SACRAMENTO RIVER FALL CHINOOK WORKGROUP PROGRESS REPORT FROM NOVEMBER 2025
AS UPDATED AND STREAMLINED FOR S_{MSY} PEER REVIEW PANEL

In preparing for the S_{MSY} Peer Review Panel, the Sacramento River Fall Chinook Workgroup (SRWG) noticed that the November 2025 progress report and appendices contained some incorrect references to Appendix A for materials that had been moved to the main text. These references have been corrected. In addition, some clarifying text was added to the legend for Figure 2, a reference to the Pacific Salmon Commission Chinook Technical Committee's recommendation on minimum sample sizes for spawner-recruit analyses was added to accompany the Scientific and Statistical Committee's (SSC's) sample size recommendations, the titles of some appendices were clarified, and some typographical errors and formatting inconsistencies in the reference sections of the main text and appendices were addressed. Finally, sections that were not relevant to the S_{MSY} peer review tasks were removed, but can still be accessed from the November 2025 briefing book (Agenda Item G.4).

Following from the SRWG Terms of Reference (TOR) and Council guidance, so far the Workgroup has prioritized reference points and the conservation objective over the control rule or other tasks, and recognizes the importance of both National Standards and Council priorities in guiding its work. Previously, the workgroup has:

- re-affirmed that the status quo conservation objective and S_{MSY} reference point are outdated and determined from flawed assumptions
- completed an update of the F_{MSY} reference point, which was adopted by the Council after methodology review.
- recommended routine implementation of a cohort reconstruction, the methodology for which was approved by the Council for phased implementation after methodology review.

In response to the first item identified in November 2024 guidance to "use the F_{MSY} value adopted under Agenda Item F.2 Salmon Methodology Review to derive an updated S_{MSY} value per the formula described in Agenda Item F.2, Attachment 2", the SRWG derived natural-area S_{MSY} values using four different approaches, identified its preferred approach and reasons for preferring it, wrote a report documenting all four alternatives, and proposed it for methodology review. The topic was added to the preliminary list of methodology review topics in April 2025, but in September 2025 the Council did not select this item for methodology review.

The SRWG realizes that the S_{MSY} value resulting from its preferred analyses is higher than recent returns. The SRWG notes that under the formula used as directed by the Council ($S_{MSY} = F_{MSY} \times S_{MP}$), S_{MSY} is sensitive to both capacity (S_{MP}, the escapement that maximizes production) and

F_{MSY} (linked to productivity, i.e., the higher productivity is the higher F_{MSY} is and the closer S_{MSY} is to S_{MP}).

It has been suggested that the Sacramento Basin may have experienced a "regime shift" that has permanently lowered the productivity and/or capacity of the system for fall Chinook, relative to the earlier years included in the fry recruitment index, which extends back to brood year 1999 in the SRWG's preferred analysis. While it seems plausible that productivity may be persistently lower now than it was prior to the return year 2008-2009 "collapse" (Lindley et al. 2009), this generally lower productivity in recent years may largely be the result of poor flow-dependent downstream migrant survival (Michel 2019) that should be reflected in the preferred model's inclusion of flow covariate (measuring conditions during rearing and outmigration) affecting productivity (Dettman et al. 1987). Use of such a covariate is common in spawner-recruit analyses informing PFMC management, for example STT (2005) and Confer and Falcy (2014).

It is unclear whether any of the recent changes hypothesized to reduce productivity would have reduced capacity as well (i.e. there is still a lot of habitat available when flow and temperature conditions allow its full use). Simulations have demonstrated that attempting to model time-dependent capacity is extremely challenging and "rarely reliable" (Wor et al. 2025), with the authors of that paper recommending "Time-varying capacity models should only be explored when there is strong corroborating evidence, with plausible mechanisms, suggesting that capacity has changed." Simply disregarding data from earlier years is not recommended (Holt and Michielsens 2020). There are examples of past declarations of permanently lower capacity that have not borne out in this system (e.g., based on then-recent declines PFMC [1984] predicted returns to the Upper Sacramento would stabilize around 50,000 adults after the mid-1980s but instead averaged just over 150,000 for 1985-2005 [Satterthwaite 2022]) and other systems (e.g., Terceiro 2011). When identifying plausible hypotheses for changes in productivity and/or capacity, **it is important to consider whether the proposed mechanism is likely to have a density-dependent effect. If density-dependence is hypothesized, it is further necessary to consider whether the relevant density would include hatchery-origin fish**.

S_{MSY} value

Direct estimation of MSY-based reference points using standard methods is not appropriate for SRFC (SRWG 2024a) due to the large contribution of hatchery-origin spawners in natural areas, meaning there is no way to define spawners and recruits such that spawners are the only source of recruits, recruits are the only source of potential harvest, and unfished recruits are the only source of future spawners. Previous SRWG reports noted that estimating S_{MP}, the natural area escapement that maximizes production of recruits (as opposed to maximizing yield), is possible. Under a Ricker spawner-recruit relationship, as is commonly assumed for PFMC-managed salmon stocks, $S_{MSY}=F_{MSY} x S_{MP}$. Thus, given the adoption of an F_{MSY} proxy value for SRFC in

November 2024, derivation of an S_{MSY} proxy could be possible if an estimate of S_{MP} can be developed. Both the Scientific and Statistical Committee (SSC 2024a) and Salmon Technical Team (STT 2024a) have noted the importance of accounting for origin (natural versus hatchery) when estimating recruitment in a spawner-recruit relationship.

