Technical Memorandum

Long-Term Operation of the Central Valley Project and State Water Project

Assessing Operations and Environmental Conditions on Central Valley Chinook Salmon and Steelhead Juvenile Movement

Introduction

Over the past 15 years, the use of acoustic telemetry to estimate juvenile salmonid survival in the Delta has steadily increased, and now thousands of tagged juvenile Chinook salmon and steelhead have been released. Although the effect of hydrology, particularly inflow and exports, on survival has been a goal of many studies, there is little information on how juvenile salmonids actually respond to specific hydrologic conditions. This happens for several reasons in individual studies, including:

1. Fish are released far upstream and few survive to the area of interest.
2. Only a fraction of fish enter routes leading into the area of interest.
3. Receiver deployments were not sufficient in the area of interest.
4. Hydrologic conditions during individual studies are limited via regulation (e.g., exports during April and May, import-to-export ratio (I:E)).
5. Many years of study are required to obtain variance in hydrologic conditions.
6. Timing of availability of hatchery fish of sufficient size for tagging.

The telemetry data was leveraged across years and releases to make inferences about juvenile salmonid behavioral responses to hydrodynamic conditions in the Delta and changes to that hydrology as influenced by operations. By combining data from multiple years and releases, it is hypothesized that a greater range of hydrologic conditions will be observed and a larger number of detections in the area of interest will be available for more robust inference. A key assumption is that all races of Chinook salmon and Steelhead salmon respond similarly to hydrologic cues. 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.

The following hypotheses were tested while simultaneously accounting for individual fish size and race/species. 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.

For tagged fish at the Head of Old River junction or the Georgiana Slough junction:

- HO_1: the probability of entry from the mainstem San Joaquin River into the Head of Old River or from the mainstem Sacramento River into Georgiana Slough is unrelated to export rates.

- HO_2: the probability of entry from the mainstem San Joaquin River into the Head of Old River or from the mainstem Sacramento River into Georgiana Slough is unrelated to flow rate at Vernalis and Freeport, respectively.

For tagged fish at the junction of the San Joaquin River and Mokelumne River:

- HO_3: the probability of moving west is unrelated to the Jersey Point flow (JPF).
- HO_4: the probability of moving west is unrelated to export rates.

