Technical Memorandum

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

Smolt-to-Adult and Smolt-to-Salvage Modeling for Central Valley Chinook Salmon and Steelhead

Introduction

Identifying drivers of change in survivorship from juveniles to subsequent life stages is critical to understanding population-level impacts of environmental variability and human-induced changes in ecosystems. Often these data are difficult to obtain for salmonids as they require monitoring of multiple generations over a broad geographical range. A unique opportunity exists in the Central Valley through analysis of release and recovery data from coded wire tags (CWT). CWTs are short lengths of wire with a binary code that can be implanted in the rostrum of juvenile salmon prior to release to identify the source hatchery, date, and place of release. The same code is used for thousands to tens of thousands of fish within a release group, and a single release may use multiple tag number-batches. Tagged fish are also marked with an adipose fin clip. Marked and tagged fish are recovered in the ocean fishery, freshwater monitoring programs, and spawning ground surveys. These tags have been used for monitoring and directed studies in the Central Valley for decades and provide a unique opportunity to test hypotheses about population-level effects of juvenile experience (Zeug and Cavallo 2013) and the fraction of juveniles that arrive at salvage under different conditions (Zeug and Cavallo 2014).

Here CWT data from releases from 1998 to 2025, are used to assess: 1) the impact of environmental and operational variables and the proportion observed at salvage on the probability of survival to adult size (smolt/adult ratio or SAR), and 2) the effects of operational and environmental variables on salvage probability. 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 distance of the release from Chipps Island, the mean size of fish in the release group, water temperature on the day of release, ocean productivity, race/species, and river basin.

The probability of survival to adult size (based on tag recovery):

- HO_1: is unrelated to the fraction of tags recovered at salvage.
- HO_2: is unrelated to export rate.
- HO_3: is unrelated to discharge from the basin where released.

The probability of tag recovery at salvage:

- HO_4: is unrelated to exports.
- HO_5: is unrelated to Jersey Point flow.

Methods

The SAR was modeled as a binomial response (number of estimated successful surviving adults; total tags released). The SAR was retrieved from the Regional Mark Information System (RMIS; rmis.org) database (SA1 Report) for every release of Chinook salmon and steelhead in the Sacramento and San Joaquin River basins over the study period 1998-2025 (Figure 1). Reported survival to adult is the combined "Expanded Fishery Contribution Rate" (fishery harvest) and "Expanded Escapement Rate" (returning spawning adults). For Hypotheses 1, 2, and 3, fishing/sampling effort is accounted for by the expansion formulas underlying both component pieces.

To test the impact of environmental conditions during the Sacramento-San Joaquin Delta (Delta) passage phase on SAR, total exports and river-basin discharge were used as predictors. Species, run, release river km, water temperature at release, and average release weight (g) were included as covariates to account for differences between release groups. To account for environmental variation during the ocean phase, two summary metrics (Principal Components 1 & 2) based on sixteen ocean productivity metrics for the year of entry to the ocean were included as covariates in the model.

Average release weight was not reported for approximately 10% of releases. Most of these releases had average fork length recorded, so for these instances, the average weight was imputed via linear regression based on the fork length. Approximately 2% of releases (N = 15) reported neither and were dropped from the analysis.

River kilometer (km) was calculated as the distance from each release site to Chipps Island using the California Streams dataset. For releases on tributaries, the river km was calculated as the length along the tributary plus the remaining length from the junction point along the downstream river down to Chipps Island.

Exports and river basin discharge (both standardized to z-scores) for the Delta passage phase for each release were calculated as the average DayFlow modeled value of each variable for the 7-day period preceding the median date of arrival at Chipps Island (i.e., when fish were estimated to be in the Delta and susceptible to these influences). For release groups that were not observed at Chipps Island, the average arrival date was estimated using a Gamma-distributed Generalized Linear Model (GLM) fit to the observed groups.