The SRWG discussed four approaches (Appendices A-L) that might inform estimation of S_{MP} for SRFC. Each varies in the brood years for which estimates can be made (Figure 1) and has strengths and weaknesses, as described below. The SRWG previously (SRWG 2024b) identified estimates from a cohort reconstruction as the preferred long-term alternative, but noted the **limited number of estimates currently available, covering a limited range of escapements and environmental conditions, with severe confounding between escapement and flow** (i.e. very low flow during rearing and outmigration for the offspring produced from the highest escapement year, low escapements in the years with high flow for offspring, see Figure 2). The SRWG continues to hold this view, and so still sees merit in revisiting spawner-recruit relationships using outputs from a cohort reconstruction in the future, but our currently preferred option would be based on the juvenile production index first developed by Munsch et al. (2020), as presented in Appendix A. Table 1 summarizes the pros and cons of each recruitment metric for the purpose of estimating a spawner-recruit relationship at this time.

Table 1. Pros and cons of each recruitment metric for estimating a spawner-recruit relationship at this time. NOR = natural-origin. HOR = hatchery-origin.

Natural production estimate	Best brood years (see Figure 1)	Pros	Cons	Reference
Fry passing through lower Sacramento River (preferred method)	1999-2020	• Long time series **• Accounts for all natural area sources of NOR juveniles** • Minimal confounding by HOR fish • Geographically and temporally matched to flow covariate **• Parent escapement not confounded with flow conditions during subsequent rearing and outmigration** **• Includes years with high escapement accompanied by high flow for ensuing rearing and outmigration period** • Peer reviewed	• Additional density dependence possible downstream • Poorer prediction in years with larger-sized outmigrants • Some confounding with spring- and winter-run (but note that there are instances where natural-area spring run spawners in the Feather River could be counted as SRFC)	Munsch et al. (2020)
Pre-harvest adults from cohort reconstruction	2007-2016	• Run reconstruction: **Preferred method to estimate recruitment for cohorts with sufficient data** • Endorsed by methodology review, established method for Klamath River Fall Chinook	• Lowest number of data points **• Limited range of escapement** **• Escapement confounded with subsequent flow conditions for offspring** • Contribution of marine life stage to density dependence • Need to account for fry releases in recent years if extended	Chen et al. (2024)

SI * pr(natural-origin spawners)	2007-2018	• Less demanding of data than cohort reconstruction, may be easier to continue into future	• Relatively short time series • **Limited range of escapement** • **Escapement confounded with subsequent flow conditions for offspring** • Contribution of marine life stage to density dependence • **Inaccuracies of SI** • No contribution of multiple adult age classes • Assumes escapement composition of HOR and NOR is the same as ocean harvest	O'Farrell et al. (2013), annual CWT recovery reports
Natural-origin migrants at Red Bluff Diversion Dam	1998-2020	• Long time series • Better sampling of fall run juvenile timing? • Includes years with high flow/ escapement • Deemed suitable to inform rebuilding plan (PFMC 2019)	• **NOR production from Upper Sac only** • Additional possible density dependence downstream • Likely stronger effects of flow downstream	Voss and Poytress (2022)

Figure 1. Brood years for which each of the natural production indices can be estimated based on data currently available to the SRWG. Dark fill indicates estimates can be made, no fill indicates estimates cannot be made (based on the data in hand), and light fill indicates that estimates can be made, with year-specific caveats that do not apply to the years with dark fill.

