).

Date	Daily # Fall-Run in River	Daily # Spring-Run in River	Daily # Winter-Run in River	Daily # Late Fall-Run in River	% Sac R flow onto Bypass: Alt. #1	# Fall-Run Entrain	% Fall-Run Entrain	# Spring-Run Entrain	% Spring-Run Entrain	# Winter-Run Entrain	% Winter-Run Entrain	# Late Fall-Run Entrain	% Late Fall-Run Entrain
12/8/1996	1	2	3	5	11%	0	0.001%	0	0.017%	0	0.203%	1	0.758%
12/9/1996	16	11	4	3	11%	2	0.007%	1	0.106%	0	0.305%	0	0.493%
12/10/1996	11	15	5	2	10%	1	0.005%	2	0.134%	0	0.291%	0	0.269%
12/11/1996	106	147	12	9	15%	16	0.064%	22	1.899%	2	1.100%	1	1.618%
12/12/1996	285	159	9	2	20%	57	0.235%	32	2.766%	2	1.064%	0	0.581%
12/13/1996	259	131	5	4	24%	62	0.259%	32	2.769%	1	0.757%	1	1.100%
12/14/1996	91	82	4	2	22%	20	0.082%	18	1.584%	1	0.512%	0	0.456%
12/15/1996	161	126	3	3	53%	86	0.355%	67	5.902%	2	1.087%	2	1.976%

Daily estimates of proportion entrained were summed to derive the estimated annual average proportion of juvenile Chinook salmon entrained onto the Yolo Bypass (by run) for each alternative, as well as under existing conditions. The calculated entrainment of juvenile Chinook Salmon under existing conditions (i.e., entrainment only occurs via Fremont Weir overtopping) was used as a benchmark to compare the calculated entrainment values from each gated notch alternative. Using existing conditions as a baseline allows for a standardized, unbiased method of assessing the entrainment potential of each project alternative.

5. Key Assumptions and Limitations

The data input into the JEET have been verified by CDFW and DWR staff. The results are intended to represent the relative entrainment potential across alternatives based on flow and fish abundance. To better understand how fish are actually distributed across the Sacramento River at Fremont Weir and how they might interact with a proposed notch, a multi-agency telemetry study was conducted by the United States Army Corps of Engineers, USGS, Reclamation and DWR in the winter of 2015. The two-dimensional tracks generated by this study were used to validate an existing fish behavior model (Smith et al. 2017) developed for use on the Yolo Bypass notch development. The results of the telemetry study and the associated behavioral model (Smith et al. 2017), the Juvenile Salmon Benefits Model (Hinkelman et al. 2017), and a critical streakline analysis (Blake et al. 2017) will be used to determine fish response to different notch locations and configurations in an effort to optimize the ratio of fish entrained to flow diverted.

The key assumptions and limitations of the JEET are as follows:

- The juvenile entrainment analysis uses the total annual sum of daily CPUE (Roberts et al. 2013) for each run as a surrogate for the entire juvenile population.
    - While these annual sums are substantially lower than their respective juvenile production estimates (JPE), it is an acceptable means of providing a standardized method of evaluating entrainment across multiple years by using empirical catch data.
    - Because this tool uses proportion entrained based on empirical data (i.e., a small percentage of the actual JPE) as the primary metric for evaluating notch alternatives, the total calculated number of individuals entrained is of little importance and is therefore not reported.
    - The proportion of the total population of a given run present in the Sacramento River at Knights Landing on a given day (P_i) is the key input.

P_i is derived from empirical catch data, and provides an accurate means of comparison.

- Substituting JPE for the annual $CPUE_i$ sum would yield identical entrainment proportions, and is thereby an unnecessary step for the purpose of this evaluation.

- CDFW's rotary screw traps at Knights Landing are not sampled every day. Days in which sampling did not occur include (but are not limited to): weekends, holidays, and high flow events. Similarly, trap efficiency may vary due to debris load, trap malfunctions, etc.
  - Roberts et al. (2013) adjusted daily CPUE to account for gaps in sampling. However, these estimates are extrapolations and are not expected to be 100% accurate. Dates with missing fish CPUE data were eliminated from this analysis.
  - Trap efficiency data are not available; therefore the estimated proportion sampled by the rotary screw traps may not accurately reflect the actual population at large (see Roberts et al. 2013).
  - Rotary screw trap catch data represents a sub-sample of the total daily abundance in-river. The proportion captured is likely to differ day-to-day based on variances in fish distribution across the channel, the presence of predators, boating activity in the vicinity of the trap, or any number of factors contributing to a change in trap efficiency. As a result, fish may have passed the Knights Landing rotary screw traps in abundances greater than or less than the daily values extrapolated from the CPUE conversion.
  - Mortality was not estimated for the stretch of river from the Knights Landing rotary screw traps to the Fremont Weir. This tool assumes that 100% of the fish represented by the Knights Landing screw trap data will make it to the Fremont Weir.
- Fish were assigned to a run based on length-at-date criteria derived from the River Model (Appendix A of del Rosario et al. 2013), which genetic sampling has shown to be less than 100% accurate. Based on genetic analyses, Merz et al. (2014) found that the River Model length-at-date criteria correctly classified fall/late fall-run Chinook Salmon about 89% of the time, winter-run Chinook Salmon about 77% of the time, and spring-run Chinook Salmon about 22% of the time. Fall-run and late fall-run Chinook Salmon were lumped together due to similarities in allele frequency. These results were based on fish sampled at the Knights Landing rotary screw traps from 2010 to 2011.
  - Roberts et al. (2013) reclassified several fish that were originally identified as spring-run by the trap servicing crew between April and June. Though the size of these fish met spring-run assignment criteria, hatchery release

records indicate that they were more than likely hatchery-released fall-run Chinook Salmon. Central Valley hatchery fall-run Chinook Salmon are not all adipose-fin clipped, which makes it difficult to distinguish natural from hatchery origin fish.

- Entrainment onto the Yolo Bypass was estimated using a "proportion of flow" approach. With this approach, it was assumed that fish are entrained onto the floodplain proportional to the amount of flow diverted from the Sacramento River.
  - In other reaches of the Sacramento River, studies have shown that juvenile Chinook Salmon are generally not equally entrained in a 1:1 proportion to the flow (Burau et al. 2007). It is hypothesized that salmon distributions concentrate toward the outside of channel bends as a result of the higher flows found in these bends. As a result, the ratio of fish entrained could be greater than the proportion of flow diverted for notches located on the outside of channel bends (Burau et al. 2007).
  - The telemetry study mentioned at the beginning of this section was conducted to better understand how hatchery late fall-run Chinook Salmon and hatchery winter-run Chinook Salmon are distributed in the river at the western end of the Fremont Weir. Based on preliminary results, distributions of both runs of salmon appeared to follow the bulk flow path and were biased toward the outside of bends more frequently than the inner bend (Steel et al. 2017).
  - The JEET was designed to focus on fish abundance and flow as the primary inputs to evaluate the effects of timing and magnitude of operation on entrainment for each alternative. Fish abundance and flow inputs come from documented, quality-checked field observations. Fish behavior was deliberately excluded as an additional component. The inclusion of a behavioral component is likely to increase the accuracy of results, but could introduce a fair amount of scientific uncertainty which could make it difficult to compare the timing and magnitude of operation between alternatives.

While the results of the model developed by Smith et al. (2017) represent a more accurate predictor of entrainment, the JEET yields a more precise, relative comparison of potential entrainment amongst project alternatives. By taking multiple approaches at evaluating the entrainment potential of each project alternative, the results of each approach can be used to either confirm or deny one another. Similar results would help to confirm the validity of the various analytical approaches, whereas dissimilar findings would help to: a) highlight the influence each potential driver (i.e., flow, fish abundance, location, notch configuration, or fish behavior) has on determining entrainment; or b) identify tool deficiencies that need to be further addressed.

- Alternatives 1, 2, and 3 are essentially the same structure located at different points along the Fremont Weir. To account for the slope of the Sacramento River, the invert elevations for each site had to be adjusted to maintain the same flow pattern (Table 1). Though there is 2.1' of difference in the invert elevation between the eastern- and the western-most alternatives (Alternative 1 and 3, respectively), they each divert the same proportion of flow from the Sacramento River. For the purpose of this report, they are assumed to function the same, and therefore their fish entrainment potentials are assumed to be identical.
    - The actual extent of location-specific entrainment effects will be analyzed by Smith et al. (2017).
- Daily flow splits (the amount of total river flow diverted onto the Yolo Bypass) were developed for each alternative by inputting station gauge data into the TUFLOW model developed for the Sacramento River/Yolo Bypass region. All data was quality-checked for accuracy and consistency by NCRO. Some daily mean stage height data were based on estimates, but the majority of the data were labeled as "good, continuous records" by NCRO.
    - The effects of backwatering from flow coming from the west side tributaries are highly variable and are therefore difficult to account for. Backwatering conditions may impact rating curve development more or less than what has been predicted by the TUFLOW model, though these deviations are unlikely to result in significant variances in notch discharge.
- TUFLOW modeling results included periods of reverse flows for some alternatives. A modified intake channel would slope from the weir towards the Sacramento River, and under periods of rapid stage decrease the model allowed for flows to reverse through the structure and drain into the Sacramento River. Negative flows were changed to zero to more accurately reflect gate operation.
- This tool estimates the <u>relative entrainment potential</u> of various project alternatives, therefore the results should be used as a basis of comparison rather than predicting values.

6. Results

The average annual proportion of juvenile Chinook Salmon entrained (by run) for each alternative is one of the principal performance metrics by which alternatives were compared.

Table 6. Calculated average annual proportion of the juvenile Chinook Salmon population entrained onto the Yolo Bypass under proposed alternatives and existing conditions (by run).

Run	Existing Conditions	Alt 1 (East 6,000 cfs)	Alt 2 (Central 6,000 cfs)	Alt 3 (West 6,000 cfs)	Alt 4 (West 3,000 cfs)	Alt 4b (Mar 7 end date)	Alt 5 (Central 3,400 cfs)	Alt 6 (West 12,000 cfs)
Fall	7.1%	15.4%	15.4%	15.4%	13.0%	12.6%	13.3%	21.3%
Late Fall	2.6%	5.9%	5.9%	5.9%	5.2%	5.2%	5.4%	8.5%
Winter	3.9%	11.3%	11.3%	11.3%	9.5%	9.2%	9.8%	17.4%
Spring	3.1%	10.3%	10.3%	10.3%	8.4%	8.2%	8.8%	16.1%

Figures 3–6 illustrate how the annual average entrainment values in Table 6 are distributed via boxplots by salmon run. Figure 2 shows how to interpret these box plots, while Helsel and Hirsch (2002) provides a full description on the interpretation and creation of boxplots. Essentially, the diamond shape in each boxplot represents the average annual proportion of a Chinook salmon population entrained onto the Yolo Bypass across water years, as displayed in Table 6.

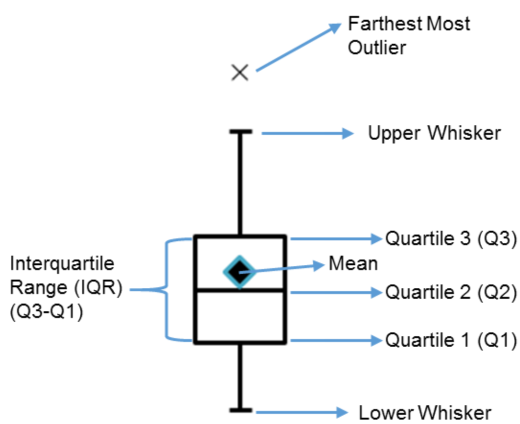

Figure 2. Elements of a boxplot used in this technical memorandum. For Figures 2-5, boxplots are plotted against the proposed alternative on the x-axis and entrainment on the y-axis.

The top and bottom of the box in Figure 2 represents the first and third quartiles (Q1, Q3). Q1 denotes that about 25% of the entrainment calculations are below this value and 75% of the entrainment calculations are above this value. In comparison, Q3 denotes that about 75% of the entrainment calculations are below this value, and 25% of the values are above this value. For existing conditions in Figures 3–6, Q1 falls on zero (the x-axis), so it appears truncated in the graphics.

The second quartile or the median is represented by the line within the box, while the box itself represents the interquartile range (IQR), which is the difference between the first and third quartile. The IQR represents the middle 50% of the distribution and is used to determine outliers.

The upper and lower whiskers represent the upper or lower 25% of the distribution with the exclusion of outliers. The endpoints of the whiskers represent the minimum (lower whisker) or maximum (upper whisker) annual average entrainment with the exclusion of outliers.

Outliers were determined if the entrainment fell below Q1−1.5 IQR or above Q3+1.5 IQR. For simplicity, this technical memorandum only displays the farthest most outlier in the dataset, which is represented with an “X.” Even so, there were typically no more than two outliers above the upper whisker. There were no outliers below the lower whisker.

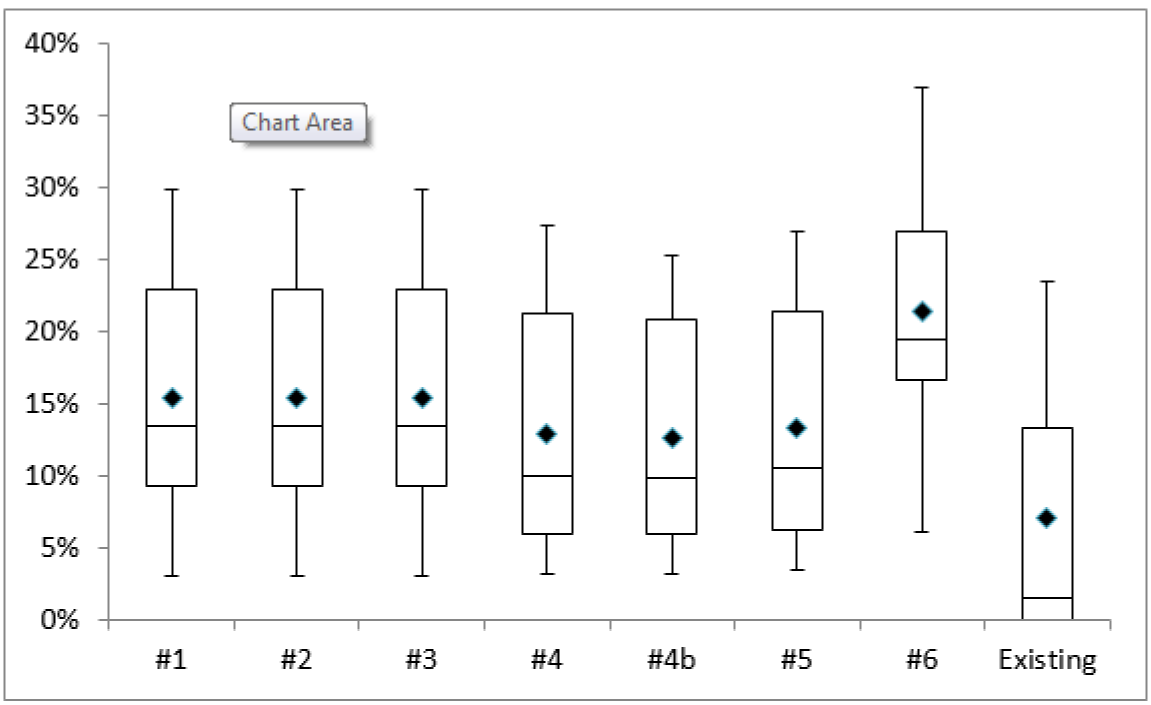

Figure 3. Boxplots of the calculated average annual proportion of the fall-run Chinook Salmon population entrained onto the Yolo Bypass under proposed alternatives and existing conditions, water years 1997-2011. Diamond shapes represent the mean, top and bottom of the box represent the first and third quartiles, line inside the box represents the median, and whiskers represent the minimum/maximum.

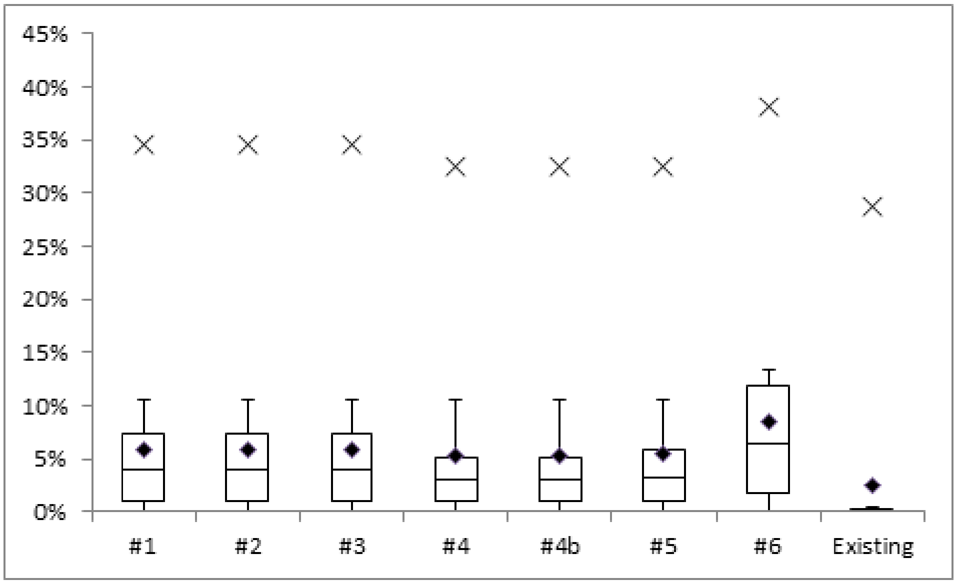

Figure 4. Boxplots of the calculated average annual proportion of the late fall-run Chinook Salmon population entrained onto the Yolo Bypass under proposed alternatives and existing conditions, water years 1997-2011. Diamond shapes represent the mean, top and bottom of the box represent the first and third quartiles, line inside the box represents the median, whiskers represent the minimum/maximum (excluding outliers), and X represents the farthest most outlier.

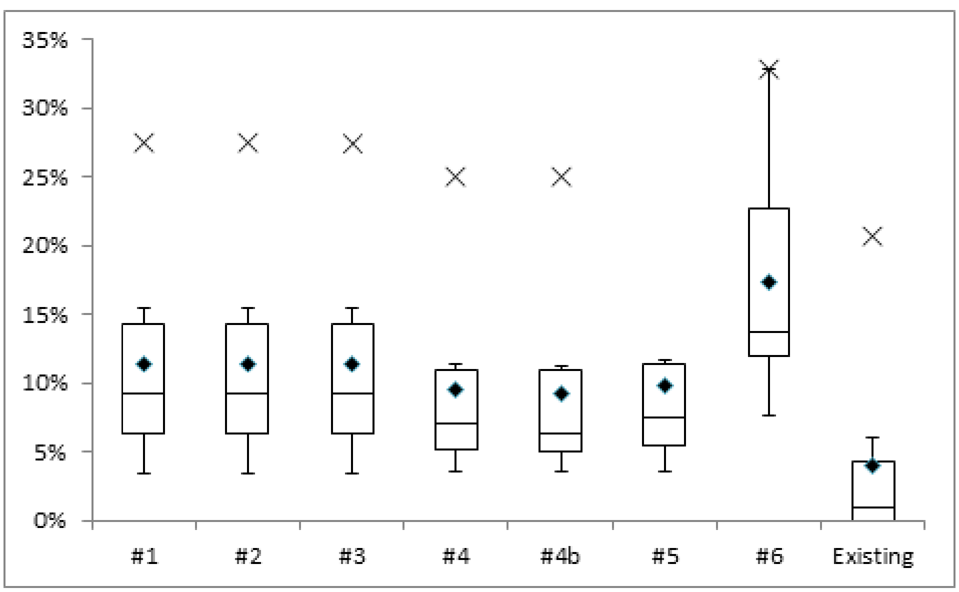

Figure 5. Boxplots of the calculated average annual proportion of the winter-run Chinook Salmon population entrained onto the Yolo Bypass under proposed alternatives and existing conditions, water years 1997-2011. Diamond shapes represent the mean, top and bottom of the box represent the first and third quartiles, line inside the box represents the median, whiskers represent the minimum/maximum (excluding outliers), and X represents the farthest most outlier.

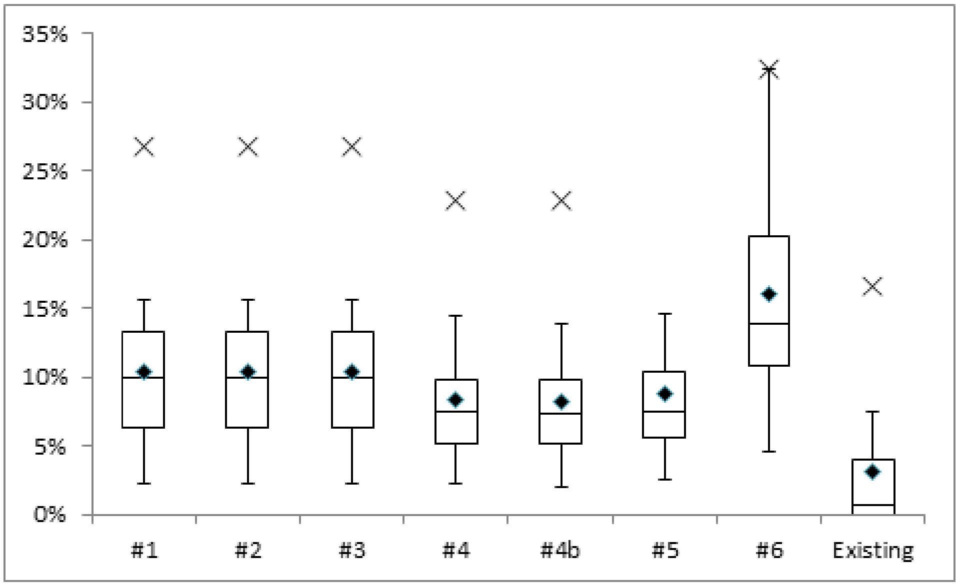

Figure 6. Boxplots of the calculated average annual proportion of the spring-run Chinook Salmon population entrained onto the Yolo Bypass under proposed alternatives and existing conditions, water years 1997-2011. Diamond shapes represent the mean, top and bottom of the box represent the first and third quartiles, line inside the box represents the median, whiskers represent the minimum/maximum (excluding outliers), and X represents the farthest most outlier.

Comparing the entrainment potential between existing conditions and each alternative provides the average annual increase in the proportion of the population entrained (Figure 7).

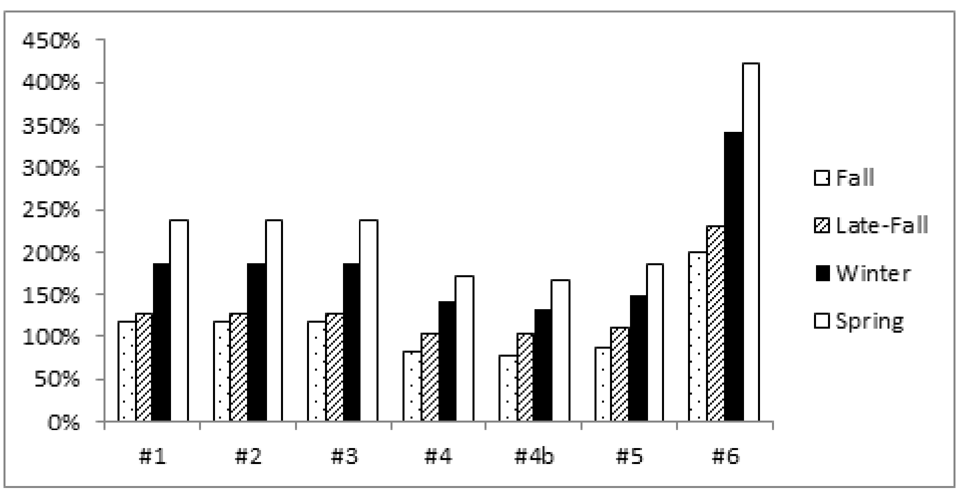

Figure 7. Relative comparison of the calculated mean annual increase in the proportion of the total population of juvenile Chinook Salmon entrained onto the Yolo Bypass over existing conditions (by run), water years 1997-2011.

Estimated entrainment was further broken down by water year type as defined in Table 7. Figures 8 and 9 illustrate the calculated mean annual entrainment of juvenile spring-run and winter-run Chinook Salmon (respectively) under wet and dry years as defined by the Sacramento Valley Water Year Hydrologic Classification (California Data Exchange Center, 2017). Wet years include years categorized as wet or above normal, and dry years include years categorized as dry or critical.

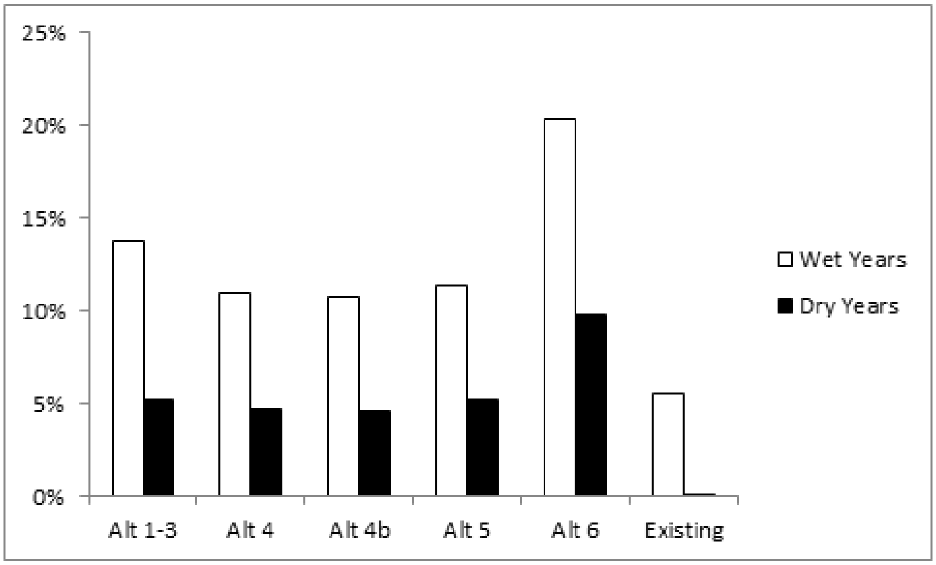

Figure 8. Calculated mean entrainment of juvenile spring-run Chinook Salmon onto the Yolo Bypass under proposed alternatives and existing conditions, by water year type. "Wet Years" include years categorized as wet or above normal. "Dry Years" include years categorized as dry or critical.

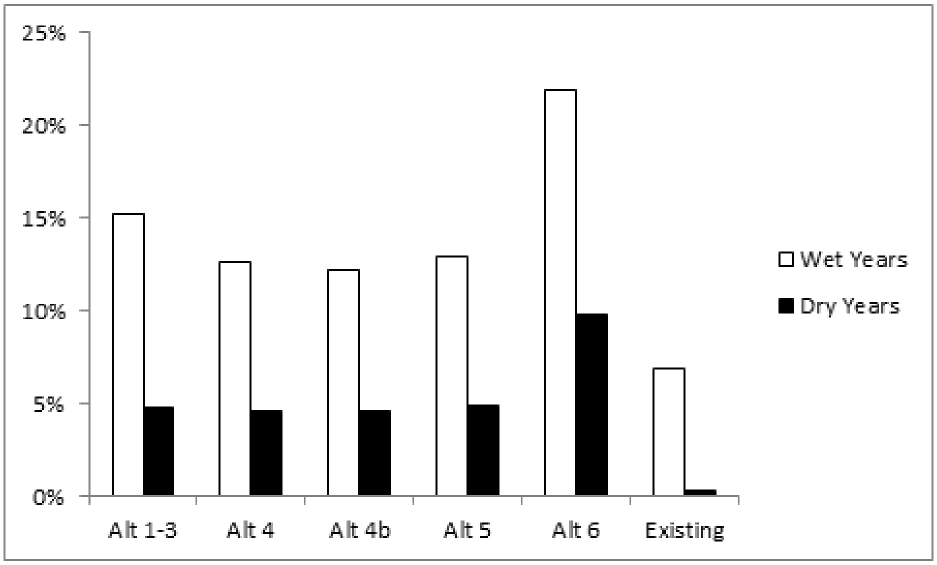

Figure 9. Calculated mean entrainment of juvenile winter-run Chinook Salmon onto the Yolo Bypass under proposed alternatives and existing conditions, by water year type. "Wet Years" include years categorized as wet or above normal. "Dry Years" include years categorized as dry or critical.

7. Discussion

Our results indicate that notching the Fremont Weir would greatly increase the proportion of emigrating juvenile Chinook Salmon that are entrained onto the Yolo Bypass. While considerable increases in entrainment occurred across all water year types, notch alternatives were particularly effective at increasing entrainment during dry and critical water years (Table 8). During dry and critical years, naturally occurring overtopping events are rare and are often short in duration providing minimal opportunities for juveniles to enter the Yolo Bypass. Though not as high as in dry years, notch entrainment during wet and above normal years was still substantially improved over existing conditions (Table 9).

Table 7. Calculated mean annual increase in the proportion of the total population of juvenile spring- and winter-run Chinook Salmon entrained onto the Yolo Bypass over existing conditions during dry and critical water years.

Run	Alternatives 1-3 6,000 cfs	Alternative 4 3,000 cfs	Alternative 4b Mar 7 end date	Alternative 5 3,400 cfs	Alternative 6 12,000 cfs
Spring	3,474.6%	3,109.9%	3,051.1%	3,478.2%	6,560.4%
Winter	1,677.1%	1,590.9%	1,570.0%	1,716.4%	3,488.3%

Table 8. Calculated mean annual increase in the proportion of the total population of juvenile spring- and winter-run Chinook Salmon entrained onto the Yolo Bypass over existing conditions during wet and above normal water years.

Run	Alternatives 1-3 6,000 cfs	Alternative 4 3,000 cfs	Alternative 4b Mar 7 end date	Alternative 5 3,400 cfs	Alternative 6 12,000 cfs
Spring	148.8%	97.7%	94.8%	105.8%	267.7%
Winter	121.8%	83.8%	77.2%	87.8%	218.6%

The JEET suggests that Alternative 6, because it would divert the largest volume of water from the Sacramento River (12,000 cfs), would have the potential to entrain the most juveniles. In general, alternatives with higher maximum flow capacities outperform those with lower capacities, provided the invert elevation is sufficiently deep to allow the alternative to operate during a broad range of flows. Whereas Alternative 6 unanimously entrains the most fish across all runs, Alternatives 4 and 4b, the alternatives with the lowest design flow (3,000 cfs), almost always entrain the fewest amounts of fish across all runs. This trend is because one of the primary assumptions of the JEET is that the proportion of the juvenile salmonid population entrained is directly related to the proportion of Sacramento River water diverted onto the Yolo Bypass.

However, though fish are unlikely to be entrained at a 1:1 ratio in relation to flow, given the inputs of flow and fish abundance in this analysis, it is reasonable to assume that the entrainment performance between alternatives would more-or-less still hold true (i.e., the alternatives that divert the largest volume will outperform those that divert smaller volumes). Location-specific effects (e.g., high concentration of fish at outside bends, more uniform distribution in straight channels, etc.) would not be accounted for in this analysis, but will be addressed by Smith et al. (2017).

Though fall-run entrainment is higher than all other runs across all notch alternatives (Table 6), spring- and winter-run Chinook Salmon are most likely to experience the greatest benefits from this project in terms of increased entrainment over existing conditions (Figure 7). This predicted outcome is due to the timing of spring- and winter-run emigration past Fremont Weir in comparison to fall-run. The majority of the spring- and winter-run juvenile populations typically arrive in the vicinity of the Fremont Weir earlier in the season than their fall-run counterparts (Figure 10). More than half of the winter-run population and a substantial portion of the spring-run population will have already passed the weir by January 1 on average (Table 10). For comparison, only 5.4% of the fall-run population will have passed the weir by January 1 (Table 10). This is significant because the Sacramento River is much more likely to overtop the Fremont Weir after January 1, and fish that arrive prior to this wet period (i.e. large portions of the winter- and spring-run populations) are less likely to be entrained onto the floodplain under existing conditions than fish that arrive later (i.e., fall-run). This highlights the importance of alternatives having sufficiently deep invert elevations to successful entrain the relatively high numbers of target species that migrate early in the season when the Sacramento River stage is low.