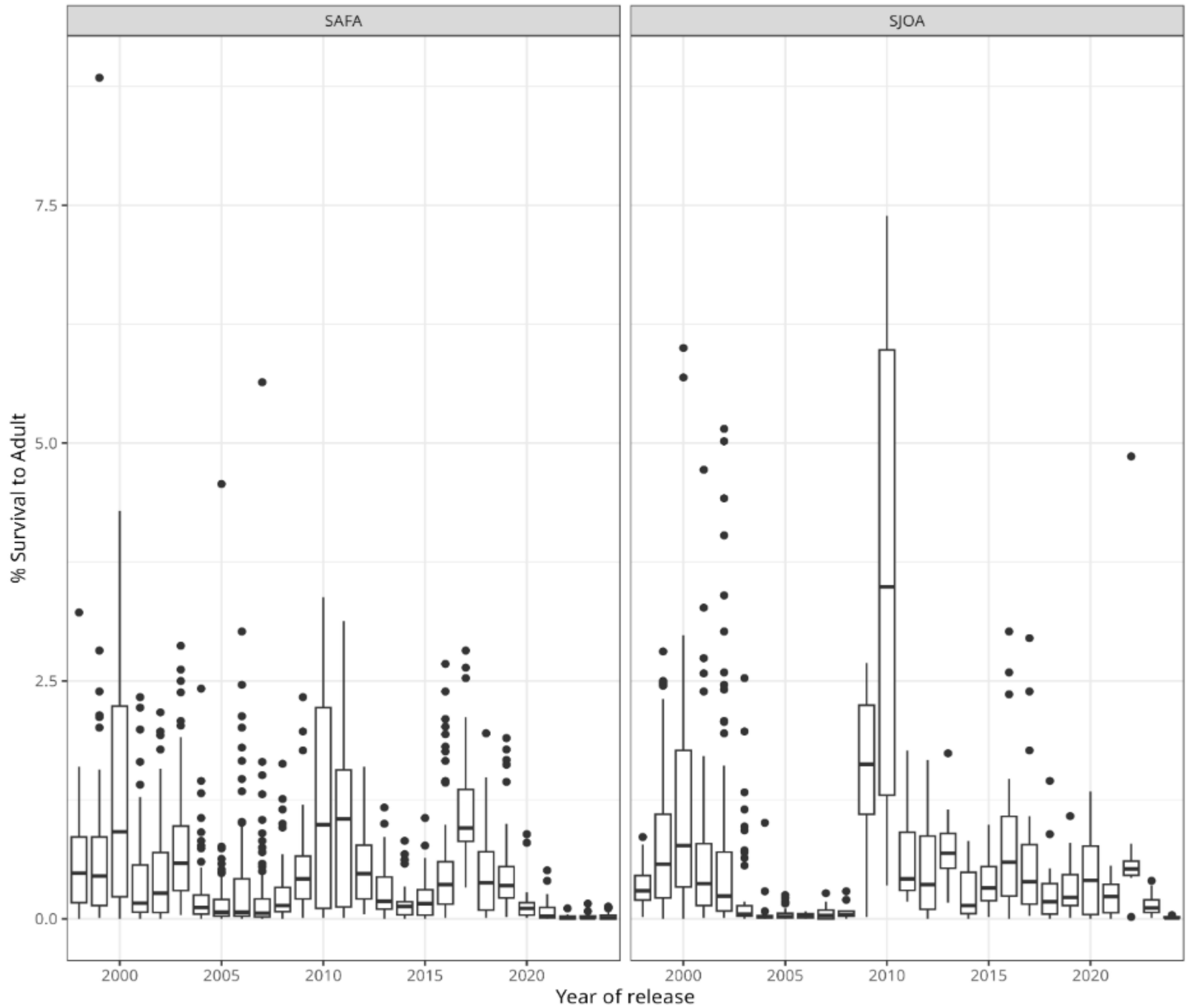


Figure 1. Range of Percent Survival to the Adult Lifestage for Chinook Salmon and Steelhead Released in the Sacramento (SAFA) and San Joaquin (SJOA) River Basins between 1998 and 2025

Daily average water temperature values for each release were accessed from the closest available California Data Exchange Center (CDEC) station on the river basin. In 1998-2000, there was no available data from the CDEC network for some releases (48 releases), on the Mokelumne, Merced, Tuolumne, and Feather Rivers. For these few releases, modeled water temperature from DSM2 was used instead. It was determined that DSM2-modeled river temperatures were poor for the Mokelumne and Feather Rivers. However, the modeled temperatures for the Cosumnes and Yuba Rivers were tightly correlated with observed values from the Mokelumne and Feather Rivers (respectively) and were thus deemed to be suitable surrogate water temperature measures.