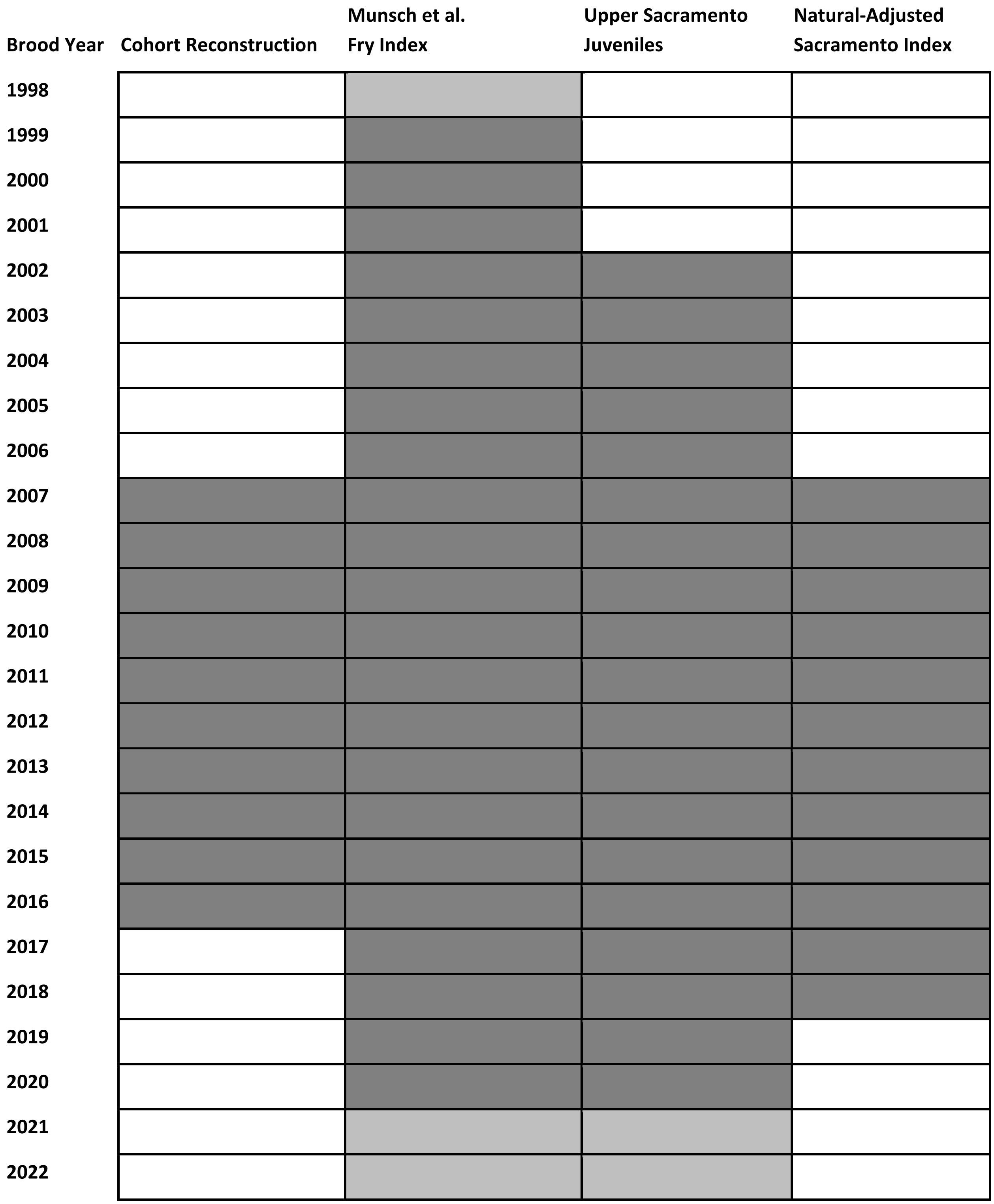
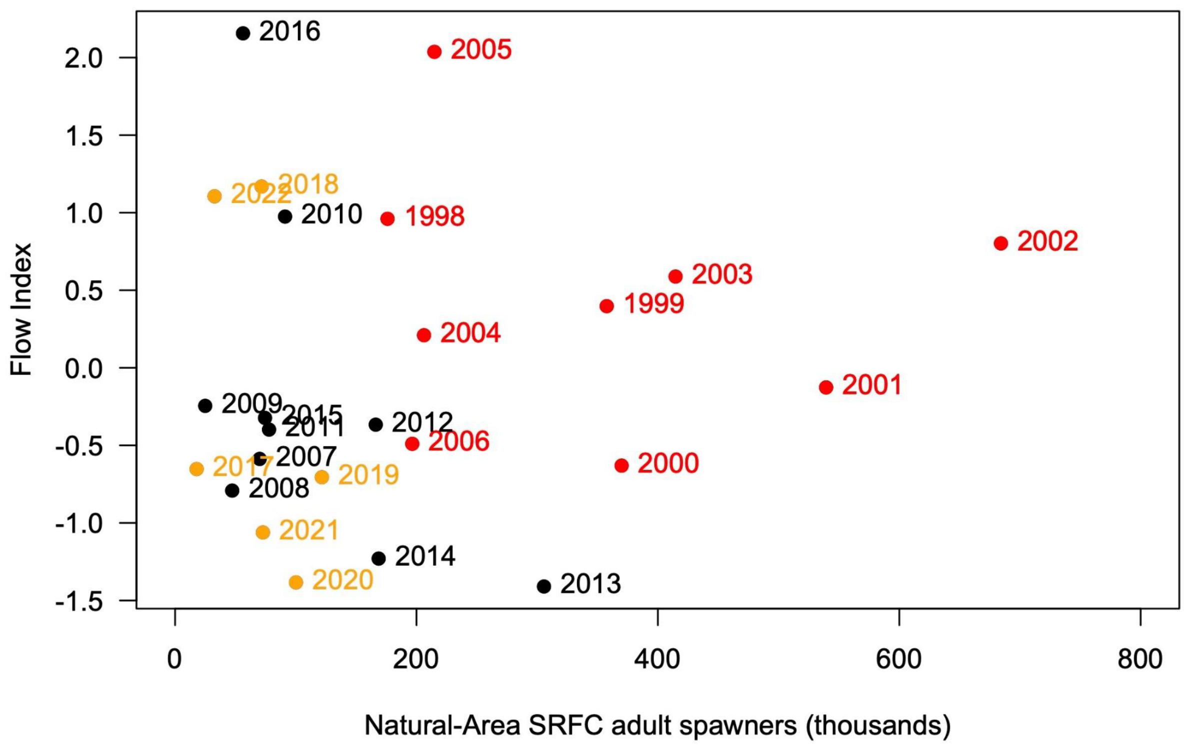