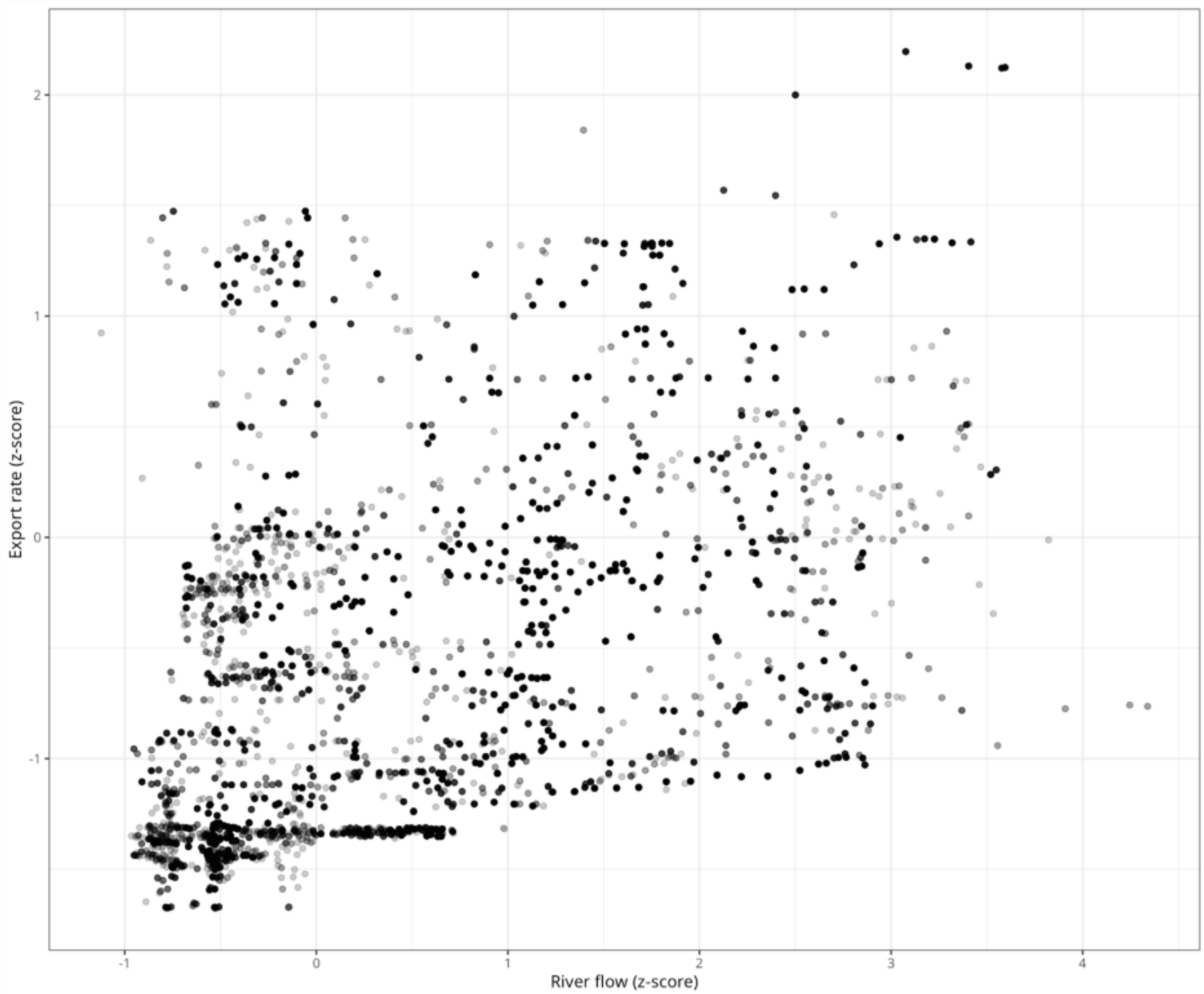
For tagged fish detected at Rio Vista:

- HO_5: the probability of remaining in the mainstem Sacramento River is unrelated to exports and/or Sacramento River flow.

Methods

To test the above hypotheses, Environmental Research Division's Data Access Program (ERRDAP) Juvenile Salmon Acoustic Telemetry System (JSATS) detections from 2012 to 2025 were subset to detections around the four locations of interest: 1) the junction of the Sacramento River and Georgiana Slough, 2) the junction of the Head of Old River and the San Joaquin River, 3) the junction of the Lower Mokelumne River and the San Joaquin River, and 4) the Sacramento River at Rio Vista. Of the total JSATS dataset (N = 65,709), 14,014 individuals were observed at one or more of these locations.

For each detection event at a location, the next movement was classified as "success" if the movement was remaining in a mainstream river channel rather than entering an interior Delta channel. Specifically, "success" was defined as continued downstream movement in the Sacramento River mainstem at Georgiana Slough and Rio Vista, continued downstream movement in the San Joaquin River mainstem at the Head of Old River, and moving downstream in the San Joaquin River mainstem towards Jersey Point at Mokelumne River. Detections where the route was ambiguous were not analyzed. For each fish, a single event constituting the latest observed was used as the transition (i.e., no back-and-forth movements). For each detection event, the daily average exports and river flows from the DayFlow dataset were linked to the date of observation. For detections at Georgiana Slough junction, Sacramento River flows were used; for detections at Rio Vista junction, the Sacramento River at Rio Vista flows were used; for the detections at the Head of Old River junction, the San Joaquin River flows were used; and for the detections at Mokelumne River junction, the San Joaquin at Jersey Point flows were used. Flows for each of these detection events were standardized to a z-score (by location) to allow for comparisons across locations despite differences in flow magnitude between rivers. There was little correlation between the export rates and river flows ($R^2 = 0.17$), suggesting they captured different variability in environmental conditions (Figure 1).



Note: Correlation between export rates and river flows was low (R^2 = 0.17).

