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Estimating juvenile winter-run and spring-run Chinook salmon entrainment onto the Yolo Bypass over a notched Fremont Weir

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In this study, a proposed notching of the Fremont Weir was analyzed compared to existing conditions using empirical data to estimate the proportion of juvenile Sacramento River winter-run and Central Valley spring-run Chinook salmon (*Oncorhynchus tshawytscha*) entrained onto the Yolo Bypass. Using historic flow and rotary screw trap data from water years 1997-2011, we found that entrainment of listed juvenile salmon onto the Yolo Bypass was higher on average across all water year types under evaluated notch conditions than occurred under existing conditions. We found that notching the weir resulted in increased listed juvenile salmon entrainment onto the Yolo Bypass in the months of November through March, but not in April. Our results indicate that lowering the required river stage for Sacramento River flows to enter the Yolo Bypass by notching the Fremont Weir is likely to increase entrainment of listed juvenile salmon onto the bypass for the majority of the listed juvenile salmon emigration seasons.

Key words: Fremont Weir, Chinook salmon, *Oncorhynchus tshawytscha*, notch, Yolo Bypass, entrainment, winter-run, spring-run

Construction of dams and levees for flood control and water distribution in the Central Valley (California, USA) has resulted in substantial decreases in the available floodplain habitat for native fish species (Sommer et al. 2001, NMFS 2009a). Restoration of floodplain habitat has been identified as a key action to contribute to the recovery of Sacramento River winter-run Chinook salmon and Central Valley spring-run Chinook salmon (*Oncorhynchus tshawytscha*), which are listed under the state and federal endangered species acts (NMFS 2009a, 2009b). The Yolo Bypass (Figure 1), which is an integral part of the

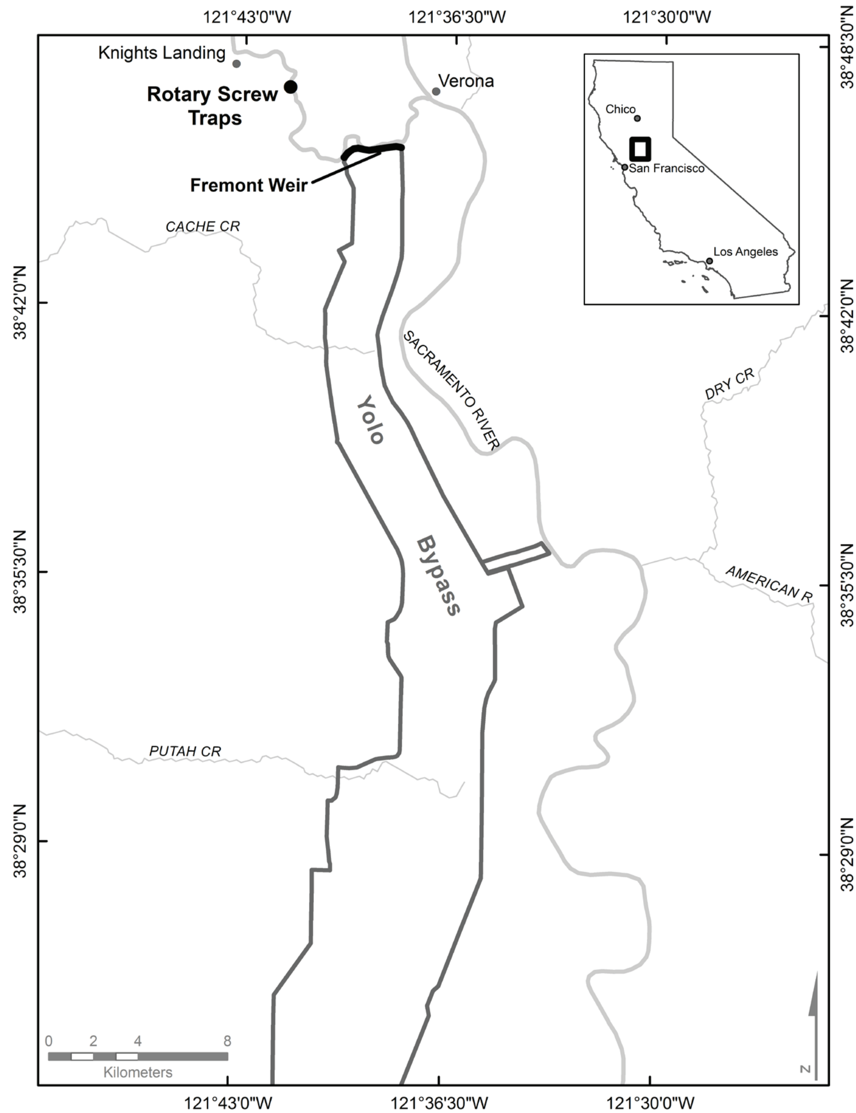

Figure 1.—Location of the California Department of Fish and Wildlife's Juvenile Salmonid Emigration Monitoring Program rotary screw traps (38° 47' N, 121° 41' W) and Fremont Weir (38° 45' N, 121° 38' W).