Figure 2. Brood years plotted by natural-area parent escapement (x-axis) and a metric of flow (Munsch et al. 2020) during rearing and outmigration of the offspring of that escapement (y-axis). Brood years in red lack, and always will lack (due to a lack of sufficient tagging and scale reading) the data required for a cohort reconstruction, but allow estimation of a juvenile production index. Brood years in orange have juvenile production index estimates but have not had complete cohort reconstructions performed yet, and may face challenges related to a 2020 gap in ocean fisheries sampling due to COVID-19 and unmarked fry releases increasing from low levels beginning with brood year 2021.



[Munsch et al. (2020)](#) juvenile production index (with flow covariate)

[Munsch et al. (2020)](#) developed an index of natural-origin juvenile (fry, defined here as <55mm) Chinook abundance passing through the lower Sacramento River, which they modeled as a function of natural-area spawners (including fall, spring, and winter-runs; but fall run dominates numerically by a large margin) as well as a covariate characterizing flow levels during rearing and outmigration. The published paper spanned brood years 1998-2015, and further work has extended the index through brood year 2022. Thus, this analysis spans a much wider range of escapements and conditions than currently-available cohort reconstructions, while capturing production throughout the Sacramento basin. Although the SRWG acknowledges the potential for density-dependence after the fry stage, and notes a modest (r=0.34) correlation between the fry index and recruitment (assessed here as natural-origin ocean age-2 abundance) estimates from the cohort reconstruction for common brood years, the SRWG nevertheless finds the peer-reviewed Munsch et al. (2020) fry index a sound metric of natural production, and notes that when escapement (re-parameterized for these purposes to include adult SRFC in natural areas only) and the flow covariate are both included in a spawner-recruit relationship, the explanatory power is acceptable (R^2=0.53).

Thus, the SRWG's preferred approach to derive a natural-area S_{MSY} at this time in is to estimate S_{MP} using an extended version of the Munsch et al. (2020) fry index and flow covariate to model recruitment as a function of natural-area adult SRFC escapement, and multiply the resulting S_{MP} by F_{MSY} to derive S_{MSY}. Due to the potential for the cohort reconstruction to provide better estimates of year-specific recruitment, but its currently limited temporal coverage, the SRWG recommends revisiting the S_{MSY} analysis once cohort reconstruction results are available from a sufficient number of years covering a range of escapements and environmental conditions, particularly higher flow conditions. It is difficult to identify in advance when sufficient data from a sufficient range of conditions will accumulate, but the cohort reconstruction's coverage should be periodically re-assessed, and then S_{MSY} revisited when appropriate.

Although the Munsch et al. (2020) index can be extended further back in time than the cohort reconstruction, **continuing to develop the index for future years will require a way of accounting for unmarked hatchery fry releases when they are recovered in juvenile sampling efforts.**

Cohort reconstruction

The newly completed cohort reconstruction for SRFC (Chen et al. 2024) likely provides the highest-quality estimates of natural-origin SRFC recruitment possible from existing data sources. The SRWG views these estimates as the "gold standard" for SRFC recruitment estimates (especially when recruitment is defined as potential escapement in the absence of fishing), and thinks the cohort reconstruction has considerable short- and long-term potential for informing multiple aspects of management. However, currently the cohort reconstruction only covers brood years 2007-2016. For the purpose of estimating a spawner-recruit relationship, this is a modest sample size with statistical power on the low end compared to typical recommendations (e.g. SSC [2024b] recommended 10-15 years minimum, the Pacific Salmon Commission's Chinook Technical Committee recommended more than 15 year classes [CTC 1999], and Adkison [2022] noted that "for short time series, high values of recruitment tend to be overrepresented at low spawner abundances, and vice versa"). This range of years is also lacking in high escapement years (only one with natural-area escapement above 200,000) and the only high escapement year was accompanied by very low flow during rearing and outmigration (and overall the correlation between spawners and flow for these brood years was -0.49, versus 0.11 for brood years 1999-2020). The combination of small sample size, low contrast in the range of escapements covered, and strong confounding between parent escapement and the flow faced by resultant offspring makes statistical inference from this severely limited dataset unreliable. Therefore, **the SRWG recommends revisiting S_{MSY} based on a spawner-recruit analysis using the cohort reconstruction once estimates are available from a larger number of years covering a broader range of conditions, but does not recommend its use for estimating a spawner-recruit relationship at this time**.