Figure 1. Export Rates Versus River Flow (both standardized to z-scores)

The data were analyzed using a Hierarchical Binomial Generalized Linear Model (logit-link) with the observed "success" of not entering an interior Delta channel at each location as a response variable. Location, river flows, and exports, as well as the interaction terms for each were included as predictors. These interaction terms allow river flow and export to have different effects at each location, thus accounting for differences between locations while also leveraging the full dataset to increase the statistical power and avoid overfitting. Fish fork length and the random effects of water year and run/race were included to account for differences between individuals and years not captured in the other predictors. 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

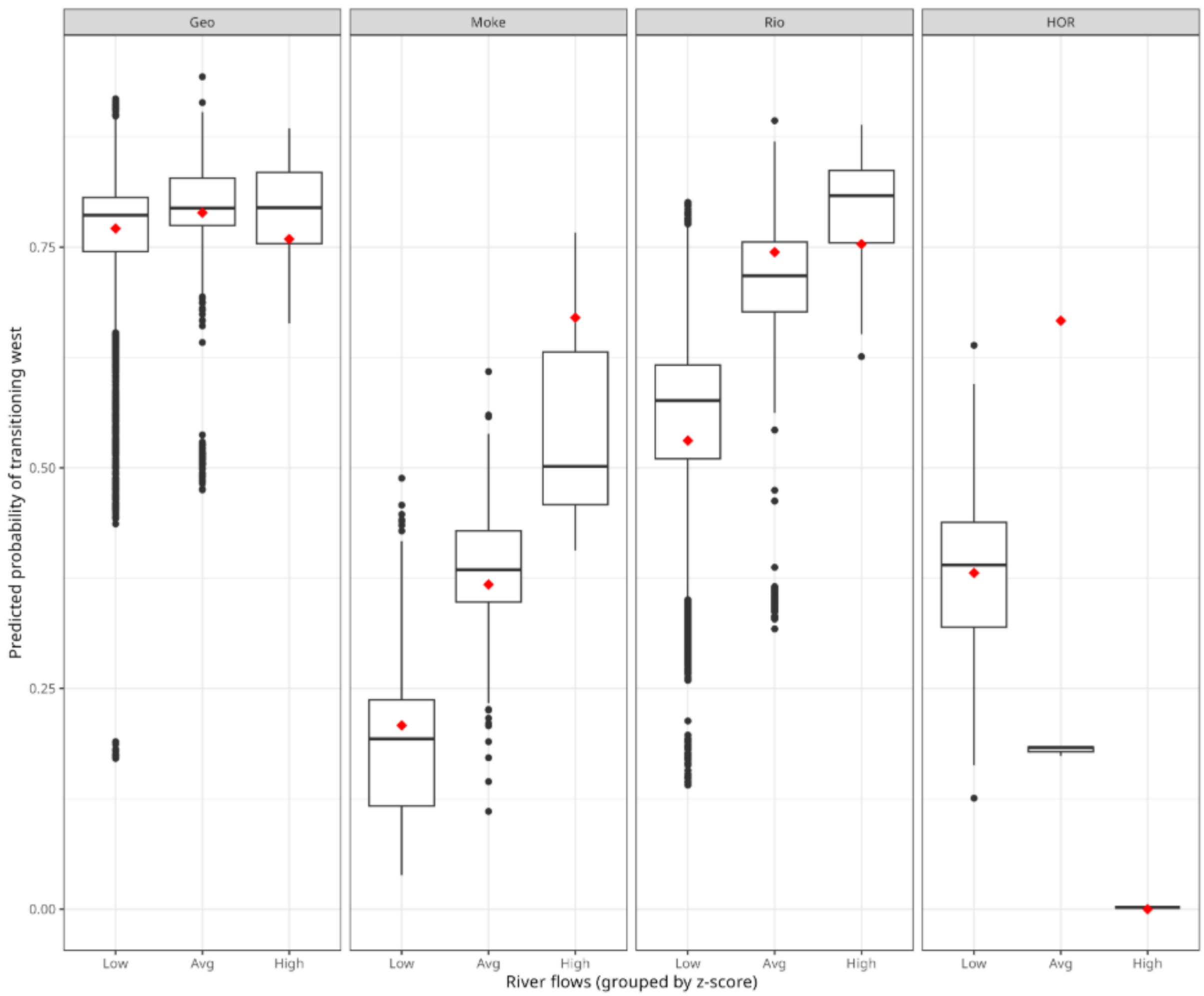
The model estimated that the probability of remaining in the mainstem was different for each location (Table 1). Model results are presented using values for Georgiana Slough as the baseline condition for comparison. Remaining in the mainstem at Rio Vista was estimated to be more probable relative to the probability of remaining in the mainstem at Mokelumne and Head of Old River junctions, but all three of these locations had lower probabilities of remaining in the mainstem compared to the Georgianna Slough junction. Larger fish were expected to be more likely to remain in the mainstem (Table 1).

