Data and Literature Review on Entrainment Versus Environmental Conditions for Central Valley Chinook Salmon and Steelhead

Introduction

Early coded wire tags (CWT) studies suggested that juvenile Chinook salmon migrating through the Old River survived at a lower rate than fish released in the mainstem San Joaquin River (Newman 2008). Similarly, fish entering Georgiana Slough or the Delta Cross Channel (DCC) experienced lower survival than fish remaining in the Sacramento River (Newman 2008, Newman and Brandes 2010). It was assumed that the lower survival was due in part to entrainment at the State Water Project (SWP) or Central Valley Project (CVP) export facilities. Because CWT fish can only be analyzed as batches with recoveries occurring at specific collection locations (e.g., salvage, trawls, ocean, carcass survey), there is uncertainty about the behavior and fate of individuals that experienced a certain set of conditions (e.g., entrainment, volitional migration, export rates) between the time they are released and the time they are collected. Acoustic tagging technology provides a way to track individual behavior and fate in response to conditions experienced in space and time to make more robust inferences about the effect of entrainment on survival.

Acoustic tagging studies performed to date have not supported differences in survival between fish in the Old River and mainstem San Joaquin River detected in previous CWT studies (Buchanan et al. 2013, Buchanan et al. 2018). However, few attempts have been made to quantify the success of fish moving through the CVP salvage facilities relative to fish that pass by the facilities without being entrained. Often, acoustic detections are aggregated at Chipps Island (Sacramento-San Joaquin Delta (Delta) exit) to estimate route-specific survival without considering the detection history in the CVP. Buchanan et al. (2018) reported the proportion of all tags arriving at Chipps Island that came through salvage at the CVP facility. They found that in the three years when the Head of Old River barrier was not installed, the percentage of tags arriving at Chipps Island that went through the CVP ranged from 63.6% to 66.7%. The large proportion of tags coming through the CVP facility suggests that in many years, salvage could be the highest survival route in the South Delta. This may account for the lack of difference in survival between routes. Further, a study by Karp et al. (2017) found that both facility efficiency and survival through the CVP increased with export rate, which could indicate a mechanism for the effect.

Buchanan et al. (2018) were the only authors to include in their manuscript the salvage history of tags arriving at Chipps Island. However, since 2011, thousands of acoustically tagged juvenile Chinook salmon and steelhead have been released to estimate survival through the Delta. Data from receivers deployed in and around the export facilities and at other locations in the Interior Delta are available in databases. Here, the available acoustic data is leveraged to test hypothesized relationships between key hydrologic variables, entrainment, volitional migration, and survival for juvenile salmonids entering the Interior Delta. In this context, the hypotheses represent proposed models for the data generating process. Each hypothesis will be rejected or not based on whether the observed data support the proposed model. Appendix A includes the initial Study Plan for this analysis; however, revisions to the analysis were made that were not included in the Study Plan.

Specific hypotheses tested include:

HO_1: For fish detected south of the San Joaquin River:

- $HO_{1.1}$: the probability of subsequently being detected at Chipps Island is similar between fish detected in the CVP holding tanks and those that are not, regardless of:
  - $HO_{1.1a}$: total export rates (including both CVP and SWP exports).
  - $HO_{1.1b}$: river discharge rates from the Sacramento or San Joaquin Rivers.

HO_2: For fish detected at the CVP trash rack:

- $HO_{2.1}$: the probability of subsequently being detected at Chipps Island is not affected by CVP export rates.
- $HO_{2.2}$: the probability of subsequently being detected at Chipps Island without being routed through the CVP holding tanks is unrelated to CVP exports.

Methods

To test the above hypotheses, we used the Environmental Research Division's Data Access Program (ERRDAP) Juvenile Salmon Acoustic Telemetry System (JSATS) release and detection data between 2020 and 2025. Detection data was subset to only those tags observed at least once in the south Delta (channels south of the San Joaquin River). These detections were classified by discrete outcomes: 1) observed at Chipps Island, 2) observed at the CVP trash rack, and 3) observed at the CVP holding tanks (Table 1).

To account for environmental conditions experienced by each fish in the interior Delta, individual detection history was linked to relevant modeled exports and river flows from the DayFlow dataset. Total exports (QEXPORTS) and river flow data were averaged for the observed time for each fish in the interior Delta, with river flow representing the flow into the Delta from the corresponding release river basin of each fish. River flows were scaled by the average flow experienced by fish in each river basin. Exports were similarly scaled to ease interpretability. For fish that went unobserved inside the Delta, a minimum averaging interval of seven days following the first detection inside the Delta was used. For the second analysis of fish detected at the trash rack, CVP exports and flows were averaged starting from the first date of detection at the CVP trash rack.

The data were analyzed using a Binomial Generalized Mixed-Effects Linear Model (logit-link). Fish fork length and point of entry into the Delta were used as covariates to account for differences between individuals. To allow for the possibility that flows differentially affected fish arriving from different basins, random effects of flow and exports (continuous) by point of entry were included in the model. Other random effects include water year and run/race (categorical). The models were fit using the `rstanarm` package in R (v. 2.32.2; Goodrich et al. 2025) using default priors. Model diagnostics and posterior predictive checks were inspected to ensure model validity and goodness-of-fit (including over-dispersion) prior to reporting.