Although the value of the cohort reconstruction is expected to increase over time as additional data become available, this will take considerable time. It is difficult to predict when the next high escapement year might be, and **current management does not generally target high escapements, such that even a strong recruitment event may not lead to high escapement. Even once a high escapement year occurs, there will be a 4-5 year lag before the cohort produced from that high escapement year can be reconstructed**. In addition, there will need to be a commitment to ongoing collection and processing of the required data, including developing new methods to **sample for unmarked fry releases that can only be identified through genetic sampling, which needs to take place wherever SRFC might be recovered (e.g., ocean fisheries along the U. S. West Coast, river harvest, natural spawning areas, and hatcheries).**

Sacramento Index (SI) times Proportion Natural-Origin Escapement

Prior to the availability of cohort reconstruction results, members of the SRWG explored a crude index of natural-origin production based on the Sacramento Index (SI, O'Farrell et al. [2013], an index of potential escapement in the absence of fishing that includes both natural and hatchery-origin fish) times the proportion of escapement that was of natural-origin three years after parent spawning. This suffers from all of the inaccuracies of the SI relative to the cohort reconstruction (Chen et al. 2024) and also relies on the assumption that the composition (hatchery- versus natural-origin) of harvest is the same as the composition of escapement, which would not be the case if hatchery- and natural-origin fish differ in their maturation rates or other aspects of their behavior affecting exposure to the fishery. Given that Chen et al. (2024) estimated natural-origin SRFC age-3 maturation rates ranging from 0.53 to 0.90 with median 0.69, **assuming that potential recruitment from a brood year in the absence of fishing can be fully characterized by returns three years later is not supported**.

Because the estimates of the proportion of escapement that is natural-origin depend on the same constant fractional marking program that enabled the cohort reconstruction, this approach is largely restricted to the same set of years as the cohort reconstruction, with the same resulting limitations in terms of escapements and environmental conditions covered, and therefore is less informative than the Munsch et al. index that covers a wider range of escapements and flows.

In practice, the natural-adjusted SI and the recruitment estimates from the cohort reconstruction were well correlated (i.e. both high in high abundance years, both low in low abundance years) and gave similar results for S_{MP}. The cohort reconstruction approach would be preferred based on first principles because it provides more accurate year-specific estimates, and the SI was developed as an interim measure due to data deficiencies at the time. However, if data deficiencies persist, it might be easier to extend the SI-based approach into the future (and indeed, with the publication of White et al. [2025], it is possible to extend the SI-based approach to two more brood years than those covered by the Chen et al. [2024] cohort reconstruction). Both approaches would require a way of accounting for hatchery-origin fish in the escapement, including unmarked fry releases, but an SI-based approach would not depend on scale aging and might be able to accommodate a lack of genetic sampling of ocean harvest. The SRWG recommends further consideration of this approach only in the event that future data streams are insufficient for cohort reconstructions but sufficient to estimate the SI and the proportion of escapement that is natural-origin.

Upper Sacramento Juvenile Production

The SRWG discussed spawner-recruit relationships fit to fry equivalents (with larger fish included using a correction for expected survival differences) passing downstream of the Red Bluff Diversion Dam rotary screw trap (Voss and Poytress 2022) as a function of females spawning in natural areas above it, as done previously in the SRFC rebuilding plan (PFMC 2019). However, similar to the Munsch et al. index, there is the potential for density dependence after the fry stage, and in this case additional lower river mortality (that might have a density-dependent component) going unmeasured as well. This also represents only a portion of the Sacramento basin, albeit an important one that has had recent escapement shortfalls. Therefore, this data source is not the SRWG's preferred approach for developing S_{MSY}.

References Cited

Adkison, M. D. 2022. A review of salmon spawner-recruitment analysis: The central role of the data and its impact on management strategy. Reviews in Fisheries Science and Aquaculture 30:391-427. Available from: https://doi.org/10.1080/23308249.2021.1972086

Chen, E. K., W. H. Satterthwaite, M. R. O'Farrell, and S. M. Carlson. 2024. Cohort Reconstruction for Sacramento River Fall Chinook salmon and Comparison with the Sacramento Index. Report to Pacific Fishery Management Council. Available from: https://www.pcouncil.org/documents/2024/09/cohort-reconstruction-for-sacramento-fall-chinook-salmon-and-comparison-with-the-sacramento-index.pdf/

Confer, T. and M. Falcy. 2014. Conservation Objective for Southern Oregon Coastal Chinook. Report to Pacific Fishery Management Council. Available from: https://www.pcouncil.org/documents/2014/11/f-salmon-management-november-2014.pdf/#page=123

CTC [Chinook Technical Committee of the Pacific Salmon Commission]. 1999. Maximum sustained yield or biologically based escapement goals for selected chinook salmon stocks used by the Pacific Salmon Commission's Chinook Technical Committee for escapement assessment. Pacific Salmon Commission, Joint Chinook Technical Committee Report TCCHINOOK (99)-3, Vancouver. Available from: https://www.psc.org/download/35/chinook-technical-committee/2172/tcchinook99-3.pdf

Dettman, D. H., D. W. Kelley, and W. T. Mitchell. 1987. The influence of flow on Central Valley salmon. Report to California Department of Water Resources. Available from: https://www.waterboards.ca.gov/waterrights/water_issues/programs/bay_delta/deltaflow/docs/exhibits/cspa/spprt_docs/1987/cspa_dettman_1987.pdf