The SAR data was analyzed using a Binomial Generalized Linear Mixed-Effects Model (GLMM) (logit-link). The random effects included species, run/race, release year, and release river basin. The models were fit using the \`rstanarm\` package in R (v. 2.32.2; Goodrich et al. 2025). For the salvage analysis, the Binomial GLMM could not capture the high number of zero values in the salvage data, so a zero-inflated GLMM was used instead. The same predictors and random effects were used for both the zero- and non-zero components. The zero inflated model was fit using the `cmdstanr` package in R (v. 0.9.0; Gabry et al. 2025). Both models used default/weakly informative priors. Model diagnostics and posterior predictive checks were inspected to ensure model validity and goodness-of-fit (including over-dispersion) prior to reporting.

See Table 1 for data sources and dates of access.

Table 1. Data Sources

Data	Source	Date Accessed
Coded Wire Tag Smolt/Adult ratios	RMIS[1]	January 14, 2026
Release location and date of release	RMIS[1]	January 14, 2026
Release species, race, and average length	RMIS[1]	January 14, 2026
Recovery at Chipps Island	RMIS[1]	February 1, 2026
Recovery at Salvage (CVP and SWP)	SacPAS[2]	January 16, 2026
Ocean Productivity Indices	NOAA[3]	January 16, 2026
Exports during Delta Passage*	Dayflow[4]	December 30, 2025
River Flows on Delta Entrance*	Dayflow[4]	December 30, 2025
Water Temperature at Release	CDEC[5]	February 2, 2026
Release river kilometer	*Derived from California Streams[6]	February 16, 2026

Notes:
[1] rmis.org
[2] https://www.cbr.washington.edu/sacramento/data/query_loss_detail.html
[3] https://www.fisheries.noaa.gov/west-coast/science-data/ocean-conditions-indicators-trends
[4] https://data.cnra.ca.gov/dataset/dayflow
[5] https://cdec.water.ca.gov/
[6] https://data.cnra.ca.gov/dataset/california-streams
* Delta passage assumed to be the 7-day period before arrival at Chipps Island. For releases not observed at Chipps Island, the arrival timing was estimated based on similar release groups.
Key:
CDEC = California Data Exchange Center
NOAA = National Oceanic and Atmospheric Administration
RMIS = Regional Mark Information System