Results

A total of 4,125 juvenile salmon and steelhead were observed south of the San Joaquin River (Table 1, Figure 1), representing approximately 6% of the total tagged fish in the JSATS database (N = 65,709). Of these, 24% were later detected at Chipps Island (N = 994). A minority of these were detected at the CVP trash rack before being detected at Chipps Island (11%; N = 111). Of these fish, 69 were detected in the CVP holding tanks (62%). This suggests that most fish do not transit to Chipps Island via the CVP fish facility. For fish detected at the CVP trash rack, approximately half of fish that successfully transited to Chipps Island do so via entrainment at the CVP fish facility. However, not all fish entrained in the CVP holding tanks were later detected at Chipps Island – 16 of 69 (23%) were not later detected at Chipps Island. Taken together, the observed data suggest that entering the CVP through the trash rack increases a fish's changes of transiting to Chipps Island relative to migrating past the CVP trash rack. Additionally, the overall likelihood of successfully transiting to Chipps Island from the CVP trash rack is lower than other potential routes.

Table 1. Observed Number of Acoustically Tagged Chinook Salmon at Various Locations of Interest over the Study Period 2020 to 2025

Location	Total Number of Observations	Number of Observations at CVP Trash Rack	Number of Observations at CVP Holding Tanks
South of San Joaquin	4,125	576	69
Chipps Island	994	111	53

Key:
CVP = Central Valley Project

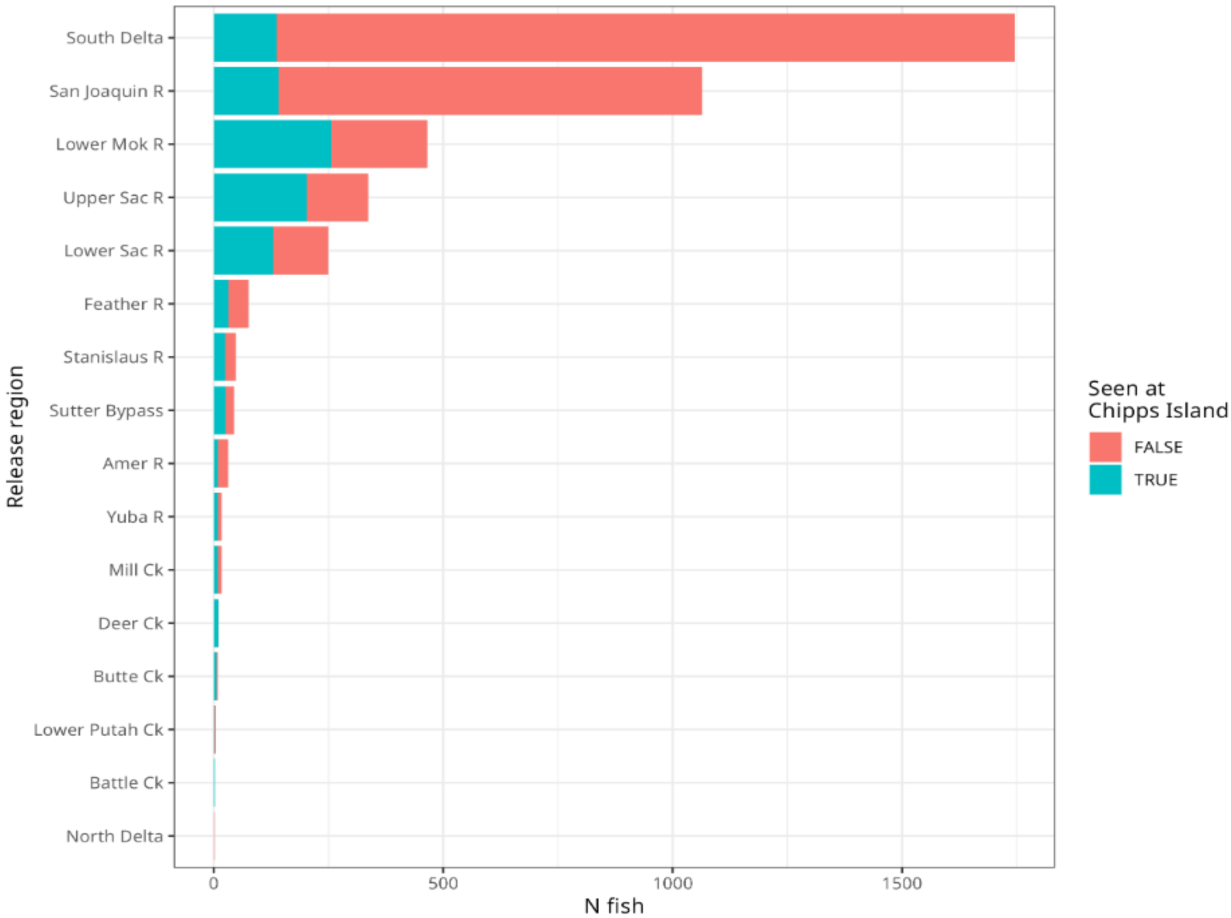


Figure 1. The Observed Status at Chipps Island for Acoustically Tagged Fish Observed South of the San Joaquin River (South Delta) by Initial Release Region