Holt, C. A. and C. G. J. Michielsens. 2020. Impact of time-varying productivity on estimated stock-recruitment parameters and biological reference points. Canadian Journal of Fisheries and Aquatic Sciences 77:836-847. Available from: https://doi.org/10.1139/cjfas-2019-0104

Lindley, S. T., C. B. Grimes, M. S. Mohr, W. Peterson, J. Stein, J. T. Anderson, L. W. Botsford, D. L. Bottom, C. A. Busack, T. K. Collier, et al. 2009. What caused the Sacramento River fall Chinook stock collapse? US Department of Commerce. NOAA Technical Memorandum NOAA-TM-NMFS-SWFSC-447. Available from: https://www.noaa.gov/sites/default/files/legacy/document/2020/Oct/07354626592.pdf

Michel, C. J. 2019. Decoupling outmigration from marine survival indicates outsized influence of streamflow on cohort success for California's Chinook salmon populations. Canadian Journal of Fisheries and Aquatic Sciences 76:1398–1410. Available from: dx.doi.org/10.1139/cjfas-2018-0140

Munsch, S. H., C. M. Greene, R. C. Johnson, W. H. Satterthwaite, H. Imaki, P. L. Brandes, and M. R. O'Farrell. 2020. Science for integrative management of a diadromous fish stock: interdependencies of fisheries, flow, and habitat restoration. Canadian Journal of Fisheries and Aquatic Sciences 77:1487-1504. Available from: https://doi.org/10.1139/cjfas-2020-0075

O'Farrell, M. R., M. S. Mohr, M. L. Palmer-Zwahlen, and A. M. Grover. 2013. The Sacramento Index (SI). NOAA-TM-NMFS-SWFSC-512:1–41. Available from: https://repository.library.noaa.gov/view/noaa/4449

PFMC (Pacific Fishery Management Council), 1984. Framework amendment for managing the ocean salmon fisheries off the coasts of Washington, Oregon and California commencing in 1985. Pacific Fishery Management Council, 7700 NE Ambassador Place, Suite 101, Portland, Oregon 97220-1384. Available from: https://www.pcouncil.org/documents/1995/10/final-framework-amendment-for-managing-the-ocean-salmon-fisheries-off-the-coasts-of-washington-oregon-and-california-commencing-in-1985.pdf/

PFMC [Pacific Fishery Management Council]. 2019. Salmon Rebuilding Plan for Sacramento River Fall Chinook. Pacific Fishery Management Council, 7700 NE Ambassador Place, Suite 101, Portland, Oregon 97220-1384. Available from: https://www.pcouncil.org/documents/2019/07/sacramento-river-fall-chinook-salmon-rebuilding-plan-regulatory-identifier-number-0648-bi04-july-2019.pdf/

PFMC [Pacific Fishery Management Council]. 2019. Salmon Rebuilding Plan for Sacramento River Fall Chinook. Pacific Fishery Management Council, 7700 NE Ambassador Place, Suite 101, Portland, Oregon 97220-1384. Available from: https://www.pcouncil.org/documents/2019/07/sacramento-river-fall-chinook-salmon-rebuilding-plan-regulatory-identifier-number-0648-bi04-july-2019.pdf/

PFMC [Pacific Fishery Management Council]. 2022. Pacific Coast Salmon Fishery Management Plan for Commercial and Recreational Salmon Fisheries off the Coasts of Washington, Oregon, and California as Revised through Amendment 24. PFMC, Portland, OR. 84 p. Available from: https://www.pcouncil.org/documents/2022/12/pacific-coast-salmon-fmp.pdf

SAS [Salmon Advisory Subpanel of the Pacific Fishery Management Council]. 2025. Salmon Advisory Subpanel Report on Methodology Review - Final Topic Selection. Available from: https://www.pcouncil.org/documents/2025/09/f-1-a-supplemental-sas-report-1-sas-report-on-methodology-review-final-topic-selection.pdf/

Satterthwaite, W. 2022. Literature review for Sacramento River Fall Chinook conservation objective and associated S_{MSY} reference point. Report to Pacific Fishery Management Council. Available from: https://www.pcouncil.org/documents/2022/10/d-2-attachment-1-methodology-review-materials-electronic-only.pdf/#page=50

SRWG [Sacramento River Fall Chinook Workgroup of the Pacific Fishery Management Council]. 2024a. Sacramento River Fall Chinook ad hoc Workgroup Progress Report, June 2024. Report to Pacific Fishery Management Council. https://www.pcouncil.org/documents/2024/05/e-1-a-srwg-report-1.pdf/

SRWG [Sacramento River Fall Chinook Workgroup of the Pacific Fishery Management Council]. 2024b. Sacramento River Fall Chinook ad hoc Workgroup Progress Report, November 2024. Report to Pacific Fishery Management Council. Available from:

https://www.pcouncil.org/documents/2024/10/f-6-a-srwg-report-1-sacramento-fall-chinook-ad-hoc-workgroup-progress-report.pdf/

SSC [Scientific and Statistical Committee of the Pacific Fishery Management Council]. 2024a. Scientific and Statistical Committee report on Sacramento River fall Chinook workgroup - progress report. Available from: https://www.pcouncil.org/documents/2024/06/e-1-b-supplemental-ssc-report-1.pdf/