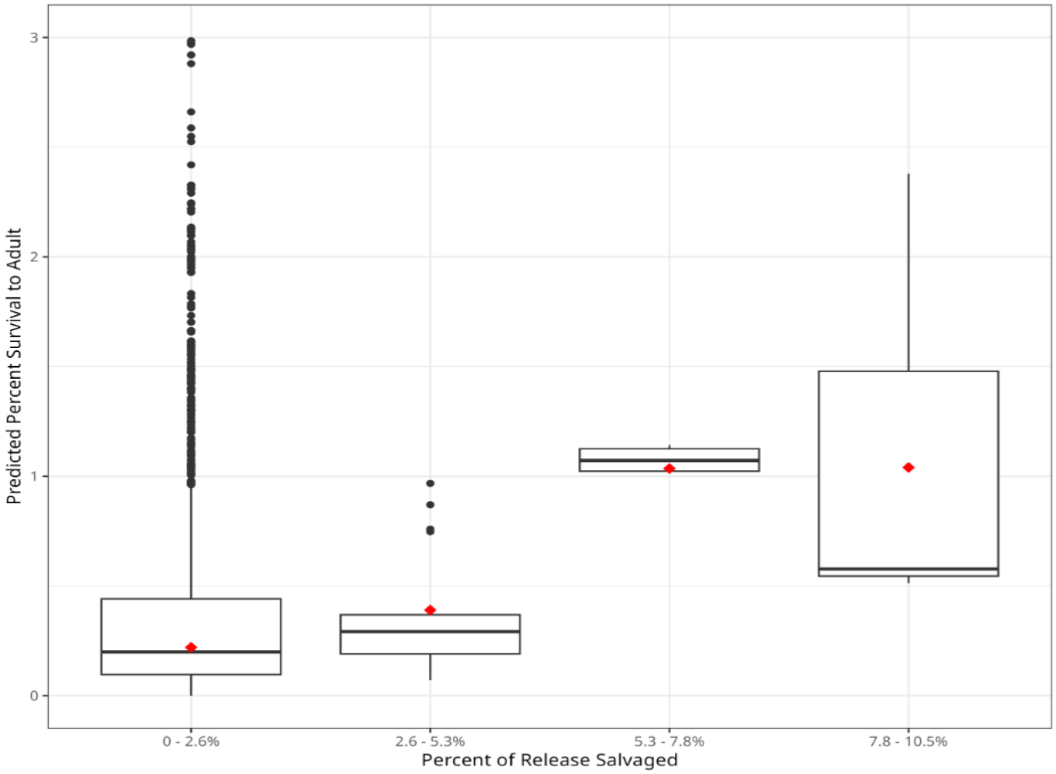
Results

The SAR model estimated that survival to adult was influenced by predictors for each stage of survival. For the release stage, releases farther from Chipps Island and at higher water temperatures were both associated with reduced survival to adult, while larger average weight release cohorts were associated with higher survival to adult (Table 2). River discharge and exports were uncorrelated (Appendix B). Increased river flow, exports, and the percent salvaged were all associated with increased survival to adult (Figures 2 and 3; Table 2). For the ocean stage, PC1 of the National Oceanic and Atmospheric Administration (NOAA) ocean indices had an inconsistent effect (parameter estimate spanned zero effect), while PC2 had a consistent negative effect. This suggests some of the ocean variability was being accounted for in the PCs (Table 2).

Table 2. Parameter Estimates for a Binomial (logit-link) Mixed—Effects GLM for Survival to Adult in Chinook Salmon and Steelhead Coded-Wire Tag Releases

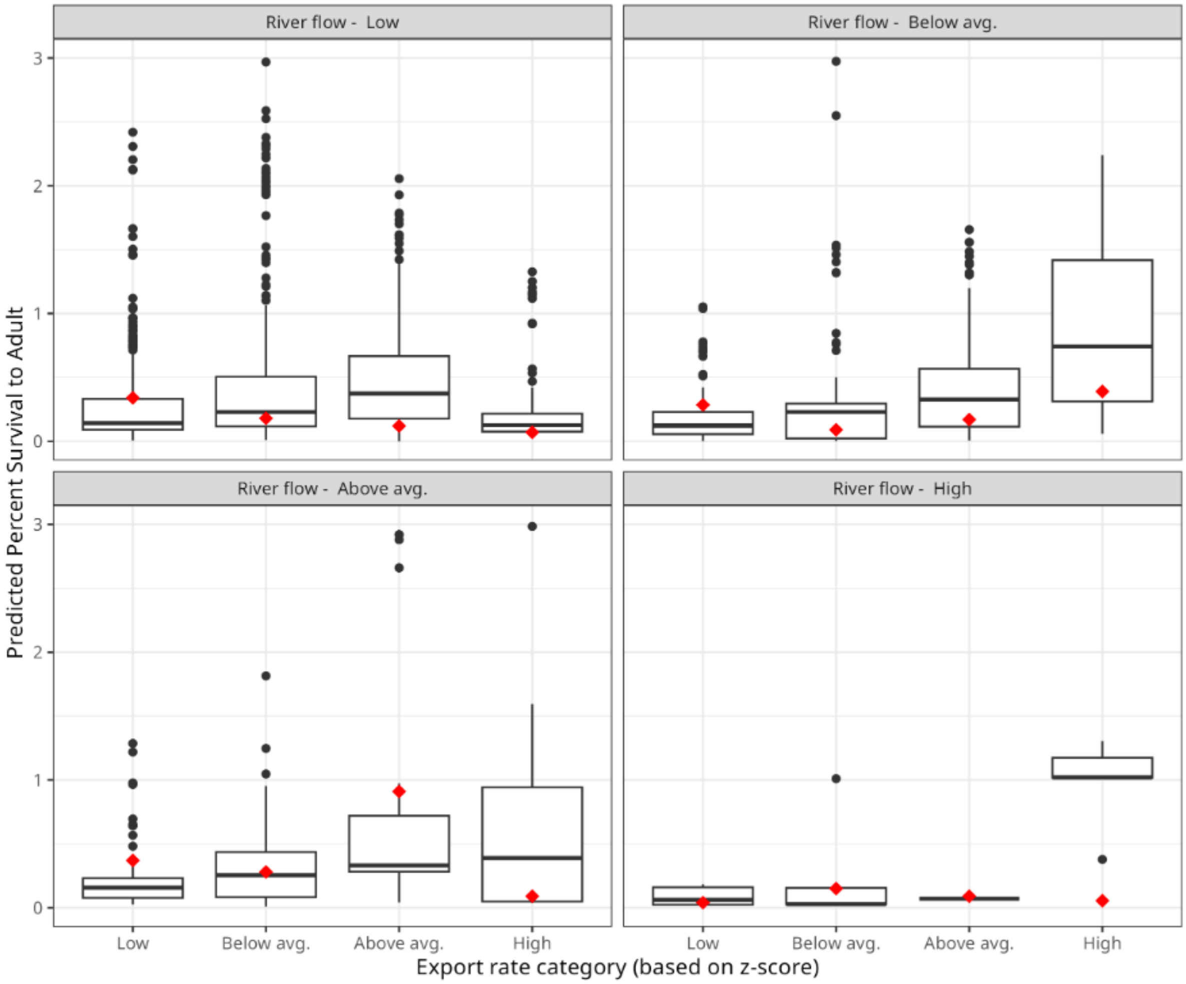
Parameter	Mean Estimate	5% CI	95% CI
(Intercept)	-4.45	-7.6	-0.529
Release – River km	-0.526	-0.532	-0.52
Release – avg. weight	0.881	0.873	0.889
Release – water temperature	-0.00419	-0.00751	-0.00073
Delta - river flow	0.0579	0.0553	0.0605
Delta - exports	0.2	0.197	0.203
Delta – percent recovered salvage	0.189	0.185	0.193
Ocean – Indices PC1	-0.037	-0.166	0.0932
Ocean – Indices PC2	-0.258	-0.495	-0.0272