The model estimates for all fish observed south of the San Joaquin River (Table 2) reflected the observed patterns (Table 1, Appendix B). Fish length was consistently associated with higher probability of being observed at Chipps Island. For those fish observed at the CVP holding tank, there was a dramatic increase in the probability that they would be subsequently observed at Chipps Island. Higher exports were related to higher probability of being detected at Chipps Island, but both interaction terms were inconsistent (i.e. credible intervals included zero effect). This suggests that exports and river flows did not differentially affect the fish routed through the CVP holding tanks compared to those that did not route through the CVP holding tanks.

Table 2. Model Estimates (log-odds scale) for the Probability of Being Observed at Chipps Island for All Fish Observed South of the San Joaquin River

Parameter	Mean Estimate for Probability of Being Observed	90% Credible Interval
(Intercept)	-4.3	-5.1 to -3.4
Detected at CVP Holding Tank	3.7	3.3 to 4.1
Fork Length	0.18	0.014 to 0.022
Exports	0.5	0.20 to 0.85
River flows	0.1	-0.20 to 0.40
Detected at CVP HT:Exports	0.0	-1.0 to 1.6
Detected at CVP HT:River flows	-0.5	-1.3 to 0.47

Key:
CVP = Central Valley Project
HT = holding tank

The model of the probability of being observed at Chipps Island for fish detected at the CVP trash rack (Table 3) estimated similar general effects as the overall model (Table 2). Being routed through the CVP holding tank increased the likelihood that a fish would be detected at Chipps Island, and larger fish were more likely to be observed at Chipps Island. However, exports at the CVP were associated with lower probability of being later observed at Chipps Island, and the interaction term was inconsistent (Figure 2). That suggests that increased exports lowered the probability of being observed at Chipps Island overall and did not differentially benefit those fish that were routed through the CVP holding tanks. There was no consistent effect of Jersey Point flows on the probability of being later observed at Chipps Island. A competing model using Old and Middle River flows instead of Jersey Point flows showed similar results.

Table 3. Model Estimates (log-odds scale) for the Probability of Being Observed at Chipps Island for Fish Observed at the CVP Trash Rack.

Parameter	Mean Estimate for Probability of Being Observed	90% Credible Interval
(Intercept)	-3.7	-5.9 to -1.3
Detected at CVP Holding Tank	3.7	3.0 to 4.4
Fork Length	0.09	0.0012 to 0.017
Jersey Point Flow	0.4	-0.03 to 0.71
CVP Exports	-0.6	-1.2 to -0.13
CVP Exports:Detected at HT	0.5	-0.06 to 1.2

Key:
CVP = Central Valley Project
HT = holding tank

Discussion

HO_1: For fish detected south of the San Joaquin River:

- $HO_{1.1}$: the probability of subsequently being detected at Chipps Island is similar between fish detected in the CVP holding tanks and those that are not, regardless of:
  - $HO_{1.1a}$: export rates.
  - $HO_{1.1b}$: river discharge rates from the Sacramento or San Joaquin Rivers.

Model parameters indicate support for rejecting $HO_{1.1.}$ For fish detected south of the San Joaquin River, detection at the CVP holding tanks had a positive and well-supported (the credible interval did not include zero) effect on the probability of subsequently being detected at Chipps Island. Thus, although most fish that ultimately arrived at Chipps Island were not detected in the CVP holding tanks, those that were detected in the CVP holding tanks had a greater probability of reaching Chipps Island compared to fish detected south of the San Joaquin River and not detected at the CVP holding tanks.

The interaction terms of the model indicate that both $HO_{1.1a,}$ and $HO_{1.1b}$ cannot be rejected (i.e. the credible interval includes zero effect). This is an important finding because it suggests alterations of flows and exports are unlikely to have impacts on the ability of salmonids in the south Delta to successfully arrive at Chipps Island via the CVP holding tanks or other routes.