On average, 98.0% of winter-run juveniles and 80.8% of spring-run juveniles will have passed the Fremont Weir by the proposed March 15 operational end date compared to 78.8% of fall-run and only 68.3% of late fall-run (Table 10). While most winter-run salmon migrate past the Fremont Weir prior to the proposed March 15 operational end date, spring-run Chinook Salmon may experience further benefits by extending the operational end date to late March or early April as conditions permit (Table 10). Late fall-run Chinook Salmon typically emigrate as yearlings, meaning they rear in the upstream reaches longer and emigrate at a larger size than other runs. It is unknown how the larger late fall-run fish would benefit from floodplain rearing in comparison to the smaller, more numerous fall-run juveniles given that smolts may be more motivated to continue migrating toward saline environments than to rearing.

Therefore, it is possible that late fall-run fish may actually benefit from lower entrainment rates than fall- winter- and spring-run Chinook Salmon by being able to stay in the Sacramento River and continue emigrating.

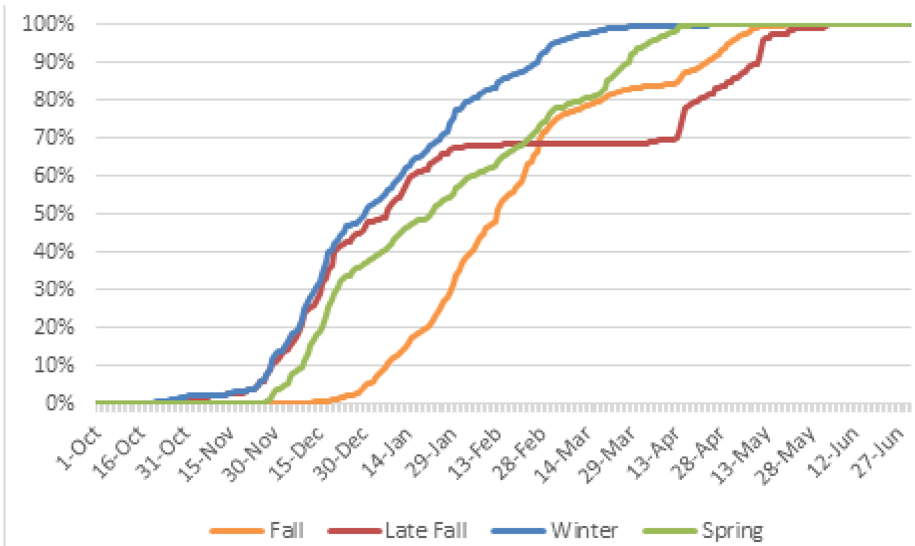

Figure 10. Knights Landing rotary screw trap average annual cumulative catch of juvenile Chinook Salmon by run, water years 1997-2011.

Table 9. Summary table of averaged Knights Landing rotary screw trap catch of juvenile Chinook Salmon by run, water years 1997-2011. March 7 denotes the operational end date for Alternative 4b. All other alternatives have an operational end date of March 15.

Date	Fall	Late Fall	Winter	Spring
Nov 1	0.0%	1.3%	1.9%	0.0%
Dec 1	0.0%	11.4%	13.5%	3.9%
Jan 1	5.4%	48.1%	52.0%	37.8%
Feb 1	36.8%	67.6%	78.2%	57.8%
Mar 1	73.2%	68.3%	94.4%	76.6%
Mar 7	76.6%	68.3%	96.3%	78.8%
Mar 15	78.8%	68.3%	98.0%	80.8%
Mar 31	83.3%	68.3%	99.4%	93.7%
Apr 30	94.6%	84.7%	99.9%	100.0%

The relative juvenile population size of each run may play an additional role in determining the expected benefit provided to each species as a result of implementing a notch alternative. Winter- and spring-run Chinook Salmon entrained onto the Yolo Bypass are likely to experience increased survival by increasing their physical body size as a result of floodplain rearing (Ward et al. 1989, McGurk 1996, Satterthwaite et al. 2014). Though fall-run would also experience this size-related survival increase, they have the additional advantage of being able to overcome significant predation losses by overwhelming predators with their sheer numbers, a luxury not available to the more imperiled winter- and spring-run populations.

The JEET represents a method of comparing the entrainment potential of project alternatives against entrainment potential under existing conditions based on fish abundance and flow, and is not intended to serve as a predictive model. Though many of the assumptions taken in the development of this tool may limit the accuracy of predicted entrainment, they do not necessarily diminish the ability of this tool to provide a meaningful, quantitative comparison of alternatives with a high degree of precision. This tool examines a wide range of flows and fish presence, which provides insight as to how variances in timing and magnitude of operation could affect entrainment across a broad spectrum of conditions.

There are multiple design modifications that could be implemented to guide or divert greater quantities of fish from the river into the Yolo Bypass (e.g., channel geometry modifications, guidance booms, etc.). Location-specific variables notwithstanding (i.e. varying salmonid concentrations at bends vs. in straight sections), most of these modifications could be applied to any one of the alternatives and would therefore not substantially affect the relative comparison of the alternatives analyzed.

It is also important to note that this tool is not intended to address other potential benefits of the different alternatives. For example, some alternatives will increase the frequency and duration of flooding, generating increased habitat benefits for fish. Similarly, the tool does not address other issues, including increased food web subsidies to downstream areas or adult fish passage efficiency. Hence, the current analysis should be considered alongside a full suite of other engineering, fisheries, and food web evaluations.

Finally, the relative differences between alternatives offer some assurance that substantial improvements to entrainment can be made while adjusting the design to meet other objectives, such as adult fish passage. Alternatives will continue to be refined to optimize their ability to pass adult fish without diminishing their capacity to entrain juvenile salmonids or to provide access to rearing habitat (California Department of Water Resources 2017c). As the level of project design advances beyond the conceptual level, further consideration will be given to performance metrics beyond juvenile entrainment and adult fish passage evaluation.

8. References

Acierto, K.A., J. Israel, J. Ferreira, and J. Roberts. 2014. Estimating juvenile winter-run and spring-run Chinook Salmon entrainment onto the Yolo Bypass over a notched Fremont Weir. California Fish and Game 100 (4): 630–639.

Blake, A., P. Stumpner, and J. Burau. 2017. A Simulation Method for Combining Hydrodynamic Data and Acoustic Tag Tracks to Predict the Entrainment of Juvenile Salmonids onto the Yolo Bypass under Future Engineering Scenarios. United States Geologic Survey.

Burau, J., A. Blake, and R. Perry. 2007. Sacramento/San Joaquin River Delta Regional Salmon Outmigration Study Plan: Developing Understanding for Management and Restoration. 172 pages.

California Data Exchange Center. California Department of Water Resources. Web. 25 July 2017. http://cdec.water.ca.gov/cgi-progs/iodir/WSIHIST.

California Department of Water Resources and United States Bureau of Reclamation. 2012. Yolo Bypass salmonid habitat restoration and fish passage implementation plan. Long-term operation of the Central Valley Project and State Water Project Biological Opinion Reasonable and Prudent Alternative Actions 1.6.1 and 1.7.

California Department of Water Resources. 2017a. Evaluating adult salmonid and sturgeon passage potential for multiple modified Fremont Weir configurations: application of the *Yolo Bypass Passage for Adult Salmonid and Sturgeon (YBPASS) Tool*. Technical memorandum for the Yolo Bypass Salmonid Habitat Restoration and Fish Passage Project. Sacramento, California.

California Department of Water Resources. 2017b. Adult fish passage criteria for federally listed species within the Yolo Bypass and Sacramento River. Technical memorandum for the Yolo Bypass Salmonid Habitat Restoration and Fish Passage Project. Sacramento, California.

California Department of Water Resources. 2017c. Yolo Bypass Salmonid Habitat Restoration and Fish Passage Hydrodynamic Modeling Draft Report. Technical memorandum for the Yolo Bypass Salmonid Habitat Restoration and Fish Passage Project. Prepared by HDR and cbec, Inc. Sacramento, California.

Claiborne, A. M., J. P. Fisher, S. A. Hayes, and R. L. Emmett. 2011. Size at release, size-selective mortality, and age of maturity of Willamette River hatchery yearling Chinook Salmon. Transactions of the American Fisheries Society 140:1135–1144.

Cramer Fish Sciences. 2014. Modeling the Benefits of Yolo Bypass Restoration Actions on Chinook Salmon. Draft report (August 19, 2014) to the California Department of Water Resources. 20 pages.

del Rosario, R.B., Y.J. Redler, K. Newman, P.L. Brandes, T. Sommer, K. Reece, and R. Vincik. 2013. Migration patterns of juvenile winter-run-sized Chinook Salmon (*Oncorhynchus tshawytscha*) through the Sacramento–San Joaquin Delta. San Francisco Estuary and Watershed Science 11(1): Article 3.

Fisher, F.W. 1992. Chinook salmon, Oncorhynchus tshawytscha, growth and occurrence in the Sacramento-San Joaquin River system. California Department of Fish and Game.

Greene, S. 1992. Daily fork-length table from data by Frank Fisher, California Department of Fish and Game. California Department of Water Resources, Environmental Services Division, Sacramento.

Helsel, D.R. and R.M. Hirsch, 2002. Statistical Methods in Water Resources Techniques of Water Resources Investigations, Book 4. U.S. Geological Survey. 522 pages.

Hinkelman, T., J. Merz. 2017. Modeling the Benefits of Yolo Bypass Restoration Actions on Chinook Salmon. Technical Report to U.S. Bureau of Reclamation and California Department of Water Resources.

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

Merz, J.E., T. M. Garrison, P.S. Bergman, S. Blankenship, and J.C. Garza. 2014. Morphological discrimination of genetically distinct Chinook Salmon populations: an example from California's Central Valley. North American Journal of Fisheries Management 34 (6): 1259-1269.

Roberts, J., J. Israel, and K. Acierto. 2013. An Empirical Approach to Estimate Juvenile Salmon Entrainment over Fremont Weir. California Department of Fish and Wildlife, Fisheries Branch Administrative Report 2013-01. 89 pages.

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.

Schindler, D.E., R. Hilborn, B. Chasco, C.P. Boatright, T.P. Quinn, L.A. Rogers, and M.S. Webster. 2010. Population diversity and the portfolio effect in an exploited species. Nature 465:609-612.

Smith, D.L., T. Threadgill, Y. Lai, C. Woodley, R.A. Goodwin, and J. Israel. 2017. Scenario Analysis of Fremont Weir Notch – Integration of Engineering Designs, Telemetry, and Flow Fields. United States Army Corps of Engineers, Engineer Research and Development Center Report.

Sommer, T., M. L. Nobriga, W.C. Harrell, W. Batham, and W. J. Kimmerer. 2001. Floodplain rearing of juvenile Chinook Salmon: evidence of enhanced growth and survival. Canadian Journal of Fisheries and Aquatic Sciences 58:325–333.

Steel, A.E., B. Lemasson, D.L. Smith, and J.A. Israel. 2017. Two-Dimensional Movement Patterns of Juvenile Winter-Run and Late-Fall-Run Chinook Salmon at the Fremont Weir, Sacramento River, CA. July 2017. United States Army Corps of Engineers, Engineer Research and Development Center Report.

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

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Supplemental analysis of fry-sized juvenile Chinook Salmon entrainment calculations.

Introduction

The Juvenile Entrainment Evaluation Tool (JEET) calculates the entrainment of juvenile Chinook Salmon (*Oncorhynchus tshawytscha*) through a suite of proposed Fremont Weir notch alternatives. This version of the JEET calculates the potential entrainment of only fry-sized Chinook Salmon (*Oncorhynchus tshawytscha*).

Rationale for Multiple Fry-Sized Fork Length Designations

In order to modify the JEET spreadsheet to evaluate the entrainment of only fry-sized salmon, the team had to select a size range that accurately represented this life stage. Chinook Salmon life stages are defined by changes in behavioral traits, physiology, and morphology, and there are no formal length-associated delineations between stages used by State or federal resource agencies. A literature review yielded maximum fork lengths ranging from 45-72 mm for the fry life stage for Chinook Salmon in California. The California Salmonid Stream Habitat Restoration Manual (California Department of Fish and Wildlife 2010) and the Anadromous Salmonid Passage Facility Design manual (National Marine Fisheries Service 2008) each use 60 mm as the maximal fork length for fry-sized Chinook Salmon. These length designations are intended to categorize swimming performance for fish passage applications.

This analysis calculates entrainment for 3 different size classes of juvenile salmon:

- ≤60 mm
- ≤70 mm
- ≤80 mm

Winter-run fry ≤60 mm make up less than 14% of the catch (Table 1). Those that were observed in the 1997-2011 period of record usually occurred from October to mid-November when the Sacramento River is typically at or near its lowest stage of the year (Figure 1).

Table 1. Size distribution of measured juvenile Chinook Salmon captured in the California Department of Fish and Wildlife's Knights Landing rotary screw traps, water years 1997-2011.

Fork Length (mm)	Fall-Run		Late Fall-Run		Winter-Run		Spring-Run	
	Count	%	Count	%	Count	%	Count	%
0-50	177,463	73.36	881	32.44	191	1.86	5,693	62.81
0-60	188,743	78.02	883	32.51	1,420	13.85	6,385	70.44
0-70	199,888	82.63	889	32.73	4,098	39.98	7,362	81.22
0-80	227,619	94.09	897	33.03	6,417	62.60	8,456	93.29
0-90	241,192	99.70	922	33.95	7,975	77.80	8,976	99.03
0-100	241,868	99.98	1,008	37.11	9,037	88.16	9,058	99.93
>100	45	0.02	1,708	62.89	1,214	11.84	6	0.07
Total	**241,913**		**2,716**		**10,251**		**9,064**	

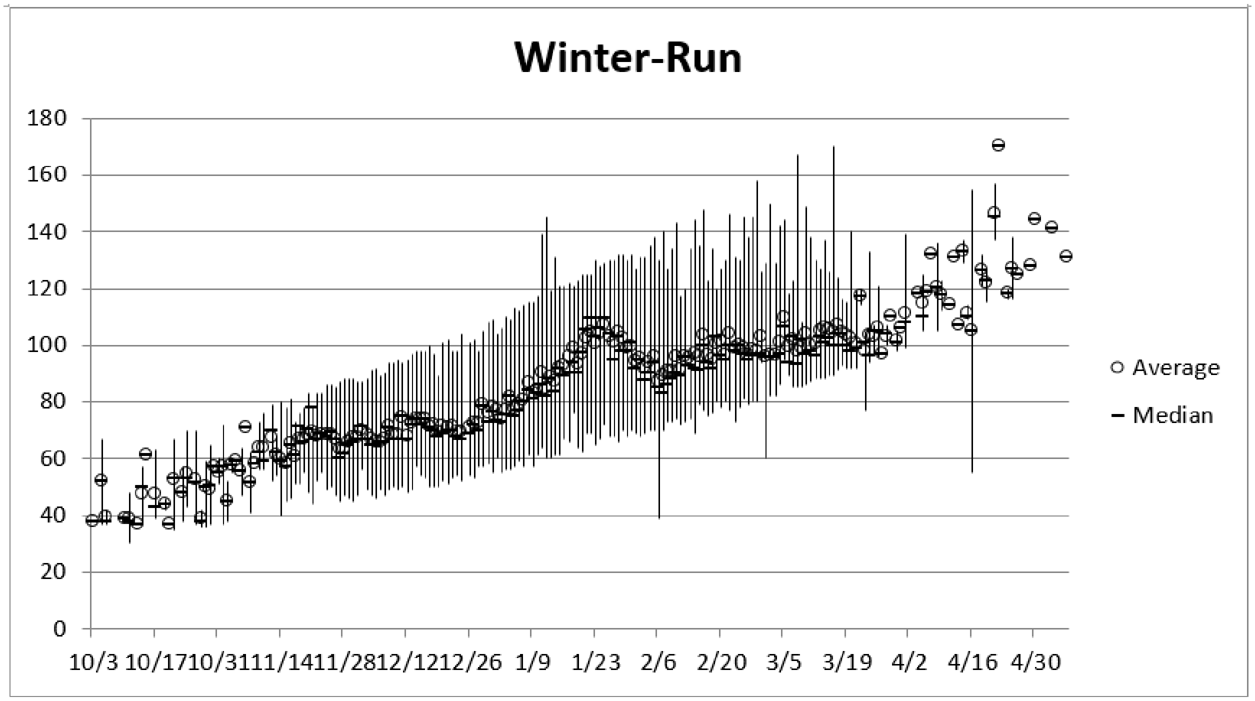

Figure 1. Fork length distribution, in millimeters, of juvenile winter-run Chinook Salmon captured in the Knights Landing rotary screw traps by date during water years 1997-2011.

We examined entrainment values for maximum fork lengths of 70, and 80 mm to include slightly larger fish that might be identified as fry or behave similarly to fry.

Methodology

During the JEET development, the California Department of Fish and Wildlife's Juvenile Salmonid Emigration Monitoring Program provided two forms of juvenile Chinook Salmon catch data for the period of record: 1) Excel spreadsheets containing quality checked juvenile salmonid daily fork length and run assignment data for all measured fish from the Knights Landing rotary screw traps; and 2) a summary report of daily catch and CPUE calculations for each run (Roberts et al. 2013). The summary reports also included plus-counted fish (fish that were assigned a run but not measured), however there is no way to know the fork lengths for these fish and therefore plus-counted fish were not included in this analysis. All fish included in this analysis were measured (fork length) and assigned a run using the length-at-date criteria described by Del Rosario et al. (2013, Appendix A).

In an effort to calculate entrainment for a specific size class of fish, the JEET had to be modified to include fork length data. Initially, the daily average fork length was used as the input to the JEET. However, using a daily average would not have accurately captured variance in observed daily fork length and would have potentially overestimated or underestimated the number of fry-sized fish.

The next step was to calculate catch per unit effort (CPUE) for each of the size classes. To do this, the JEET has been modified to remove all fish larger than the specified size class. For more details on the methodology refer to Appendix F1 Evaluating Juvenile Chinook Salmon Entrainment Potential for Multiple Modified Fremont Weir Configurations.

Additional Assumptions and Limitations

- All assumptions and limitations listed in the previous entrainment analysis technical memorandum apply to this fry entrainment analysis.
- Unlike the original entrainment analysis that included all fish observed in the CDFW Knights Landing rotary screw trap, including "plus-counted" fish that were counted but not measured, this analysis is limited to only include fish that had reliable fork length measurements. Plus counted fish were not included in the analysis.
- This analysis assumes that the CDFW fork length measurements and corresponding run assignments are accurate.
    - The CDFW post-processing effort re-classified several spring-run fish as fall-run to correspond with known hatchery releases.
    - There were minor discrepancies between the daily catch datasheets provided by CDFW and the summary sheets reported in Roberts et al. 2013. In the event of a discrepancy in reporting, the data from the daily catch datasheets was used.

Results

Entrainment results for each run will be reported in three separate sections for the following size classes of juvenile Chinook Salmon: ≤60, ≤70, and ≤80 mm. As in the previous entrainment technical memorandum, the combined average annual calculated proportion of the juvenile Chinook Salmon population entrained (by run) over the 15-year period of record for each notch alternative and existing conditions will continue to be a metric by which the alternatives are compared.

Finer-scale entrainment figures for late fall-run were omitted from this report. Entrainment of fry-sized late fall-run fish was limited to only one day in water year 2011, and not enough fry-sized late fall-run fish were observed to yield high confidence results (two individuals ≤60 mm, one in the 60-70 mm, and one in the 70-80 mm range).

60 mm Fork Length

Table 2. Calculated average annual proportion of the juvenile Chinook Salmon population ≤60 mm entrained onto the Yolo Bypass under proposed alternatives and existing conditions (by run).

Run	Existing Conditions	Alt 1 (East 6,000 cfs)	Alt 2 (Central 6,000 cfs)	Alt 3 (West 6,000 cfs)	Alt 4 (West 3,000 cfs)	Alt 4b (Mar 7 end date)	Alt 5 (Central 3,400 cfs)	Alt 6 (West 12,000 cfs)
Fall	11.0%	18.1%	18.1%	18.1%	16.1%	15.4%	16.4%	23.5%
Late Fall	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.6%
Winter	5.0%	8.8%	8.8%	8.8%	8.2%	8.2%	8.3%	12.1%
Spring	3.8%	12.0%	12.0%	12.0%	9.8%	9.8%	10.4%	18.5%

The following figures containing boxplots illustrate how the annual average entrainment values in Table 2 are distributed via boxplots by salmon run. Similar figures are used in the 70mm and 80mm results section. Figure 2 shows how to interpret these box plots, while Helsel and Hirsch (2002) provides a full description on the interpretation and creation of boxplots. Essentially, the diamond shape in each boxplot represents the average annual proportion of a Chinook salmon population entrained onto the Yolo Bypass across water years, as displayed in Table 2.

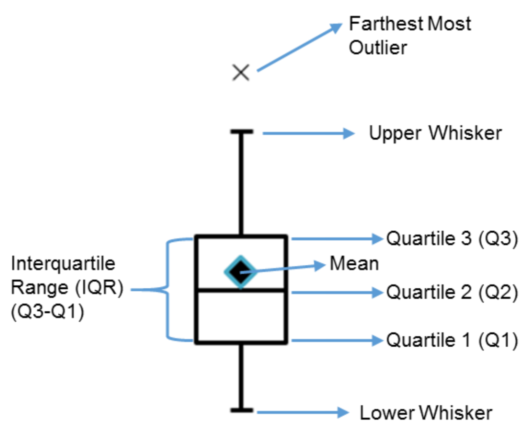

Figure 2. Elements of a boxplot used in this technical memorandum. For the following figures, boxplots are plotted against the proposed alternative on the x-axis and entrainment on the y-axis.

The top and bottom of the box in Figure 2 represents the first and third quartiles (Q1, Q3). Q1 denotes that about 25% of the entrainment calculations are below this value and 75%

of the entrainment calculations are above this value. In comparison, Q3 denotes that about 75% of the entrainment calculations are below this value, and 25% of the values are above this value. In the following figures, Q1 may fall on zero (the x-axis), so it appears truncated in the graphics.

The second quartile or the median is represented by the line within the box, while the box itself represents the interquartile range (IQR), which is the difference between the first and third quartile. The IQR represents the middle 50% of the distribution and is used to determine outliers.

The upper and lower whiskers represent the upper or lower 25% of the distribution with the exclusion of outliers. The endpoints of the whiskers represent the minimum (lower whisker) or maximum (upper whisker) annual average entrainment with the exclusion of outliers.

Outliers were determined if the entrainment fell below Q1−1.5 IQR or above Q3+1.5 IQR. For simplicity, this technical memorandum only displays the farthest most outlier in the dataset, which is represented with an "X." Even so, there were typically no more than two outliers above the upper whisker. There were no outliers below the lower whisker.

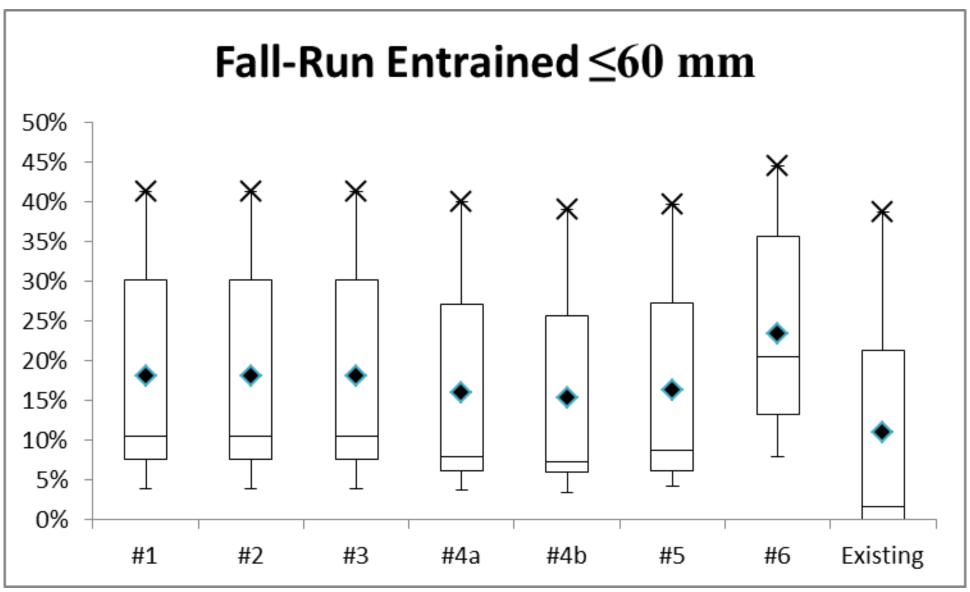

Figure 3. Boxplots of the calculated average annual proportion of the fall-run Chinook Salmon population ≤60 mm entrained onto the Yolo Bypass under proposed alternatives and existing conditions, water years 1997-2011. Diamond shapes represent the mean, top and bottom of the box represent the first and third quartiles, line inside the box represents the median, and whiskers represent the minimum/maximum.

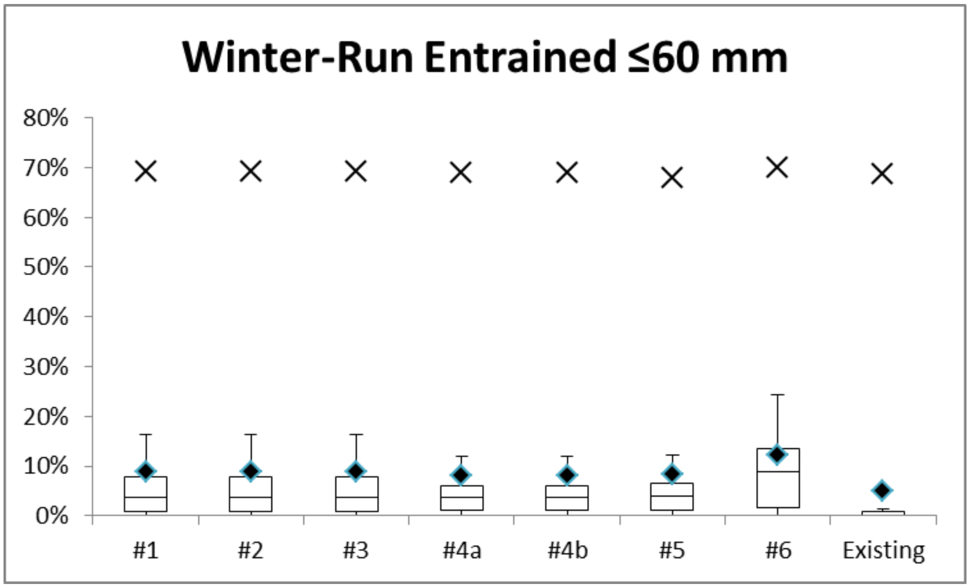

Figure 4. Boxplots of the calculated average annual proportion of the winter-run Chinook Salmon population ≤60 mm entrained onto the Yolo Bypass under proposed alternatives and existing conditions, water years 1997-2011. Diamond shapes represent the mean, top and bottom of the box represent the first and third quartiles, line inside the box represents the median, and whiskers represent the minimum/maximum.

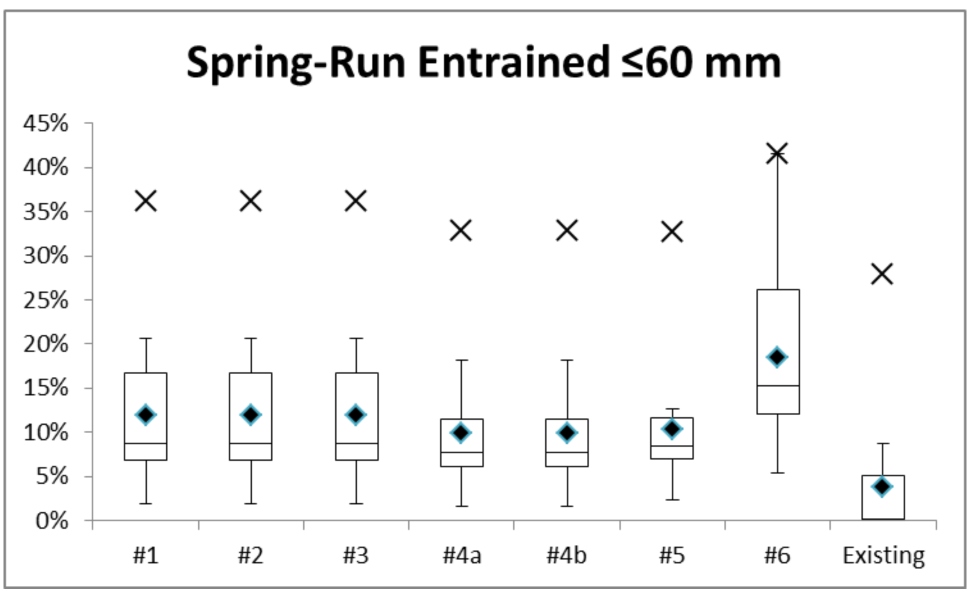

Figure 5. Boxplots of the calculated average annual proportion of the spring-run Chinook Salmon population ≤60 mm entrained onto the Yolo Bypass under proposed alternatives and existing conditions, water years 1997-2011. Diamond shapes represent the mean, top and bottom of the box represent the first and third quartiles, line inside the box represents the median, and whiskers represent the minimum/maximum.

Comparing the entrainment potential between existing conditions and each alternative provides the average annual increase in the proportion of the population of juvenile Chinook Salmon ≤60 mm that become entrained onto the Yolo Bypass (Figure 6).

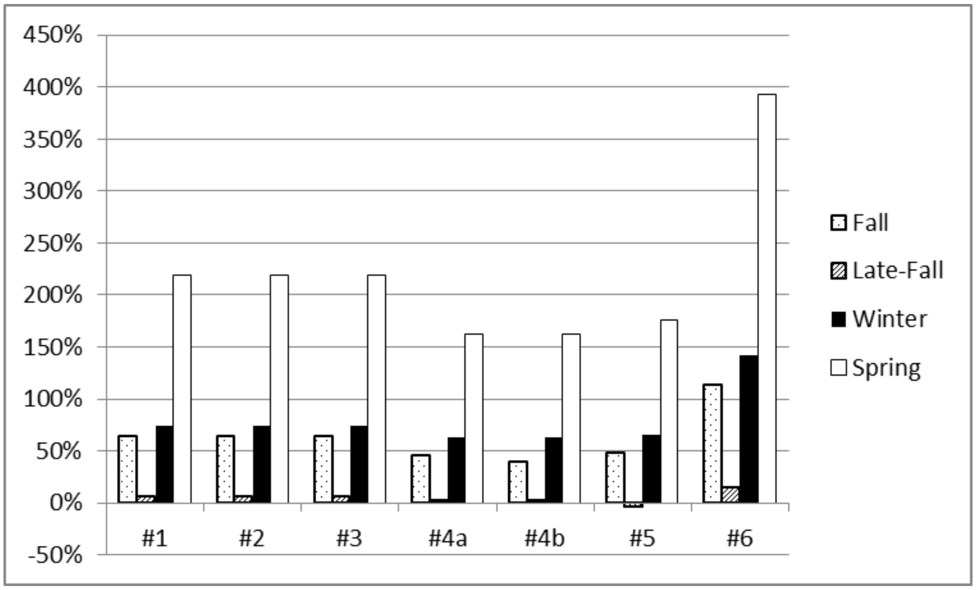

Figure 6. Relative comparison of the calculated mean annual increase in the proportion of the total population of juvenile Chinook Salmon ≤60 mm entrained onto the Yolo Bypass over existing conditions (by run), water years 1997-2011.

Estimated entrainment was further broken down by water year type as defined in

Table 3. Figure 7 and Figure 8 illustrate the calculated mean annual entrainment of juvenile spring-run and winter-run Chinook Salmon (respectively) under wet and dry years as defined by the Sacramento Valley Water Year Hydrologic Classification (California Data Exchange Center, 2017). Wet years include years categorized as wet or above normal, and dry years include years categorized as dry or critical.

Table 3. Sacramento Valley Water Year Hydrologic Classification (CDEC), where W = Wet, AN = Above Normal, BN = Below Normal, D = Dry, and C = Critical.