Key:
CI = Credible Interval
PC = Principal Component



Note: Red diamonds are the median observed survivals to adult life-stage for each group. Salvage was modeled as a continuous variable – categorization (via equal bin-width method) only for illustrative purposes.

Figure 2. Predicted Percent Survival to the Adult Lifestage by the Percentage of the Release Observed in Salvage for Chinook Salmon and Steelhead Released in the Sacramento and San Joaquin River Basins Between 1998 and 2025



Note: Red diamonds are the median observed survival to adult life-stage for each group. Both export rate and river basin flows were modeled as continuous variables – categorization (via equal bin-width method) only for illustrative purposes.

Figure 3. Range of Percent Survival to the Adult Lifestage by Export Rate and River Flow (categorized by z-score) for Chinook Salmon and Steelhead Released in the Sacramento and San Joaquin River Basins Between 1998 and 2025

The results of the salvage model largely reflected the results of the SAR analysis. Average weight, river flow, and exports were all associated with increased probability of being salvaged (Table 3). Unlike the SAR analysis, the release river km was positively associated with the probability of being salvaged, likely due to an increased number of fish being exposed to the salvage facilities from the nearer release locations (Table 3). Increased water temperatures were associated with lower probability of being salvaged, likely reflecting reduced survival overall (Table 3). This is reflected in water temperatures having a positive effect in the zero-inflated component of the model. Export rates and Jersey Point river flows increased the probability in the zero-component, suggesting higher flows reduced the number of fish exposed to salvage (Table 3).

Table 3. Hierarchical Zero-inflated Binomial Generalized Linear Model (logit-link) Estimates for the Probability of being Salvaged as a Response to Jersey Point Flows and Export Rates While Accounting for Release Covariates

Parameter	Mean Estimate	5% CI	95% CI
(Intercept)	-7.06	-9.71	-3.9
Release – river kilometer	0.558	0.523	0.593
Release – average weight	0.878	0.859	0.896
Release – water temperature	-0.0765	-0.0807	-0.0724
River flow	0.465	0.453	0.476
Exports	0.337	0.328	0.346
Zero-inflated components			
(Intercept)	3.26	3.22	2.46
Release – river kilometer	-1.67	-1.67	0.282
Release – average weight	-1.14	-1.13	0.257
Release – water temperature	0.421	0.418	0.106
River flow	0.311	0.309	0.114
Exports	0.00434	0.00416	0.1

Key:
CI = Credible Interval

Discussion

The probability of tag recovery in the ocean:

- HO_1: is unrelated to the fraction of tags recovered at salvage.
- HO_2: is unrelated to export rate.
- HO_3: is unrelated to discharge from the basin where released.

Model results indicate that all three of the above hypotheses can be rejected. For HO_1, there was a well-supported positive relationship between SAR and percent salvage. This finding suggests that survival to adult size is not negatively impacted by salvage at the observed rates. It is not logical that there would be a mechanistic basis for the relationship as fish lost at salvage cannot become adults. Instead, salvage likely indexes good conditions for through-Delta survival when greater numbers make it both to salvage and the ocean. For HO_2, exports also had a positive, well-supported effect on ocean tag recovery. This is notable, as previous findings by Zeug and Cavallo (2013) found no significant correlation between exports and ocean tag recovery. For HO_3, river flows had positive and well-supported effects on SAR and this variable has been positively associated with migration survival in multiple studies where water movement is unidirectional (Perry et al. 2018, Hassrick et al. 2022, Zeug et al. 2020).