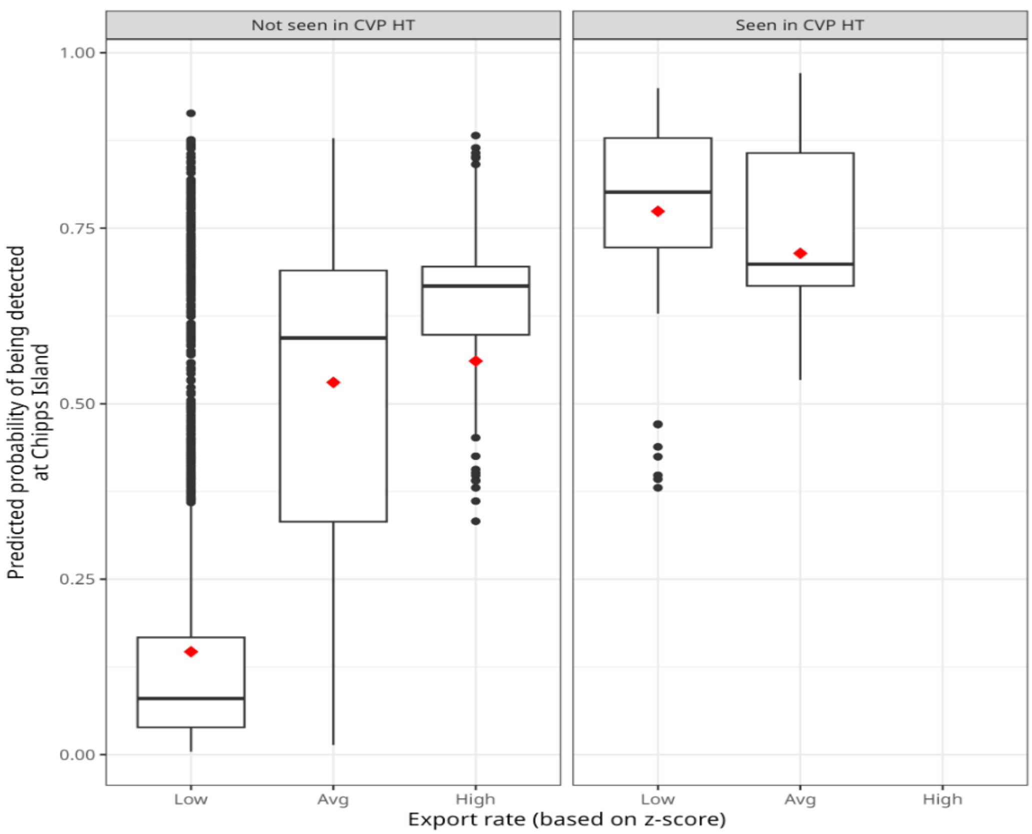
Other covariates (i.e., fork length, CVP exports, and river inflow) used to model detection at Chipps regardless of detection at the CVP holding tanks were included to avoid confounding the hypothesis tests. Fork length had a positive and well supported effect on being detected at Chipps Island. Size has been shown to positively influence juvenile salmonid survival probabilities in this region (Zeug and Cavallo 2013, Perry et al. 2018, Brodsky et al. 2020). However, in this model, fork length may also serve to separate salmonids that migrate as yearlings from those that migrate as young-of-the-year. Exports had a positive and well-supported effect on the probability of detection at Chipps Island. CVP exports have a direct effect on salvage rates at the CVP (Zeug and Cavallo 2014), and this analysis suggested encountering the CVP holding tank increased the probability of reaching Chipps Island. However, the relationship is driven largely by low export conditions which may indicate poor migratory conditions in the Delta overall when exports were often constrained as a management action (Figure 2). Flow at Jersey Point did not have well-supported effects, and similar findings have been reported for other regions of the Delta where tidal movement is always bidirectional (Buchanan et al. 2018, Perry et al. 2018).

HO_2: For fish detected at the CVP trash rack:

- $HO_{2.1}$: the probability of subsequently being detected at Chipps Island is not affected by CVP export rates.
- $HO_{2.2}$: the probability of subsequently being detected at Chipps Island without being routed through the CVP holding tanks is unrelated to CVP exports.

Model results indicate that hypothesis $HO_{2.1}$ can be rejected. Exports had a negative and well-supported relationship with subsequent detection at Chipps Island. This was the opposite relationship of the first model. However, like the first model, detection in the holding tank had a positive effect on detection at Chipps Island. Additionally, there was no effect of exports on fish that encountered the trash rack but not the holding tank, indicating we could not reject $HO_{2.2.}$

Both model results taken together may reflect a near-field versus far-field effect. When fish are very close to the export facility (e.g., in the vicinity of the CVP trash racks), higher exports can reduce the probability of arrival at Chipps Island regardless of route and getting into the holding tank is the better option. However, for fish that are farther from the facility but still in the south Delta, higher export rates correlate with better conditions for making it to Chipps via all routes including CVP salvage. This suggests that the near-field effects of exports are negative. The mechanism involved here is unclear but may index poor conditions when exports are restricted as mitigation. An alternative mechanism is that reduced exports result in lower efficiency in the facility resulting in increased loss rather than salvage, which would improve the probability that a fish would be observed at Chipps Island.



Export rates were modeled as a continuous variable – classification only for illustrative purposes.

Figure 2. Predicted Probability of Being Detected at Chipps Island by Export Rate (boxplots) for All Fish Detected South of the San Joaquin with Observed Proportions (red diamonds)

Key Findings

1. Relatively few fish from the total population (4,125 of 65,709) were observed south of the San Joaquin River, though this might reflect poor receiver deployment in the Delta prior to 2021.
2. Fish routed through the CVP holding tanks had substantially higher probability of being subsequently observed at Chipps Island, both overall and for fish observed at the CVP trash racks.
3. Exports were positively correlated with the probability that a fish would be observed at Chipps Island overall yet negatively correlated for fish at the CVP trash rack. There was no indication that fish entrained in the CVP were differentially affected by exports.
4. There was no consistent effect of river basin flows.