Water Year	Water Year Classification
1997	W
1998	W
1999	AN
2000	AN
2001	D
2002	D
2003	BN
2004	D
2005	W
2006	W
2007	C
2008	C
2009	BN
2010	AN
2011	W

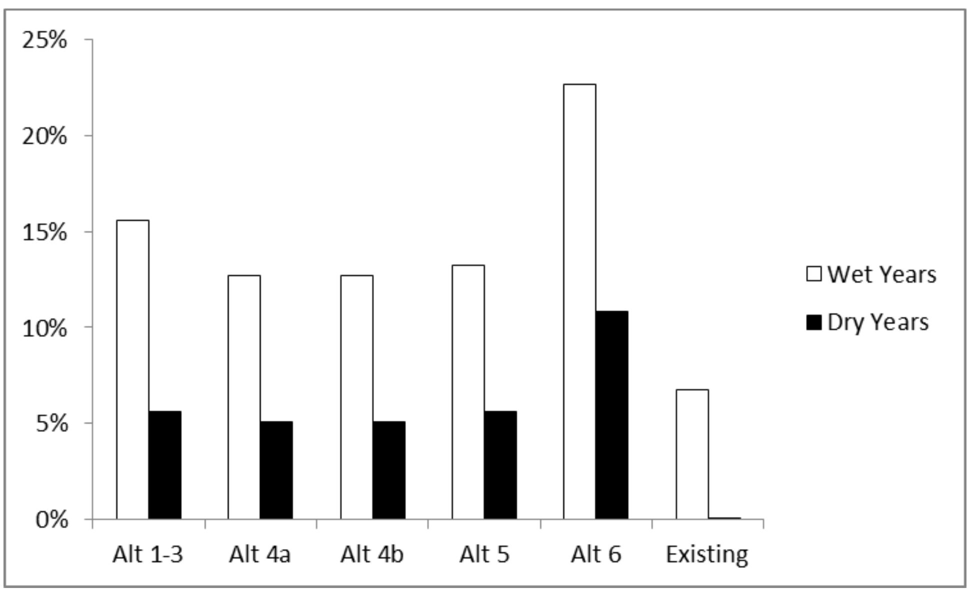

Figure 7. Calculated mean entrainment of juvenile spring-run Chinook Salmon ≤60 mm onto the Yolo Bypass under proposed alternatives and existing conditions, by water year type. “Wet Years” include years categorized as wet or above normal. “Dry Years” include years categorized as dry or critical.

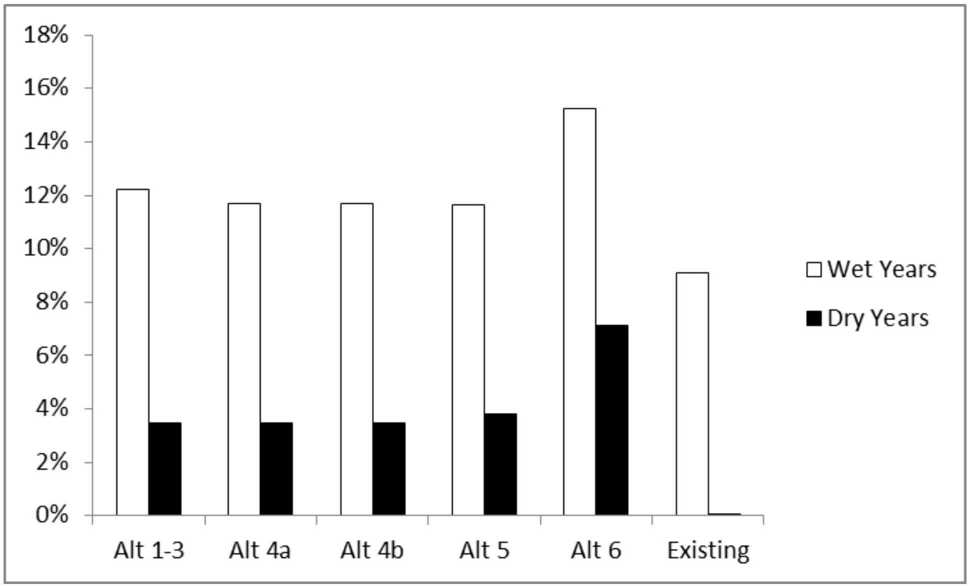

Figure 8. Calculated mean entrainment of juvenile winter-run Chinook Salmon ≤60 mm onto the Yolo Bypass under proposed alternatives and existing conditions, by water year type. "Wet Years" include years categorized as wet or above normal. "Dry Years" include years categorized as dry or critical.

70 mm Fork Length

Table 4. Calculated average annual proportion of the juvenile Chinook Salmon population ≤70 mm entrained onto the Yolo Bypass under proposed alternatives and existing conditions (by run).

Run	Existing Conditions	Alt 1 (East 6,000 cfs)	Alt 2 (Central 6,000 cfs)	Alt 3 (West 6,000 cfs)	Alt 4 (West 3,000 cfs)	Alt 4b (Mar 7 end date)	Alt 5 (Central 3,400 cfs)	Alt 6 (West 12,000 cfs)
Fall	10.4%	17.2%	17.2%	17.2%	15.2%	14.5%	15.5%	22.4%
Late Fall	1.1%	1.2%	1.2%	1.2%	1.1%	1.1%	1.1%	1.3%
Winter	1.4%	6.7%	6.7%	6.7%	5.5%	5.5%	5.8%	11.1%
Spring	4.1%	12.2%	12.2%	12.2%	10.2%	10.1%	10.8%	18.6%

The following boxplots can be interpreted as displayed in Figure 2 and in the accompanying summary text in the 60 mm Fork Length results.

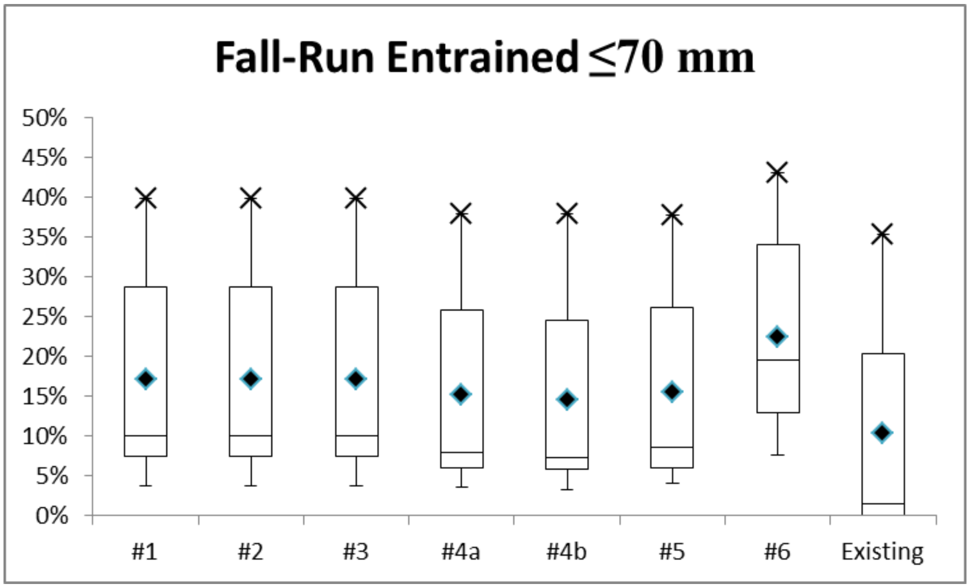

Figure 9. Boxplots of the calculated average annual proportion of the fall-run Chinook Salmon population ≤70 mm entrained onto the Yolo Bypass under proposed alternatives and existing conditions, water years 1997-2011. Diamond shapes represent the mean, top and bottom of the box represent the first and third quartiles, line inside the box represents the median, and whiskers represent the minimum/maximum.

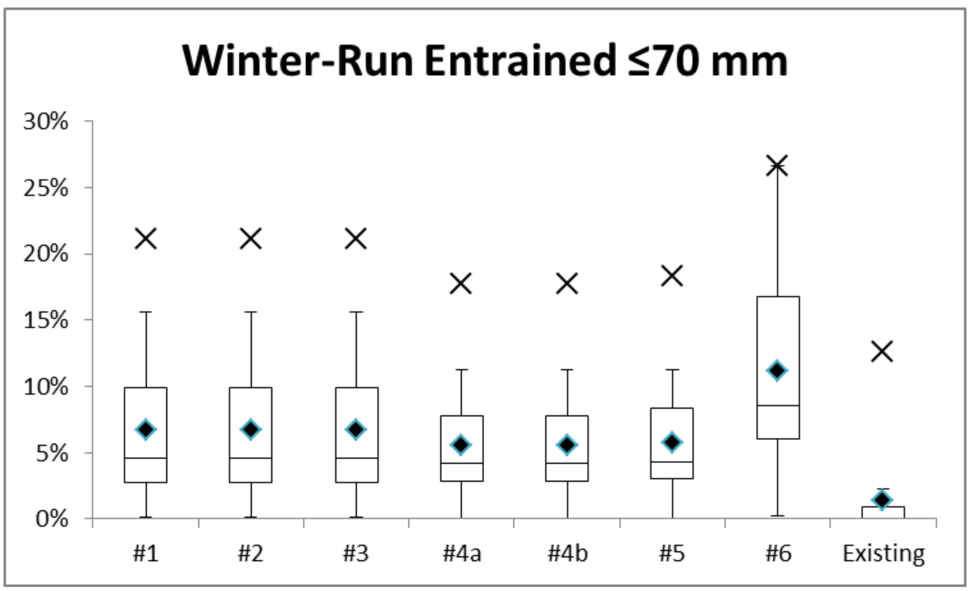

Figure 10. Boxplots of the calculated average annual proportion of the winter-run Chinook Salmon population ≤70 mm entrained onto the Yolo Bypass under proposed alternatives and existing conditions, water years 1997-2011. Diamond shapes represent the mean, top and bottom of the box represent the first and third quartiles, line inside the box represents the median, and whiskers represent the minimum/maximum.

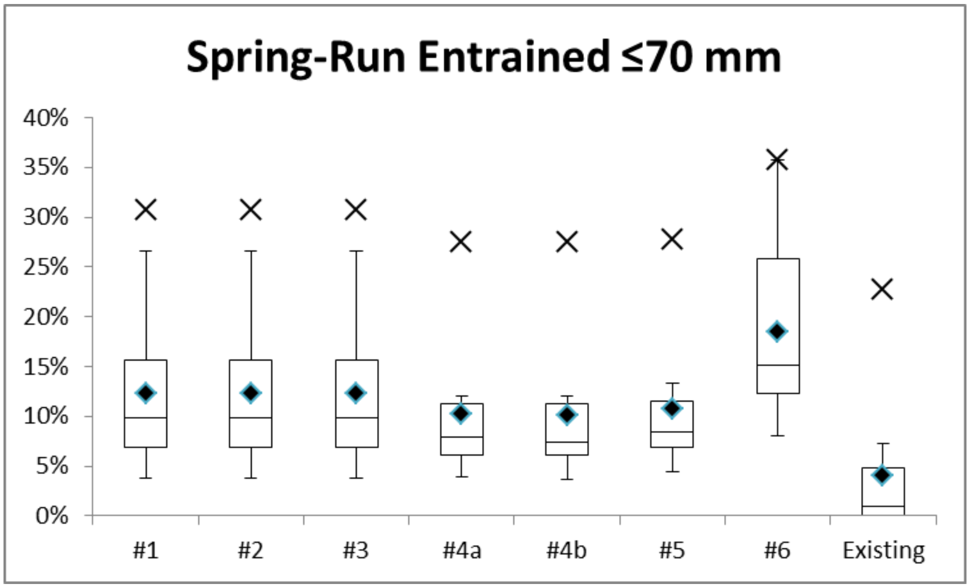

Figure 11. Boxplots of the calculated average annual proportion of the spring-run Chinook Salmon population ≤70 mm entrained onto the Yolo Bypass under proposed alternatives and existing conditions, water years 1997-2011. Diamond shapes represent the mean, top and bottom of the box represent the first and third quartiles, line inside the box represents the median, and whiskers represent the minimum/maximum.

Comparing the entrainment potential between existing conditions and each alternative provides the average annual increase in the proportion of the population of juvenile Chinook Salmon ≤70 mm that become entrained onto the Yolo Bypass (Figure 12).

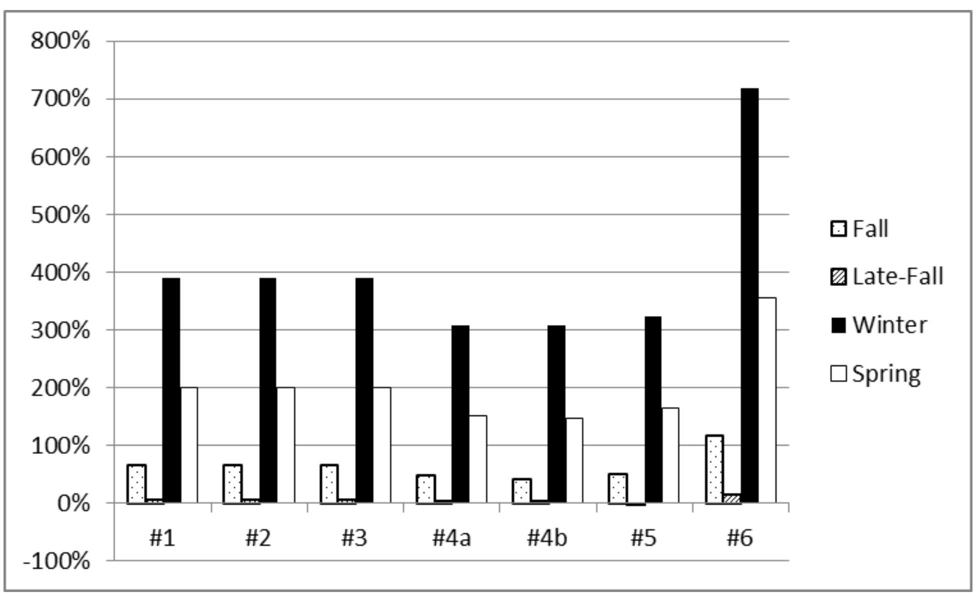

Figure 12. Relative comparison of the calculated mean annual increase in the proportion of the total population of juvenile Chinook Salmon ≤70 mm entrained onto the Yolo Bypass over existing conditions (by run), water years 1997-2011.

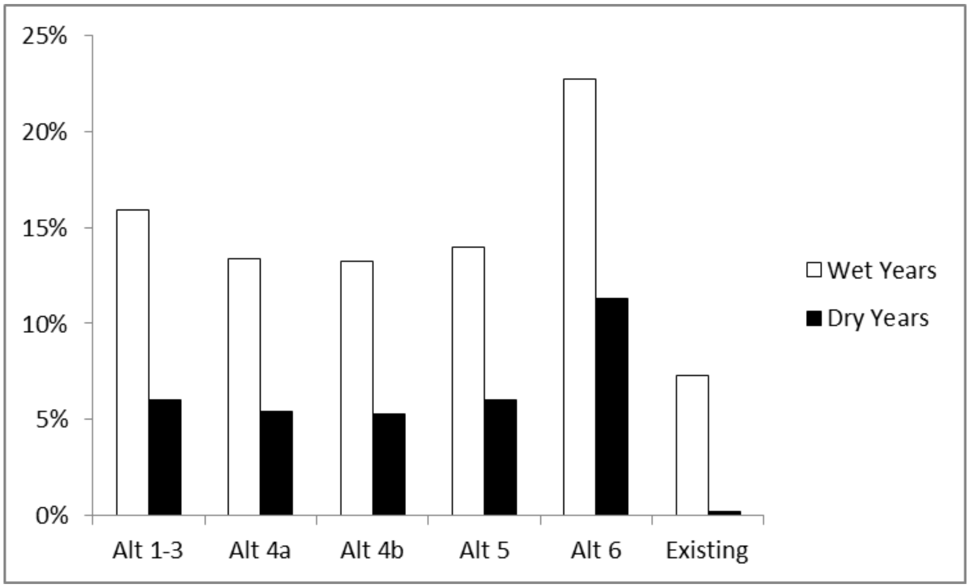

Figure 13. Calculated mean entrainment of juvenile spring-run Chinook Salmon ≤70 mm onto the Yolo Bypass under proposed alternatives and existing conditions, by water year type. "Wet Years" include years categorized as wet or above normal. "Dry Years" include years categorized as dry or critical.

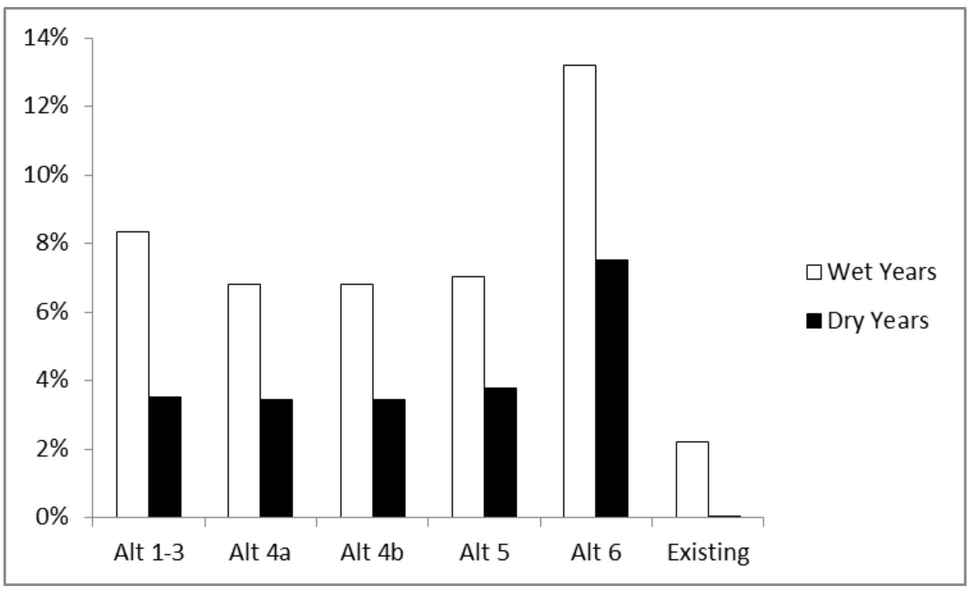

Figure 14. Calculated mean entrainment of juvenile winter-run Chinook Salmon ≤70 mm onto the Yolo Bypass under proposed alternatives and existing conditions, by water year type. "Wet Years" include years categorized as wet or above normal. "Dry Years" include years categorized as dry or critical.

80 mm Fork Length

Table 5. Calculated average annual proportion of the juvenile Chinook Salmon population ≤80 mm entrained onto the Yolo Bypass under proposed alternatives and existing conditions (by run).

Run	Existing Conditions	Alt 1 (East 6,000 cfs)	Alt 2 (Central 6,000 cfs)	Alt 3 (West 6,000 cfs)	Alt 4 (West 3,000 cfs)	Alt 4b (Mar 7 end date)	Alt 5 (Central 3,400 cfs)	Alt 6 (West 12,000 cfs)
Fall	9.2%	15.3%	15.3%	15.3%	13.6%	12.9%	13.8%	19.9%
Late Fall	1.0%	1.1%	1.1%	1.1%	1.1%	1.1%	1.0%	1.2%
Winter	1.2%	7.1%	7.1%	7.1%	5.9%	5.9%	6.2%	12.0%
Spring	3.6%	10.6%	10.6%	10.6%	8.9%	8.7%	9.4%	16.1%

The following boxplots can be interpreted as displayed in Figure 2 and in the accompanying summary text in the 60 mm Fork Length results.

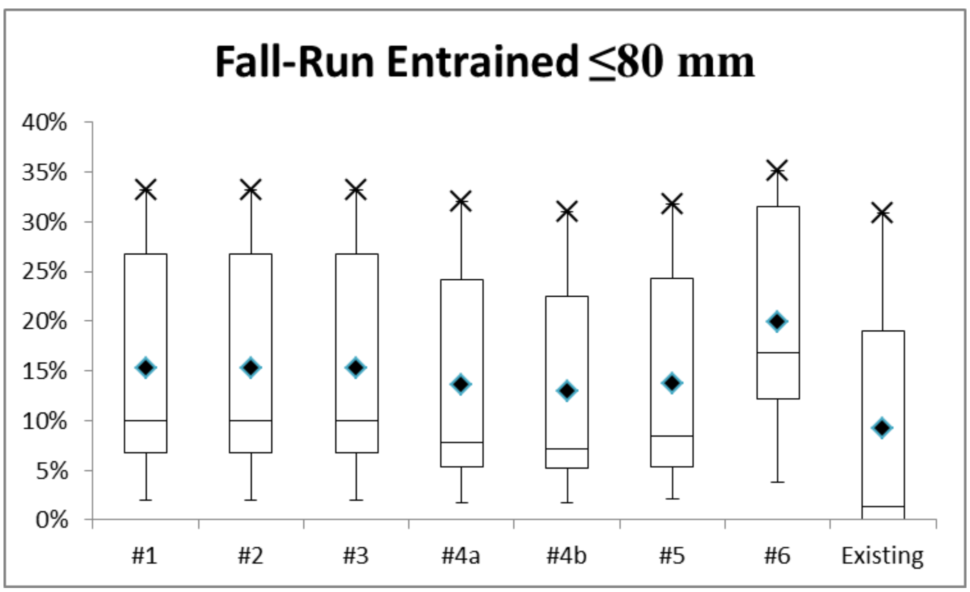

Figure 15. Boxplots of the calculated average annual proportion of the fall-run Chinook Salmon population ≤80 mm entrained onto the Yolo Bypass under proposed alternatives and existing conditions, water years 1997-2011. Diamond shapes represent the mean, top and bottom of the box represent the first and third quartiles, line inside the box represents the median, and whiskers represent the minimum/maximum.

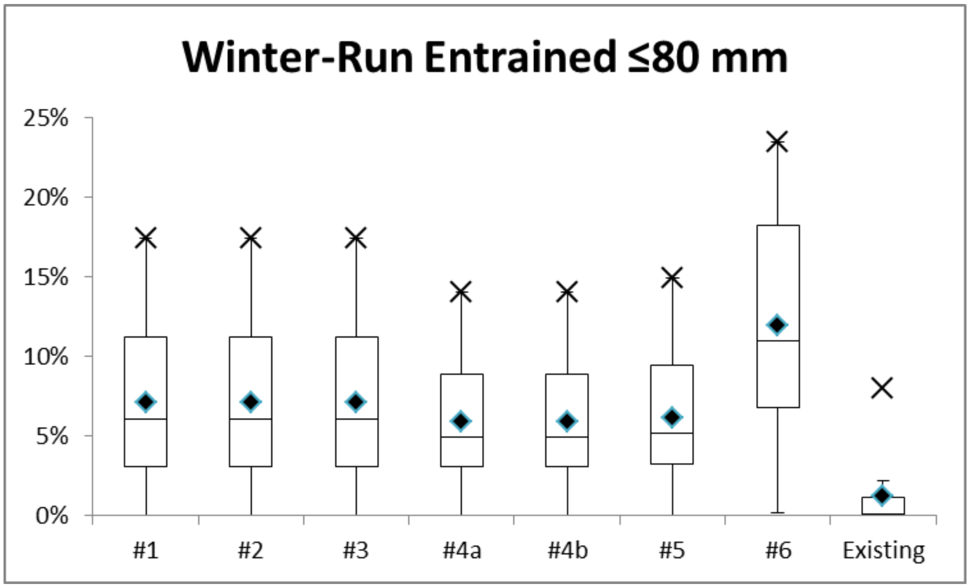

Figure 16. Boxplots of the calculated average annual proportion of the winter-run Chinook Salmon population ≤80 mm entrained onto the Yolo Bypass under proposed alternatives and existing conditions, water years 1997-2011. Diamond shapes represent the mean, top and bottom of the box represent the first and third quartiles, line inside the box represents the median, and whiskers represent the minimum/maximum.

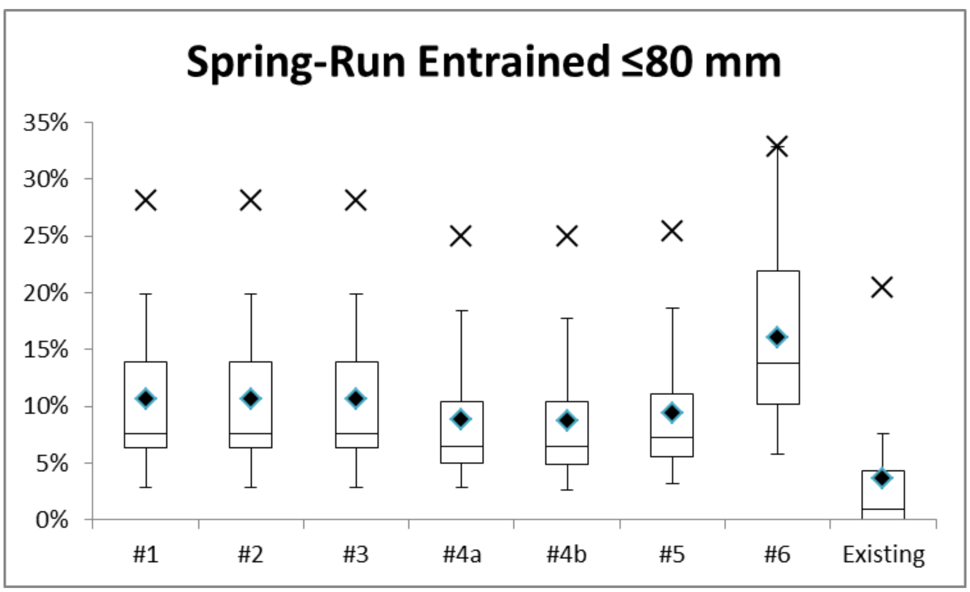

Figure 17. Boxplots of the calculated average annual proportion of the spring-run Chinook Salmon population ≤80 mm entrained onto the Yolo Bypass under proposed alternatives and existing conditions, water years 1997-2011. Diamond shapes represent the mean, top and bottom of the box represent the first and third quartiles, line inside the box represents the median, and whiskers represent the minimum/maximum.

Comparing the entrainment potential between existing conditions and each alternative provides the average annual increase in the proportion of the population of juvenile Chinook Salmon ≤80 mm that become entrained onto the Yolo Bypass (Figure 18).

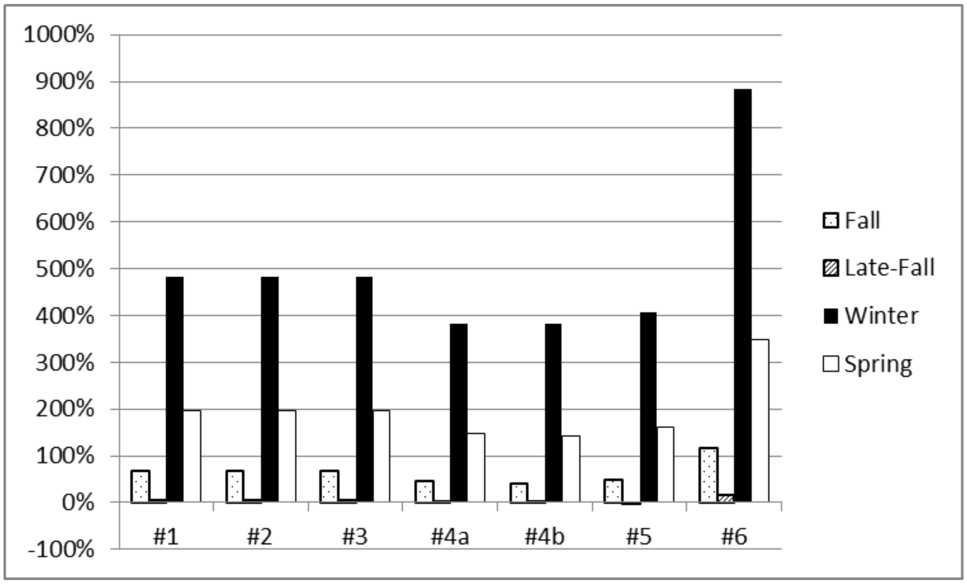

Figure 18. Relative comparison of the calculated mean annual increase in the proportion of the total population of juvenile Chinook Salmon ≤80 mm entrained onto the Yolo Bypass over existing conditions (by run), water years 1997-2011.

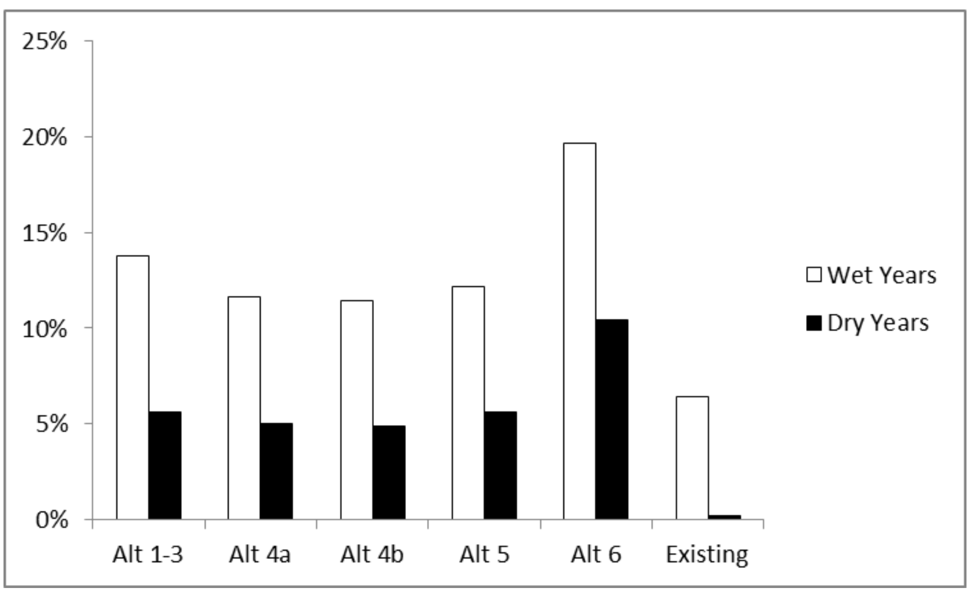

Figure 19. Calculated mean entrainment of juvenile spring-run Chinook Salmon ≤80 mm onto the Yolo Bypass under proposed alternatives and existing conditions, by water year type. "Wet Years" include years categorized as wet or above normal. "Dry Years" include years categorized as dry or critical.

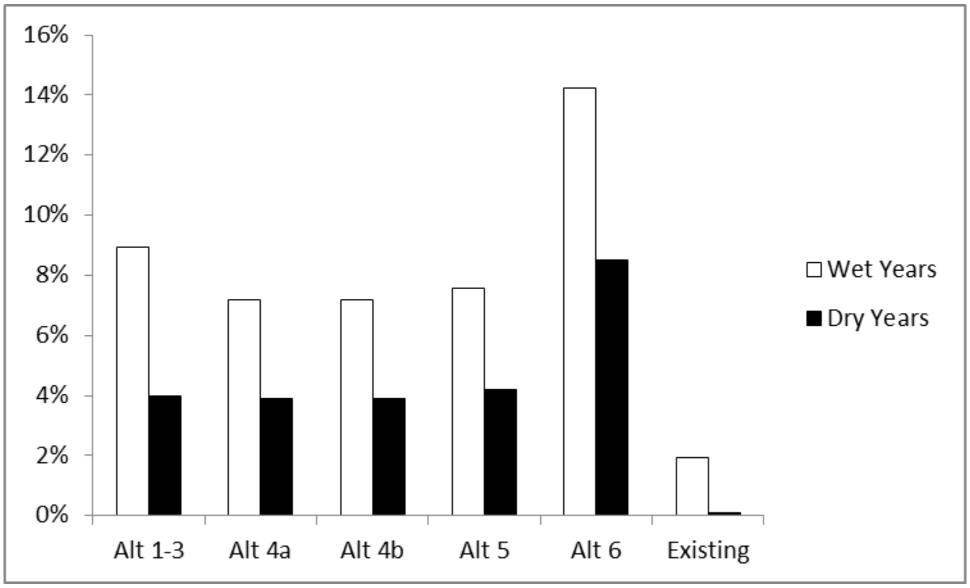

Figure 20. Calculated mean entrainment of juvenile winter-run Chinook Salmon ≤80 mm onto the Yolo Bypass under proposed alternatives and existing conditions, by water year type. "Wet Years" include years categorized as wet or above normal. "Dry Years" include years categorized as dry or critical.

Discussion

The results of this fry-sized entrainment analysis indicate that notching the Fremont Weir would lead to an increase in the proportion of emigrating juvenile Chinook Salmon fry that are entrained onto the Yolo Bypass for every run except for the late fall-run. This is not surprising, as many late fall-run juveniles rear for several months upriver after emergence before emigrating downstream. Most of the late fall-run Chinook Salmon that are in the vicinity of the Fremont Weir during the proposed operational window are typically these larger fish that exceed our 60-80 mm fry-size classification due to having reared over the summer in upstream reaches (Figure 21). The smaller, newly emerged fry that elect to migrate immediately do not tend to arrive until after the operational end date proposed for this project. As a result, very few fry-sized juvenile late fall-run Chinook Salmon are predicted to be entrained, with calculated entrainment only being predicted for a single date in water year 2011.