Table 1. Model Estimates for a Hierarchical Binomial Generalized Linear Model Using the Probability of Remaining in the Mainstem at 1 of 4 Locations

Factor	Mean Estimate	5% CI	95% CI
(Intercept)	-0.21	-0.94	0.51
Exports	-0.17	-0.24	-0.1
River flow	-0.11	-0.17	-0.047
Fork length	0.0087	0.007	0.011
Junction – Mokelumne	-2.7	-2.9	-2.5
Junction – Rio Vista	-0.93	-1	-0.83
Junction – San Joaquin River	-2.6	-3	-2.2
Exports:Junction – Mokelumne	0.078	-0.061	0.21
Exports:Junction – Rio Vista	0.18	0.1	0.26
Exports:Junction – San Joaquin River	0.018	-0.31	0.34
River flow:Junction – Mokelumne	0.52	0.39	0.64
River flow:Junction – Rio Vista	0.32	0.25	0.39
River flow:Junction – San Joaquin River	-1.4	-1.8	-1.1

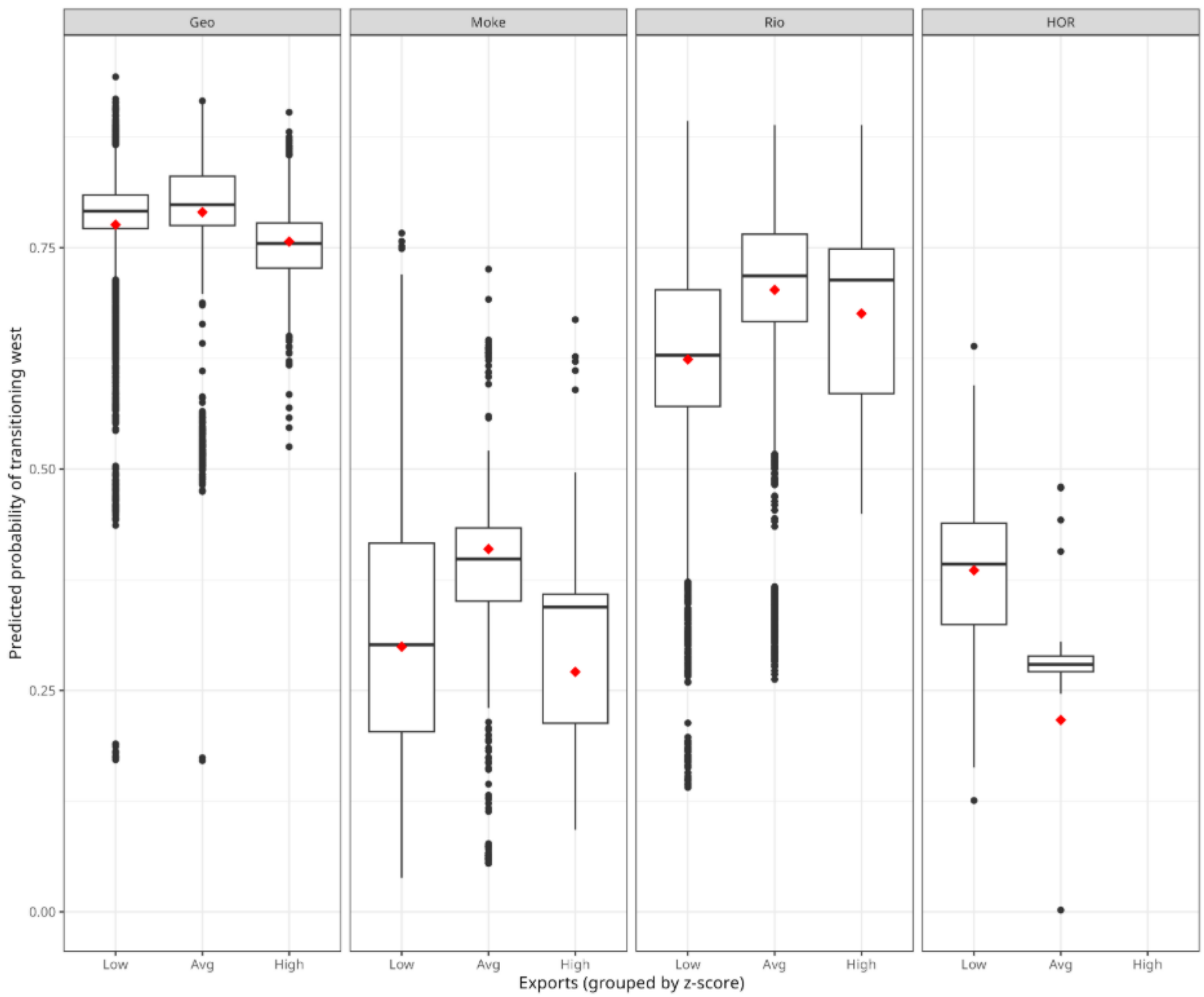
Note: Georgiana Slough is the baseline value to which other junctions are compared.
Key: CI = Credible Interval