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Appendix A

Study Plan

Appendix A
Study Plan

Introduction

Early studies with coded wire tags (CWT) suggested that fish migrating through Old River survived at a lower rate than fish released in the mainstem San Joaquin River. It was assumed this was due to entrainment or other export-related effects since the Old River route passes both export facilities. However, comprehensive analysis of CWT data have only found weak or insignificant effects of exports on survival (Newman 2008, Newman and Brandes 2010, Zeug and Cavallo 2013). Subsequent acoustic tagging studies have not supported differences in survival between fish in the Old River and mainstem San Joaquin River (Buchanan et al. 2013, Buchanan et al 2018). However, few attempts have been made to quantify the success of fish moving through the Central Valley Project (CVP) relative to fish that either pass by the facilities without being entrained or migrate through routes that do not intersect with the facilities (San Joaquin River mainstem). Often, acoustic detections are aggregated at Chipps Island (Delta exit) to estimate route-specific survival without considering detection history in the CVP. Buchanan et al. (2018) reported the proportion of all tags arriving at the exit of the Delta (Chipps Island) that came through salvage at CVP. They found that in the three years when the Head of Old River (HOR) barrier was not installed, the percentage of tags arriving at Chipps Island that went through CVP ranged from 63.6%-66.7%. The large number of tags coming through CVP suggests that in many years, salvage could be the highest survival route in the South Delta. This may account for the lack of survival differences in route survival and weak relationships between exports and survival. Further, a study by Karp et al. (2017) found that both facility efficiency and survival through the CVP increased with export rate which could indicate a mechanism for the effect.

Buchanan et al. (2018) were the only authors to include in their manuscript the salvage history of tags arriving at Chipps Island. However, since 2011, thousands of acoustically tagged juvenile Chinook Salmon and steelhead have been released to estimate survival through the Delta. Receivers deployed at the CVP and State Water Project detect fish in and around these facilities and those data are often made available in reports and in databases. We propose to leverage these data to make inferences about the contribution of the salvage route survival outcomes in the Delta. The study plan for this effort is described below.

Methods

Define Hypotheses to be Tested (Proposed for Discussion)

- $H_{0,1}$: The proportion of tags moving south from the San Joaquin River is unrelated to Old and Middle River (OMR) flow.
- $H_{0,1}$: For fish that are detected south of the San Joaquin River, the probability they are detected at Chipps is unrelated to CVP experience.

- $H_{0,2}$: The fraction of tags detected at Chipps that were previously detected at CVP is independent of export rate

Define Variables

- Response variables
  - Differential survival to Chipps Island for fish that enter HOR and are detected at CVP vs any other route
  - Differential survival for fish via CVP vs, any other route including the mainstem San Joaquin River
  - Proportion of tags detected at Chipps Island that were previously detected in the CVP holding tank.
- Independent variables
  - Defined based on hypotheses
    - Export rate at CVP
    - OMR flow
    - Others? JPF, NDOI, Vernalis, Freeport
    - Jersey Point flow, Net Delta Outflow (Day Flow)

Identify Data

Relevant Releases

- Sacramento River: Any releases with detections of study fish entering the interior Delta (via Georgiana, Delta Cross Channel (DCC), or Three Mile Slough).
- San Joaquin River: Releases that occurred when the Head of Old River barrier was not installed.

Environmental and Operational Data

- Use the detection data identified in 2.1 to define the temporal period to acquire operational and environmental variables.

Confer with Reclamation on Approach to Analysis

- Based on the data identified in Item 3 (Identify Data) above, options for analysis with anticipated levels of certainty/reliability will be developed.
- The Stantec team will meet with Reclamation to discuss the identified data and analysis options and together determine the analyses to be performed. This will include narrowing the list of explanatory variables that colinear.

Analysis and Reporting

- Quantitative analyses identified in Item 4 above will be performed.
- A draft technical report describing data identification, analysis, and results will be provided to Reclamation and/or peer review panel for review.
- Comments from Reclamation and/or peer review panel will be addressed and a final report will be provided.
- All data and code resulting from this effort will be archived and delivered to Reclamation.