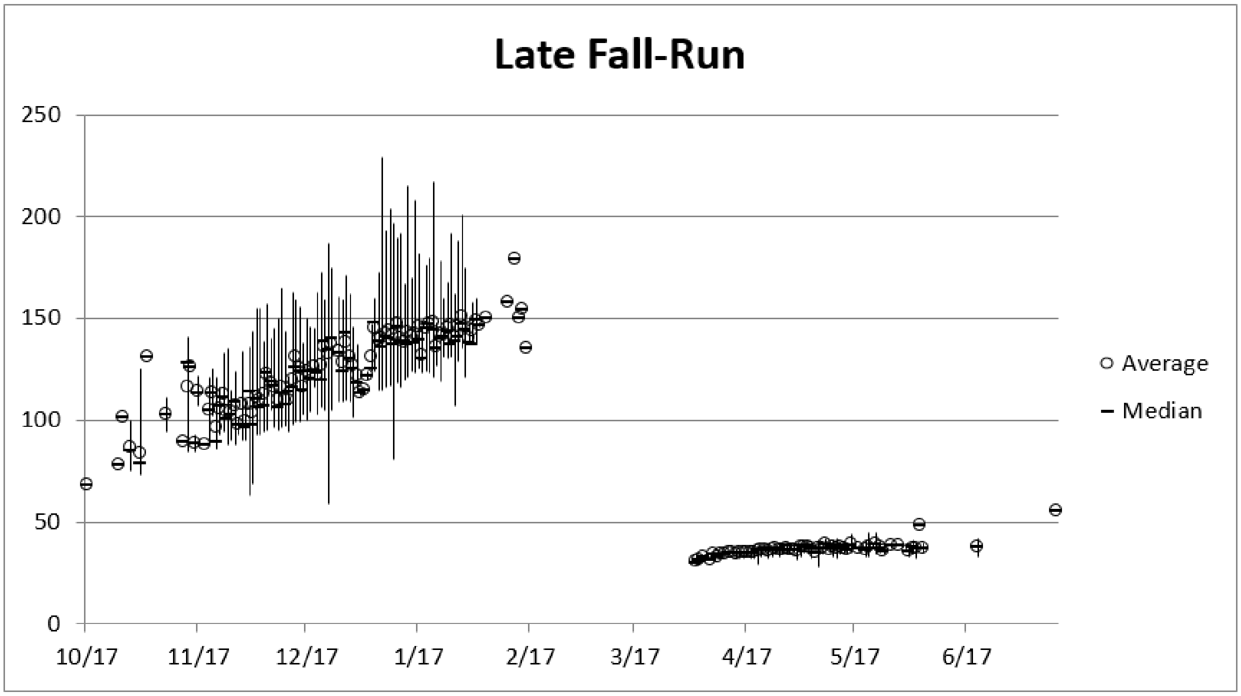

Figure 21. Fork length distribution, in millimeters, of juvenile late fall-run Chinook Salmon captured in the Knights Landing rotary screw traps by date during water years 1997-2011.

The results of this analysis indicate that the entrainment of fry-sized fish would increase for all other runs with the construction and operation of any of the six potential notch alternatives when compared to existing conditions.

Alternative 6 is the alternative with the highest calculated entrainment and the greatest increase in entrainment over existing conditions. However, the separation between Alternative 6 and the next best performer is more truncated than in the previous analysis which incorporated all size classes. This truncation particularly evident for the entrainment of winter-run fish ≤60 mm where the alternatives that divert smaller volumes of water, Alternatives 4a/b and 5 (3,000 and 3,500 max cfs, respectively), have entrainment values that are similar to Alternatives 1-3 with a max design flow of 6,000 cfs (Figure 4 and Figure 6). The alternatives perform similarly due to their similar invert elevations that allow them to divert water onto the Yolo Bypass during the lower flow periods that often occur early in the season when the smallest winter-run fish tend to arrive. Still, the rankings follow the same trend displayed in the original analysis where the alternatives that divert the largest volumes of water outperform those that divert smaller volumes.

While considerable increases in entrainment occurred across all water year types, notch alternatives were particularly effective at increasing entrainment during dry and critical water years (Table 6 and Table 7). During dry and critical years, naturally occurring overtopping events are rare and are often short in duration providing minimal opportunities for juveniles to enter the Yolo Bypass. Though not as high as in dry years, notch entrainment during wet and above normal years was still substantially improved over existing conditions.

Table 6. Calculated mean annual increase in the proportion of the total population of juvenile winter-run Chinook Salmon ≤60, 70, and 80 mm entrained onto the Yolo Bypass over existing conditions by water year type.

Size	Water Year Type	Alternatives 1-3 6,000 cfs	Alternative 4 3,000 cfs	Alternative 4b Mar 7 end date	Alternative 5 3,400 cfs	Alternative 6 12,000 cfs
60 mm	Wet	34.8%	28.6%	28.6%	28.3%	68.0%
	Dry	31,837.4%	32,130.1%	32,130.1%	35,148.4%	65,534.7%
70 mm	Wet	274.3%	205.3%	205.3%	215.2%	491.5%
	Dry	5,637.6%	5,519.6%	5,519.6%	6,049.7%	12,092.6%
80 mm	Wet	357.2%	267.2%	267.2%	286.1%	628.0%
	Dry	4,798.9%	4,690.0%	4,690.0%	5,031.2%	10,362.0%

Table 7. Calculated mean annual increase in the proportion of the total population of juvenile spring-run Chinook Salmon ≤60, 70, and 80 mm entrained onto the Yolo Bypass over existing conditions by water year type.

Size	Water Year Type	Alternatives 1-3 6,000 cfs	Alternative 4 3,000 cfs	Alternative 4b Mar 7 end date	Alternative 5 3,400 cfs	Alternative 6 12,000 cfs
60 mm	Wet	129.7%	87.6%	87.6%	95.4%	233.9%
	Dry	7,813.8%	7,042.8%	7,042.8%	7,848.1%	15,195.5%
70 mm	Wet	118.0%	83.0%	80.6%	90.9%	211.1%
	Dry	2,762.9%	2,470.1%	2425.4%	2,774.5%	5,254.2%
80 mm	Wet	115.0%	81.1%	78.1%	89.6%	206.3%
	Dry	2,643.6%	2,348.6%	2,299.3%	2,642.8%	4,996.4%

References

These references are in addition to those included in the main body of the technical memorandum.

California Department of Fish and Game. 2010. California Salmonid Stream Habitat Restoration Manual, 4th Edition. Habitat Conservation Division.

National Marine Fisheries Service. 2008. Anadromous Salmonid Passage Facility Design. NMFS, Northwest Region, Portland, Oregon.

YOLO BYPASS SALMON BENEFITS MODEL:
MODELING THE BENEFITS OF YOLO BYPASS RESTORATION ACTIONS ON CHINOOK SALMON

Model Documentation, Alternatives Analysis, and Effects Analysis

Prepared for:

United States Bureau of Reclamation and California Department of Water Resources

Prepared by:

Travis M. Hinkelman, Myfanwy Johnston, Joseph E. Merz

August 2, 2017

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EXECUTIVE SUMMARY

The Yolo Bypass Salmonid Habitat Restoration and Fish Passage Draft Implementation Plan (Implementation Plan) was prepared to evaluate the potential to restore floodplain rearing habitat through increased seasonal inundation within the lower Sacramento River basin, and reduce migratory delays and loss of salmon, steelhead, and sturgeon, through the modification of Fremont Weir and other structures of the Yolo Bypass. Prior to Implementation Plan execution, potential benefits of restoration actions on all four CV Chinook salmon runs are to be evaluated quantitatively through a targeted modeling effort.

The Yolo Bypass Chinook Salmon Benefits Model (SBM) is a mechanistic, deterministic simulation model that quantifies potential benefits of Yolo Bypass restoration actions on CV Chinook salmon runs that spawn upstream of the Yolo Bypass. Five key benefit measurements were identified: juvenile (1) survival, (2) size, (3) size variability, and (4) timing variability at entrance to the marine environment (Chipps Island) and (5) adult returns (escapement). Using the SBM, we quantified lifestage-specific and cumulative impacts of restoration actions on each Chinook salmon run and compared the benefits identified for the runs under each of five Implementation Plan management alternatives.

In the Alternatives Analysis, we found only small differences between alternatives in the benefits metrics. The key exception was Alternative 6 where benefits were consistently greater than for the other alternatives. Alternative 6 has the largest notch, highest max design flows (12,000 cfs), provides the most suitable habitat, and entrains the most fish of the modeled alternatives. Alternative 6 provides access to the Yolo Bypass at lower flows than under existing conditions and, presumably, introduces variability in the accessibility of suitable rearing habitat for fish that, in turn, increases fork length variation and arrival timing variation at Chipps Island.

In the Effects Analysis, we found an interactive effect of the rearing rule and rearing survival value. We suggest that both should be targets for additional investigations, but recognize the challenges in the design of such studies. This includes studies of fall- and spring-run survival through the Yolo Bypass. A better understanding of survival on and carrying capacity of the Yolo Bypass are warranted.

BACKGROUND

Significant modifications have been made to California's Central Valley (CV) floodplains for mining, agriculture, urban development, and (more recently) water supply and flood control purposes. The resulting loss of floodplain rearing habitat, migration corridors, and food web production has significantly impacted native fish species whose life history strategies depend upon seasonally inundated habitat. The Yolo Bypass, which currently experiences at least some flooding in approximately 80% of years, still retains many characteristics of historic floodplain habitat that are favorable to a suite of fish species (CDWR 2012). In approximately 70% of years, the Fremont Weir overtops, joining flows from the Sacramento River with flows entering the Yolo Bypass from western tributaries (CDWR 2012).

Although the primary function of the Yolo Bypass is to provide flood control management for the surrounding metropolitan areas, the Yolo Bypass is also managed as mixed-use, providing land for both private agriculture and public recreation. In recent years, the Yolo Bypass has also been recognized as important rearing, spawning, and migratory habitat for numerous native fish species (CDWR 2012), accessed perennially through a narrow channel that spans the eastern edge of the Yolo Bypass. Studies in the region document favorable outcomes for ecosystem functions and desirable species assemblages as a result of targeted management action (Kiernan et al. 2012, Jeffres et al. 2008, Sommer et al. 2001). When combined with the Yolo Bypass's current role in successful, multi-faceted land uses, this suggests that the floodplain can support human demands without eliminating the processes needed to sustain aquatic species (Opperman et al. 2009). Thus, the Bypass is identified by several state and federal entities as a potential site for habitat restoration, with the goal of benefitting threatened and endangered fish species.

As part of the effort to evaluate the site for restoration, the Yolo Bypass Salmonid Habitat Restoration and Fish Passage Draft Implementation Plan (Implementation Plan) was prepared jointly by the California Department of Water Resources (DWR) and the U.S. Bureau of Reclamation (Reclamation) to address two specific Reasonable and Prudent Alternative (RPA) Actions set forth in the NMFS Operation Biological Opinion:

- RPA Action I.6.1: Restoration of floodplain rearing habitat, through the increase of seasonal inundation within the lower Sacramento River basin; and
- RPA Action I.7: Reduce migratory delays and loss of salmon, steelhead, and sturgeon, through the modification of Fremont Weir and other structures of the Yolo Bypass.

Prior to execution of the Implementation Plan, the potential benefits of restoration actions (via the Implementation Plan) on all four CV Chinook salmon runs will be evaluated quantitatively through a targeted modeling effort. The goals of this modeling effort are as follows:

- Create a mechanistic, simulation model to quantify and visualize the potential benefits of Yolo Bypass restoration actions on CV Chinook salmon runs that spawn upstream of the Yolo Bypass.
- Using the simulation model, quantify lifestage-specific and cumulative impacts of restoration actions on each Chinook salmon run.
- Conduct a comparison of the benefits identified for Chinook salmon runs under each Implementation Plan management alternative.

Study Species

In the CV, Chinook salmon evolved a range of diverse life history strategies (Williams 2006). This "portfolio effect" allowed them to combat the risk posed by highly variable environmental conditions (Carlson and Satterthwaite 2011). Four distinct populations ("runs") of Central Valley Chinook are named for the timing of adult spawning migrations (fall, late-fall, winter, and spring), and are genetically distinguishable. Each run reflects genetically-based adaptations to seasonal conditions in the local environment. Through investment in this diverse portfolio, the species, as a whole, has enormous capacity for resilience and adaptation to local conditions (Carlson and Satterthwaite 2011; Hilborn et al. 2003).

Apart from those runs that remain in freshwater and migrate the following year (as yearlings), most young CV salmon migrate to the ocean during the first few months following emergence. Juveniles may rear in floodplains, mainstem rivers, and/or estuaries for varying lengths of time before entering the ocean at an appropriate size for survival (between 80-170 mm FL, depending on the run). Chinook salmon spend 1-5 years in the ocean before returning to the river as spawning adults, with a small portion of males (precocious) that may never leave freshwater (Foote et al. 1991). These runs and the large populations they once supported (at least 1 to 2 million adults annually; Yoshiyama et al. 1998, 2000) reflect the diverse and productive habitats that historically existed within the region. Over the past 180 years anthropogenic effects—including mining, flood protection, power generation, water development, stream and floodplain conversion, water quality degradation, invasive species, harvest, and hatchery management—have stressed, altered, and depleted these resources (Yoshiyama et al. 1998, 2000; Williams 2006; Israel et al. 2011). Global parameters, such as ocean conditions, have also demonstrated a marked effect on adult escapement (Lindley et al. 2007, 2009). In the past 3 decades, the CV spring and winter runs were listed under the United States Endangered Species Act (ESA) of 1973. Habitat modification on nearly all major CV rivers has resulted in selective loss of habitats, which disproportionately affect certain life history components of each run (Carlson and Satterthwaite 2011; McClure et al. 2008; Lindley et al. 2007).

Study System

The Yolo Bypass Salmon Benefits Model (hereafter SBM) is comprised of the following key locations and systems (Figure 1).

Sacramento River: The mainstem Sacramento River is the primary migratory route for model fish through the system. In the SBM, the only place where fish can choose another route is at Fremont Weir.

Knights Landing: The location of a rotary screw trap on the Sacramento River and the point where fish enter the model.

Fremont Weir: A passive weir, located about 11 km downstream of Knights Landing, that serves as the primary location for flow to enter the Yolo Bypass from the Sacramento River during periods of high flows. The alternative management scenarios involve designing a notch in the Fremont Weir to increase flow management capabilities (see Modeled Alternatives). Model fish are only able to enter the Yolo Bypass via the Fremont Weir.

Verona: Location in Sacramento River, about 3 km downstream of Fremont Weir, where Sacramento River flow is modeled. Because the hydrodynamic properties of the system are complex at Fremont Weir, the proportion of flow entering the Yolo Bypass is estimated partly based on the flow in the Sacramento River at Verona (see Entrainment).

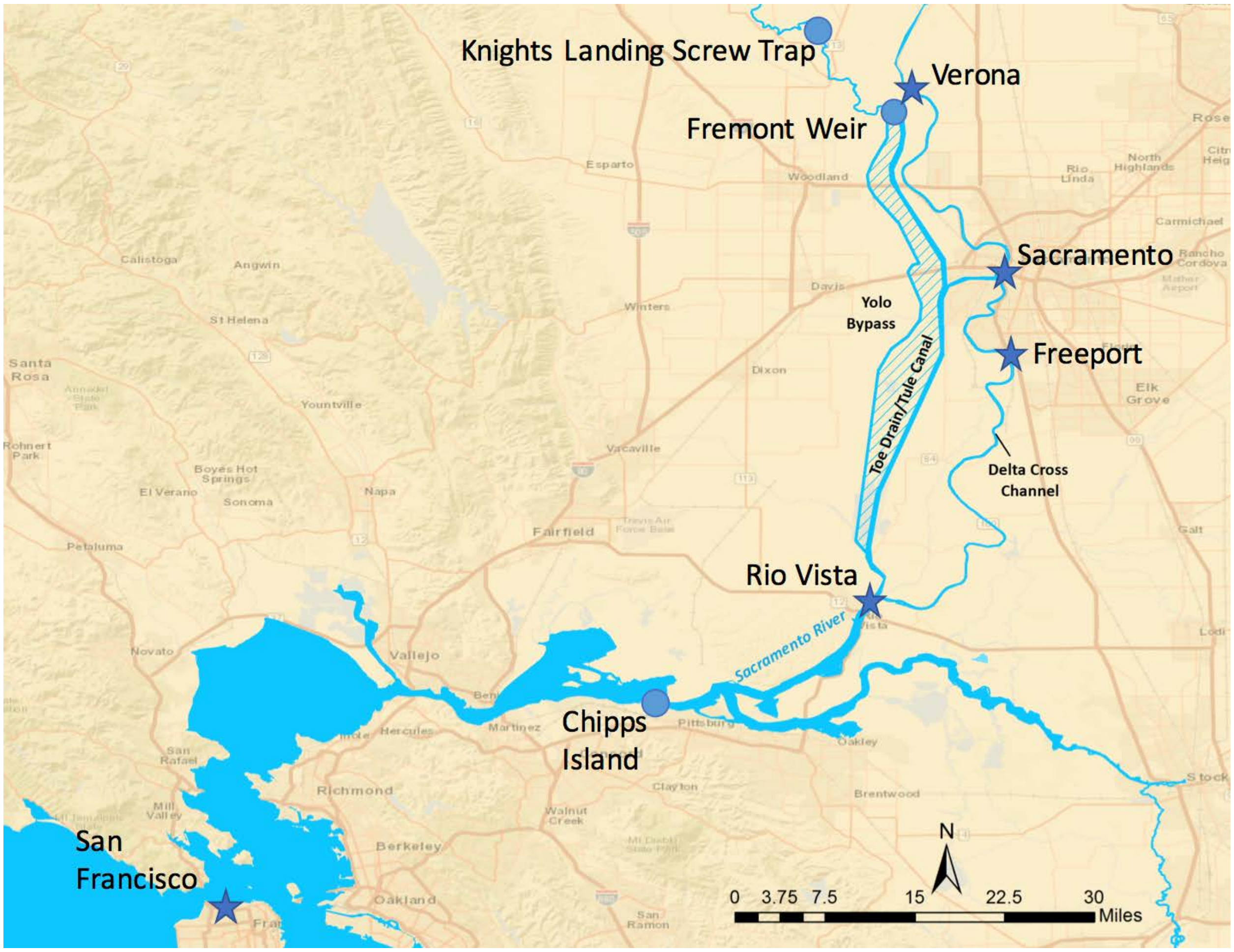

Figure 1. The spatial extent of the Salmon Benefits Model, which tracks Chinook salmon life history from emigrating juveniles to adult escapement, beginning in the mainstem Sacramento River just upstream of Fremont Weir at the location of the Knights Landing screw trap. Circles identify key locations relevant to model functions; stars represent cities.

Feather River: Flow from the Feather River enters the Sacramento River just upstream of Verona and is used in the estimation of flow into the Yolo Bypass at Fremont Weir (see Entrainment).

Canal Complex: The primary migratory pathway through the Yolo Bypass comprised of the Tule Canal and the Toe Drain. The Canal Complex is perennially watered and provides a passage route for juvenile salmon. The route through the Canal Complex is approximately 30 km shorter than staying in the Sacramento River.

Yolo Bypass: Throughout this document, Yolo Bypass is generally used inclusively to refer to the Canal Complex and the adjacent floodplain habitat.

Rio Vista: The approximate location of the confluence between the Canal Complex and the Sacramento River. Model fish from the Sacramento River and Yolo Bypass routes come back together at Rio Vista. However, fish move and survive at route-specific rates despite occupying the same reach. All fish grow at the same rate while migrating from Rio Vista to Chipps Island, though.

Modeling Approach

The primary goal of the SBM is to compare fish benefits among Fremont Weir notch alternatives (see Modeled Alternatives). The goal of the model is **not** to answer if salmon benefit from a notch in Fremont Weir. The secondary goals of the SBM are to hone our intuition about the modeled system and to identify knowledge and data gaps. The SBM cannot predict all possible trajectories of Chinook salmon populations under the proposed management alternatives. Instead, the SBM provides an experimental system in which the consequences of various sets of assumptions can be rigorously examined and the range of outcomes for modeled alternatives can be compared (Peck 2004).

The SBM is a deterministic simulation model. Parameters enter the model as a single value (or series of values) rather being drawn from a distribution of values. We recognize the value of stochastic simulation models. However, the SBM is in an active state of development and working with a deterministic model reduces time in the model development cycle because running the SBM is a computationally intensive process. Although the SBM currently does not include stochasticity, running the model across 15 years provides considerable variation in model behavior. Moreover, the effect of parameters, model rules, and interactions among parameters/rules on model outputs can be evaluated with simulation experiments. We fully expect that future work on the SBM will include the development of a stochastic version of the model.

Unlike a life cycle model, where progeny from one brood year are allowed to 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 (just upstream of the Yolo Bypass entrance) to the number of returning adults (escapement), and quantifies the potential life stage-specific and cumulative impacts of restoration actions on fish size and abundance. As a general modeling approach, simulation has been successfully applied to evaluate the effects of other restoration actions on CV Chinook salmon populations, including the following:

- The San Joaquin River Emigrating Salmonid Habitat Estimation (ESHE) model to quantify the rearing and emigration habitat needs of future restored populations of fall-run and spring-run Chinook salmon in the San Joaquin River as part of the San Joaquin River Restoration Program (SJRRP 2012).
- The Interactive Object-oriented Simulation (IOS) life cycle model (Zeug et al. 2012) to evaluate the effects of the NMFS alternative scenarios of Central Valley water operations on the life cycle and abundance trends of winter-run Chinook salmon.
- The Delta Passage Model (DPM) to evaluate the effects of Bay Delta Conservation Plan (BDCP) water scenarios on the Delta emigration survival of all Central Valley runs of Chinook salmon (BDCP 2013).

The SBM begins tracking juvenile Chinook salmon in the mainstem Sacramento River just upstream of Fremont Weir, at the location of the Knights Landing screw trap (Figure 1). The model runs on a daily time-step during the CV Chinook salmon juvenile emigration period, from October 2nd until all modeled fish have died or entered the Pacific Ocean, usually by June 30th of the following year. Although the Chinook salmon life cycle occurs over a 2 to 4-year period, the model only explicitly tracks the daily movement and abundance of Chinook salmon until ocean entry (Figure 2). Once modeled fish enter the ocean, the model instantaneously calculates ocean survival and upstream adult migration survival to estimate the number of returning adults. Importantly, the estimates of the number of returning adults for each brood year-class do not influence the number of juveniles entering the model in subsequent years.

Finally, the model quantifies the effects of management alternatives on individual life stages to estimate the number of returning adults produced under each alternative.

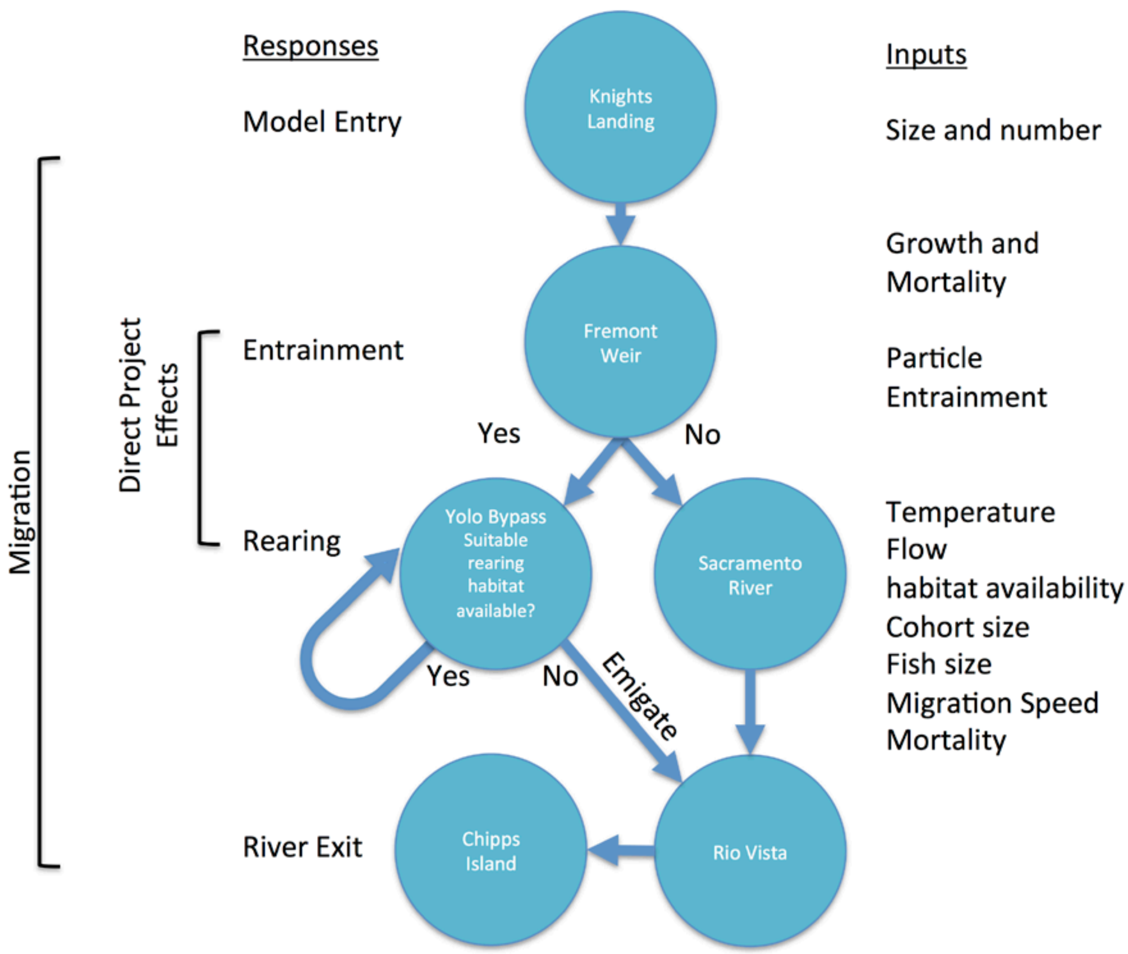

Figure 2. Conceptual overview of Salmon Benefits Model. The input parameters and relationship that affect model components are shown on the right. The potential responses of model fish are shown on the left. The project effects of the alternative management scenarios directly affect the entrainment and rearing responses of model fish.

Modeled Alternatives

The SBM uses the output of the 2D hydrodynamic model TUFLOW (BMT WBM 2013) under existing conditions and five alternatives involving a notch in Fremont Weir (Table 1). The TUFLOW output includes daily raster files (cell size = 50x50') of depth and velocity over a 15-year period (1997-2011) across the entire study area for each alternative. Depth and velocity data were aggregated to a coarser resolution (cell size = 300x300') to reduce computational demands of frequent loading of raster files in the SBM. The TUFLOW output also includes a 15-year time series of flow overtopping Fremont Weir, flow through the notches in the alternatives, Sacramento River flow at Verona, and Feather River flow entering the Sacramento River (just upstream of Verona).

Table 1. Description of alternatives evaluated with the Salmon Benefits Model. The alternatives differ in the design of a notch in Fremont Weir. Alt02 and Alt03 were not provided for analysis in the Salmon Benefits Model.

Alternative	Description	Alignment	Design Flow (cfs)	Closure Date
Alt01	30' bottom width, 30' bench, no levee	East	6,000	March 15th
Alt04	60' bottom width, 30' bench, no levee, downstream water control structures	West	3,000	March 15th
Alt04b				March 7th
Alt05	Intake A & B: 80' bottom width; Intake C: 130' bottom width; Intake D: 142' bottom width	Central	3,900	March 15th
Alt06	200' bottom width	West	12,000	March 15th
Exg	Flow over existing weir	--	--	--

MODEL DOCUMENTATION

Modeling Platform

The SBM was developed in NetLogo, an integrated modeling environment that is a powerful tool for scientific modeling (Lytinen and Railsback 2012). NetLogo is free, open source, and cross platform. The highly readable syntax of the programming language, thorough documentation, and widgets for graphical-user-interface (GUI) elements allow for rapid prototyping of new models in NetLogo.

Model Components

Model Entry

Initial Abundance

To determine the initial juvenile abundances of each Chinook salmon run entering the model, we converted historical spawner abundance estimates from each water year (California Department of Fish and Wildlife GrandTab database) to juvenile emigrants, using Chinook salmon populations that spawn upstream of Fremont Weir in the Sacramento River Basin (Table 2). We achieved this first by converting spawner abundance to number of female spawners, assuming a sex ratio of 0.5. Next, the number of female spawners was converted to number of deposited eggs by multiplying female spawners by run-specific estimates of fecundity (spring-run = 4,900; fall-run = 5,500, late-fall-run = 5,800, winter-run = 3,700; Moyle 2002). Finally, the number of eggs was converted to juveniles by multiplying estimated deposited eggs by 0.25, which is the average egg-fry survival estimate for the Upper Sacramento River (Martin et al. 2001). The resulting numbers of juveniles entering the model for each run are presented in Table 2.

Table 2. Annual run-specific historical estimated escapement values for Chinook salmon populations that spawn upstream of Fremont Weir in the Sacramento River Basin and resulting number of Chinook salmon juveniles of each run entering the Salmon Benefits Model under each water year.

Water Year	Spring-run		Fall-run		Late-fall-run		Winter-run	
	Escapement	Juveniles	Escapement	Juveniles	Escapement	Juveniles	Escapement	Juveniles
1997	2,658	1,628,025	263,653	181,261,438	1,385	1,004,125	1,012	468,050
1998	1,431	876,488	326,558	224,508,625	5,056	3,665,600	836	386,650
1999	23,677	14,502,163	166,380	114,386,250	42,965	31,149,625	2,992	1,383,800

Water Year	Spring-run		Fall-run		Late-fall-run		Winter-run	
	Escapement	Juveniles	Escapement	Juveniles	Escapement	Juveniles	Escapement	Juveniles
2000	6,092	3,731,350	329,982	226,862,625	15,758	11,424,550	3,288	1,520,700
2001	5,342	3,271,975	329,996	226,872,250	12,883	9,340,175	1,350	624,375
2002	12,952	7,933,100	446,938	307,269,875	21,813	15,814,425	8,224	3,803,600
2003	12,769	7,821,013	702,409	482,906,188	43,017	31,187,325	7,441	3,441,463
2004	8,583	5,257,088	397,094	273,002,125	11,198	8,118,550	8,218	3,800,825
2005	9,562	5,856,725	240,767	165,527,313	15,282	11,079,450	7,869	3,639,413
2006	14,044	8,601,950	329,442	226,491,375	18,614	13,495,150	15,839	7,325,538
2007	8,013	4,907,963	247,739	170,320,563	16,450	11,926,250	17,290	7,996,625
2008	6,755	4,137,438	77,836	53,512,250	13,442	9,745,450	2,541	1,175,213
2009	4,489	2,749,513	63,350	43,553,125	10,483	7,600,175	2,830	1,308,875
2010	2,492	1,526,350	39,385	27,077,188	10,084	7,310,900	4,537	2,098,363
2011	1,904	1,166,200	128,904	88,621,500	10,039	7,278,275	1,596	738,150

Entry Timing and Size

Model entry for Chinook salmon is the location of the Knights Landing (KL) rotary screw trap (RST) operated by the California Department of Fish and Wildlife (CDFW), 11 kilometers upstream of Fremont Weir (River KM 144) on the Sacramento River (Figure 1). Knights Landing RST data were then used to inform the initial entry timing and size of the daily juvenile salmon cohorts entering the model for all 15 water years (1997-2011). Because variation in daily RST catch rates can be highly influenced by variability in capture efficiency, we used catch per unit effort data (CPUE) as summarized by Roberts and Israel (2012). Daily CPUE for each run was divided by the sum of all daily run-specific CPUEs throughout a water year to estimate the daily proportion of each run entering the model each day (Figure 3).