Overall, exports and river flow were both correlated with lower probability of remaining in the mainstem consistent with observed trends (Appendix B); however, there were differences between junctions. River flows and exports had a lower impact at Georgiana Slough (Figure 2 and Figure 3), where the probability of remaining was high regardless. Higher river flows increased the probability of remaining in the mainstem at the Mokelumne and Rio Vista junctions (Figure 2), while exports had mixed impacts (Figure 3). The Head of Old River junction experienced lower probabilities of remaining in the mainstem with both increasing export rates and river flows. In most cases, this matched the observed proportions except for river flows at Head of Old River. In this case, the observed proportion was higher than expected – however, there is a small number of fish observed making this transition and thus could be an outlier.



Note: River flows were modeled as a continuous variable – classification (via equal bin-width method) only for illustrative purposes.

Figure 2. Predicted Probability of Transitioning Westward at Each Study Junction by River Flow Classified by z-score (boxplots) with Observed Proportions (red points)



Note: Exports were modeled as a continuous variable – classification (via equal bin-width method) only for illustrative purposes.

Figure 3. Predicted Probability of Transitioning Westward from Each Junction by the Observed Average Daily Export Rate (boxplots) with Observed Proportions (red points)

Discussion

For tagged fish at the Head of Old River location or the Georgiana Slough location:

- HO_1: the probability of entry from the mainstem San Joaquin River into the Head of Old River or from the mainstem Sacramento River into Georgiana Slough is unrelated to export rates. **Partially Accept**

- HO_2: the probability of entry from the mainstem San Joaquin River into the Head of Old River or from the mainstem Sacramento River into Georgiana Slough is unrelated to flow rate at Vernalis and Freeport, respectively. **Partially Accept**

Exports (HO_1) and San Joaquin River flow (HO_2) had negative and positive effects, respectively, on probability of continuing routing downstream in the San Joaquin River for fish detected at Head of Old River, but no effect was observed for exports and Sacramento River flows for fish detected at the Georgiana Slough junction.

Cavallo et al. (2015) modeled salmon routing at six junctions in the Delta and found little evidence of an export effect at tidally dominated locations. That study reported an export effect at the Head of Old River junction, which has strong riverine influence, consistent with results of this analysis, which showed exports were the only consistent predictor of routing at the Head of Old River junction.