The probability of tag recovery at salvage:

- HO_4: is unrelated to exports
- HO_5: is unrelated to Jersey Point flow

Results from the salvage model indicate that HO_4 and HO_5 can both be rejected. Exports had a positive, well-supported relationship with salvage. A similar relationship was reported in earlier analyses of CWT data (Kimmerer 2008, Zeug and Cavallo 2014). River flow also had a positive and well-supported relationship with salvage, and a similar relationship was reported by Zeug and Cavallo (2014). This may occur via the effect of flow on survival. At higher flows, more fish survive to be observed at salvage whereas in low flow conditions, abundance may be so low as to not be detected at salvage.

Collectively, the observed relationships between hydrology, salvage, and ocean tag recovery suggest that salvage serves as a metric for overall survival rather than an index of population-level impacts. Because such a small proportion of fish from a given release cohort enter salvage, the associated impacts, whether negative (loss to export facilities) or positive (increased survival from trucking), would have a negligible effect on ocean recovery. This is supported by the fact that all consistent predictors track positively with the response variable: wetter conditions increase survival for both volitional migrants and salvaged fish while allowing for greater export flexibility, whereas drier conditions coincide with restricted exports and lower survival across both pathways.

Key Findings

1. Salvage, exports, and river flows were positively associated with the probability of tag recovery in the ocean.
2. Exports and river flows were positively associated with the probability of tag recovery at salvage. This is likely due to positive effects of flow on through-Delta survival, meaning more fish survive to salvage facilities.
3. These data indicate salvage serves as a metric for overall survival rather than an index of population-level impacts.

References

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Appendix A

Study Plan

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A key uncertainty in evaluating entrainment and operational effects on salmon survival is that the magnitude of potential effects cannot be quantified without scaling to the size of the cohort. For example, loss of 100 fish is a larger magnitude effect for a cohort of 1,000 migrants (10%) than a cohort of 1,000,000 (0.01%). When analyzing raw salvage/loss, this magnitude cannot be estimated. Further, the effect of entrainment and operations on survival to subsequent life stages cannot be quantified with unscaled data (e.g., what level of entrainment results in a detectable decline in adult abundance). Releases of coded wire tagged (CWT) juvenile salmon provide a way to estimate entrainment and operational effects with a scalable population. Every year, millions of coded wire tagged Chinook Salmon are released upstream of the Delta as part of mitigation and conservation releases. This includes both Endangered Species Act listed (spring run and winter run) and unlisted (fall run, late fall run) Chinook Salmon. Fish that receive a CWT are also marked with an adipose fin clip and when they are encountered in freshwater monitoring programs, ocean fisheries, or spawning surveys, fish are retained and linked via the CWT code to a specific release group, release time, and location.

This Study Plan proposes to take advantage of these data to estimate, 1) the effects of operational and environmental variables on salvage probability, and 2) the relationship between salvage and the probability of survival to adult size (SAR). Two previous peer reviewed publications performed similar analyses (Zeug and Cavallo 2013, Zeug and Cavallo 2014). Since those studies were published, over a decade of new data have become available including CWT releases of San Joaquin River Restoration Program spring run which is a component that was not available in the previous efforts. In general, we will follow a similar procedure to the previous efforts by developing a priori hypotheses represented by statistical model structure and evaluate those hypotheses with information theoretic methods.