References

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Appendix B

Supplemental Figures

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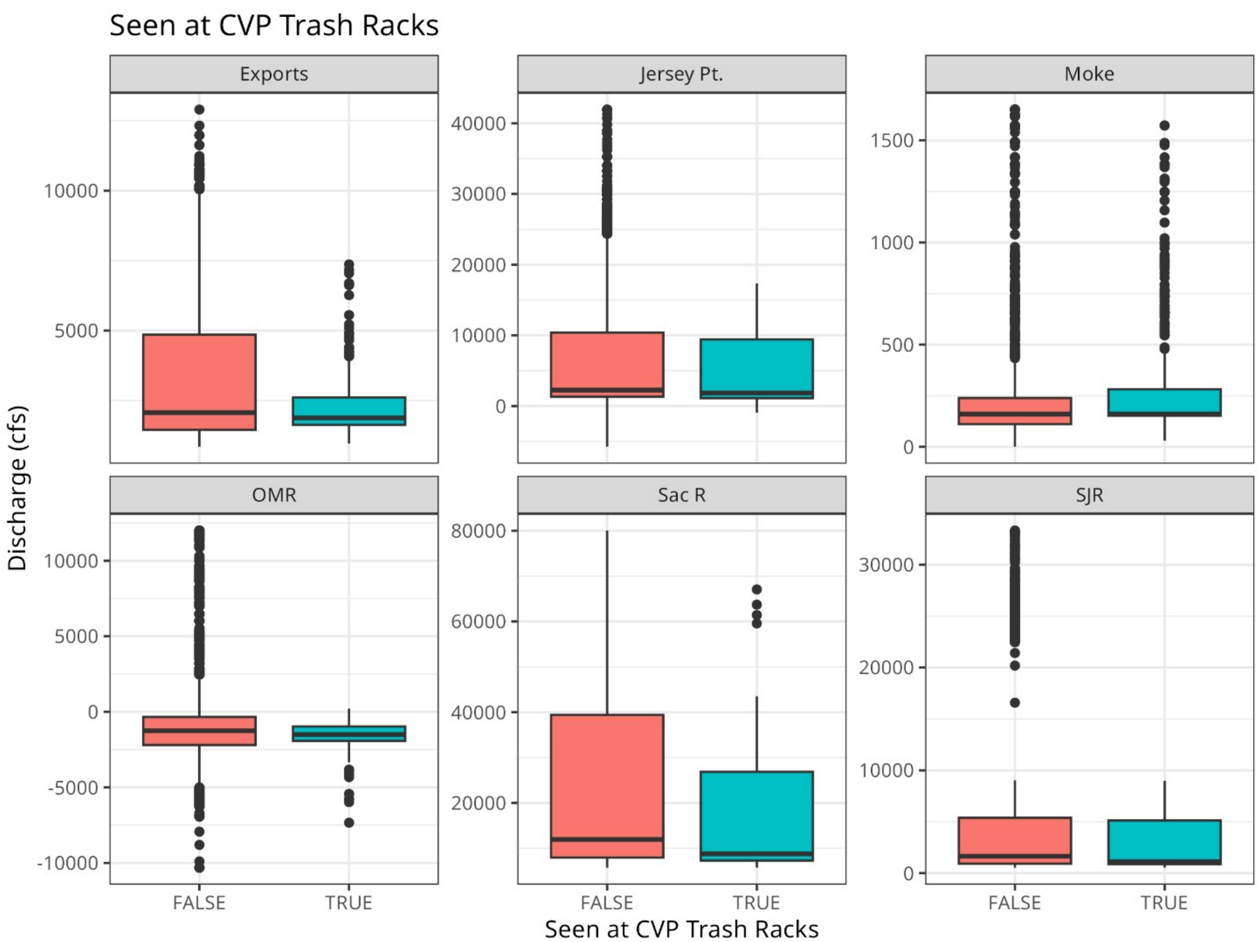
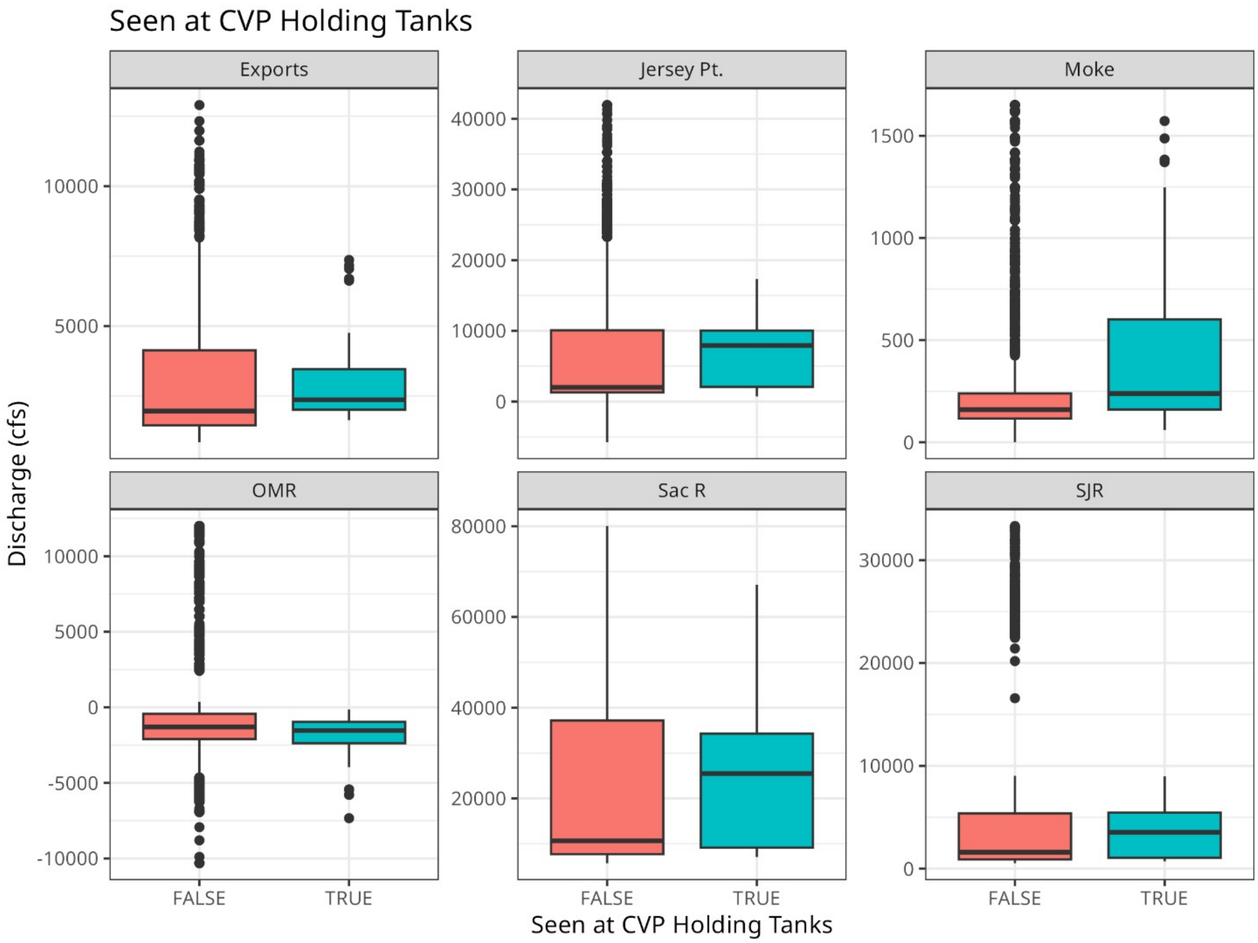
Supplemental Figures