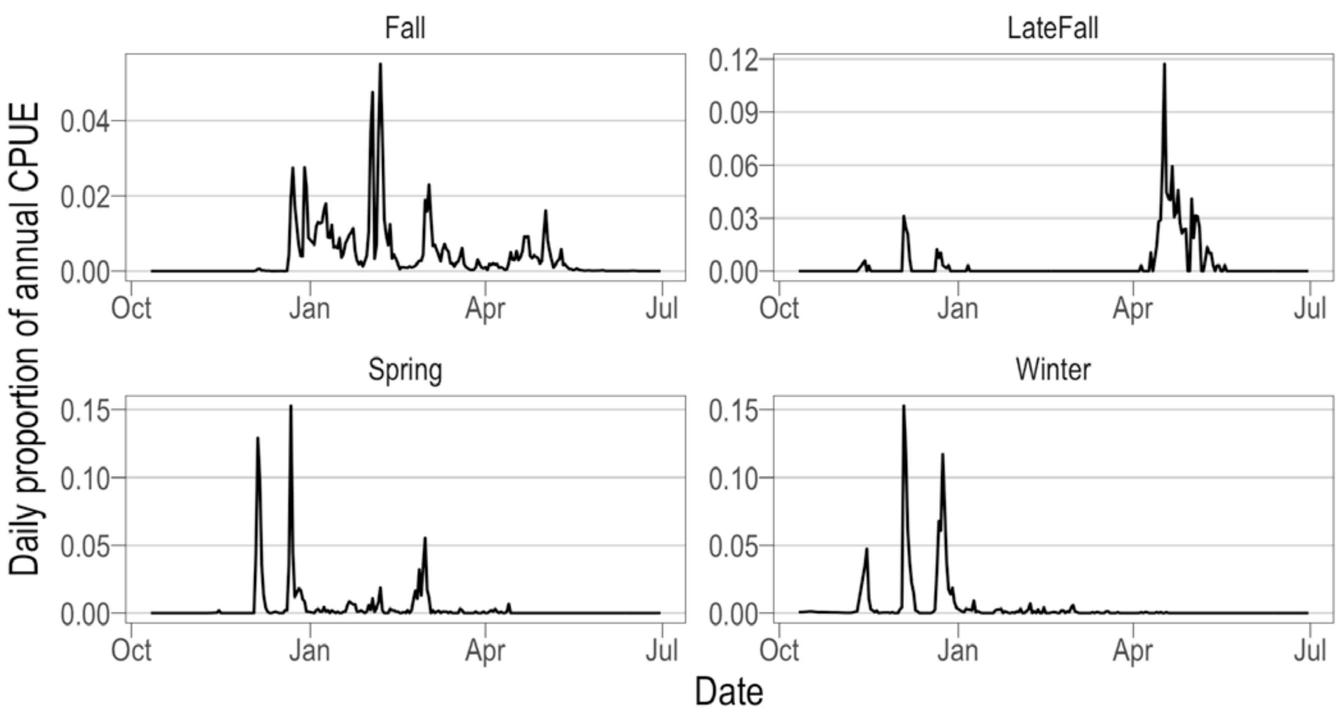

Figure 3. The daily proportion of juvenile Chinook salmon of each run entering the model during water year 2006**.** Note, the y-axes are not all set to the same scale.

We used generalized additive models (GAMs) to fit smooth functions of fork length (FL) versus date for each run and water year. The GAMs were used to estimate the fork length of daily cohorts of each run entering the model and allow for predictions on days where fish were caught in the RST but not measured (Figure 4). There is a strong correlation (r = 0.98) between the GAM predictions and the mean daily fork length.

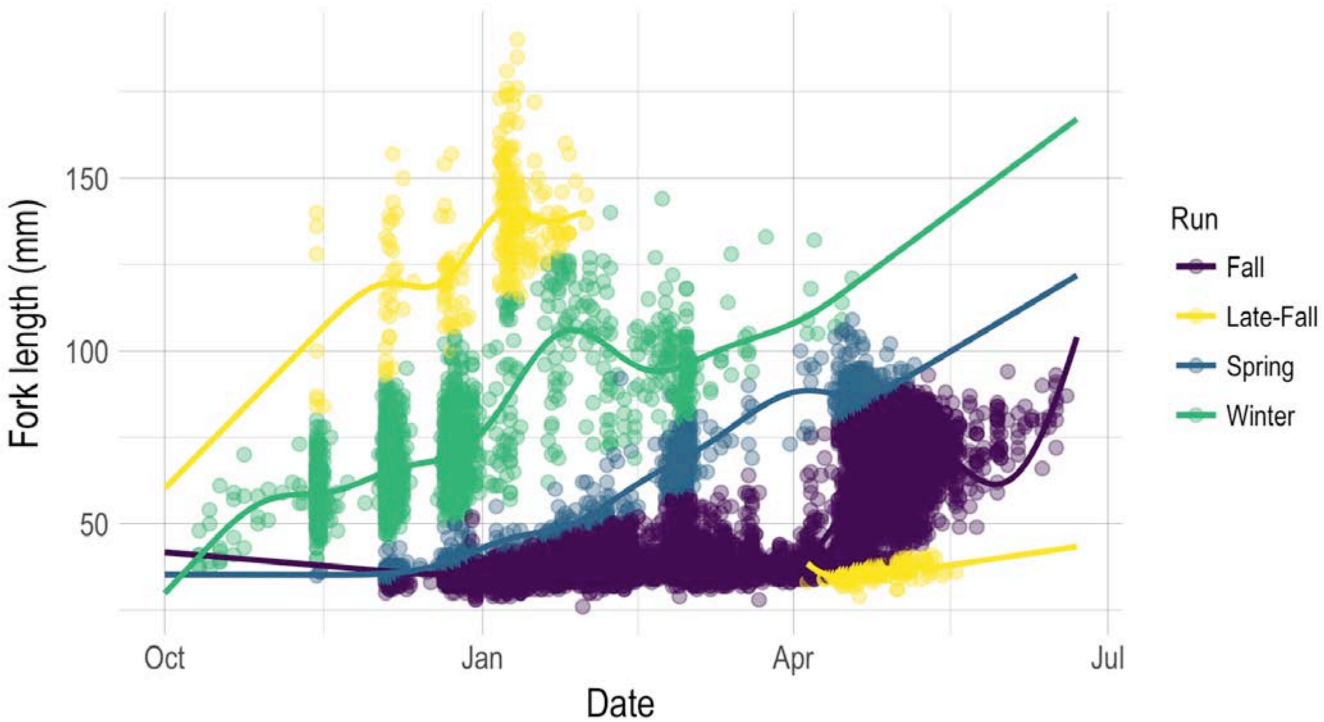

Figure 4. The size of fish captured in the Knights Landing RST (points) and the GAM smooth functions (lines) for water year 2006.

Length-at-date criteria were used to assign fish captured at KL RST to each run. Specifically, fish were assigned to a run using the River Model, which was developed by CDFW to classify individual salmon to temporal runs in the upper Sacramento River (Fisher 1992). The logic behind length-at-date criteria is that CV Chinook salmon runs spawn at different times of year, and if the same growth trajectory is assumed, the size of any run is unique on any date, therefore allowing for differentiation of these stocks.

Entrainment

The daily proportion of juvenile Chinook salmon of each run entrained onto the Yolo Bypass is estimated by multiplying the daily abundance of juvenile salmon of each run arriving at Fremont Weir by the proportion of Sacramento River flow entering the Bypass. We followed the approach of DWR (2017) and calculated the proportion of flow entering the Yolo Bypass (P_{YB}) through the notch as

$$P_{YB} = Q_{Notch}/(Q_{Notch} + Q_{VON} - Q_{FEA} - Q_{SUT} - Q_{NCC}) \quad \text{(Eq. 1)}$$

where Q_{Notch} is the flow through the proposed notch, Q_{VON} is the Sacramento River discharge at Verona, Q_{FEA} is the Feather River discharge as it enters the Sacramento River (upstream of Verona), Q_{SUT} is the discharge from the Sutter Bypass, and Q_{NCC} is the discharge from the Natomas Cross Canal. When Fremont Weir is overtopping, the proportion of flow entering the Yolo Bypass is calculated as

$$P_{YB} = (Q_{FRE} + Q_{Notch})/(Q_{FRE} + Q_{Notch} + Q_{VON} - Q_{FEA} - Q_{NCC}) \quad \text{(Eq. 2)}$$

where Q_{FRE} is the flow overtopping Fremont Weir. In this equation, the Sutter Bypass discharge is removed from the denominator, which makes the flow proportion based on the combined flow from the Sacramento River and Sutter Bypass (DWR 2017). Daily values of P_{YB} below zero or above one (based on above calculation) are set to zero and one, respectively. Similar to Roberts and Israel (2012), we assume that juvenile Chinook salmon (regardless of size or abundance) are equally distributed across and throughout the water column and enter the Yolo Bypass in proportion to the flow at the Weir.

Migration

The survival and movement behavior of SBM model juvenile salmon depends on their migratory route and the water year in which the cohort emigrates. Model fish migrating through the Sacramento River do not engage in explicit rearing behavior during their migration. The primary migratory pathway through the Yolo Bypass is the Canal Complex, which remains inundated year-round and provides a passage route for juvenile salmon. Model salmon migrating through the Yolo Bypass will stop their migration and engage in rearing behavior based on the availability of suitable adjacent rearing habitat. After rearing, Yolo Bypass fish move back to the Canal Complex and resume their migration downstream when floodplain habitat recedes or when they experience a migration trigger (see Floodplain Rearing).

There is very little data available on the survival and migratory behavior of juvenile Chinook salmon in the Yolo Bypass. Slightly more data is available for the Sacramento River (see Perry et al. 2010, Michel et al. 2015), but comparison is problematic in the absence of Yolo Bypass estimates in the same years and hydrological conditions. For the SBM, we have incorporated empirical data on migration and survival rates for the three years where data from both the Sacramento River and the Yolo Bypass are available, so that assumptions inherent in extrapolating the empirical data to all 15 modeled water years would be consistently applied throughout the model.

Migration and survival rates are available for both the Sacramento River and the Yolo Bypass in three years: 2012, 2013, and 2016 (Johnston, *unpublished data*, Perry, *unpublished data*). To apply results from these studies across all 15 water years modeled in the SBM, we calculated the Euclidean distance between the Fremont stage (NAVD88) time series in each data year (2012, 2013, 2016) and each modeled water year (1997-2011). The lowest Euclidean distance across data years indicates the best match for a given water year (Table 3). The estimated migration and survival rate values from the data years (see below) were then applied to each modeled water year according to their best matching data year.

Table 3. Euclidean distances for comparisons of Fremont stage time series across modeled water years (1997-2011) and data years (2012, 2013, 2016). The smallest value in a row indicates the best match between the modeled water year and the data year.

Water Year	2012	2013	2016
1997	164.72	132.81	154.50
1998	207.48	219.93	190.63
1999	148.09	145.31	141.59
2000	129.82	150.50	112.48
2001	72.70	95.02	94.15
2002	98.26	66.07	110.51

2003	132.42	128.37	136.30
2004	132.75	120.28	121.46
2005	110.53	110.11	121.98
2006	202.89	205.18	183.72
2007	65.15	81.40	109.03
2008	81.71	93.83	103.75
2009	83.82	111.79	116.34
2010	82.82	117.00	96.14
2011	142.12	145.22	144.17

Migration Rates

Migration rates for emigrating cohorts in each route were calculated from available empirical data from the modeled routes (Table 4). Migration rate data were available for hatchery, late-fall run juvenile Chinook salmon emigrating through the Sacramento River and the 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 4. Mean migration rates (km/day) 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

Survival

In the SBM, overall mortality in the Yolo Bypass includes mortality while migrating through the Canal Complex (gauntlet model) and mortality while rearing on the floodplain (exposure model). All fish that migrate through the Canal Complex experience migrating mortality. However, fish that rear on the floodplain also experience rearing mortality. Estimates of migrating survival are based on acoustic telemetry studies of large, late-fall run juvenile Chinook salmon that are not expected to stop to rear while emigrating through the Yolo Bypass. Values of rearing survival are not based on empirical data, but the effect of the rearing survival value is explored in the Effects Analysis. Additionally, only SBM fish that migrate down the Yolo Bypass have the opportunity to engage in rearing. Thus, all mortality for fish migrating down the Sacramento River originates from migration mortality because no explicit rearing takes place along the Sacramento River route in the SBM.

Migrating Survival

In the SBM, cohorts actively migration downstream via either the mainstem Sacramento River, or the Canal Complex in the Yolo Bypass. 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 5). The survival values were converted to survival per kilometer (S_{km}) as follows:

$$S_{km} = S^{\left(\frac{1}{reach\ length}\right)} \qquad \text{(Eq. 3)}$$

Table 5. 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 5) 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.

Rearing Survival

In the SBM, cohorts rearing on the floodplain experience a daily survival of 0.99. A survival model with survival as a function of time is known as an exposure model (Anderson et al. 2005) because the probability of survival is decreased with an increase in time spent rearing and exposure to predators. In the model, fish are trading off increased growth on the floodplain (see Growth) with the additional mortality incurred during rearing (relative to not rearing). [Note, this is not an optimality model; the rearing rules could produce sub-optimal rearing durations depending on the value chosen for rearing survival.] 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 (see Ocean Residence). 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 migration, the minimum daily rearing survival value to make rearing worthwhile (i.e., growth benefit outweighs rearing mortality) is approximately 0.99 (see https://fishsciences.shinyapps.io/yolo-bypass-rearing-survival/). This rearing survival value is not based on empirical data. However, in the Effects Analysis, we explore the implications of lower rearing survival on the conclusions drawn from the SBM.

Floodplain Rearing

Suitable Habitat

We took a simplified approach to movement through the Yolo Bypass. For example, all cohorts move downstream along the eastern edge of the Yolo Bypass in the Canal Complex and movement between the Canal Complex and suitable habitat on the floodplain is instantaneous and incurs no mortality. Also, cohorts have perfect knowledge of the current (but not future) availability of suitable habitat. However, because the Yolo Bypass covers a large geographic extent, we included a spatial constraint and divided the Yolo Bypass into 5 bands that are roughly 14-km long from north to south. Cohorts are only able to access suitable floodplain habitat located within the band that they are currently moving through. The length of the bands (14 km) is longer than the width (~ 3-9 km) of a fully inundated Yolo Bypass. If suitable habitat is available within a band for a given cohort on a given day, the cohort will move onto the available suitable habitat and rear on the floodplain. Habitat suitability criteria for Sacramento River juvenile Chinook salmon (USFWS 2005) were used to define suitable floodplain rearing habitat for fry (<70 mm FL) and smolts (≥70 mm FL; Kjelson et al. 1982). Suitable habitat for fry was characterized as 0.39–4 ft deep with velocities less than 1.6 ft/s, and for smolts as 0.39–8 ft deep with velocities less than 1.6 ft/s (USFWS 2005).

On any given day, the model estimates the daily habitat area requirements of the cohort to determine whether enough suitable floodplain rearing habitat is available to support all or a part of the cohort. The territory size required by each fish is estimated with a linear model on a log-log scale as a function of fish fork length based on data collected for salmonids (Grant and Kramer 1990; Figure 5)

$$\tau = 10^{-5.44+2.61*\log_{10} L} \qquad \text{(Eq. 4)}$$

where τ is territory size (m^2) and L is fork length (mm). The amount of suitable habitat claimed by a given cohort is the sum of the territory sizes of all individuals in the cohort. Suitable habitat is occupied in 900-ft^2 patches by the first cohort that reaches the unoccupied habitat. If there is enough suitable habitat for the full cohort, then the cohort claims the number of habitat patches that it needs. If there is only enough suitable habitat for part of the cohort, then the cohort is split, with part of the cohort claiming the available patches, and the other cohort part continuing to migrate downstream in the Canal Complex. Each day the amount of suitable habitat is updated and the above process is repeated.

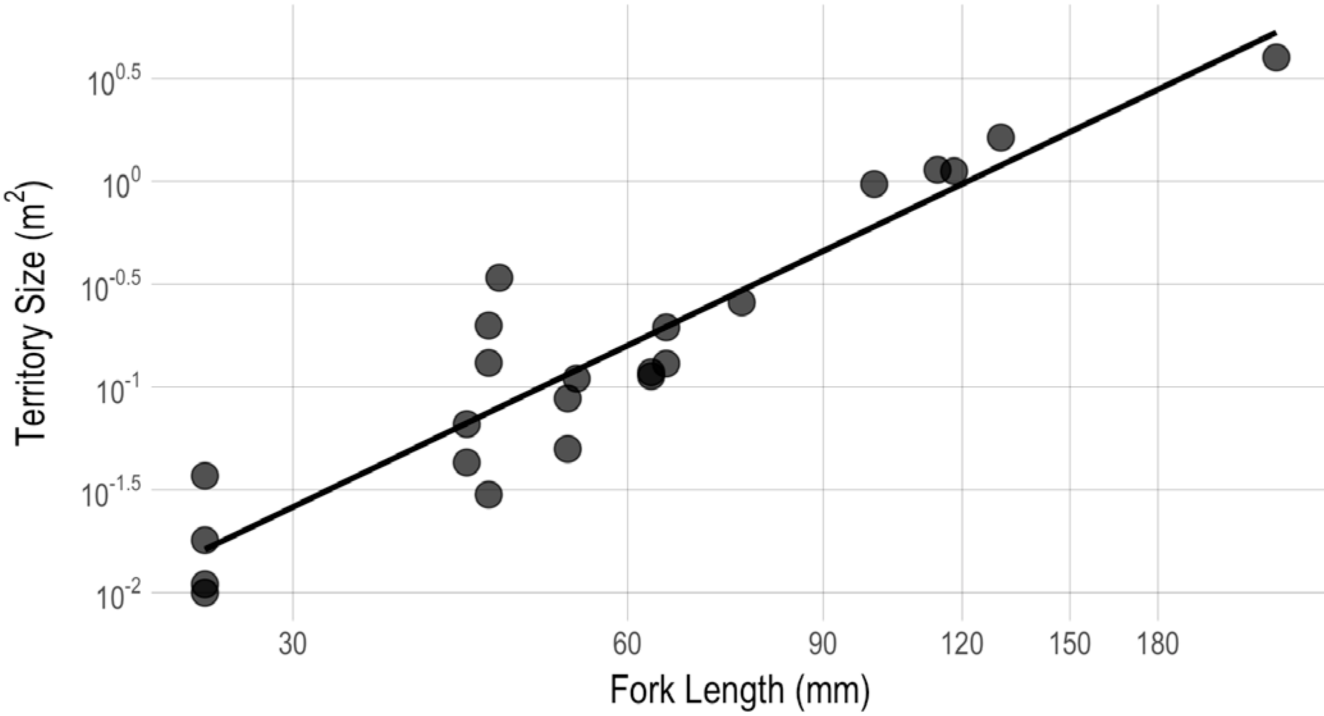

Figure 5. Territory size versus fork length relationship for salmonids based on data from Grant and Kramer (1990). Circles are observations and line is fitted relationship used in the Salmon Benefits Model.

Rearing Rules

Although some precocious males never leave freshwater, we assume the value/numbers of these fish are negligible. Therefore, in the model, Chinook salmon do not rear in freshwater indefinitely, and we incorporated rearing rules that constrain the time that a cohort spends rearing on the floodplain. The model uses these rearing rules to decide whether a cohort migrating through the Canal Complex continues to migrate or whether it will rear in adjacent suitable habitat. The rearing rules are simple heuristics based on temperature, fish size, and time of year.

The water temperature rule is based on daily water temperature data collected by the California Department of Water Resources (DWR) Aquatic Ecology Section RST site located in the Toe Drain near the north-east tip of Little Holland Tract for years 1998-2011. Because both growth rates and smoltification (ATPase activity) of juvenile Chinook salmon have been shown to decrease at water temperatures above 20°C (Marine 1997; Marine and Cech 2004), the first day that average water temperatures exceeded 20°C was set as a maximum date that fish would rear on the floodplain. The Toe Drain water temperature data indicated that June was the first month that average daily water temperatures consistently exceeded the 20°C threshold across nearly every year. Thus, June 1st was set as the date when rearing fish would stop rearing and continue migrating through the Canal Complex.

Under the assumption that there is a theoretical maximum size when fish smoltification and resulting directed movement toward the ocean will occur, the largest Chinook salmon juvenile observed to be entering the ocean in recent years was used to determine a threshold size used to move fish off of the floodplain and back to the Canal Complex to resume downstream migration. The threshold fish size was based on the maximum size of Chinook salmon historically observed to emigrate out of the Central Valley. The maximum fork length of un-marked Chinook salmon observed migrating past Chipps Island in 2010 and 2011 was 120 mm (Speegle et al. 2013). Therefore, modeled fish move back to the Canal Complex and resume downstream migration once reaching a fork length of 120 mm.

One of the main seasonal triggers of smoltification and resulting downstream migration for salmonids is changes in photoperiod as the season progresses (Thorpe 1988). Because photoperiod is tied to time-of-year, a second migration trigger was applied (run timing trigger) that was based on the last dates that each run was observed passing Chipps Island during years 2007-2011 (USFWS 2010; USFWS 2012; Speegle et al. 2013). The last observed dates at Chipps Island were May 15 for winter-run, May 31 for spring-run, July 31 for fall-run, and February 15 for late-fall-run. For each cohort, the model back-calculates the date to stop rearing based on the distance to Chipps Island, migration rate, and run-timing trigger date.

Growth

In the SBM, growth is calculated as

$$L_t = g^t L_0 \quad \text{(Eq. 5)}$$

where L_t is fork length at time t, L_0 is fork length at time 0, and g is the daily proportional growth rate. The key assumption of this model is that fish of all sizes grow by the same proportion in a day, but larger fish will increase their size by a greater absolute amount. For example, if g is 1.01, a 30-mm fish will grow 0.3 mm in one day, but a 100-mm fish will grow 1.0 mm in one day.

The proportional growth rate can be estimated from empirical studies of fish growth (e.g., Jeffres et al. 2008) by re-arranging the growth equation as follows

$$g = (L\_t/L\_0)\hat{}(1/t) \quad \text{(Eq. 6)}$$

We used this equation to estimate growth rates from empirical studies of juvenile Chinook salmon in California's Central Valley (Table 6). In the model, we set daily growth rates at 1.005, 1.006, and 1.012 for the Sacramento River, Canal Complex, and Yolo Bypass floodplain, respectively. We arrived at these values by averaging the values from Table 6. When a study included multiple replicates or treatments within a year, we first averaged across those replicates/treatments and then averaged across all studies and years.

Table 6. Growth rates from empirical studies of juvenile Chinook salmon in California's Central Valley.

Location	Year	Initial Fork Length (mm)	Final Fork Length (mm)	Days	Daily Growth Rate	Notes	Source
Sacramento River	2016	54.8	58.2	21	1.003	--	Jeffres 2016
Toe Drain	2016	54.8	62.0	21	1.006	--	
Yolo Bypass floodplain (Knaggs Ranch)	2016	54.8	76.7	21	1.016	--	
	2014	61.0	81.0	15	1.019	PIT tag study; enclosure 1	Katz et al. 2014
		60.6	81.7	15	1.020	PIT tag study; enclosure 2	
		61.9	81.0	15	1.018	PIT tag study; enclosure 3	
		43.0	77.8	35	1.017	Volitional outmigrant study; hatchery origin	
		33.9	53.5	25	1.018	Volitional outmigrant study; wild origin	

Location	Year	Initial Fork Length (mm)	Final Fork Length (mm)	Days	Daily Growth Rate	Notes	Source
	2013	53.6	92.1	39	1.014	Free-swimming; disc field	Katz et al. 2013
		53.6	90.3	39	1.013	Free-swimming; stubble field	
		53.6	88.4	39	1.013	Free-swimming; fallow field	
		52.2	63.9	16	1.013	Penned; hatchery origin	
		52.4	65.9	16	1.014	Penned; wild origin	
	2012	48.0	75.5	42	1.011	Free-swimming	Katz 2012
		48.0	78.0	42	1.012	Penned	
Cosumnes River floodplain	2004	54.9	71.4	32	1.008	FP Veg	Jeffres et al. 2008
		54.9	72.2	32	1.009	Upper pond	
		54.9	66.2	32	1.006	Lower pond	
	2005	54.0	86.6	56	1.008	FP Veg	
		54.1	79.7	56	1.007	Upper pond	
		54.0	74.6	56	1.006	Lower pond	
Yolo Bypass floodplain	1998	57.5	93.7	46.2	1.011	--	Sommer et al. 2001
	1999	56.8	89.0	58.2	1.008	--	
Sacramento River	1998	57.5	85.7	55.4	1.007	--	
	1999	56.8	82.1	58.6	1.006	--	

Ocean Residence

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.

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

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

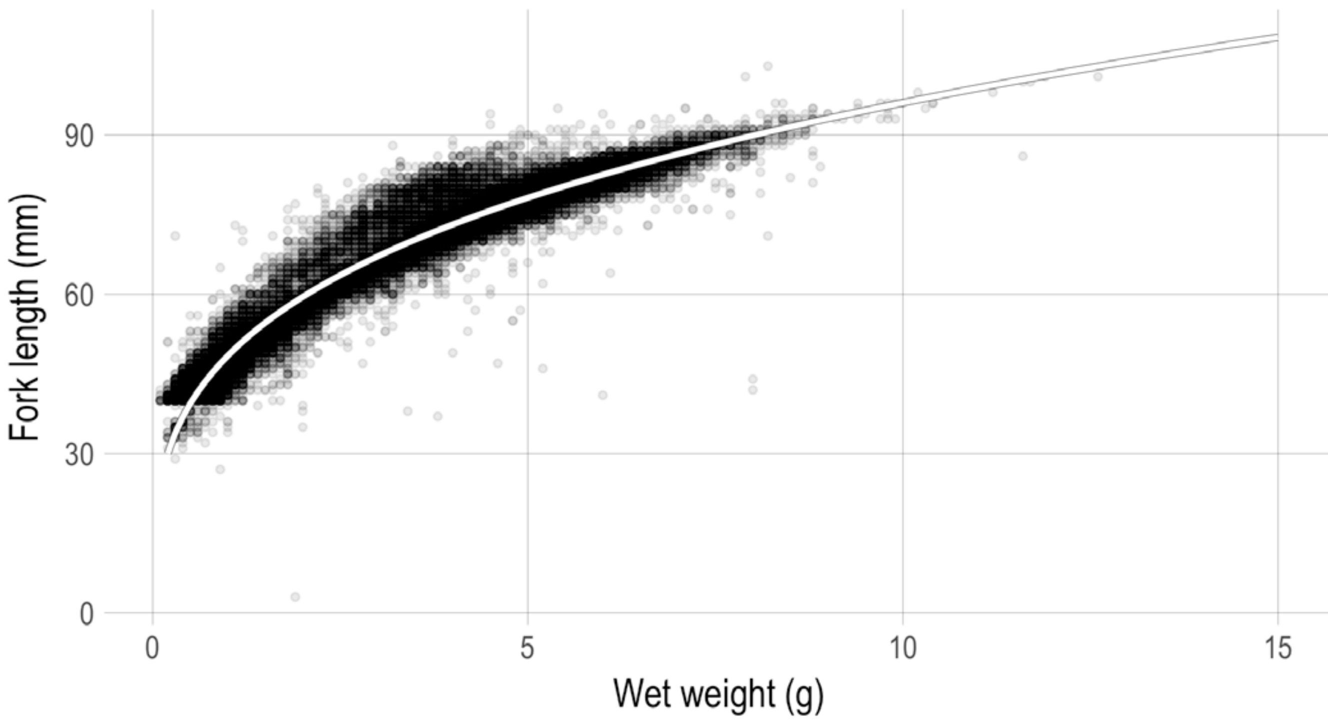

Figure 6. Fork length and wet weight of fall-run Chinook salmon caught at the Knights Landing Rotary Screw Trap from 2000-2012. Circles are observed values and white line is fitted relationship.

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):

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

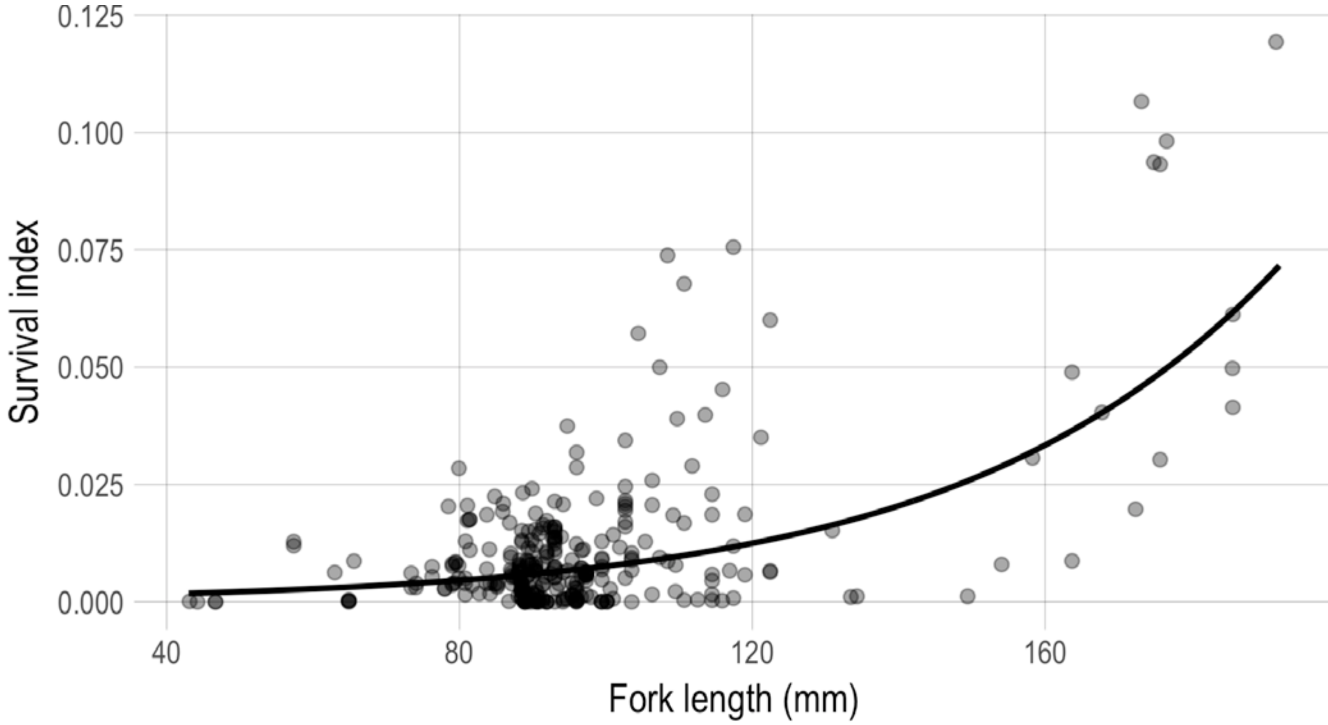

Figure 7. Age 3 survival index versus fish fork length at release for hatchery fall-run juvenile Chinook salmon released in the San Francisco Bay, 1978-2011. Circles are observed values and line is fitted relationship, which is used in the Salmon Benefits Model.

Upstream Migration

Following ocean residence, upstream migration of returning adults from the Bay to Fremont Weir on the Sacramento River was modeled. As a simplifying assumption, the SBM does not include any mortality during the upstream migration of adult returners. In the SBM, we only track the run and number, not size, of returning adults. Thus, upstream migration mortality would not impact comparison of alternatives within a run.

Model Assumptions and Limitations

Due to limited data available for several CV Chinook salmon life stages, traditional statistical estimation 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 of Yolo Bypass restoration actions on Chinook salmon with a level of complexity that captures the most recent 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 tagged hatchery surrogates. 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 and animal husbandry. In addition to limited data on naturally-produced fish, many of our relationships are informed by data from a single Chinook salmon run (i.e., fall-run), thereby assuming that all runs move, grow, and survive according to the same rules.

Habitat Suitability

For juvenile salmon to successfully rear, numerous physical requirements must be met including suitable cover (McMahon and Hartman 1989), food availability and water quality (Marine and Cech 2004). Furthermore, flood duration of seasonally inundated habitats can dictate the strength of biotic response to the flood (King et al. 2003). Unfortunately, spatial modeling of water temperature, cover, and biotic production were not available to inform the complex response between Bypass inundation duration and juvenile growth. However, a key assumption of salmonid rearing habitat modeling is that depth and velocity are major predictors of habitat suitability (Raleigh et al. 1986; Keeley and Slaney 1996). Therefore, we simplified our approach and defined suitable habitat based on water depths and velocities alone and modeled juvenile salmon to exhibit an average, consistent growth rate while rearing on the floodplain. We currently assume depth and velocity suitability criteria developed in the adjacent habitat of the Sacramento River (USFWS 2005) is transferable to Yolo floodplain. However, if more information becomes available to inform a more sophisticated relationship between floodplain habitat and juvenile salmon rearing success, model functionality can be changed.

Water Temperature

Water temperature can affect juvenile Chinook salmon survival and health (Marine and Cech 2004), and migratory behavior has been associated with long-term accumulated response to water temperatures, with smoltification rates increasing with increased accumulated thermal units unless the upper threshold is met (ATU; Sykes and Shrimpton 2010; Marine and Cech 2004). However, apart from the water temperature movement trigger, these temperature effects are excluded from the model due to lack of modeled temperature data. The water temperature movement trigger assumes that historical Yolo Bypass water temperatures will likely relate to future water temperatures under the different management alternatives, at least in a very coarse way. If water temperatures are modeled for Yolo Bypass management alternatives in the future, new model functionality could be incorporated to evaluate how different temperature regimes under each alternative affect model outcomes.