SSC [Scientific and Statistical Committee of the Pacific Fishery Management Council]. 2024b. Scientific and Statistical Committee report on Klamath River fall Chinook workgroup report and 2024 management options – final guidance. Available from: https://www.pcouncil.org/documents/2024/03/agenda-item-c-4-b-supplemental-ssc-report-1-scientific-and-statistical-committee-report-on-klamath-river-fall-chinook-workgroup-report-and-2024-management-options-final-guidance.pdf/

STT [Salmon Technical Team of the Pacific Fishery Management Council]. 2005. Klamath River Fall Chinook Stock-Recruitment Analysis. Report to PFMC. Available from: https://www.pcouncil.org/documents/2005/09/klamath-river-fall-chinook-stock-recruitment-analysis.pdf/

STT [Salmon Technical Team of the Pacific Fishery Management Council]. 2024a. Salmon Technical Team report on Sacramento River fall Chinook workgroup progress report (June 2024). Available from: https://www.pcouncil.org/documents/2024/06/e-1-b-supplemental-stt-report-1.pdf/

STT [Salmon Technical Team of the Pacific Fishery Management Council]. 2024b. Salmon Technical Team report on Sacramento River fall Chinook workgroup progress report (November 2024). Available from: https://www.pcouncil.org/documents/2024/11/f-6-b-supplemental-stt-report-1-stt-report-on-sacramento-river-fall-chinook-workgroup-progress-report-and-recommendations.pdf/

Terceiro, M. 2011. The summer flounder chronicles II: new science, new controversy, 2001-2010. Revies in Fish Biology and Fisheries 21:681-712. Available from: https://www.researchgate.net/publication/251269270_The_summer_flounder_chronicles_II_New_science_new_controversy_2001-2010

Voss, S. D. and W. R. Poytress. 2022. 2020 Red Bluff Diversion Dam Rotary Trap Juvenile Anadromous Fish Abundance Estimates. Report of U.S. Fish and Wildlife Service to U.S. Bureau of Reclamation, Sacramento, CA. Available from: https://www.researchgate.net/publication/363414690_2020_RED_BLUFF_DIVERSION_DAM_ROTARY_TRAP_JUVENILE_ANADROMOUS_FISH_ABUNDANCE_ESTIMATES

White, S, C. Lindley, and I. Pritchard. 2025. Recovery of Coded-Wire Tags from Chinook Salmon in California's Central Valley Escapement, Inland Harvest, and Ocean Harvest in 2021. Report funded by the U.S. Bureau of Reclamation, East Bay Municipal Utilities District, and the California Department of Water Resources contracts with the Pacific States Marine Fisheries Commission (PSMFC). Available from:

https://www.calfish.org/Portals/2/Programs/CentralValley/CFM/docs/2021_CFM_CWT_Report.pdf

Wor, C,. D. A. Greenberg, C. A. Holt, B. Connors, M. L. Feddern, C. Freshwater, G. I. Britten, and M. Mazur. 2025. Recommendations for estimating and detecting time-varying spawner-recruit dynamics in fish populations. Ecological Modelling 507:11159. Available from: https://doi.org/10.1016/j.ecolmodel.2025.111159

Appendices A-L: S_{MSY} Documentation

Appendix A. Derivation of natural-area S_{MSY} for Sacramento River Fall Chinook

Prepared by Sacramento River Fall Chinook Work Group and Stuart Munsch (NWFSC)
Contact authors:
Will Satterthwaite, SWFSC, will.satterthwaite@noaa.gov
Correigh Greene, NWFSC/Skagit River System Cooperative, correigh@gmail.com
Stuart Munsch, NWFSC, stuart.munsch@noaa.gov

Introduction

November 2024 Council guidance, as captured in the Decision Summary, instructed the Sacramento River Fall Chinook (SRFC) Work Group (SRWG) to "use the F_{MSY} value adopted under Agenda Item F.2 Salmon Methodology Review to derive an updated S_{MSY} value per the formula described in Agenda Item F.2, Attachment 2". The referenced document describes how, for a Ricker spawner-recruit relationship as applied to salmon, S_{MSY}=F_{MSY}xS_{MP} where S_{MP} is the escapement that maximizes production of recruits and F_{MSY} is the exploitation rate corresponding to maximum sustainable yield. A proxy value of F_{MSY}=0.58 was adopted for SRFC based on this same agenda item.

The decision summary document further stated that "S_{MSY} [be] based on natural-area spawners". Therefore, the SRWG performed an analysis to estimate S_{MP} from a spawner-recruit relationship fitted to a dataset where spawners were natural-area adult SRFC and recruits were a measure of natural-origin SRFC production. Both the Scientific and Statistical Committee (SSC 2024) and Salmon Technical Team (STT 2024) have noted the importance of accounting for origin (natural versus hatchery) when estimating recruitment in a spawner-recruit relationship. Given Council direction to derive a natural-area S_{MSY}, natural-origin recruits were the most appropriate metric of production.