The figures below provide additional context and information for the Data and Literature Review on Entrainment Versus Environmental Conditions for Central Valley Chinook Salmon and Steelhead Technical Memorandum.



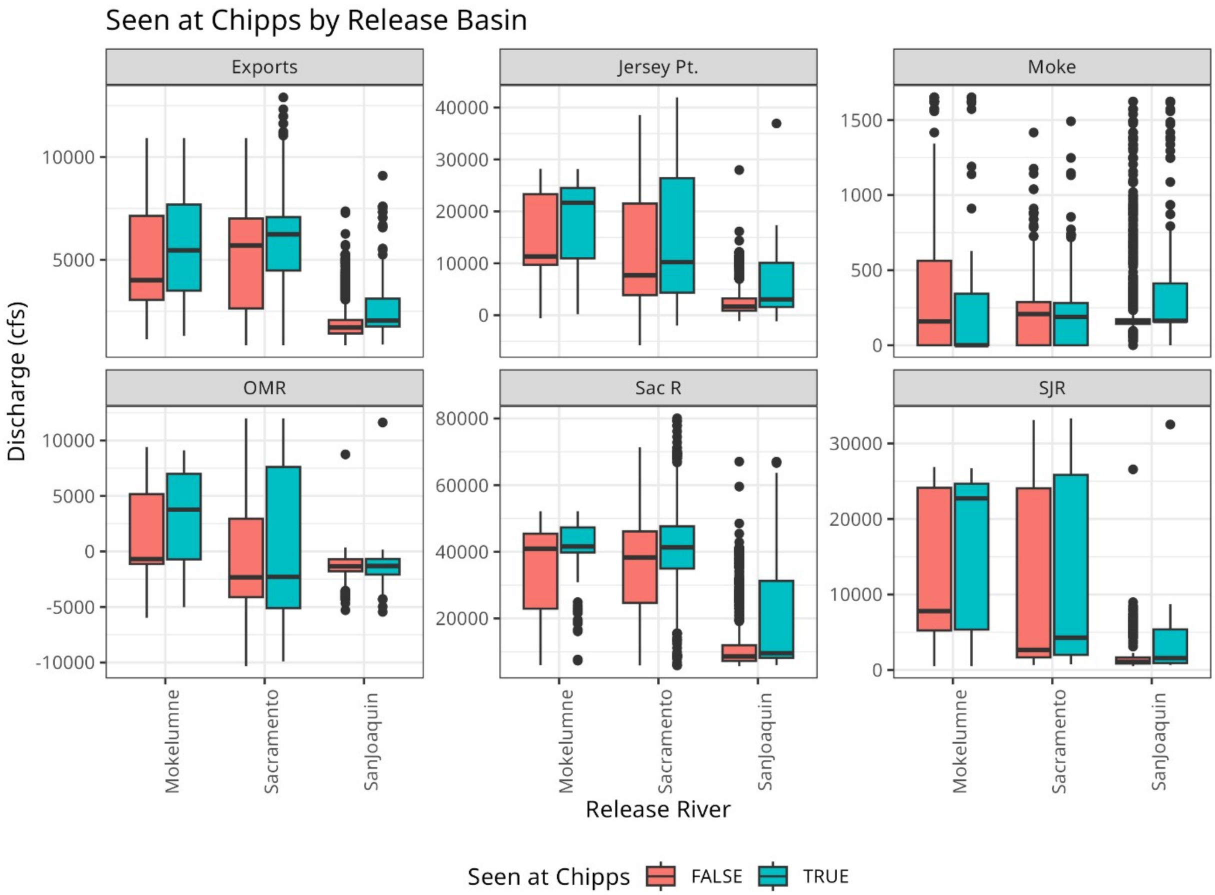
Note: Flows are the average value for the period each fish was observed in south of the San Joaquin River.