Yolo Bypass Entrainment

Models for how juvenile Chinook salmon are distributed in the channel and throughout the water column at the Fremont Weir junction are currently unavailable. Therefore, we assumed that juvenile Chinook salmon are equally distributed across the channel and throughout the water column and enter the Yolo Bypass in proportion to the flow entering the bypass. Similar dispersion assumptions have been used to estimate juvenile salmon entrainment (Kimmerer and Nobriga 2008). However, if more information becomes available to inform a more sophisticated relationship 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.

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 and Canal Complex move one-dimensionally and at an average rate. 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 based on simple movement rules. 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 territorial behavior on floodplains. Therefore, the model allows fish to immediately colonize proximate habitat, without explicitly modeling individual movement. We assume that all juvenile Chinook set up a territory in the most immediately available and suitable habitat, without prioritization for juveniles of different sizes or runs.

Growth

We assumed that growth rate depends only on fork length and approximate location (i.e., Sacramento River, Canal Complex, floodplain). It is unlikely that growth is homogenous throughout each of these locations, but we assume that our estimates of growth rate reflect average behavior across these locations.

Survival

River

We assumed that juvenile Chinook salmon survive according to a gauntlet model of survival. 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. We also assumed that mortality was evenly applied from Fremont Weir to Chipps Island along both the Sacramento River and Canal Complex routes. On the Sacramento River route, this is simply an implementation detail because where fish die along that route is not important for the metrics used to evaluate alternatives. On the Canal Complex route, where fish die along the route may have implications for accessing suitable rearing habitat, particularly if most of the mortality occurs from Rio Vista to Chipps Island when fish no longer have access to floodplain. We assumed that survival estimates from studies of large, hatchery, late-fall run Chinook salmon conducted in 2012, 2013, and 2016 apply to wild fish of other runs and sizes in water years 1997-2011. We also assumed that migrating survival is constant throughout the migration season.

Floodplain

We assumed that floodplain survival operates under an exposure model where time spent rearing reduces the overall survival. Other factors that may influence floodplain survival include the behavior (e.g., habitat selection, activity level) and physical attributes of the fish (e.g., size). We also assumed that floodplain survival is the same throughout the migration season, across Chinook salmon runs and years, and over the whole floodplain. The floodplain survival component of the model can be updated as more data becomes available.

Ocean

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 (Satterwaite et al. 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.

ALTERNATIVES ANALYSIS

In this section, we present the results of an analysis of alternatives involving different designs for a notch in Fremont Weir (see Modeled Alternatives). The analysis of the SBM focused on five metrics to assess the relative benefits of the management alternatives: (1) juvenile survival from Knights Landing to Chipps Island, (2) mean fork length of fish at Chipps Island, (3) coefficient of variation of fork length of fish at Chipps Island, (4), coefficient of variation of arrival timing at Chipps Island, and (5) number of returning adults.

The benefits metrics consider the population as a whole rather than by route (i.e., Sacramento River and Yolo Bypass). The proportion of the population entrained onto the Yolo Bypass is relatively small and highly variable. Across all years, runs, and alternatives, the average proportion entrained is 13% (range: 0-61%). Thus, big effects on the Yolo Bypass route can be misleading if not placed in context of the whole population.

The benefits metrics are calculated on a yearly time scale. Within-year results are available for additional analysis, but are not presented here. The benefits metrics figures are presented on a relative scale to highlight differences between alternatives.

$$relative\ change = \frac{alternative - existing}{existing} \qquad \text{(Eq. 9)}$$

Percentage change can be calculated by multiplying relative change by 100. The difference between each alternative and existing conditions is calculated on an annual basis because of large inter-annual variation in the benefits metrics. The values used to calculate the relative change in benefits metrics are included as tables in Appendix A.

Juvenile Survival to Estuary Entry

Juvenile survival is calculated as the total number of juvenile Chinook salmon that arrive at Chipps Island divided by the total number that entered the model at Knights Landing for each water year. Juvenile survival is lower under alternatives than existing conditions (Figure 8; Table A-1).

Juvenile fish migrating from Fremont Weir to Chipps Island on the Yolo Bypass route have lower survival in all years than fish migrating through the Sacramento River. Fish that rear on the floodplain during their migration through the Yolo Bypass incur additional mortality while rearing. Relative to existing conditions, the alternatives increase entrainment and generally increase time spent rearing on the floodplain. Late-fall fish experience the lowest relative change (least negative) in juvenile survival because they enter the model at a larger size and exhibit very little rearing behavior.

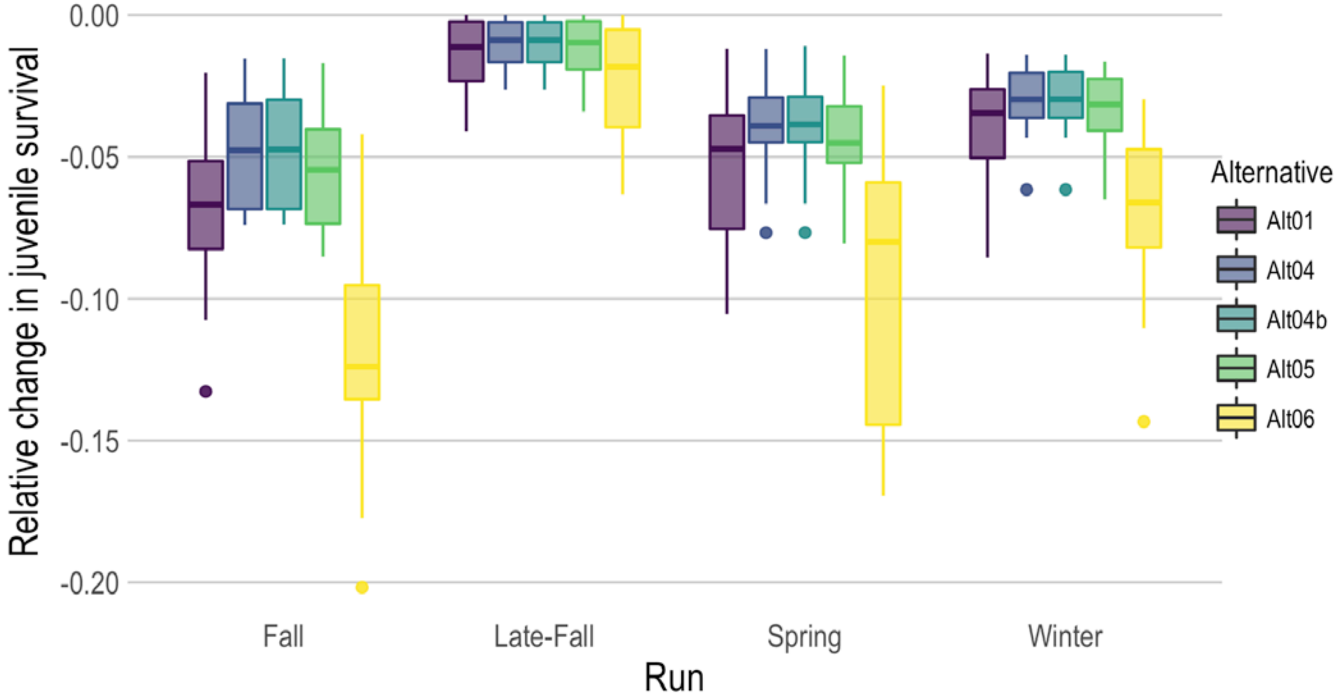

Figure 8. Relative change in juvenile survival from Knights Landing to Chipps Island for 15 years under five alternatives for notches in Fremont Weir. The line near the center of the box is the median, the bottom and top of the box are the 25th and 75th percentiles, respectively, the whiskers show the min/max (unless there are outliers), and the points are outliers (+/- 1.5x interquartile from 75th and 25th percentile, respectively). Note, the y-axis has been truncated to exclude some outliers. See Table A-1 for full set of values.

Juvenile Fork Length at Estuary Entry

Fork length is calculated as the mean fork length of all juvenile Chinook cohorts that arrive at Chipps Island weighted by the abundance of fish in the cohort. Fish grow faster on the floodplain than in the Sacramento River and, thus, mean fork length at Chipps Island is generally higher under the alternatives than under existing conditions (Figure 9; Table A-2). Late-fall fish are the exception because they enter the model at a larger average size, often above the rearing size threshold (120 mm), and do not benefit from the increased floodplain rearing opportunities provided by the alternatives.

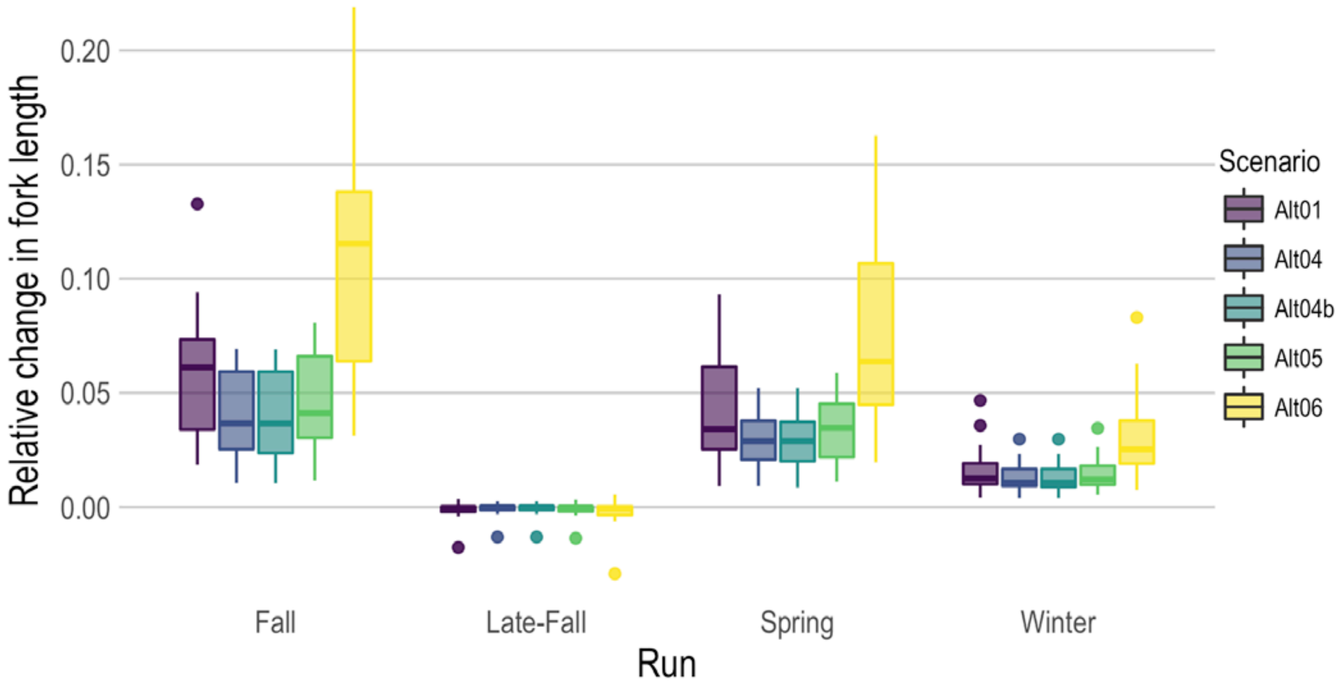

Figure 9. Relative change in mean fork length at Chipps Island for 15 years under five alternatives for notches in Fremont Weir. The line near the center of the box is the median, the bottom and top of the box are the 25th and 75th percentiles, respectively, the whiskers show the min/max (unless there are outliers), and the points are outliers (+/- 1.5x interquartile from 75th and 25th percentile, respectively).

Juvenile Fork Length Variation at Estuary Entry

Fork length variation is calculated as the coefficient of variation in fork length of all cohorts that arrive at Chipps Island weighted by the abundance of fish in the cohort. Using fork length variation as a fish benefits metric reflects the importance of trait variation in ecological dynamics, including those assumed for CV Chinook salmon (Goertler et al. 2016; Bolnick et al. 2011). Fork length variation is higher under alternatives than under existing condition (Figure 10; Table A-3). The alternatives provide access to the Yolo Bypass at lower flows than under existing conditions and, presumably, introduce variability in the accessibility of suitable rearing habitat for fish that, in turn, increases fork length variation at Chipps Island.

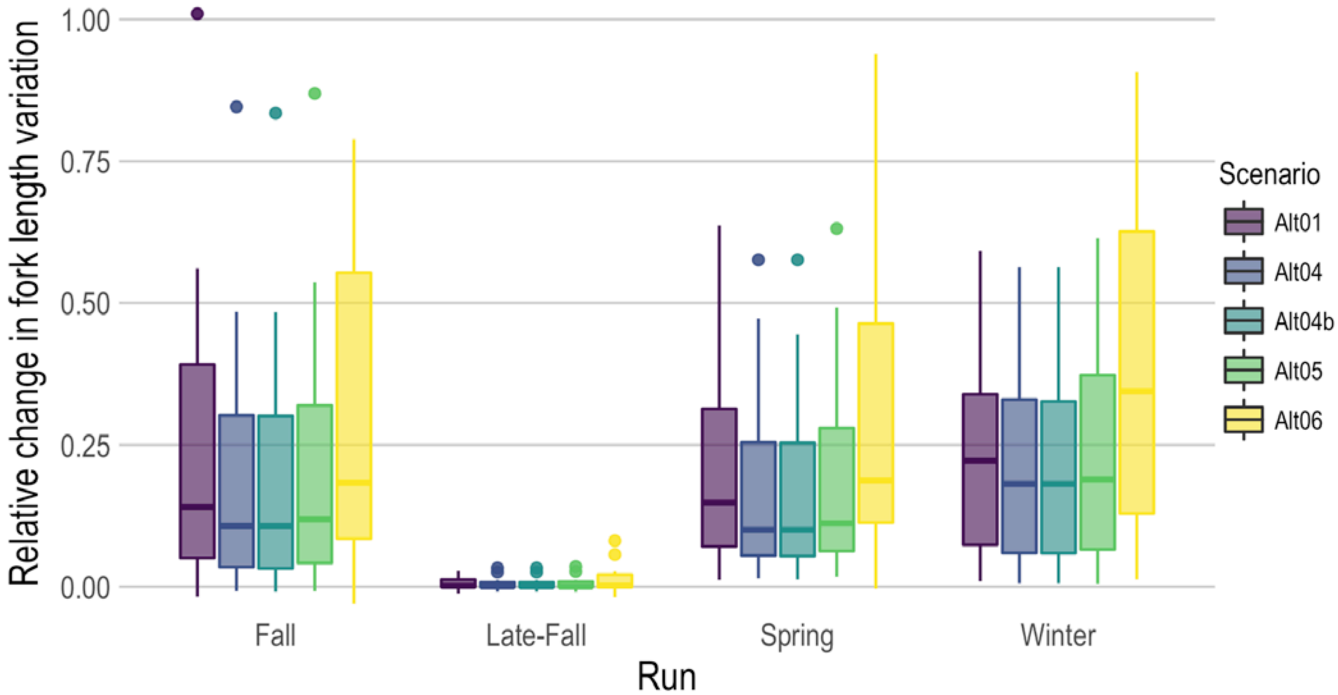

Figure 10. Relative change in coefficient of variation in fork length at Chipps Island for 15 years under five alternatives for notches in Fremont Weir. The line near the center of the box is the median, the bottom and top of the box are the 25th and 75th percentiles, respectively, the whiskers show the min/max (unless there are outliers), and the points are outliers (+/- 1.5x interquartile from 75th and 25th percentile, respectively). Note, the y-axis has been truncated to exclude some outliers. See Table A-3 for full set of values.

Juvenile Timing Variation at Estuary Entry

Entry timing variation is calculated as the coefficient of variation in timing of all cohorts that arrive at Chipps Island weighted by the abundance of fish in the cohort. Timing is measured as day of water year when a cohort arrives at Chipps Island where October 1st is day one. Ocean conditions vary within the migration season (Scheuerell et al. 2009) and variation in estuary entry timing may make the population more resilient to changing ocean conditions. Entry timing variation is higher under alternatives than under existing condition (Figure 11; Table A-4). The alternatives provide access to the Yolo Bypass at lower flows than under existing conditions and, presumably, introduce variability in the accessibility of suitable rearing habitat for fish that, in turn, increases estuary entry timing variation.

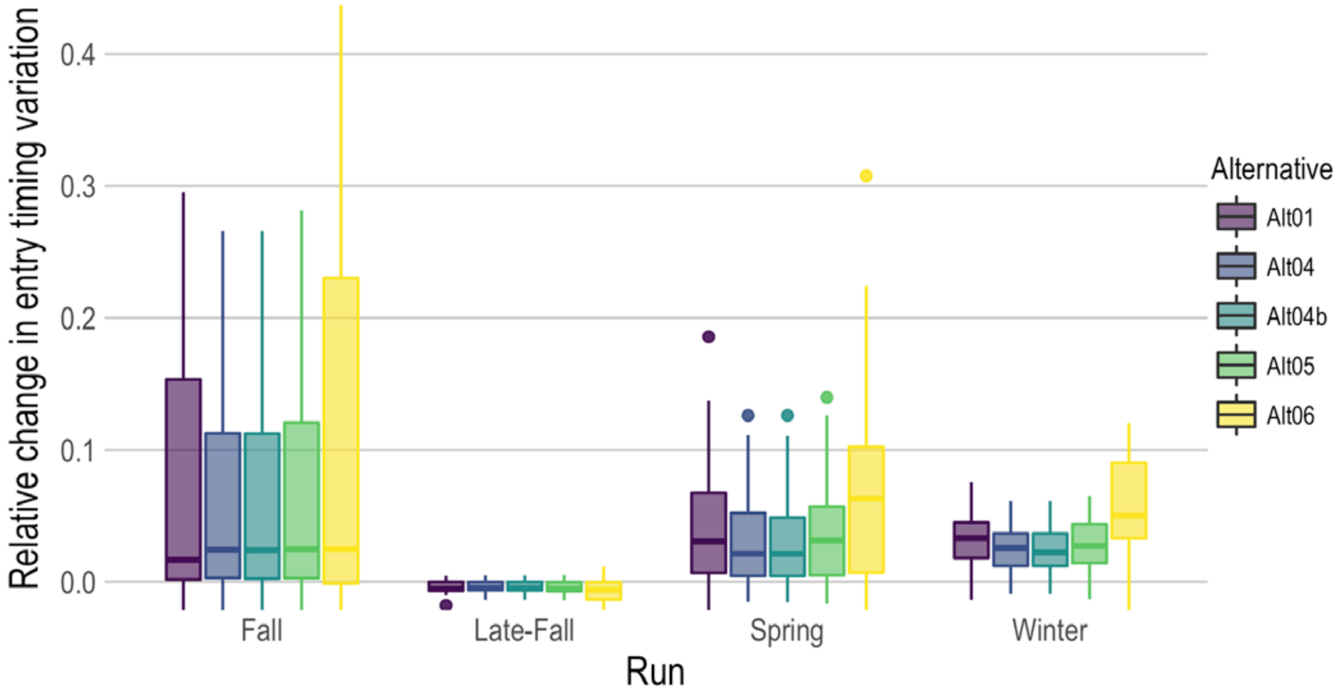

Figure 11. Relative change in coefficient of variation in estuary (Chipps Island) entry timing for 15 years under five alternatives for notches in Fremont Weir. The line near the center of the box is the median, the bottom and top of the box are the 25th and 75th percentiles, respectively, the whiskers show the min/max (unless there are outliers), and the points are outliers (+/- 1.5x interquartile from 75th and 25th percentile, respectively). Note, the y-axis has been truncated to exclude some outliers. See Table A-4 for full set of values.

Returning Adults

The number of returning adult salmon depends on both the number and size of juveniles that arrive at Chipps Island because the ocean survival relationship is a function of size. The returning adults metric shows the combined effect of the juvenile survival and fork length metrics. In other words, the number of returning adults captures the trade-off between floodplain growth and rearing survival. Under most alternatives and years, the alternatives produce more returning adults than existing conditions (Figure 12; Table A-5). Late-fall fish are the exception because they incur the juvenile survival costs of migrating through the Yolo Bypass (Figure 8), but do not reap the growth benefits (Figure 9) provided by access to the floodplain because they enter the model at a larger average size, often above the rearing size threshold (120 mm).

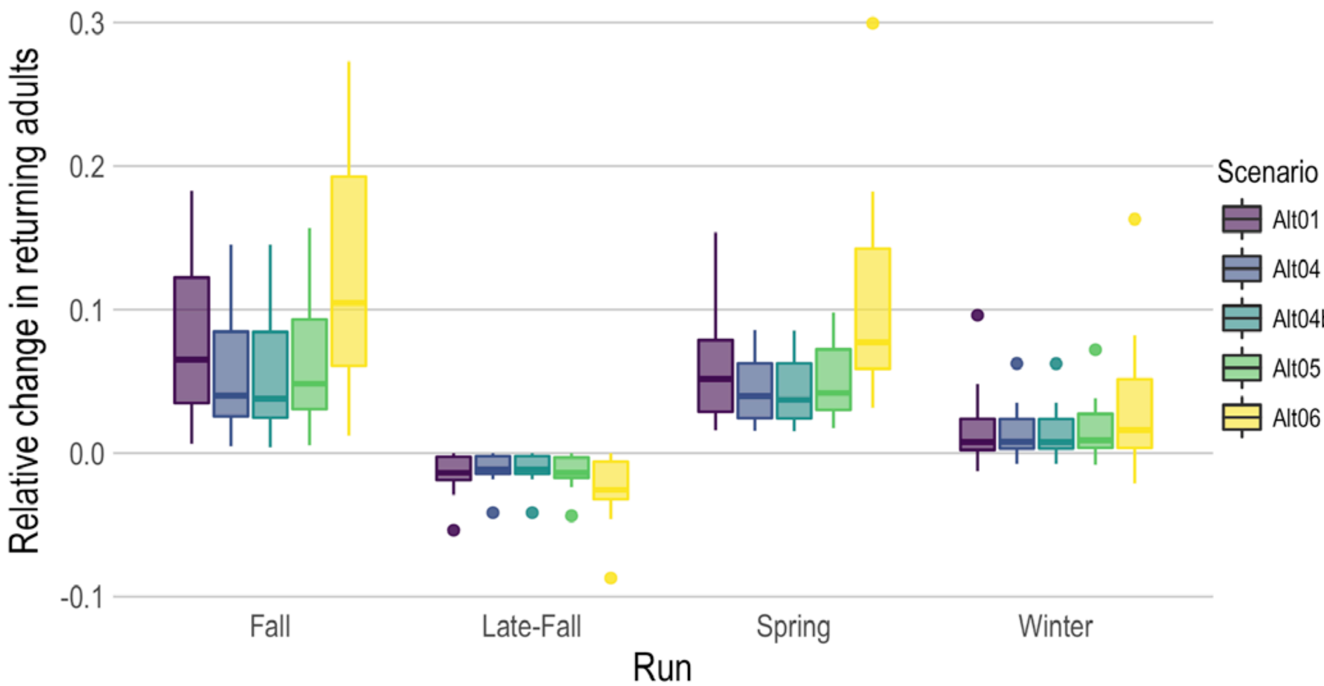

Figure 12. Relative change in number of returning adults for 15 years under five alternatives for notches in Fremont Weir. The line near the center of the box is the median, the bottom and top of the box are the 25^{th} and 75^{th} percentiles, respectively, the whiskers show the min/max (unless there are outliers), and the points are outliers (+/- 1.5x interquartile from 75^{th} and 25^{th} percentile, respectively). Note, the y-axis has been truncated to exclude some outliers. See Table A-5 for full set of values.

Conclusions

In drawing conclusions for the Alternatives Analysis, we focus on three of our fish benefits metrics: returning adults, estuary entry timing variation, and fork length variation. The number of returning adults measures the productivity of the population and incorporates the combined effects of juvenile growth and survival. Moreover, the returning adults metric includes benefits for larger fish in a couple of model components (i.e., growth, ocean survival). In contrast, estuary entry timing variation and fork length variation provide alternative benefits metrics that reflect the value of variation in traits and environmental conditions. Although fish size at ocean entry is a significant predictor of ocean survival, the relationship is noisy (Figure 7) and confounded with estuary entry timing. It's possible that smaller fish may be favored under some ocean conditions, which may increase population stability across years.

For all three focal metrics, Alt06 generated the biggest relative changes. Alt06 has the largest notch and highest max design flows (12,000 cfs) of the modeled alternatives. There is very little difference in the focal metrics among the other alternatives, but Alt01 yields noticeably different relative changes for some runs in some years. Alt01 has the second largest design flow (6,000 cfs) of the notches considered.

The relative change in fork length variation is correlated to relative change in entry timing variation for all runs, except late-fall, with correlation coefficients ranging from 0.72-0.91 across alternatives and runs.

The largest relative changes in returning adults and fork length variation generally do not occur in the same years. For example, for fall- and spring-run in 1999, Alt06 produced a much larger relative change in adult returners than the other alternatives, but there was very little difference among alternatives in fork length variation.

EFFECTS ANALYSIS

The SBM includes numerous modeling decisions derived from best available data, expert opinion, and modeling experience. The conclusions drawn from the model results depend on the details of model implementation and it is an important step in the model development process to explore the implications of changing model rules and input parameters on the model results. If changing a model rule produces little or no change in the results, then it suggests that model component is not particularly important and could be simplified or removed from the model. Conversely, if changing a model rule produces a large change in the results, then it suggests that the model component requires additional investigation and development. In this section, we report on the results of an Effects Analysis to explore how one modeling rule and one input parameter affect the results of the SBM.

Methods

As with the Alternatives Analysis, the Effects Analysis uses the relative change in the response variables, but only includes one alternative. Alt06 was chosen because it consistently showed the largest difference from existing conditions in the Alternatives Analysis. If the Effects Analysis shows a change in the results for Alt06, then we might expect a smaller magnitude change for the other alternatives.

We focused the Effects Analysis on components of the model with the highest uncertainty and largest potential impact on the Alternatives Analysis. In the next few sections, we will briefly describe the model rule used in the analysis of alternatives, which is described in detail in the Model Documentation above, and then we will describe in detail the other rules included in the Effects Analysis.

Rearing Rules

The default rearing rules are based on temperature, fish size, and run timing (see Floodplain Rearing/Rearing Rules). The temperature rule is simply a critical date (June 1st) when temperatures in the Yolo Bypass were likely to be too warm for floodplain rearing. The fish size rule is a threshold size (120 mm) above which model fish do not engage in rearing behavior. The run timing rule triggers fish to stop rearing and start migrating such that they will arrive at Chipps Island by the last date observed at Chipps Island for each run. The run timing rule applies the same date across all years and is not sensitive to changing hydrological conditions. Juvenile Chinook salmon are able to use changing hydrological conditions on the floodplain to determine when to stop rearing and begin moving downstream again (Moyle et al. 2007). In the Effects Analysis, we use changes in the total area inundated on the Yolo Bypass as the proxy measure for cues that fish might use to make rearing decision and contrast the inundation rule with the run timing rule.

The inundation rule requires two decisions: (1) how long of a time period over which to assess changes in inundation and (2) how big of a change in inundation is required to change rearing behavior. We provide a web tool for interested readers to explore the consequence of those decisions: https://fishsciences.shinyapps.io/yolo-bypass-suitable-habitat/. We used juvenile salmonid catch timing on the Yolo Bypass (Takata et al. 2017) to roughly guide our decisions about the change time period and threshold change. In the Effects Analysis, we consider two time periods 30 and 60 days, but only one threshold for each time period (±120 and ±60, respectively). The inundation change is calculated as the slope between inundation on the current day and inundation 30 (or 60) days ago. Only those two time points are used in the calculation of the slope. If the slope is above the upper threshold value, and suitable habitat is available, then a rearing-eligible cohort will start or continue rearing. If the slope is below the lower threshold value, then cohorts will stop rearing and continue migrating through the Canal Complex. If the slope is between the upper and lower threshold values, then fish do not change their current rearing status.

Rearing Survival

The default value of daily rearing survival is 0.99 based on an analysis (see https://fishsciences.shinyapps.io/yolo-bypass-rearing-survival/) of floodplain growth and ocean survival that suggested that 0.99 is an approximate minimum value of rearing survival to make rearing worthwhile (i.e., growth benefits outweigh survival costs of rearing) across the range of fish sizes in the model. In the Effects Analysis, we evaluated two additional levels of rearing survival: 0.97 and 0.95. The levels are chosen to illustrate conditions where rearing is not beneficial for small fish (0.97) and not beneficial for any fish (0.95) based on the supplementary analysis of rearing survival (see https://fishsciences.shinyapps.io/yolo-bypass-rearing-survival/).

Results

We report results of the Effects Analysis for the same five metrics (juvenile survival, fork length, fork length variation, entry timing variation, returning adults) described in the Alternatives Analysis. We also include travel time, not as a fish benefits metric, but as a metric that provides additional information for understanding the fish benefits metrics.

Juvenile Travel Time to Estuary Entry

Travel time is calculated as the mean travel time from Knights Landing to Chipps Island weighted by the abundance of fish in the cohort. For fish migrating through the Yolo Bypass route, travel time also includes time spent rearing. Travel times were longest at high rearing survival under the run timing rearing rule, particularly for fall- and spring-run fish (Figure 13). Fall- and spring-run fish enter the model at the smallest size and have the latest run timing dates, and, thus, have the longest potential rearing times under the run timing rule. If rearing survival is high, more of the fish that spent a long time rearing on the floodplain make it to Chipps Island, which increases the mean travel time. The inundation rearing rules produce shorter travel times under high rearing survival because small spring- and fall-run fish are prompted to resume migration sooner than under the run timing rule. Under the lowest rearing survival, travel times are slightly shorter for the run timing rule for fall- and spring-run fish because the long rearing fish in the run timing rule do not survive to Chipps Island. The travel time patterns for fall-, spring-, and winter-run fish generally do not hold for late-fall fish because many late-fall fish enter the model above the 120 mm threshold and, thus do not rear on the floodplain.

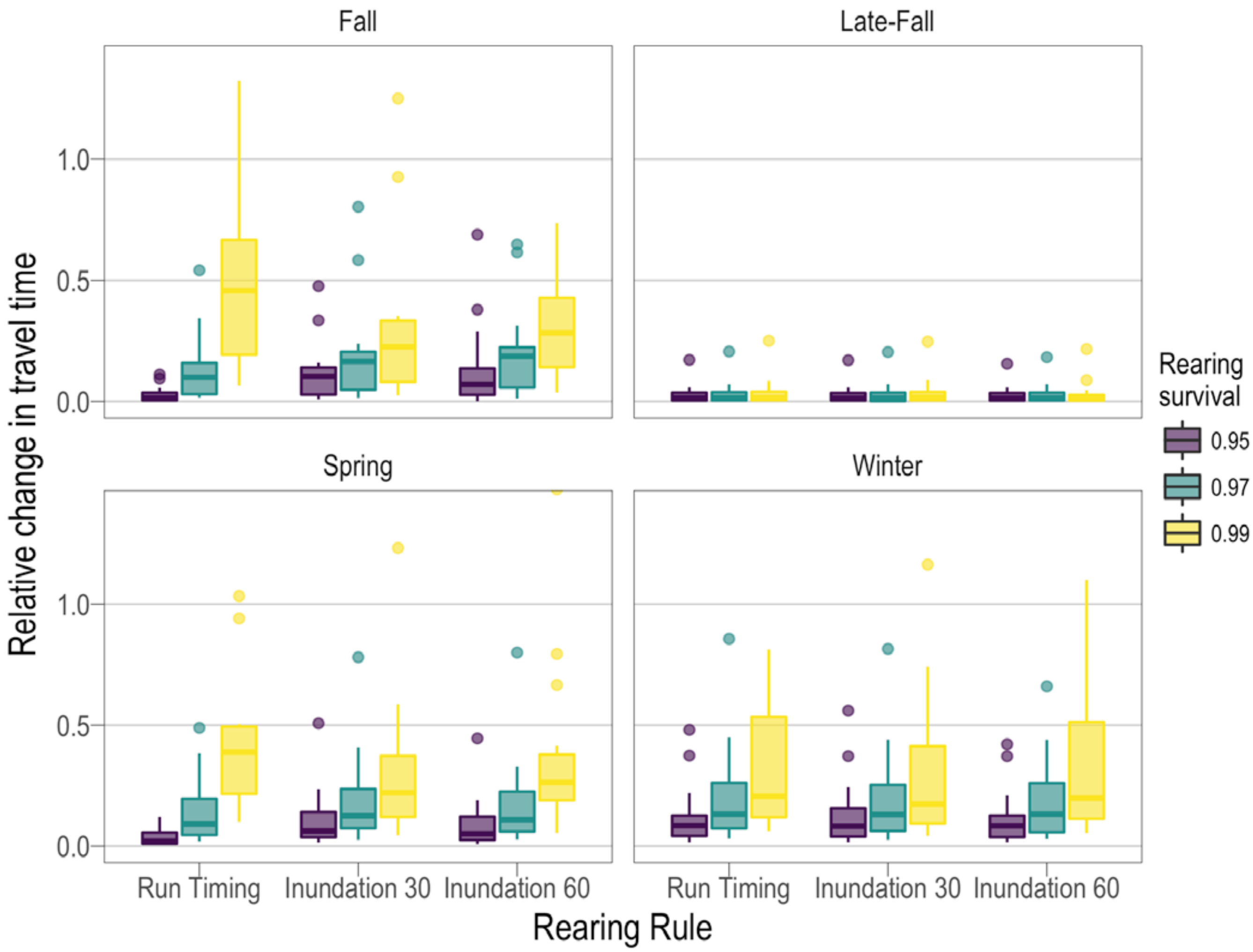

Figure 13. Relative change in mean travel time from Knights Landing to Chipps Island for 15 years under three rearing rule and three levels of rearing survival. The line near the center of the box is the median, the bottom and top of the box are the 25th and 75th percentiles, respectively, the whiskers show the min/max (unless there are outliers), and the points are outliers (+/- 1.5x interquartile from 75th and 25th percentile, respectively).