Prior studies found inverse relationships between river flows and interior Delta routing at both junctions, for late-fall Chinook salmon at Georgiana Slough (Perry et al. 2018), and for steelhead and salmon at Head of Old River (Buchanan et al. 2016, 2024), though no consistent effect was shown for winter-run Chinook salmon (Hance et al. 2021). The results of this analysis are broadly consistent with these findings.

For tagged fish at the junction of the San Joaquin River and Mokelumne River:

- HO_3: the probability of moving west is unrelated to JPF. **Reject**
- HO_4: the probability of moving west is unrelated to export rates. **Fail to Reject**

The JPF (HO_3) had a positive effect on probability of routing towards the ocean for fish detected at the Mokelumne River junction. Exports (HO4) showed no strong directional effect.

A single study on the Mokelumne River (Del Real et al. 2012) found that the majority of acoustically tagged steelhead routed primarily through this junction into the San Joaquin River and successfully migrated towards the ocean, but the study did not explicitly examine environmental determinants of routing choice. This analysis found that higher JPFs were associated with higher routing probability downstream into the San Joaquin River and towards the ocean.

As stated earlier, Cavallo et al. (2015) modeled salmon routing at six junctions in the Delta and found little evidence of an export effect at tidally dominated locations, which is consistent with the findings of this analysis on exports and routing at the San Joaquin and Mokelumne River junction.

For tagged fish detected at Rio Vista:

- HO_5: the probability of moving west to Chipps is unrelated to exports and/or Sacramento River flow. **Partially Accept**

Sacramento River flow, but not exports (HO_5), had a positive effect on routing towards the ocean for fish detected at Rio Vista.

Telemetry studies on the Sacramento River primarily focus on routing upstream of Rio Vista. Perry et al. (2012) did include a receiver in three-mile slough downstream of Rio Vista, but it was not a significant factor in the study. The results of this analysis indicate that higher river flows are a significant factor at Rio Vista in increasing routing probability downstream to the ocean. It is also important to note, however, that median routing probability was already moderately high (approximately 0.60) at this junction even under low Sacramento River flows.

Cavallo et al. (2015) findings were consistent with the findings of this analysis on exports and routing at Rio Vista.

Overall, relatively simplistic analysis was used to examine the effects of exports and river flows on the routing probabilities at various points. While this analysis is suitable for answering the research questions presented, a more complex analysis that could account for the total detection history as well as fully account for non-detection is suggested for further investigation. Potential analysis approaches include Hidden-Markov models or other Mark-Recapture models. However, these techniques can be highly technical and require time and expertise to properly implement.

Key Findings

1. In 3 of the 4 locations tested, river inflow, had a greater effect on routing towards the ocean than exports.
2. Exports had the greatest effect on routing towards the ocean at HOR, the single junction that is not tidally dominated.

References

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Appendix A

Study Plan

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This study plan proposes to leverage telemetry data across years and releases to make inferences about juvenile salmonid behavioral responses to hydrodynamic conditions in the Delta and changes to that hydrology as influenced by operations. By combining data from multiple years and releases, we hypothesize that a greater range of hydrologic conditions will be observed and a larger number of detections in the area of interest will be available for more robust inference. A key requirement will be the assumption that all races of Chinook Salmon respond similarly to hydrologic cues. Steelhead will be analyzed separately but are not composed of multiple races in the Central Valley.

Given the assumption above, this study plan proposes to query the Environmental Research Division's Data Access Program database to identify studies that have acoustically tagged fish detected in study area. The Stantec team, led by Cramer Fish Science, will then proceed to:

1. Obtain environmental variables for the time periods when the identified studies occurred to define the range of conditions for which inference could be made.
2. Produce a map of acoustic receiver distributions for each study to define the extent of potential behavior.
3. Once the data sets are assembled, meet with Reclamation staff to present findings and recommendations about the method and extent of potential analyses.
4. Proceed with analyses identified in number 3 above and produce a draft report.
5. Integrate comments from Reclamation and produce a final report by March 15, 2026.