Figure B1. Flows (river discharge or exports) for Select Locations by Whether or Not Fish Were Observed at the CVP Trash Rack



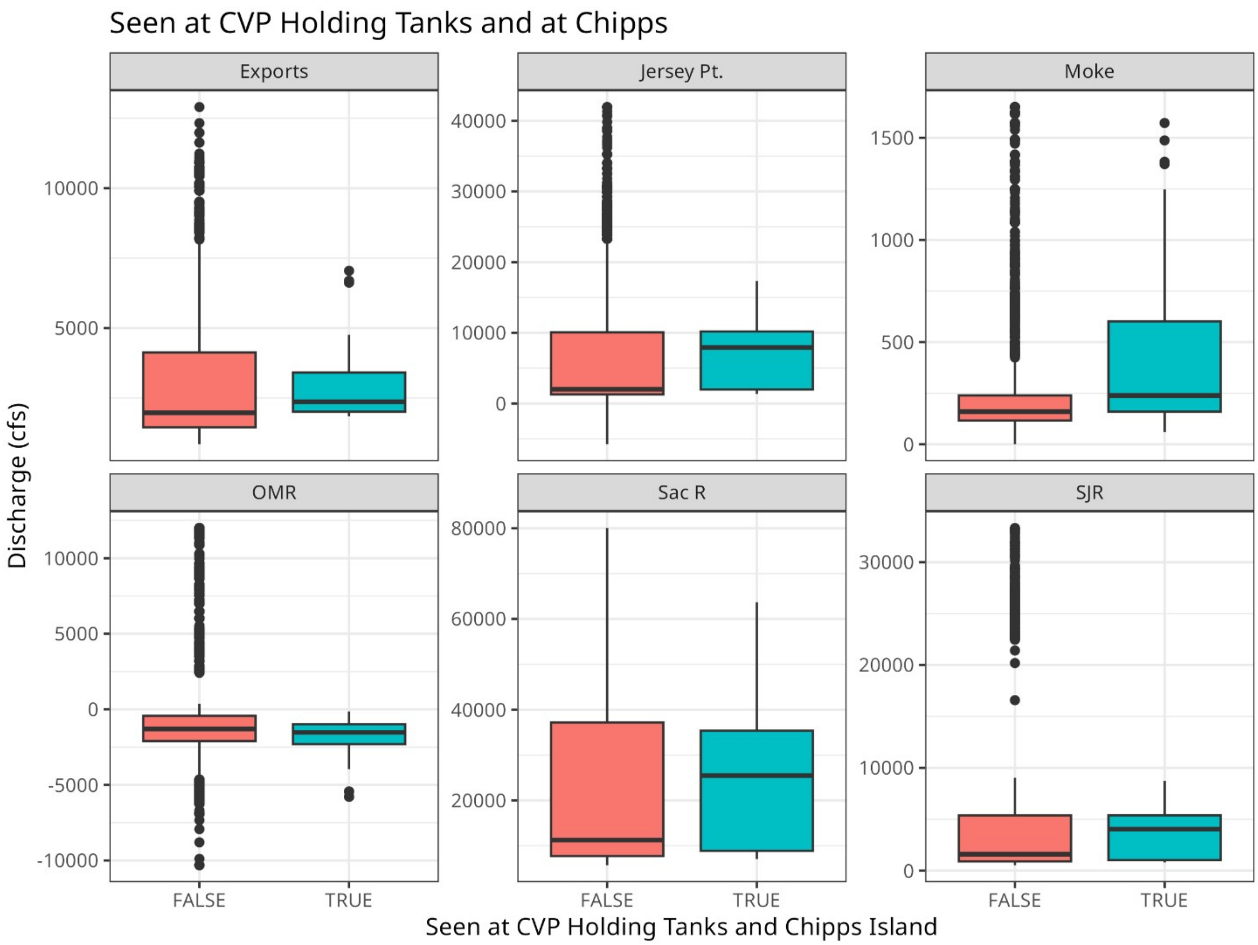
Note: Flows are the average value for the period each fish was observed in south of the San Joaquin River.

Figure B2. Flows (river discharge or exports) for Select Locations by Whether or Not Fish Were Observed at the Central Valley Project Holding Tanks



Note: Flows are the average value for the period each fish was observed in south of the San Joaquin River.

Figure B3. Flows (river discharge or exports) for Select Locations by Whether or Not Fish Were Observed at Chipps Island



Note: Flows are the average value for the period each fish was observed in south of the San Joaquin River.

Figure B4. Flows (river discharge or exports) for Select Locations by Whether or Not Fish Were Observed at Both the CVP Holding Tanks and subsequently at Chipps Island