Juvenile Survival to Estuary Entry

Juvenile survival is calculated as the proportion of fish that survive from Knights Landing to Chipps Island. Because the Canal Complex route has lower migrating survival, and floodplain rearing incurs a survival cost, the increased entrainment of fish onto the Yolo Bypass via a notch in Fremont Weir reduces juvenile survival relative to existing conditions (Figure 14). Late-fall-run fish have the smallest relative change in juvenile survival because most late-fall-run fish enter the model above the size threshold (i.e., they do not rear and incur the cost of rearing).

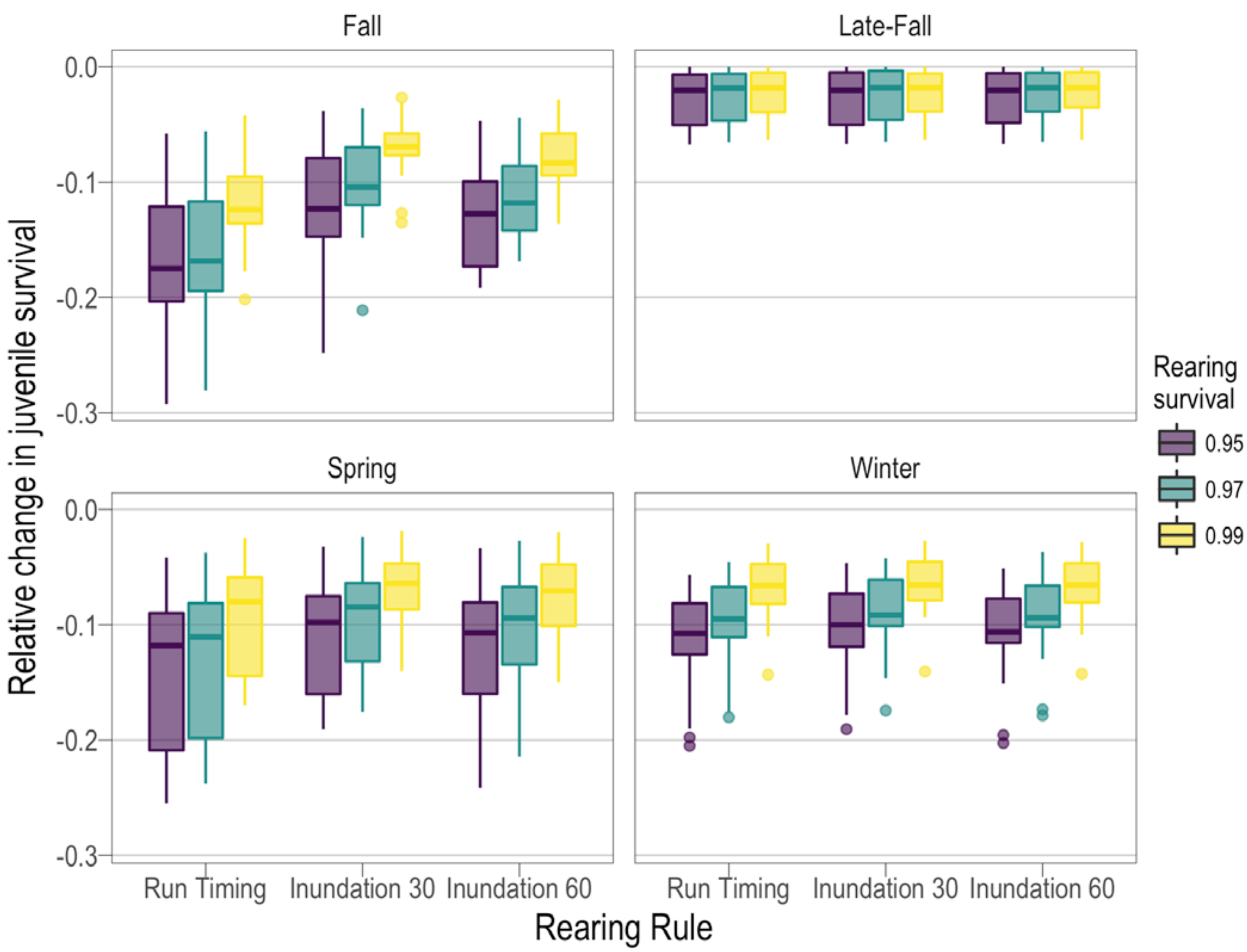

Figure 14. Relative change in juvenile survival from Knights Landing to Chipps Island for 15 years under three rearing rule and three levels of rearing survival. The line near the center of the box is the median, the bottom and top of the box are the 25th and 75th percentiles, respectively, the whiskers show the min/max (unless there are outliers), and the points are outliers (+/- 1.5x interquartile from 75th and 25th percentile, respectively).

Juvenile Fork Length at Estuary Entry

Fork length is calculated as the mean fork length of all cohorts that arrive at Chipps Island weighted by the abundance of fish in the cohort. The patterns in the effects analysis of fork length (Figure 15) resemble the patterns observed for travel time (Figure 13). The underlying mechanisms that create the patterns in travel time (see Juvenile Travel Time) are the same as for fork length.

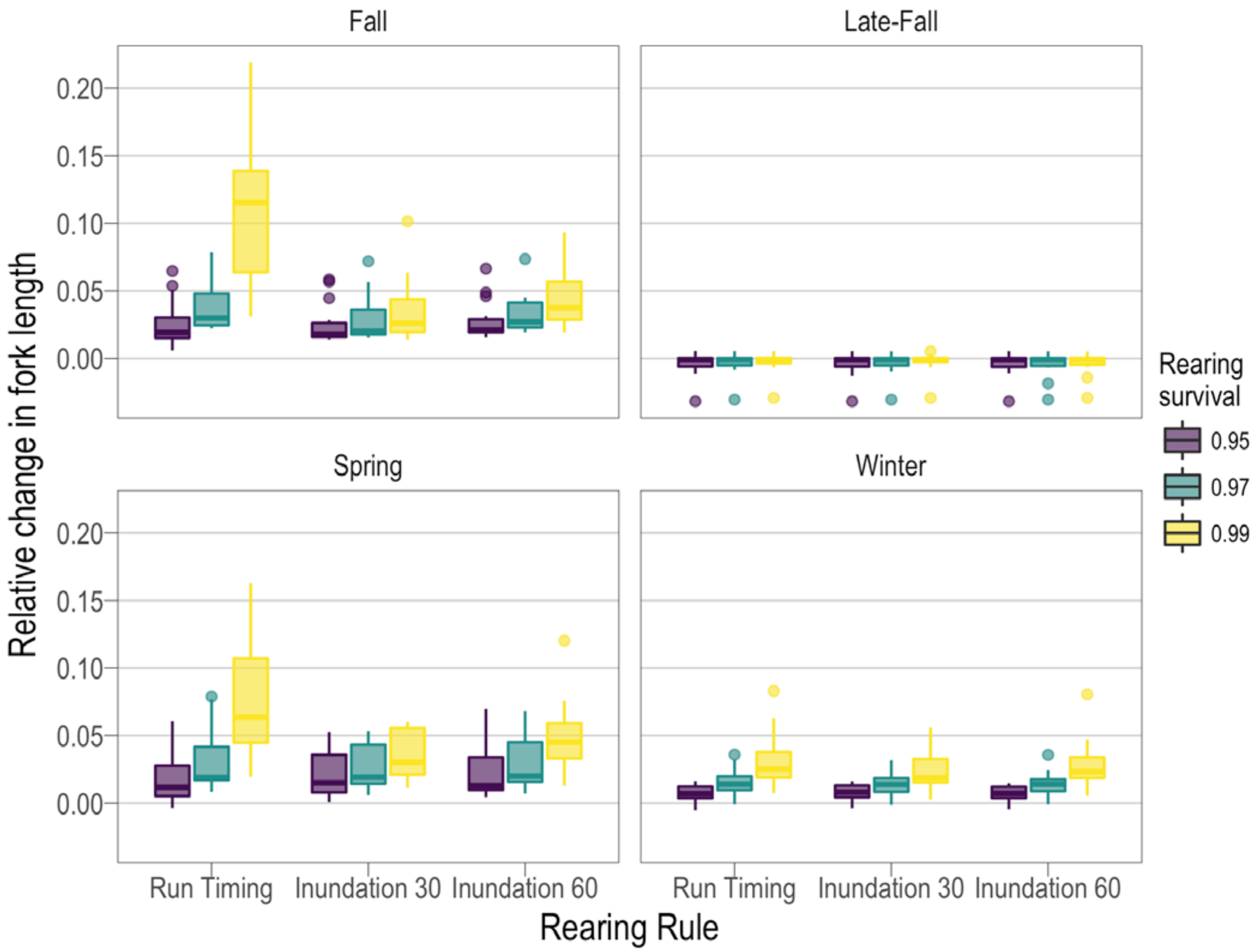

Figure 15. Relative change in mean fork length (mm) at Chipps Island for 15 years under three rearing rule and three levels of rearing survival. The line near the center of the box is the median, the bottom and top of the box are the 25th and 75th percentiles, respectively, the whiskers show the min/max (unless there are outliers), and the points are outliers (+/- 1.5x interquartile from 75th and 25th percentile, respectively).

Juvenile Fork Length Variation at Estuary Entry

Fork length variation is calculated as the coefficient of variation in fork length of all cohorts that arrive at Chipps Island weighted by the abundance of fish in the cohort. Across most effects, runs, and years, fork length variation is higher under the alternative than existing conditions (Figure 16). Late-fall-run fish show small relative change in fork length variation because most late-fall-run fish enter the model above the size threshold and do not rear on the floodplain. Relative change in fork length variation is one metric where you can see the difference between the effects of inundation window length; there is greater variation under the 60-day inundation window for fall- and spring-run. This is likely because fish rear longer under the 60-day rule and differential growth rates result in more variation at estuary entry.

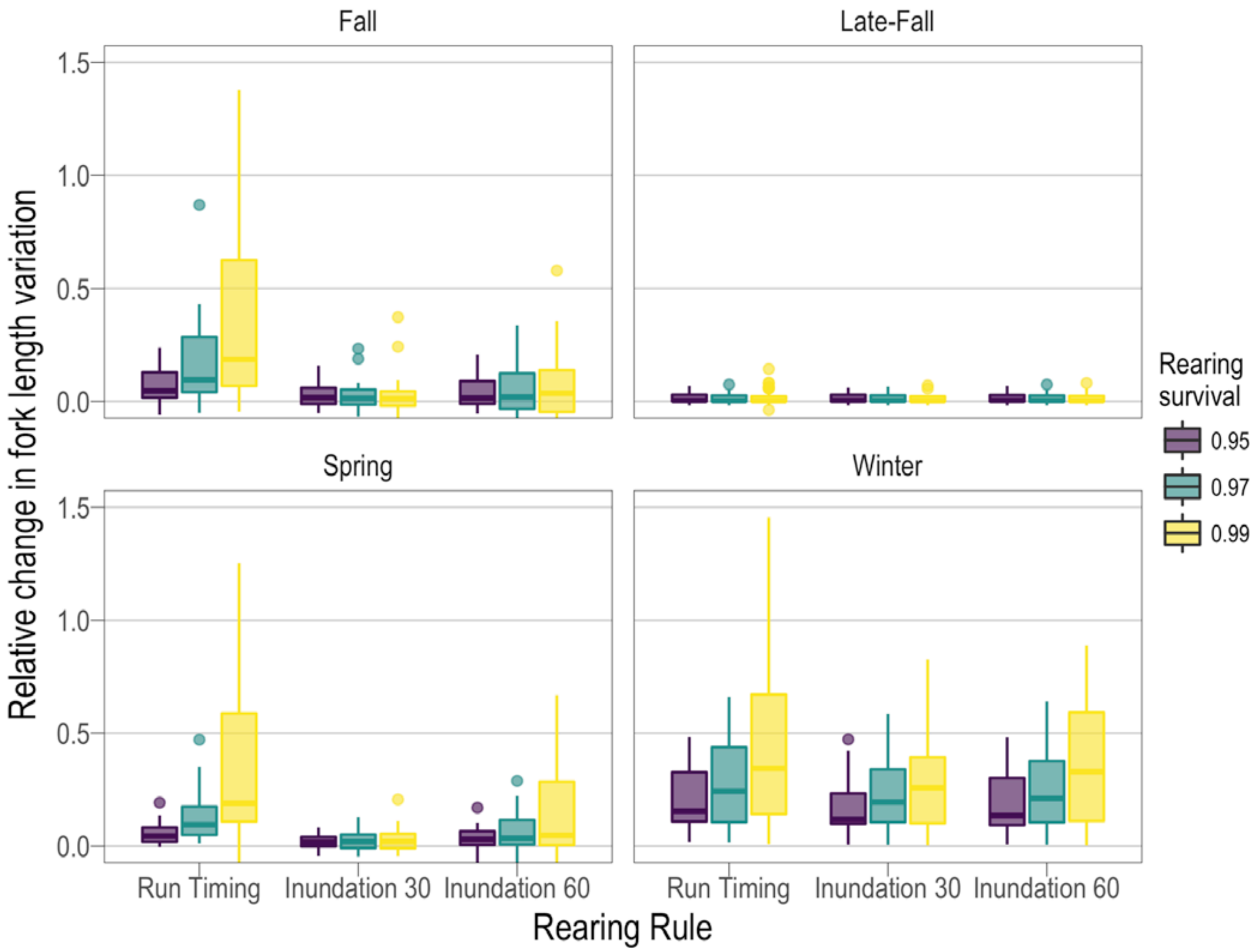

Figure 16. Relative change in coefficient of variation in fork length at Chipps Island for 15 years under three rearing rule and three levels of rearing survival. The line near the center of the box is the median, the bottom and top of the box are the 25th and 75th percentiles, respectively, the whiskers show the min/max (unless there are outliers), and the points are outliers (+/- 1.5x interquartile from 75th and 25th percentile, respectively). Note, the y-axis has been truncated to exclude some outliers. The non-truncated figure is available upon request.

Juvenile Timing Variation at Estuary Entry

Entry timing variation is calculated as the coefficient of variation in timing of all cohorts that arrive at Chipps Island weighted by the abundance of fish in the cohort. Timing is measured as day of water year when a cohort arrives at Chipps Island where October 1st is day one. For winter- and late-fall-run, there are only small effects of rearing rule and rearing survival on entry timing variation (Figure 17). For fall- and spring-run, under the run timing rearing rule, higher rearing survival yields more variation across years in entry timing variation.

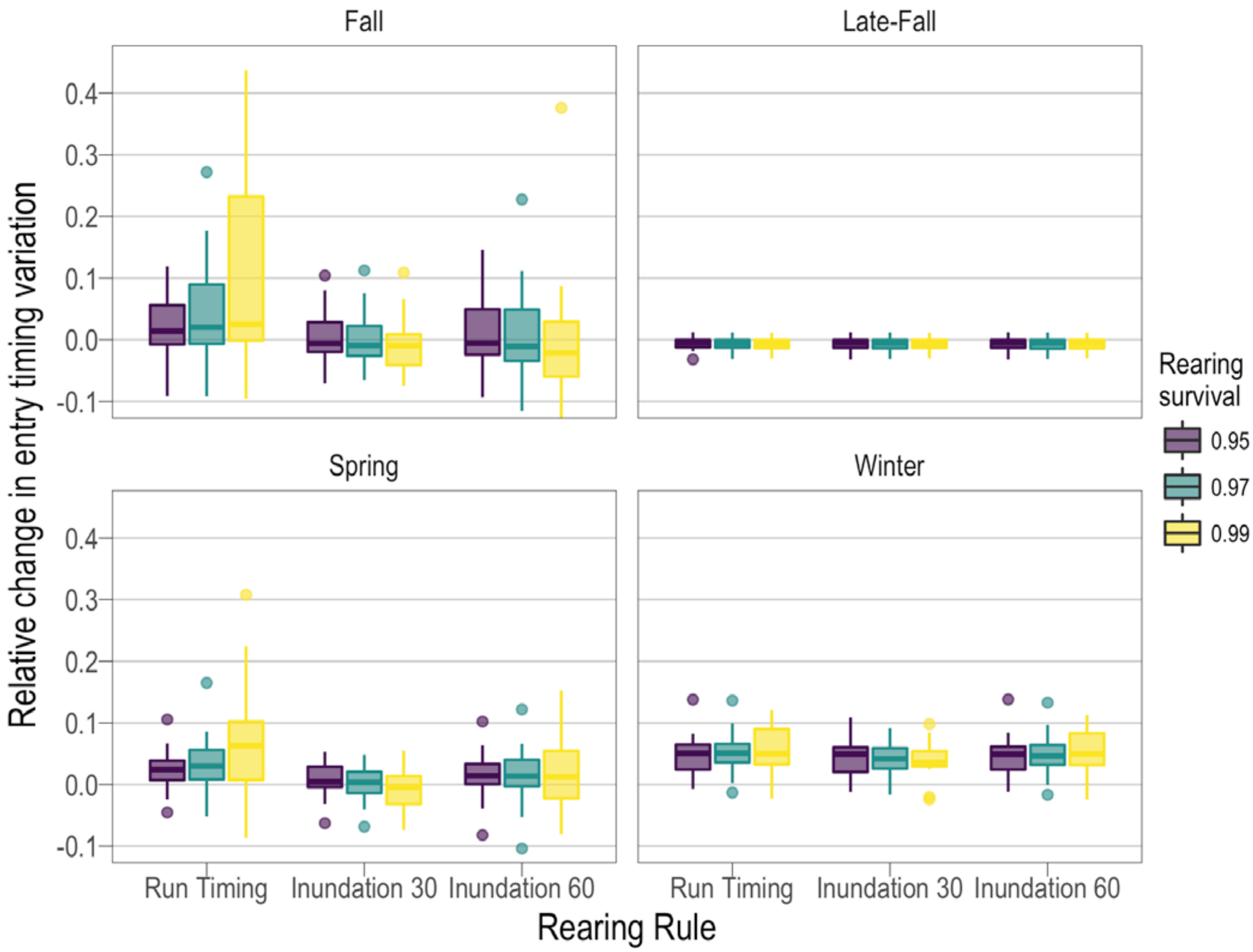

Figure 17. Relative change in coefficient of variation in estuary (Chipps Island) entry timing for 15 years under three rearing rule and three levels of rearing survival. The line near the center of the box is the median, the bottom and top of the box are the 25th and 75th percentiles, respectively, the whiskers show the min/max (unless there are outliers), and the points are outliers (+/- 1.5x interquartile from 75th and 25th percentile, respectively). Note, the y-axis has been truncated to exclude some outliers. The non-truncated figure is available upon request.

Returning Adults

The number of returning adults depends on both the number and size of fish that arrive at Chipps Island because the ocean survival relationship is a function of size. The returning adults metric shows the combined effect of the juvenile survival and fork length metrics. For all runs, except late-fall run, the potential benefits of increased floodplain access provided by the alternative only outweigh the costs of additional time spent rearing under the highest level of rearing survival but not in all years or under all rearing rules (Figure 18). The effect of rearing survival on relative returning adults is strongest for fall- and spring-run fish under the run timing rule. Across all effects and years, late-full-run benefits from the presence of a notch in Fremont Weir, mostly because they enter the model at a large size, which carries benefits throughout the model (e.g., migration survival, growth, and ocean survival). Winter-run fish exhibit the smallest effect of rearing rule, other than late-fall run, presumably because they enter the model at a relatively large size and move through the system at a time of relatively high inundation, i.e., they are most likely triggered to stop rearing by growing to the size threshold (120 mm) than by the run timing or inundation rearing rules.

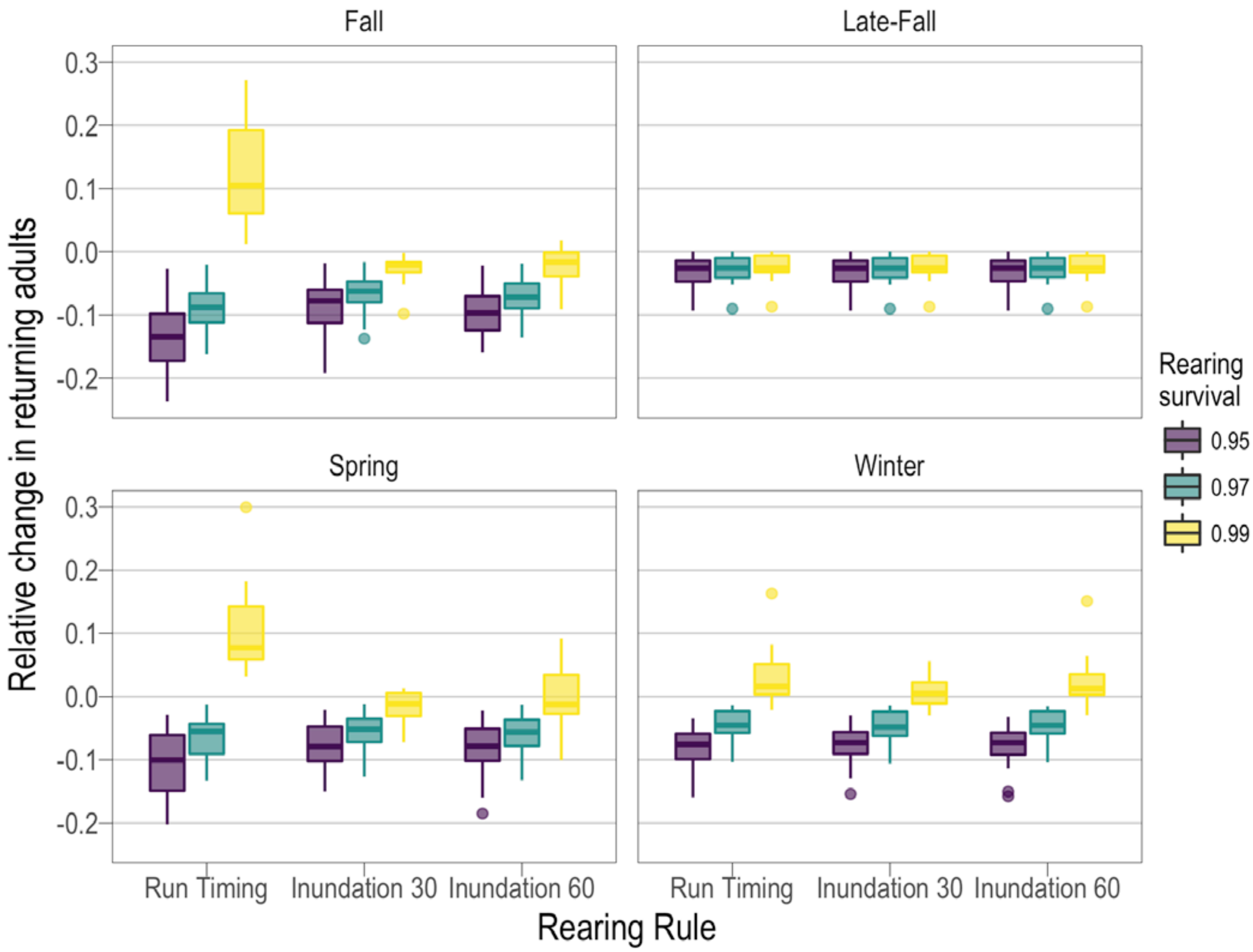

Figure 18. Relative change in number of returning adults for 15 years under three rearing rule and three levels of rearing survival. The line near the center of the box is the median, the bottom and top of the box are the 25th and 75th percentiles, respectively, the whiskers show the min/max (unless there are outliers), and the points are outliers (+/- 1.5x interquartile from 75th and 25th percentile, respectively).

Conclusions

We examined the effect of three rearing rules and three levels of rearing survival on the results produced by the SBM. We focus here on results of these model rules on fork length variation and returning adults. Fork length variation is highly correlated to entry timing variation and may reflect population resilience to changing ocean conditions from year to year. The number of returning adults measures the productivity of the population and incorporates the combined effects of juvenile growth and survival.

For all runs, except late-fall, rearing survival is the key factor in determining the benefit of Alt06; at a value of 0.95, rearing survival on the floodplain is too low to yield a benefit to implementing the Alt06 notch. Because Alt06 exhibited the biggest differences in the Alternatives Analysis, we might expect that the other notches (Alt01, Alt04, Alt04b, Alt05) would not yield a benefit at a rearing survival of 0.95 or 0.97.

There is an interactive effect of the rearing rule and rearing survival value. We suggest that both should be targets for additional study, but recognize the challenges in the design of such studies. For example, acoustic telemetry studies can estimate survival from release at the top of the Yolo Bypass to arrival at Chipps Island, but those studies are not able to partition survival into migrating and rearing components. Furthermore, acoustic telemetry cannot yet accommodate fish smaller than about 74mm FL, missing the ability to evaluate alternative effects on smaller juveniles. Using net pens to study fish on the floodplain can provide estimates of rearing survival, but those estimates are probably lower bounds on actual rearing survival because the pens constrain the juvenile salmons' ability to evade avian predators, find more suitable habitat, or migrate volitionally.

While studies that directly inform modeling rules and parameters are ideal, it is also useful to design studies that provide data to calibrate or validate the model. For example, median survival from Fremont Weir to Chipps Island through the Yolo Bypass was less than 2% for spring- and fall-run under the run timing rearing rule and rearing survival of 0.95. There are no studies of fall- and spring-run survival through the Yolo Bypass, but it seems improbable that overall survival is so low for those runs, which suggests that either 0.95 is too low of a value for rearing survival or the run timing rearing rule does not adequately capture rearing behavior (or both).

The rearing rules examined in this Effects Analysis represent different modeling approaches. The run timing rule limits rearing behavior by placing constraints on rearing that do not change from year to year. The inundation rule allows fish to respond to changing conditions. Because the SBM is not an optimality model, some combinations of the rearing rules and rearing survival potentially yield sub-optimal behavior (e.g., if goal is to optimize probability of returning as an adult).

An earlier version of the SBM identified entrainment as the key factor in maximizing fish benefits from a notch in the Fremont Weir. That version of the model was parameterized such that fish did not incur a survival cost for rearing. Thus, more time spent rearing yielded the benefit of increased growth without the cost of increased mortality. That earlier model also suggested that suitable habitat on the Yolo Bypass, based on depth and velocity, was not often limiting. The combination of high rearing survival and abundant suitable habitat meant that the limiting factor was entrainment onto the Yolo Bypass. If the current version of the model is underestimating rearing survival, or implementing sub-optimal rearing rules, then the importance of entrainment for fish benefits may be underestimated. As it is, addition of rearing mortality to fish entrained on the Yolo Bypass. It is also important to note that while the effects analysis shows a net decrease in juvenile survival across alternatives due to rearing mortality (Figure 14), the juvenile survival effects analysis does not incorporate the presumed survival benefits received for having grown while rearing. These benefits are presumably captured by the effects analysis of rearing rules on adult returns (Figure 18) and fork length variation (Figure 16), which do exhibit some large net positive changes for all runs under Alternative 6.

REFERENCES 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.

Bay Delta Conservation Plan (BDCP). 2013. Bay Delta Conservation Plan. Public draft, November 2013.

Bolnick, D.I., P. Amarasekare, M.S. Araujo, R. Burger, J.M. Levine, M. Novak, V.H.W. Rudolf, S.J. Screiber, M.C. Urban, and D.S. Vasseur. 2011. Why intraspecific trait variation matters in community ecology. Trends in Ecology and Evolution 26:183-192.

WBM, B., 2013. TUFLOW FV Science Manual. Brisbane, Queensland.

California Department of Water Resources (CDWR). 2012. Yolo Bypass salmonid habitat restoration and fish passage implementation plan. Long-term operation of the Central Valley Project and State Water Project Biological Opinion Reasonable and Prudent Alternative Actions 1.6.1 and 1.7.

Carlson, S.M., and W.H. Satterthwaite. 2011. Weakened portfolio effect in a collapsed salmon population complex. Canadian Journal of Fisheries and Aquatic Sciences 68:1579-1589.

DWR (California Department of Water Resources). 2017. Evaluating juvenile Chinook salmon entrainment potential for multiple modified Fremont Weir configurations: Application of *Estimating juvenile winter-run and spring-run Chinook salmon entrainment onto the Yolo Bypass over a notched Fremont Weir, Acierto et al. (2014).* Technical memorandum for the Yolo Bypass Salmonid Habitat Restoration and Fish Passage Project. Sacramento, California.

Fisher, F.W. 1992. Chinook salmon, Oncorhynchus tshawytscha, growth and occurrence in the Sacramento-San Joaquin River System. IFD Office Report. June 1992. California Department of Fish and Game. 45 p.

Foote, C.J., Clarke, W.C. and Blackburn, J., 1991. Inhibition of smolting in precocious male chinook salmon, Oncorhynchus tshawytscha. Canadian Journal of Zoology, 69:1848-1852.

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

Goertler, P.A., Scheuerell, M.D., Simenstad, C.A. and Bottom, D.L., 2016. Estimating Common Growth Patterns in Juvenile Chinook Salmon (Oncorhynchus tshawytscha) from Diverse Genetic Stocks and a Large Spatial Extent. PLOS ONE, 11(10), p.e 0162121.

Grant, J.W.A., and D.L. Kramer. 1990. Territory size as a predictor of the upper limit to population density of juvenile salmonids in streams. Canadian Journal of Fisheries and Aquatic Sciences 47:1724-1737.

Hilborn, R., T.P. Quinn, D.E. Schindler, and D.E. Rogers. 2003. Biocomplexity and fisheries sustainability. Proceedings of the National Academy of Sciences 100:6564-6568.

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

Israel, J.A., K.M. Fisch, T.F. Turner, and R.S. Waples. 2011. Conservation of Native Fishes of the San Francisco Estuary: Considerations for Artificial Propagation of Chinook Salmon, Delta Smelt, and Green Sturgeon. San Francisco Estuary and Watershed Science, 9(1). jmie_sfews_11026. Retrieved from: http://escholarship.org/uc/item/9r80d47p

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

Jeffres, C.A. 2016. From subduction to salmon: understanding physical process and ecosystem function in aquatic ecosystems. Doctoral dissertation. University of California, Davis.

Jeffres, C.A., J.J. Opperman, and P.B. Moyle. 2008. Ephemeral floodplain habitats provide best growth conditions for juvenile Chinook salmon in a California river. Environmental Biology of Fishes 83:449-458.

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

Katz, J. 2012. The Knaggs Ranch experimental agricultural floodplain pilot study 2011-2012: Year One Overview. A cooperative project of the Center for Watershed Sciences at the University of California, Davis and the California Department of Water Resouces. Technical report of year one results.

Katz, J., C. Jeffres, L. Conrad, T. Sommer, N. Corline, J. Martinez, S. Brumbaugh, L. Takata, N. Ikemiyagi, J. Kiernan, and P. Moyle. 2013. The experimental agricultural floodplain habitat investigation at Knaggs Ranch on Yolo Bypass 2012-2013. Preliminary report to the US Bureau of Reclamation, October 1, 2013.