Appendix B

Supplemental Figures

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The figures below provide additional context and information for the Assessing Operations and Environmental Conditions on Central Valley Chinook Salmon and Steelhead Juvenile Movement Technical Memorandum.

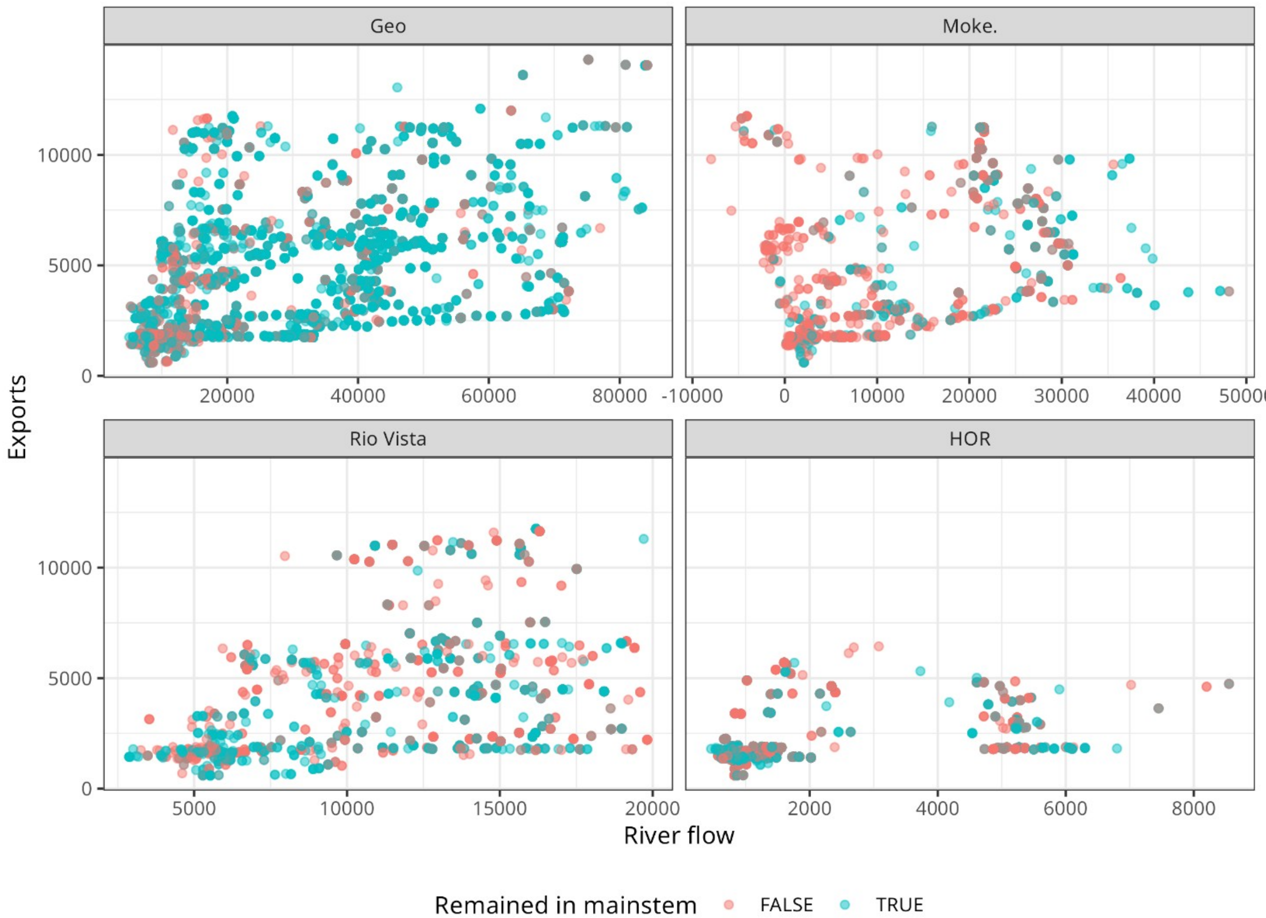

Figure B1: Scatterplot of River Discharge by Exports and Observed Routing for Acoustically Tagged Chinook Salmon and Steelhead in the Sacramento and San Joaquin Rivers