flood control system in the Sacramento River basin of the Central Valley, has been shown to provide habitat conducive of enhanced growth and survival of juvenile salmon (Sommer et al. 2001). Currently, floodwaters passively enter the Yolo Bypass over the Fremont Weir when the Sacramento River stage, or height of the river, reaches an elevation of 10 m North American Vertical Datum 1988 (NAVD88). Modifying a section of the Fremont Weir (evaluated notch) to allow for inundation of the Yolo Bypass at lower Sacramento River flow stages has been proposed as a regionally important restoration action necessary to increase the frequency and duration of flooding events and, thus, increase the availability of beneficial floodplain rearing habitat for winter-run and spring-run Chinook salmon (listed juvenile salmon) (NMFS 2009a). The purpose of this study is to evaluate a proposed notch configuration in the Fremont Weir to determine how lowering the Sacramento River stage requirements to overtop Fremont Weir might contribute to listed juvenile salmon entrainment onto the Yolo Bypass. Decreasing the river stage required for overtopping the weir is hypothesized to allow greater numbers of listed juvenile salmon to access the beneficial floodplain in all water year types, and in all months when listed juvenile salmon are emigrating past Fremont Weir.

Methods

The Fremont Weir is located on the Sacramento River at River Kilometer (RK) 132.77 (38° 45' N, 121° 38' W) (Figure 1). Flows currently enter the 61 km long Yolo Bypass when the Sacramento River stage exceeds the existing weir elevation of 10 m NAVD88, which occurs in approximately 60–70% of years depending on the historical time period used (Feyrer et al. 2004, DWR 2012). When the Sacramento River overtops the Fremont Weir into the Yolo Bypass, emigrating listed juvenile salmon can potentially leave the main stem river and enter the bypass to use the floodplain as highly-productive rearing habitat. Lowering the Fremont Weir elevation to allow flows to enter the bypass at lower river stages may provide increased access to rearing habitat for emigrating juveniles. In 2009, a technical team evaluated a Fremont Weir notch configuration with a 68.58 meter wide channel bottom, 2 to 1 side slopes, and an invert elevation of 5.33 m NAVD 88 (BDCP Integration Team 2009). In this study, we evaluated this notch's ability to divert water over the weir at lower river stages compared to existing conditions in order to estimate listed juvenile salmon entrainment onto the Yolo Bypass. We used rotary screw trap data, historic flow data, and the assumption that listed juvenile salmon are equally distributed throughout the water column and enter the Yolo Bypass proportionally to the flow split at the weir to derive this flow-entrainment relationship.

Salmon data.—The California Department of Fish and Wildlife (CDFW) has operated rotary screw traps on a daily basis from October through June since 1996 to monitor juvenile salmonid emigration timing, composition, and abundance on the Sacramento River near Knight's Landing at RK 132.77 (38° 47' N, 121° 41' W). The rotary screw traps are located approximately 8 kilometers upstream of the Fremont Weir (Figure 1). We analyzed rotary screw trap data for water years 1997-2011 to determine the daily catch by run (winter-run or spring-run Chinook salmon) based on size-at-date criteria (Fisher 1992, Rosario et al. 2013), as well as trap effort, in order to determine the daily catch per unit effort (CPUE). Observed raw catch data from rotary screw traps is affected by variability in trapping efficiency, diel migration patterns, and water quality. Since these data contain periods affected by these factors, catch per unit effort provides a better measurement of potential fish entrainment than raw catch data because it reduces the influence of trap servicing, diel operations, and high debris loads.

Daily catch per unit effort (by run) was calculated using the following equation:

$$CPUE_i = C_i /(E_i/24) \quad \text{(Eq. 1)}$$

where *CPUE* is daily catch per unit effort (by run), *C* is daily catch, *E* is daily effort, and *i* is day index. Daily proportion of salmon catch was calculated using the following equation:

$$P_i = CPUE_i / \Sigma_i CPUE_i \quad \text{(Eq. 2)}$$

where *P* is the daily proportion of salmon catch (by run).