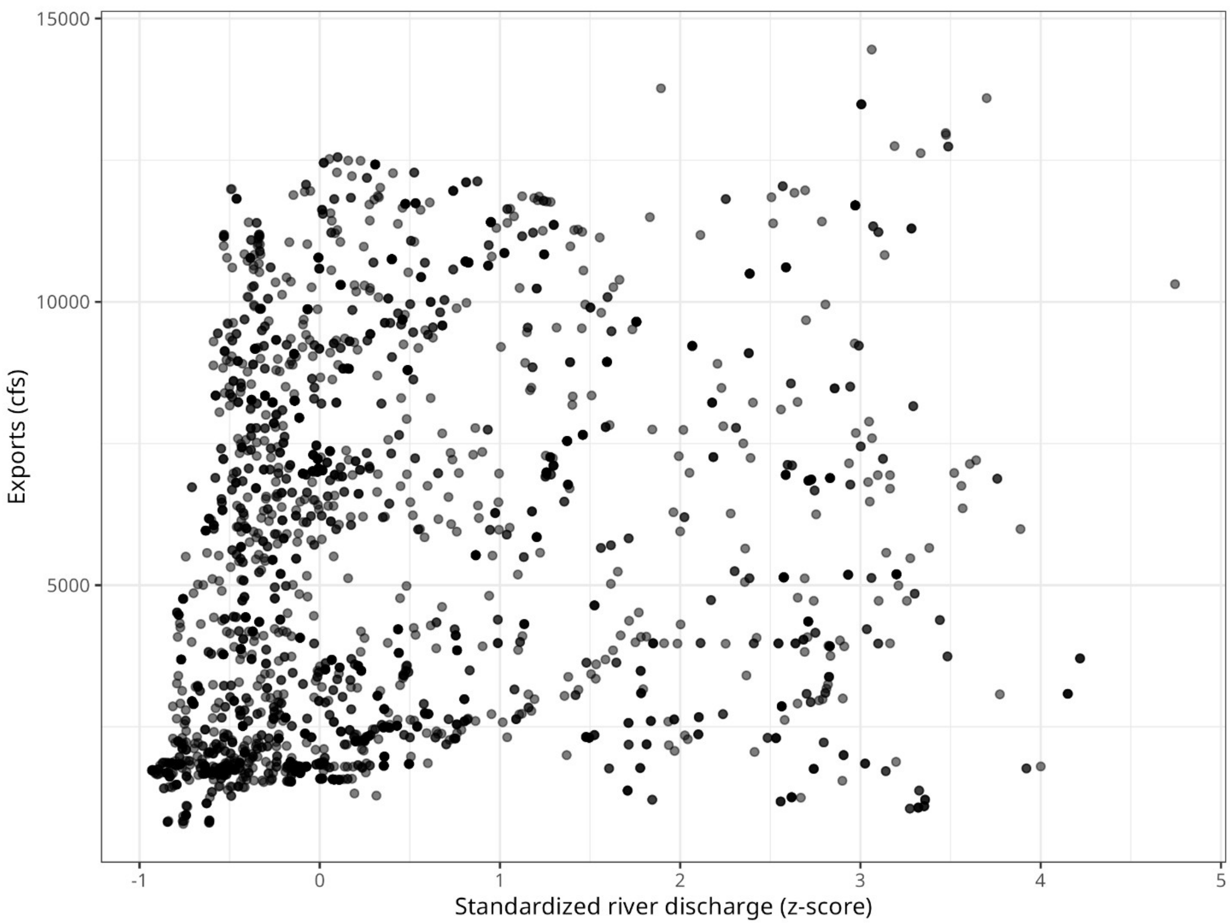
Many hydrologic variables used in Delta operational management are correlated (e.g., OMR, exports, inflow, I:E). Thus, after the CWT and environmental data set are obtained, a meeting with Reclamation staff is proposed to discuss the specific hypotheses and hydrologic parameters to be included and/or decide on the quantitative method used to pare down to a variable set with an acceptable level of multicollinearity. Additionally, we will discuss with Reclamation the appropriate averaging period for release groups to best describe the time period when CWT release groups are exposed to Delta conditions. Once there is agreement on hypotheses and variable structure, model construction and evaluation will be completed.

Appendix B

Supplemental Figures for Smolt-to-Adult and Smolt-to-Salvage Modeling for Central Valley Chinook Salmon and Steelhead

Appendix B
Supplemental Figures for Smolt-to-Adult and Smolt-to-Salvage Modeling for Central Valley Chinook Salmon and Steelhead

The figure in Appendix B provides supplemental information to the Smolt-to-Adult and Smolt-to-Salvage Modeling for Central Valley Chinook Salmon and Steelhead Technical Memorandum.



Note: The Delta passage stage was defined as the 7-day interval prior to average release arrival at Chipps Island. Arrival date was estimated for releases not observed at Chipps Island.

Figure B1: River Discharge (standardized to z-score by river basin) by Exports for the Delta Passage Stage of Coded Wire Tag Releases from 1998 to 2025 in the Sacramento and San Joaquin River Basins