Katz, J., C. Jeffres, L. Conrad, T. Sommer, L. Takata, N. Ikemiyagi, E. Holmes, M.B. Tilcock. 2014. The experimental agricultural floodplain habitat investigation at Knaggs Ranch on Yolo Bypass 2013-2014. Report to the US Bureau of Reclamation.

Keeley, E. R. and P. A. Slaney. 1996. Quantitative measures of rearing and spawning habitat characteristics for stream-dwelling salmonids: implications for habitat restoration. Province of B.C. Ministry of Environment, Lands and Parks; Watershed Restoration Project Report 231 p.

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

Kiernan, J.D., P.B. Moyle, and P.K. Crain. 2012. Restoring native fish assemblages to a regulated California stream using the natural flow regime concept. Ecological Applications 22:1472-1482.

Kimmerer, W.J. and Nobriga, M.L., 2008. Investigating Particle Transport and Fate in the Sacramento–San Joaquin Delta Using a Particle-Tracking Model. San Francisco Estuary and Watershed Science, 6(1). jmie_sfews_10997. Retrieved from: https://escholarship.org/uc/item/547917gn

King, A.J., P. Humphries, and P.S. Lake. 2003. Fish recruitment on floodplains: the roles of patterns of flooding and life history characteristics. Canadian Journal of Fisheries and Aquatic Sciences 60:773-786.

Kjelson, M. A., P. F. Raquel, and F. W. Fisher. 1982. Life history of fall-run juvenile Chinook salmon, Oncorhynchus tshawytscha, in the Sacramento-San Joaquin estuary, California. In V.S. Kennedy (editor), Estuarine comparisons: 393-411. Academic Press, New York, New York.

Lindley, S.T., Schick, R.S., Mora, E., Adams, P.B., Anderson, J.J., Greene, S., Hanson, C., May, B.P., McEwan, D.R., MacFarlane, R.B., Swanson, C., and Williams, J.G. 2007. Framework for assessing viability of threatened and endangered Chinook Salmon and Steelhead in the Sacramento–San Joaquin Basin. San Francisco Estuary and Watershed Science, 5(1). jmie_sfews_10986. Retrieved from: https://escholarship.org/uc/item/3653x9xc

Lindley, S.T., C.B. Grimes, M.S. Mohr, W. Peterson, and J. Stein. 2009. What caused the Sacramento River fall Chinook stock collapse? NOAA Technical Memorandum NOAA-TM-NMFS-SWFSC-447.

Lytinen, S. L., & Railsback, S. F. 2012. The evolution of agent-based simulation platforms: A review of NetLogo 5.0 and ReLogo. Proceedings of the fourth international symposium on agent-based modeling and simulation (21st European Meeting on Cybernetics and Systems Research [EMCSR 2012]). Vienna, Austria, April 2012.

Marine, K. R. 1997. Effects of elevated water temperature on some aspects of the physiological and ecological performance of juvenile Chinook salmon (*Oncorhynchus tshawytscha*): implications for management of California's Central Valley salmon stocks. Series: Master of Science in Ecology Thesis, UC Davis.

Marine, K.R., and J.J. Cech. 2004. Effects of High Water Temperature on Growth, Smoltification, and Predator Avoidance in Juvenile Sacramento River Chinook Salmon. North American Journal of Fisheries Management 24:198–210.

Martin, C.D., P. D. Gaines and R.R. Johnson. 2001. Estimating the abundance of Sacramento River juvenile winter Chinook salmon with comparisons to adult escapement. Red Bluff Research Pumping Plant Report Series, Volume 5. U. S. Fish and Wildlife Service, Red Bluff, CA.

McClure, M.M., Carlson, S.M., Beechie, T.J., Pess, G.R., Jorgensen, J.C., Sogard, S.M., Sultan, S.E., Holzer, D.M., Travis, J., Sanderson, B.L., Power, M.E., and Carmichael, R.W. 2008. Evolutionary consequences of habitat loss for Pacific anadromous salmonids. Evol. Appl. 1(2): 300–318. doi:10.1111/j.1752-4571. 2008.00030.x.

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

McMahon, T. E., and G. F. Hartman. 1989. Influence of cover complexity and current velocity on winter habitat use by juvenile coho salmon (*Oncorhynchus kisutch*). Canadian Journal of Fisheries and Aquatic Science 46: 1551–1557.

Michel, C.J., A.J. Ammann, S.T. Lindley, P.T. Sandstrom, E.D. Chapman, M.J. Thomas, G.P. Singer, A.P. Klimley, and R.B MacFarlane. 2015. Chinook salmon outmigration survival in wet and dry years in California's Sacramento River. Canadian Journal of Fisheries and Aquatic Science 72: 1749-1759.

Moyle, P. B., 2002. Inland fishes of California, Revised edition, University of California Press, Berkeley.

Moyle, P.B., Crain, P.K. and Whitener, K., 2007. Patterns in the use of a restored California floodplain by native and alien fishes. San Francisco Estuary and Watershed Science, 5(3).

Opperman, J.J., G.E. Galloway, J. Fargione, J.F. Mount, B.D. Richter, and S. Secchi. 2009. Sustainable floodplains through large-scale reconnection to rivers. Science 326:1487-1488.

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

Perry, R.W. 2010. Survival and Migration Dynamics of Juvenile Chinook Salmon in the Sacramento–San Joaquin River Delta. Doctoral dissertation. University of Washington.

Perry, R.W. USGS Yolo Bypass Study (2016). Unpublished data.

Raleigh, R. F., W. F. Miller, and P. C. Nelson. 1986. Habitat suitability index models and instream flow suitability curves: Chinook salmon. U.S. Fish Wildlife Service Biological Report 82(10.122). 64 p.

Roberts, J., and J. Israel. 2012. An empirical approach to estimate juvenile salmon entrainment over Fremont Weir. August 2012.

San Joaquin River Restoration Program (SJRRP). 2012. Minimum floodplain habitat area for spring and fall-run Chinook salmon in the SJRRP.

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.

Scheuerell, M.D., R.W. Zabel, and B.P. Sandford. 2009. Relating juvenile migration timing and survival to adulthood in two species of threatened Pacific salmon (*Oncorhynchus* spp.). Journal of Applied Ecology 46:983-990.

Sommer, T.R., M.L. Nobriga, W.C. Harrell, W. Batham, and W.J. Kimmerer. 2001. Floodplain rearing of juvenile chinook salmon: evidence of enhanced growth and survival. Canadian Journal of Fisheries and Aquatic Science 58:325-333.

Speegle, J., J. Kirsch, and J. Ingram. 2013. Annual report: juvenile fish monitoring during the 2010 and 2011 field seasons within the San Francisco Estuary, California. U. S. Fish and Wildlife Service Report.

Sykes, G.E., and J.M. Shrimpton. 2010. Effect of temperature and current manipulation on smolting in Chinook salmon (*Oncorhynchus tshawytscha*): the relationship between migratory behavior and physiological development. Canadian Journal of Fisheries and Aquatic Science 67:191-201.

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

Thorpe, J. E. 1988. Salmon migration. Science Progress 72:345-370.

U. S. Fish and Wildlife Service (USFWS). 2005. Flow-habitat relationships for Chinook salmon rearing in the Sacramento River between Keswick Dam and Battle Creek. Energy Planning and Instream Flow Branch Sacramento River (Keswick Dam to Battle Creek) Rearing Final Report, Sacramento, CA.

U. S. Fish and Wildlife Service (USFWS). 2010. Juvenile fish monitoring and abundance and distribution of Chinook salmon in the Sacramento-San Joaquin Estuary. 2007-2008 Annual Report. Stockton, CA.

U. S. Fish and Wildlife Service (USFWS). 2012. Abundance and distribution of Chinook salmon and other catch in the Sacramento-San Joaquin Estuary. 2009 Annual Report. Stockton, CA.

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

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

Yoshiyama, R.M., F.W. Fisher, and P.B. Moyle. 1998. Historical abundance and decline of Chinook salmon in the Central Valley region of California. North American Journal of Fisheries Management. 18:487–521.

Yoshiyama, R.M., E.R. Gerstung, F.W. Fisher, and P.B. Moyle. 2000. Chinook salmon in the California Central Valley: an assessment. Fisheries. 25:6-20.

Zeug, S. C., P. S. Bergman, B. J. Cavallo, and K. S. Jones. 2012. Application of a life cycle simulation model to evaluate impacts of water management and conservation actions on an endanged population of Chinook salmon. Environmental Modeling and Assessment 17:455-467.

APPENDIX A: ALTERNATIVES ANALYSIS TABLES

Tables of Salmon Benefits Metrics

Table A-1. Juvenile survival from Knights Landing to Chipps Island under existing conditions (Exg) and five alternatives for notches in Fremont Weir.

Run	Water Year	Exg	Alt01	Alt04	Alt04b	Alt05	Alt06
Fall	1997	0.177	0.172	0.174	0.174	0.174	0.169
Fall	1998	0.562	0.535	0.547	0.550	0.544	0.520
Fall	1999	0.596	0.517	0.552	0.552	0.545	0.476
Fall	2000	0.620	0.566	0.578	0.578	0.575	0.534
Fall	2001	0.415	0.407	0.406	0.407	0.405	0.398
Fall	2002	0.225	0.216	0.218	0.218	0.216	0.206
Fall	2003	0.219	0.196	0.204	0.204	0.202	0.180
Fall	2004	0.213	0.199	0.202	0.202	0.201	0.190
Fall	2005	0.226	0.214	0.214	0.214	0.213	0.202
Fall	2006	0.505	0.471	0.484	0.484	0.480	0.438
Fall	2007	0.415	0.385	0.391	0.391	0.387	0.368
Fall	2008	0.415	0.383	0.387	0.387	0.385	0.364
Fall	2009	0.415	0.376	0.386	0.386	0.384	0.356
Fall	2010	0.414	0.384	0.399	0.399	0.397	0.360
Fall	2011	0.360	0.338	0.349	0.349	0.345	0.312
Late-Fall	1997	0.184	0.176	0.179	0.179	0.178	0.172
Late-Fall	1998	0.659	0.656	0.656	0.656	0.655	0.651
Late-Fall	1999	0.686	0.669	0.675	0.675	0.673	0.660
Late-Fall	2000	0.686	0.678	0.680	0.680	0.679	0.673
Late-Fall	2001	0.415	0.414	0.414	0.414	0.414	0.414
Late-Fall	2002	0.226	0.224	0.223	0.223	0.222	0.220
Late-Fall	2003	0.226	0.219	0.221	0.221	0.221	0.215
Late-Fall	2004	0.226	0.221	0.221	0.221	0.221	0.213
Late-Fall	2005	0.220	0.220	0.220	0.220	0.220	0.220
Late-Fall	2006	0.486	0.485	0.485	0.485	0.485	0.483
Late-Fall	2007	0.415	0.413	0.413	0.413	0.413	0.410
Late-Fall	2008	0.415	0.408	0.409	0.409	0.407	0.403
Late-Fall	2009	0.415	0.415	0.415	0.415	0.415	0.415
Late-Fall	2010	0.415	0.415	0.415	0.415	0.415	0.415
Late-Fall	2011	0.400	0.389	0.393	0.393	0.392	0.384
Spring	1997	0.187	0.167	0.175	0.175	0.173	0.157

Spring	1998	0.653	0.640	0.642	0.642	0.637	0.621
Spring	1999	0.678	0.611	0.639	0.639	0.634	0.570
Spring	2000	0.642	0.618	0.623	0.623	0.621	0.605
Spring	2001	0.415	0.410	0.410	0.411	0.409	0.405
Spring	2002	0.226	0.220	0.220	0.220	0.219	0.213
Spring	2003	0.224	0.202	0.207	0.207	0.206	0.186
Spring	2004	0.225	0.214	0.216	0.216	0.215	0.203
Spring	2005	0.226	0.216	0.218	0.218	0.217	0.208
Spring	2006	0.649	0.613	0.621	0.621	0.616	0.580
Spring	2007	0.415	0.398	0.401	0.401	0.398	0.385
Spring	2008	0.415	0.397	0.399	0.399	0.397	0.383
Spring	2009	0.415	0.402	0.405	0.405	0.404	0.395
Spring	2010	0.413	0.379	0.394	0.394	0.392	0.346
Spring	2011	0.367	0.342	0.352	0.353	0.349	0.319
Winter	1997	0.192	0.182	0.185	0.185	0.184	0.175
Winter	1998	0.671	0.660	0.659	0.659	0.658	0.644
Winter	1999	0.678	0.632	0.648	0.648	0.645	0.604
Winter	2000	0.642	0.617	0.623	0.623	0.622	0.600
Winter	2001	0.415	0.410	0.409	0.409	0.408	0.403
Winter	2002	0.226	0.220	0.221	0.221	0.220	0.215
Winter	2003	0.223	0.204	0.209	0.209	0.208	0.191
Winter	2004	0.225	0.217	0.218	0.218	0.217	0.207
Winter	2005	0.226	0.216	0.218	0.218	0.217	0.208
Winter	2006	0.657	0.633	0.636	0.636	0.634	0.608
Winter	2007	0.415	0.408	0.408	0.408	0.407	0.398
Winter	2008	0.415	0.404	0.405	0.405	0.403	0.395
Winter	2009	0.415	0.402	0.405	0.406	0.405	0.396
Winter	2010	0.415	0.402	0.409	0.409	0.407	0.389
Winter	2011	0.407	0.380	0.389	0.389	0.387	0.362

Table A-2. Mean fork length (mm) at Chipps Island under existing conditions (Exg) and five alternatives for notches in Fremont Weir.

Run	Water Year	Exg	Alt01	Alt04	Alt04b	Alt05	Alt06
Fall	1997	72.8	74.1	73.6	73.6	73.6	75.1
Fall	1998	52.4	54.6	53.6	53.4	53.9	56.0
Fall	1999	47.1	53.4	50.4	50.4	50.9	57.5
Fall	2000	43.1	46.6	45.7	45.7	45.9	48.9
Fall	2001	57.7	58.8	58.9	58.8	59.0	60.0
Fall	2002	52.6	53.9	53.5	53.5	53.8	55.5
Fall	2003	41.9	44.4	43.5	43.5	43.6	46.4
Fall	2004	47.7	49.4	49.0	49.0	49.2	50.8
Fall	2005	45.8	47.3	47.3	47.3	47.3	48.7
Fall	2006	53.6	57.0	55.7	55.7	56.1	60.9
Fall	2007	43.6	46.7	46.1	46.1	46.4	48.6
Fall	2008	41.2	44.3	43.9	43.9	44.2	46.5
Fall	2009	44.2	48.3	47.2	47.1	47.3	50.7
Fall	2010	55.3	59.3	57.3	57.3	57.6	63.1
Fall	2011	53.5	56.7	55.1	55.0	55.6	61.0
Late-Fall	1997	135.3	135.8	135.6	135.6	135.7	136.0
Late-Fall	1998	89.6	89.6	89.7	89.7	89.6	89.6
Late-Fall	1999	97.2	97.1	97.2	97.2	97.1	97.0
Late-Fall	2000	128.8	128.7	128.8	128.8	128.8	128.7
Late-Fall	2001	126.3	126.3	126.3	126.3	126.3	126.2
Late-Fall	2002	121.8	121.8	121.9	121.9	121.8	121.7
Late-Fall	2003	77.1	75.8	76.1	76.1	76.1	74.9
Late-Fall	2004	119.5	119.6	119.7	119.7	119.7	119.9
Late-Fall	2005	46.4	46.2	46.2	46.2	46.2	46.1
Late-Fall	2006	60.9	60.7	60.7	60.7	60.6	60.5
Late-Fall	2007	113.3	113.4	113.4	113.4	113.4	113.6
Late-Fall	2008	138.8	138.9	138.9	138.9	138.9	138.9
Late-Fall	2009	149.0	149.0	149.0	149.0	149.0	149.0
Late-Fall	2010	56.9	56.9	56.9	56.9	56.9	56.8
Late-Fall	2011	90.5	90.2	90.3	90.3	90.3	90.0
Spring	1997	52.1	55.6	54.2	54.2	54.6	57.8
Spring	1998	41.5	42.2	42.1	42.1	42.4	43.3
Spring	1999	52.5	57.4	55.3	55.3	55.6	61.0
Spring	2000	70.7	72.9	72.5	72.5	72.6	74.2

Spring	2001	70.1	70.8	70.8	70.7	70.9	71.5
Spring	2002	52.6	53.4	53.4	53.4	53.5	54.2
Spring	2003	46.8	49.6	48.9	48.9	48.9	51.7
Spring	2004	48.2	49.4	49.3	49.3	49.4	50.8
Spring	2005	58.8	60.4	60.1	60.1	60.2	61.6
Spring	2006	49.6	51.7	51.3	51.3	51.6	54.0
Spring	2007	55.6	57.5	57.2	57.2	57.5	59.1
Spring	2008	52.1	54.0	53.9	53.9	54.1	55.7
Spring	2009	72.9	74.8	74.4	74.3	74.5	75.8
Spring	2010	56.8	61.1	59.0	59.0	59.4	66.0
Spring	2011	65.4	69.6	67.8	67.7	68.4	74.1
Winter	1997	104.0	105.6	105.0	105.0	105.3	106.6
Winter	1998	76.4	77.1	77.3	77.3	77.4	78.3
Winter	1999	80.1	82.9	81.9	81.9	82.2	85.1
Winter	2000	103.4	104.8	104.5	104.5	104.5	105.8
Winter	2001	101.4	102.0	102.1	102.0	102.2	102.8
Winter	2002	76.4	76.7	76.8	76.8	76.8	77.0
Winter	2003	83.0	85.2	84.6	84.6	84.7	87.0
Winter	2004	76.2	76.9	76.9	76.9	77.0	78.1
Winter	2005	85.5	86.5	86.3	86.3	86.3	87.2
Winter	2006	71.7	73.4	73.2	73.2	73.4	75.3
Winter	2007	76.8	77.6	77.7	77.7	77.8	78.9
Winter	2008	93.2	94.5	94.5	94.5	94.6	95.7
Winter	2009	104.9	106.2	105.9	105.8	106.0	106.9
Winter	2010	98.4	99.1	98.8	98.8	98.9	99.8
Winter	2011	75.6	79.1	77.9	77.9	78.2	81.9

Table A-3. Coefficient of variation in fork length at Chipps Island under existing conditions (Exg) and five alternatives for notches in Fremont Weir.

Run	Water Year	Exg	Alt01	Alt04	Alt04b	Alt05	Alt06
Fall	1997	0.308	0.302	0.305	0.305	0.305	0.299
Fall	1998	0.472	0.493	0.484	0.479	0.486	0.503
Fall	1999	0.464	0.537	0.514	0.514	0.519	0.549
Fall	2000	0.415	0.512	0.497	0.496	0.501	0.545
Fall	2001	0.366	0.374	0.374	0.374	0.375	0.381
Fall	2002	0.386	0.408	0.403	0.403	0.407	0.426
Fall	2003	0.260	0.403	0.364	0.363	0.371	0.466
Fall	2004	0.348	0.397	0.387	0.387	0.392	0.424
Fall	2005	0.293	0.354	0.353	0.353	0.356	0.397
Fall	2006	0.547	0.556	0.554	0.554	0.555	0.556
Fall	2007	0.269	0.421	0.400	0.400	0.414	0.472
Fall	2008	0.129	0.384	0.367	0.367	0.378	0.461
Fall	2009	0.213	0.427	0.392	0.390	0.397	0.481
Fall	2010	0.357	0.399	0.383	0.382	0.385	0.416
Fall	2011	0.411	0.442	0.429	0.428	0.435	0.459
Late-Fall	1997	0.143	0.143	0.143	0.143	0.143	0.143
Late-Fall	1998	0.511	0.512	0.512	0.512	0.513	0.514
Late-Fall	1999	0.445	0.451	0.449	0.449	0.450	0.454
Late-Fall	2000	0.223	0.224	0.224	0.224	0.224	0.224
Late-Fall	2001	0.131	0.131	0.131	0.131	0.131	0.131
Late-Fall	2002	0.109	0.108	0.108	0.108	0.108	0.108
Late-Fall	2003	0.623	0.633	0.630	0.630	0.630	0.640
Late-Fall	2004	0.045	0.046	0.046	0.046	0.047	0.049
Late-Fall	2005	0.583	0.576	0.578	0.578	0.578	0.572
Late-Fall	2006	0.508	0.508	0.508	0.508	0.508	0.507
Late-Fall	2007	0.067	0.069	0.069	0.069	0.069	0.071
Late-Fall	2008	0.073	0.073	0.073	0.073	0.073	0.073
Late-Fall	2009	0.133	0.133	0.133	0.133	0.133	0.133
Late-Fall	2010	0.962	0.962	0.962	0.962	0.962	0.962
Late-Fall	2011	0.444	0.450	0.448	0.448	0.448	0.454
Spring	1997	0.458	0.495	0.482	0.482	0.486	0.506
Spring	1998	0.395	0.428	0.422	0.422	0.435	0.469
Spring	1999	0.381	0.438	0.420	0.420	0.424	0.452

Spring	2000	0.257	0.271	0.269	0.269	0.269	0.277
Spring	2001	0.193	0.208	0.208	0.207	0.211	0.221
Spring	2002	0.350	0.371	0.369	0.369	0.373	0.392
Spring	2003	0.303	0.403	0.381	0.381	0.385	0.450
Spring	2004	0.317	0.370	0.361	0.360	0.365	0.410
Spring	2005	0.327	0.348	0.345	0.345	0.346	0.362
Spring	2006	0.411	0.471	0.457	0.457	0.464	0.511
Spring	2007	0.250	0.324	0.312	0.312	0.322	0.360
Spring	2008	0.175	0.282	0.276	0.276	0.285	0.336
Spring	2009	0.102	0.161	0.150	0.147	0.152	0.181
Spring	2010	0.200	0.328	0.284	0.284	0.293	0.388
Spring	2011	0.432	0.437	0.438	0.437	0.439	0.430
Winter	1997	0.184	0.185	0.185	0.185	0.185	0.186
Winter	1998	0.220	0.231	0.232	0.231	0.233	0.244
Winter	1999	0.197	0.235	0.222	0.222	0.225	0.250
Winter	2000	0.124	0.133	0.131	0.131	0.131	0.138
Winter	2001	0.048	0.063	0.064	0.063	0.065	0.076
Winter	2002	0.192	0.207	0.204	0.204	0.206	0.220
Winter	2003	0.102	0.156	0.142	0.142	0.145	0.182
Winter	2004	0.119	0.151	0.147	0.147	0.150	0.183
Winter	2005	0.123	0.151	0.146	0.146	0.146	0.166
Winter	2006	0.210	0.244	0.239	0.239	0.242	0.272
Winter	2007	0.102	0.135	0.136	0.136	0.141	0.170
Winter	2008	0.058	0.092	0.090	0.090	0.093	0.110
Winter	2009	0.048	0.072	0.068	0.066	0.069	0.081
Winter	2010	0.225	0.234	0.230	0.230	0.231	0.245
Winter	2011	0.187	0.252	0.232	0.232	0.238	0.282

Table A-4. Coefficient of variation in estuary (Chipps Island) entry timing under existing conditions (Exg) and five alternatives for notches in Fremont Weir.

Run	Water Year	Exg	Alt01	Alt04	Alt04b	Alt05	Alt06
Fall	1997	0.205	0.194	0.199	0.199	0.198	0.185
Fall	1998	0.305	0.307	0.306	0.303	0.305	0.308
Fall	1999	0.278	0.288	0.285	0.285	0.286	0.285
Fall	2000	0.207	0.241	0.234	0.234	0.236	0.257
Fall	2001	0.250	0.251	0.251	0.251	0.251	0.250
Fall	2002	0.250	0.250	0.251	0.251	0.252	0.249
Fall	2003	0.219	0.249	0.239	0.239	0.241	0.267
Fall	2004	0.233	0.240	0.239	0.239	0.240	0.244
Fall	2005	0.235	0.239	0.241	0.241	0.241	0.245
Fall	2006	0.327	0.330	0.328	0.328	0.329	0.329
Fall	2007	0.183	0.215	0.209	0.209	0.213	0.228
Fall	2008	0.158	0.205	0.200	0.200	0.203	0.228
Fall	2009	0.094	0.153	0.141	0.140	0.143	0.173
Fall	2010	0.263	0.263	0.264	0.264	0.264	0.259
Fall	2011	0.351	0.341	0.349	0.348	0.348	0.320
Late-Fall	1997	0.298	0.298	0.298	0.298	0.298	0.298
Late-Fall	1998	0.524	0.521	0.521	0.521	0.521	0.517
Late-Fall	1999	0.473	0.468	0.469	0.469	0.469	0.465
Late-Fall	2000	0.340	0.342	0.341	0.341	0.342	0.343
Late-Fall	2001	0.260	0.260	0.260	0.260	0.260	0.260
Late-Fall	2002	0.177	0.176	0.176	0.176	0.176	0.176
Late-Fall	2003	0.421	0.414	0.415	0.415	0.415	0.408
Late-Fall	2004	0.124	0.124	0.124	0.124	0.124	0.124
Late-Fall	2005	0.220	0.218	0.218	0.218	0.218	0.217
Late-Fall	2006	0.323	0.321	0.321	0.321	0.320	0.319
Late-Fall	2007	0.212	0.212	0.213	0.213	0.213	0.214
Late-Fall	2008	0.147	0.146	0.146	0.146	0.146	0.146
Late-Fall	2009	0.501	0.501	0.501	0.501	0.501	0.501
Late-Fall	2010	0.294	0.294	0.294	0.294	0.294	0.294
Late-Fall	2011	0.605	0.599	0.600	0.600	0.600	0.596
Spring	1997	0.378	0.382	0.381	0.381	0.381	0.382
Spring	1998	0.378	0.389	0.386	0.386	0.392	0.404
Spring	1999	0.436	0.431	0.435	0.435	0.435	0.419
Spring	2000	0.200	0.196	0.197	0.197	0.197	0.193

Spring	2001	0.173	0.175	0.175	0.174	0.175	0.176
Spring	2002	0.386	0.392	0.391	0.390	0.392	0.398
Spring	2003	0.285	0.312	0.305	0.305	0.306	0.328
Spring	2004	0.352	0.365	0.362	0.362	0.363	0.374
Spring	2005	0.343	0.344	0.343	0.343	0.344	0.344
Spring	2006	0.393	0.413	0.406	0.406	0.409	0.429
Spring	2007	0.281	0.296	0.293	0.293	0.295	0.302
Spring	2008	0.182	0.207	0.205	0.205	0.207	0.223
Spring	2009	0.095	0.102	0.101	0.100	0.101	0.105
Spring	2010	0.168	0.199	0.187	0.186	0.189	0.220
Spring	2011	0.336	0.324	0.332	0.331	0.331	0.307
Winter	1997	0.355	0.350	0.351	0.351	0.350	0.347
Winter	1998	0.458	0.457	0.456	0.456	0.457	0.455
Winter	1999	0.415	0.427	0.421	0.421	0.422	0.429
Winter	2000	0.218	0.221	0.219	0.219	0.220	0.223
Winter	2001	0.158	0.160	0.161	0.160	0.161	0.163
Winter	2002	0.308	0.314	0.312	0.313	0.313	0.321
Winter	2003	0.193	0.207	0.202	0.202	0.203	0.216
Winter	2004	0.251	0.260	0.259	0.259	0.259	0.269
Winter	2005	0.262	0.272	0.269	0.269	0.270	0.277
Winter	2006	0.330	0.347	0.344	0.344	0.345	0.364
Winter	2007	0.221	0.229	0.228	0.228	0.230	0.238
Winter	2008	0.121	0.129	0.128	0.128	0.129	0.134
Winter	2009	0.169	0.175	0.173	0.173	0.174	0.178
Winter	2010	0.354	0.360	0.357	0.357	0.358	0.368
Winter	2011	0.338	0.361	0.351	0.351	0.354	0.377

Table A-5. Number of adult returners under existing conditions (Exg) and five alternatives for notches in Fremont Weir.

Run	Water Year	Exg	Alt01	Alt04	Alt04b	Alt05	Alt06
Fall	1997	143,742	144,680	144,412	144,297	144,523	145,488
Fall	1998	379,048	396,574	388,761	385,948	391,001	406,786
Fall	1999	170,935	195,690	184,862	184,848	186,850	208,120
Fall	2000	301,757	334,844	328,261	328,143	329,831	351,424
Fall	2001	280,499	286,800	287,180	287,089	287,969	293,515
Fall	2002	181,353	185,118	184,198	184,189	184,889	188,860
Fall	2003	198,993	211,952	208,020	207,869	208,588	219,830
Fall	2004	133,484	137,955	136,898	136,931	137,442	140,723
Fall	2005	78,117	80,915	80,891	80,890	81,004	83,365
Fall	2006	381,293	401,224	393,892	393,921	396,260	421,107
Fall	2007	136,860	155,337	152,036	152,003	154,179	165,527
Fall	2008	39,065	45,448	44,744	44,744	45,193	49,314
Fall	2009	34,818	41,186	39,649	39,568	39,836	44,326
Fall	2010	31,050	34,038	32,642	32,639	32,828	36,503
Fall	2011	89,360	96,260	92,935	92,732	94,139	104,183
Late-Fall	1997	3,634	3,528	3,569	3,569	3,549	3,467
Late-Fall	1998	23,368	23,303	23,327	23,327	23,290	23,220
Late-Fall	1999	223,044	218,800	220,466	220,466	219,787	216,793
Late-Fall	2000	138,849	137,195	137,570	137,570	137,434	136,203
Late-Fall	2001	60,039	59,881	59,876	59,876	59,863	59,714
Late-Fall	2002	48,414	47,749	47,711	47,711	47,583	46,842
Late-Fall	2003	61,203	57,913	58,660	58,660	58,525	55,865
Late-Fall	2004	22,507	22,091	22,096	22,096	22,074	21,480
Late-Fall	2005	6,759	6,646	6,674	6,674	6,667	6,586
Late-Fall	2006	26,839	26,625	26,631	26,631	26,609	26,385
Late-Fall	2007	52,278	52,206	52,187	52,187	52,184	52,078
Late-Fall	2008	81,012	79,707	79,821	79,821	79,617	78,812
Late-Fall	2009	86,388	86,388	86,388	86,388	86,388	86,388
Late-Fall	2010	17,320	17,302	17,316	17,316	17,298	17,275
Late-Fall	2011	24,203	23,666	23,861	23,861	23,803	23,433
Spring	1997	876	914	900	899	903	932
Spring	1998	1,157	1,188	1,183	1,183	1,195	1,234
Spring	1999	26,018	29,016	27,781	27,781	28,006	30,762
Spring	2000	9,692	10,051	9,981	9,978	10,000	10,244

Spring	2001	5,105	5,200	5,201	5,192	5,219	5,299
Spring	2002	4,641	4,714	4,712	4,711	4,722	4,788
Spring	2003	3,783	4,015	3,963	3,960	3,969	4,165
Spring	2004	2,660	2,742	2,730	2,729	2,736	2,821
Spring	2005	3,989	4,081	4,063	4,063	4,067	4,143
Spring	2006	14,137	15,195	14,949	14,948	15,101	16,163
Spring	2007	5,357	5,799	5,723	5,724	5,793	6,114
Spring	2008	4,031	4,385	4,357	4,357	4,399	4,658
Spring	2009	4,434	4,663	4,610	4,598	4,619	4,776
Spring	2010	1,687	1,947	1,832	1,831	1,853	2,193
Spring	2011	1,828	1,949	1,901	1,898	1,920	2,060
Winter	1997	832	821	825	825	825	814
Winter	1998	1,190	1,207	1,211	1,212	1,212	1,232
Winter	1999	4,654	4,878	4,803	4,803	4,822	5,026
Winter	2000	8,329	8,363	8,359	8,359	8,359	8,378
Winter	2001	2,028	2,043	2,044	2,043	2,046	2,061
Winter	2002	3,854	3,844	3,856	3,856	3,853	3,832
Winter	2003	3,869	3,898	3,892	3,892	3,891	3,916
Winter	2004	3,650	3,669	3,670	3,672	3,672	3,700
Winter	2005	4,475	4,461	4,462	4,462	4,461	4,451
Winter	2006	19,530	20,311	20,213	20,213	20,278	21,136
Winter	2007	14,268	14,607	14,623	14,623	14,685	15,121
Winter	2008	3,118	3,192	3,188	3,188	3,197	3,253
Winter	2009	4,639	4,692	4,680	4,676	4,682	4,717
Winter	2010	7,017	7,019	7,035	7,035	7,042	7,025
Winter	2011	1,315	1,441	1,397	1,397	1,410	1,529