Spring-run sized salmon catch was adjusted to take into account fall-run hatchery releases from Coleman National Fish Hatchery (CNFH); these spring-run sized fish are not easily distinguishable from the similarly sized CNFH fall-run hatchery fish. Therefore, after CNFH release fall-run hatchery fish, which typically occurs in April, all juvenile Chinook salmon within this size range were considered hatchery fall-run fish.

Flow data.—Historic flow data for water years 1997–2011 was derived from Sacramento River stage data at Fremont Weir, spill data at Fremont Weir, and Sacramento River flow at Verona, Sutter County (Figure 1). Daily Sacramento River stage and Fremont Weir spill data were collected by the personnel from the California Department of Water Resources and the Sacramento River flow at Verona data were collected by personnel from the United States Geological Survey. Daily Sacramento River flow at Fremont Weir was calculated per the rating table developed by the National Weather Service California-Nevada River Forecast Center, using the Sacramento River flow stage level at Fremont Weir. Flow data that were not recorded on the California Data Exchange Center for Fremont Weir spills into the Yolo Bypass was calculated using the following surrogate equation (Jones and Stokes 2001):

$$\textit{Fremont Weir Spill} = 0.06(\textit{Flow at Verona} - 56{,}000)^{1.5} \quad \text{(Eq. 3)}$$

Flow relationships.—The daily proportion of Sacramento River flow entering the Yolo Bypass under existing conditions was calculated using the following equation:

$$F_e = F_w /(F_w + Fv) \quad \text{(Eq. 4)}$$

where F_e is the proportion of Sacramento River flow entering the Yolo Bypass when the weir was overtopping under existing conditions, F_w is the flow over Fremont Weir, and F_v is the flow at Verona.

Notch flow, defined as the flow of the Sacramento River at the Fremont Weir that could have entered the Yolo Bypass had the evaluated notch been in place from 1997 to 2011, was derived per the rating curve developed by the Bay Delta Conservation Plan Integration Team (BDCP Integration Team (2009)). Per the BDCP Integration Team Report, the daily proportion of Sacramento River flow entering the Yolo Bypass under the evaluated notch conditions can take two different forms depending on the river stage at the Fremont Weir.

If the river stage was between 5.3 and 10.0 m NAVD 88 (i.e. the weir was not overtopping under existing conditions, but flows would have entered through the evaluated notch), the following equation was used:

$$F_p = F_n /(F_n + F_f) \qquad \text{(Eq. 5)}$$

where F_p is the proportion of Sacramento River flow that would have entered the Yolo Bypass from the evaluated notching of the Fremont Weir, F_n is the flow through the evaluated notch, and F_f is the Sacramento River flow at Fremont Weir. If the river stage was above 10 m NAVD 88 (i.e. the weir was overtopping under existing conditions and flows would have entered through the evaluated notch), the following equation was used:

$$F_p = (F_n + F_w) / (F_n + F_w + F_v) \qquad \text{(Eq. 6)}$$

where F_p is the proportion of Sacramento River flow that would have entered the Yolo Bypass from the evaluated notching of the Fremont Weir, in addition to the spill that would have occurred under existing conditions.

Entrainment calculations.—Using the salmon and flow data above, we estimated the daily percentage of listed juvenile salmon potentially entrained onto the Yolo Bypass under existing and evaluated notch conditions. The daily percentage of listed juvenile salmon entrained onto the Yolo Bypass under existing conditions was calculated using the following equation:

$$P_e = (F_e \times P_i) \times 100 \qquad \text{(Eq. 7)}$$

where P_e is the percentage of listed juvenile salmon entrained under existing conditions. The daily percentage of listed juvenile salmon entrained onto the Yolo Bypass from the evaluated notching of Fremont Weir was calculated using the following equation:

$$P_n = (F_p \times P_i) \times 100 \qquad \text{(Eq. 8)}$$

where P_n is the percentage of listed juvenile salmon entrained from the evaluated notching of the Fremont Weir and F_p is entrainment calculated from either Eq.5 or Eq.6 above, depending on the river stage at Fremont Weir.

Data analysis.—The estimated daily percentage of listed juvenile salmon potentially entrained onto the Yolo Bypass was summed under existing conditions and the evaluated notch by water-year-type based on the Sacramento Valley Water Year Hydrologic Classification (SWRCB 2006) and by month.

Using the Shapiro-Wilk statistical test (Shapiro and Wilk 1965), it was found that the data failed to meet the normal distribution assumption. Therefore, Mann-Whitney-Wilcoxon non-parametric tests were conducted to test for differences between listed juvenile salmon entrainment under existing conditions and the evaluated notch. Differences were considered significant at $P \leq 0.05$.