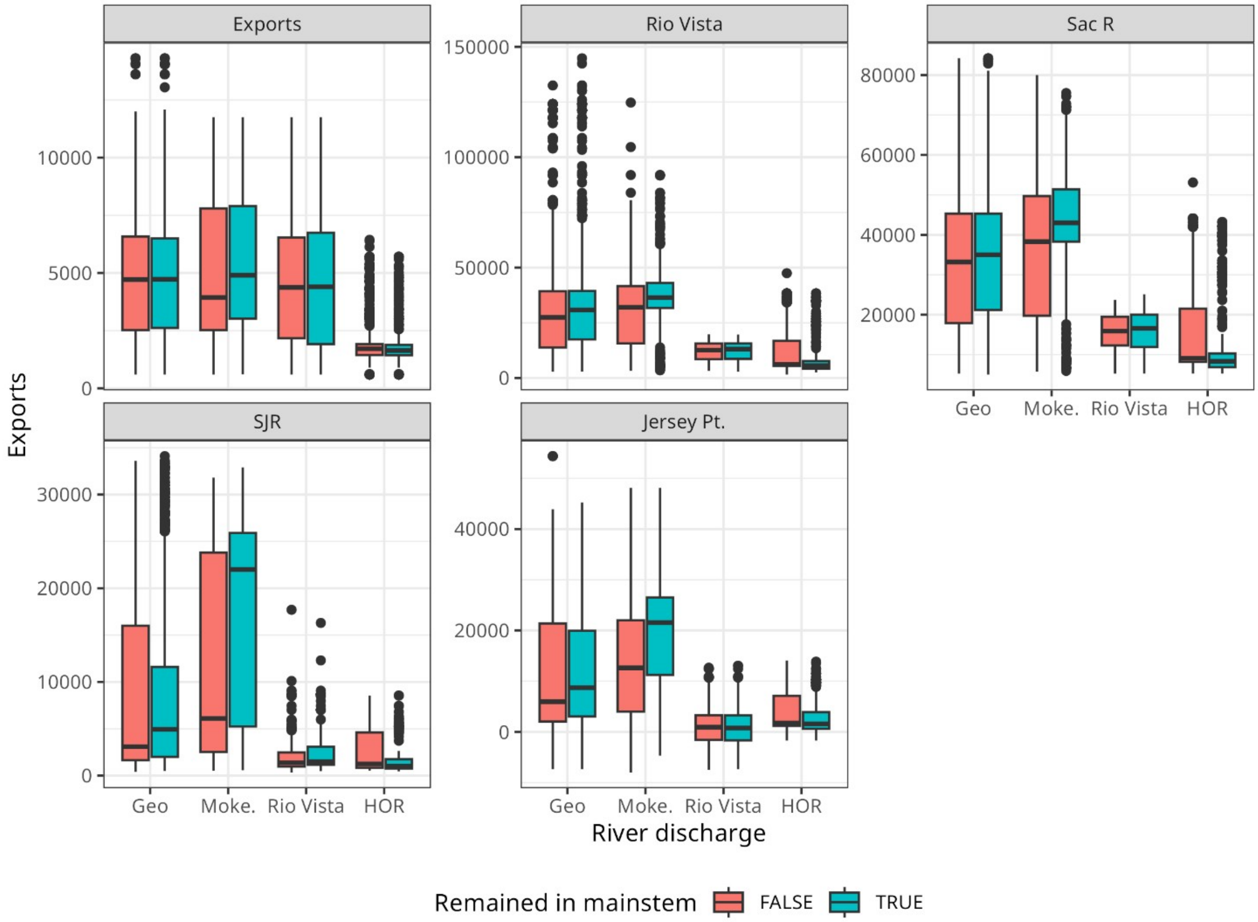

Figure B2: Boxplots of River Discharge by Exports and Observed Routing for Acoustically Tagged Chinook Salmon and Steelhead in the Sacramento and San Joaquin Rivers