Results

Using historic flow data and rotary screw trap data from water years 1997–2011, the evaluated notch significantly (W=8758.5, P < 0.001) increased the proportion of listed juvenile salmon entrained onto the Yolo Bypass compared to existing conditions for all water-year-types (Table 1; Figure 2). In wet years, above normal years, and when averaging across all years, the number of listed juvenile salmon entrained increased by 155–280% compared to existing conditions, which amounts to an approximately 9–10% increase in the proportion of listed juvenile salmon populations entrained (Table 1; Figure 2). In dry years, entrainment onto the bypass went from effectively no entrainment under existing conditions (0.02%) to approximately 8% of each of the populations with the evaluated notch, which is an increase of over two orders of magnitude compared to existing conditions (Table 1; Figure 2).

Table 1.—Percentages of juvenile winter-run (WRC) and spring-run (SRC) Chinook salmon entrained onto the Yolo Bypass under existing conditions (P_e) and the evaluated notching of Fremont Weir (P_n) by water year type for water years 1997–2011.

Water Year Type	WRC P_e	WRC P_n	*P*-value	SRC P_e	SRC P_n	*P*-value
Wet & Above Normal	6.19	15.74	0.014	6.16	16.10	<0.00
Dry & Critical	0.02	8.32	0.005	0.02	7.65	0.005
All Years	3.38	12.53	<0.001	3.35	12.66	<0.001

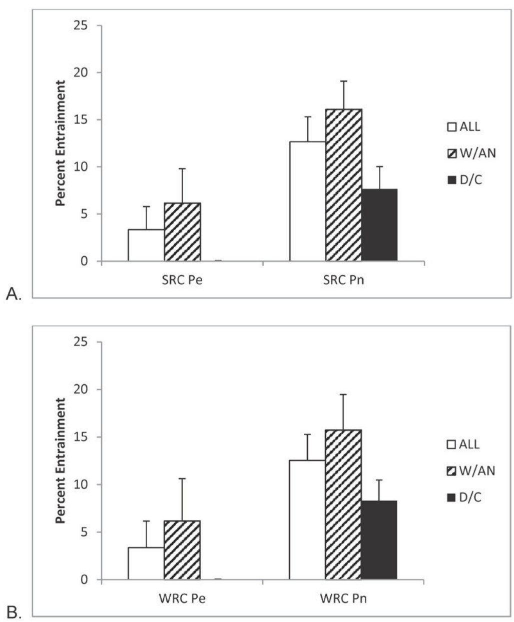

Figure 2.—Mean percentage of (A) juvenile spring-run (SRC) and (B) winter-run (WRC) Chinook salmon entrained onto the Yolo Bypass (38° 45' N, 121° 38' W) under existing conditions (P_e) and the evaluated notching of the Fremont Weir (P_n) by water year type (ALL=average of all water years, W/AN=wet and above normal, and D/C=dry and critical) for water years 1997–2011.

The number of listed juvenile salmon entrained was also significantly higher under evaluated notch conditions compared to existing conditions for the months of November through March (Table 2; Figure 3). There was no significant difference in listed juvenile salmon entrainment between the evaluated notch and existing conditions in the month of April (Table 2; Figure 3).

Table 2.—Percentages of juvenile winter-run (WRC) and spring-run (SRC) Chinook salmon entrained onto the Yolo Bypass under existing conditions (P_e) and the evaluated notching of Fremont Weir (P_n) by month for water years 1997–2011.

Month	WRC P_e	WRC P_n	*P*-value	SRC P_e	SRC P_n	*P*-value
November	0.00	0.52	0.04	0.00	0.10	0.04
December	0.52	3.96	0.004	0.95	4.28	0.011
January	1.12	3.71	0.001	0.48	2.60	<0.001
February	1.09	3.08	0.002	0.75	2.92	<0.001
March	0.62	1.21	0.002	0.87	2.16	0.001
April	0.03	0.04	0.203	0.31	0.60	0.071

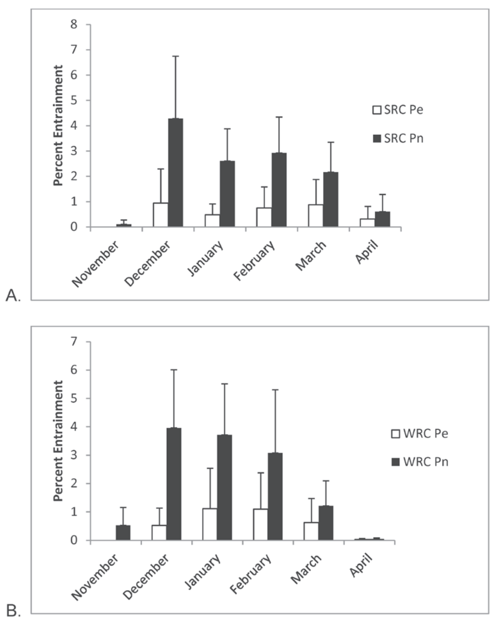

Figure 3.—Mean percentage of (A) juvenile spring-run (SRC) and (B) winter-run (WRC) Chinook salmon entrained onto the Yolo Bypass (38° 45’ N, 121° 38’ W) under existing conditions (P_e) and the evaluated notching of the Fremont Weir (P_n) by month for water years 1997–2011.

Discussion

Our results indicate that the evaluated notch would significantly increase the percentage of listed juvenile salmon entrained onto the bypass in all water-year-types, most notably in dry and critical water years. Furthermore, the notch would also allow for increased entrainment of listed juvenile salmon in the months of November through March, indicating that through all water-year-types, more juveniles will likely be entrained over numerous hydrologic conditions observed in the Sacramento Valley. This result emphasizes the importance of development and implementation of adaptive management strategies for operation of a notched weir that could be planned as part of a multi-year conservation and restoration action.

The number of listed juvenile salmon entrained onto the bypass was not significantly higher in the month of April under evaluated notch conditions when compared to existing conditions (Table 2; Figure 3). A majority of CNFH fall-run hatchery Chinook are released in April without any visual mark signifying their hatchery origin. Thus, after this date, all observed juvenile Chinook salmon captured at the rotary screw trap within the spring-run length-at-date criteria are considered unmarked hatchery origin fall-run and no spring-run are recorded. This censoring of spring-run Chinook observation during April may explain why spring-run salmon entrainment was not significantly higher under evaluated notch conditions than existing conditions. Winter-run salmon entrainment was likely not significantly higher under evaluated notch conditions because winter-run typically emigrate past Knights Landing between November and March, extending into April and May only in some years (Snider and Titus 2000a, 2000b).

The assumption that fish are equally distributed throughout the water column and enter the Yolo Bypass proportionally to the flow split at the weir was used to derive the flow-entrainment relationship. There are studies to suggest that juvenile salmonids show certain habitat preferences depending on various environmental conditions and developmental stage and may not be equally distributed in the water column (Williams 2006). Additional investigations of the ways that environmental conditions influence behavior of various juvenile lifestages is an area of research important to accurately predicting entrainment at different locations and river stages at Fremont Weir.

These results suggest that notching the Fremont Weir to increase the flow volume onto the Yolo Bypass could increase the percentage of listed juvenile salmon entrained during the majority of their emigration seasons. However, additional studies and finer scale analyses are necessary to assess how the migratory behavior of fishes and location of notches may more directly influence the percentage of fish entrained, and to determine the effectiveness of the evaluated notch post-restoration.

Increasing the percentage of listed juvenile salmon entrained onto floodplain habitat will provide a larger proportion of the population an alternate emigration corridor with potential population-level benefits. Entraining fish onto the bypass is a critically important fishery management action and may be necessary to derive increases in growth rates and survival (which ultimately may result in an increased contribution to adult production) compared to the main stem of the Sacramento River (Sommer et al. 2001). Further studies to compare survival between the Yolo Bypass and Sacramento River migration corridors are necessary to evaluate the survival benefits of floodplain entrainment.

Studies of frequency, duration, and timing of flooding events over the weir for restoration actions are needed in order to assess how each factor contributes to increased growth rates and survival, and how increased growth rates may benefit adult returns by reducing the number of smaller sized juveniles, which tend to be more susceptible to mortality (Beckman et al. 1999). In addition, it is also necessary to determine how entrainment and inundation events are timed and integrated to assess stranding risks for listed juvenile salmon. Field monitoring is necessary to evaluate when the magnitude and duration of inundation events are insufficient to provide appropriate connectivity to existing waterways, which can create stranding risks. In water years that do not provide sufficient flows onto the bypass, operation of the evaluated notch will need to be adaptively managed based on real-time monitoring.

The framework for this study can be used for management and restoration purposes as a preliminary step to assess the potential benefits from notching the Fremont Weir with the intent of increasing the proportion of juvenile salmon entrained onto the Yolo Bypass, and it utilizes fish and flow data unique to that system. Further, this approach can be used in conjunction with monitoring efforts and lifecycle models to help determine the effectiveness of fishery restoration actions in the Yolo Bypass and similar floodplain habitats.

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