Methods

The SRWG considered multiple data sources and time periods for estimating recruits (see "S_{MSY} value" section of main November 2025 SRWG Progress Report), ultimately deciding to use an index of juvenile production based on the metric first developed by Munsch et al. (2020) for brood years 1998-2015, extended through brood year 2020 with new data, and excluding brood year 1998 due to potentially significant numbers of hatchery fry releases that year (see release year 1999 in Huber and Carlson [2015], their Figure 5) similar to the fry releases in brood years 2021 and later that led the SRWG to exclude those brood years from the analysis. Results were not sensitive to the inclusion versus exclusion of brood year 1998 (changing the estimate of S_{MP} by 2%) and only moderately sensitive to the inclusion versus exclusion of brood years 2021-2022 (changing the estimate of S_{MP} by 20%). The SRWG also included a metric of flow in the lower Sacramento during rearing and outmigration as a covariate, similar to that developed in Munsch et al. (2020). See Appendix B for further details on the original Munsch et al. (2020) indices and how they were updated.

Although there was little to no statistical support for preferring a Ricker spawner-recruit relationship over a Beverton-Holt (0.22 AIC units in favor of Beverton-Holt for the original brood years 1998-2015 analyzed in Munsch et al. 2020, 0.07 units in favor of the Ricker for brood years 1999-2020), or perhaps other functional forms, it is common practice for PFMC-managed salmon to assume a Ricker, and that is the only functional form consistent with the S_{MSY}=F_{MSY}xS_{MP} approach identified in the Council guidance. There was very strong statistical support (8-11 AIC units depending on time period) for including the flow covariate. Informal exploration of alternative flow metrics or metrics of water temperature revealed them to be highly correlated, with little reason to pick one over the others, so for simplicity the SRWG used an updated version of the already peer-reviewed flow index developed in Munsch et al. (2020).

As in Munsch et al. (2020), the specific formulation of a Ricker spawner-recruit relationship with an environmental covariate used in this case was

$$log(R) = log\left(\alpha S e^{-\beta S}\right) + fz + \varepsilon$$

where R = recruits, S = spawners, α represents intrinsic productivity, β measures the strength of density dependence and is the inverse of capacity (i.e., recruitment is maximized at 1/β and so $S_{MP}=1/\beta$), f is a parameter describing the effect of flow (larger f = stronger effects of flow), z is the flow index transformed to have mean 0 and standard deviation 1, and ε is an error term assumed to be normally distributed in log space with mean 0.

This widely-used (e.g. STT [2005], Confer and Falcy [2014]) formulation assumes that the environmental covariate scales productivity in a multiplicative fashion that does not interact with density-dependent effects, instead it scales the whole spawner-recruit curve up or down by a particular ratio depending on the state of the environment. This equation was fit to the aforementioned datasets using nonlinear least squares (nls function in the R base package, R Core Team [2023]) using initial parameter estimates for α and β derived using the srStarts function in the R package FSA (Ogle et al. 2023). See Appendix C for the code used.

Results

The estimate of S_{MP} resulting from this analysis is 496,980 adult SRFC spawning in natural areas (Figure 1). Using the F_{MSY} proxy of 0.58, this implies an S_{MSY} of 288,248 adult SRFC spawning in natural areas. To not imply an inappropriate level of precision in this estimate, the SRWG recommends rounding to **S_{MSY}=290,000 adult SRFC spawning in natural areas**; although the SRWG notes there is uncertainty of considerably more than 10,000 fish. The SRWG cautions against attempts to formally quantify the uncertainty in the S_{MP} or S_{MSY} estimates given the dependence on the F_{MSY} proxy and the lack of strong support for a Ricker spawner-recruit relationship, i.e. “structural” uncertainty regarding the best model form is even greater than the statistical uncertainty in this case. However, Figure 2 gives a qualitative sense of the level of uncertainty in S_{MP} (conditional on the assumption of a Ricker spawner-recruit relationship) by showing the Ricker curves fitted to various subsets of the data. Approximate 95% confidence intervals on β calculated based on likelihood profiles using the ‘confint’ command in R correspond to S_{MP} values ranging from 280,194-2,196,108, and corresponding S_{MSY} proxies would be 58% of these.

The flow effect f was estimated as 0.523, predicting that an increase in the flow covariate by one standard deviation would be expected to increase fry production by a factor of $e^{0.523}$=1.69x.

Figure 1. Best-fit Ricker spawner-recruit relationship when spawners are measured as natural-area adult SRFC, recruits are measured using an updated Munsch et al. (2020) natural-origin juvenile production index, and a flow covariate during rearing and outmigration acts multiplicatively (additively on the log scale). The solid curve represents predicted recruitment when the flow covariate is at its mean value, the dashed curve represents predicted recruitment when the flow covariate is 1 SD above the mean, and the dotted curve represents predicted recruitment when the flow covariate is 1 SD below the mean. Points are labeled by brood year, with brood years not included in the original Munsch et al. (2020) analysis shown in red. The darkness of individual points corresponds to the flow index for that year (darker fill = higher flow). The vertical dashed line shows S_{MP}, the escapement predicted to maximize recruitment.

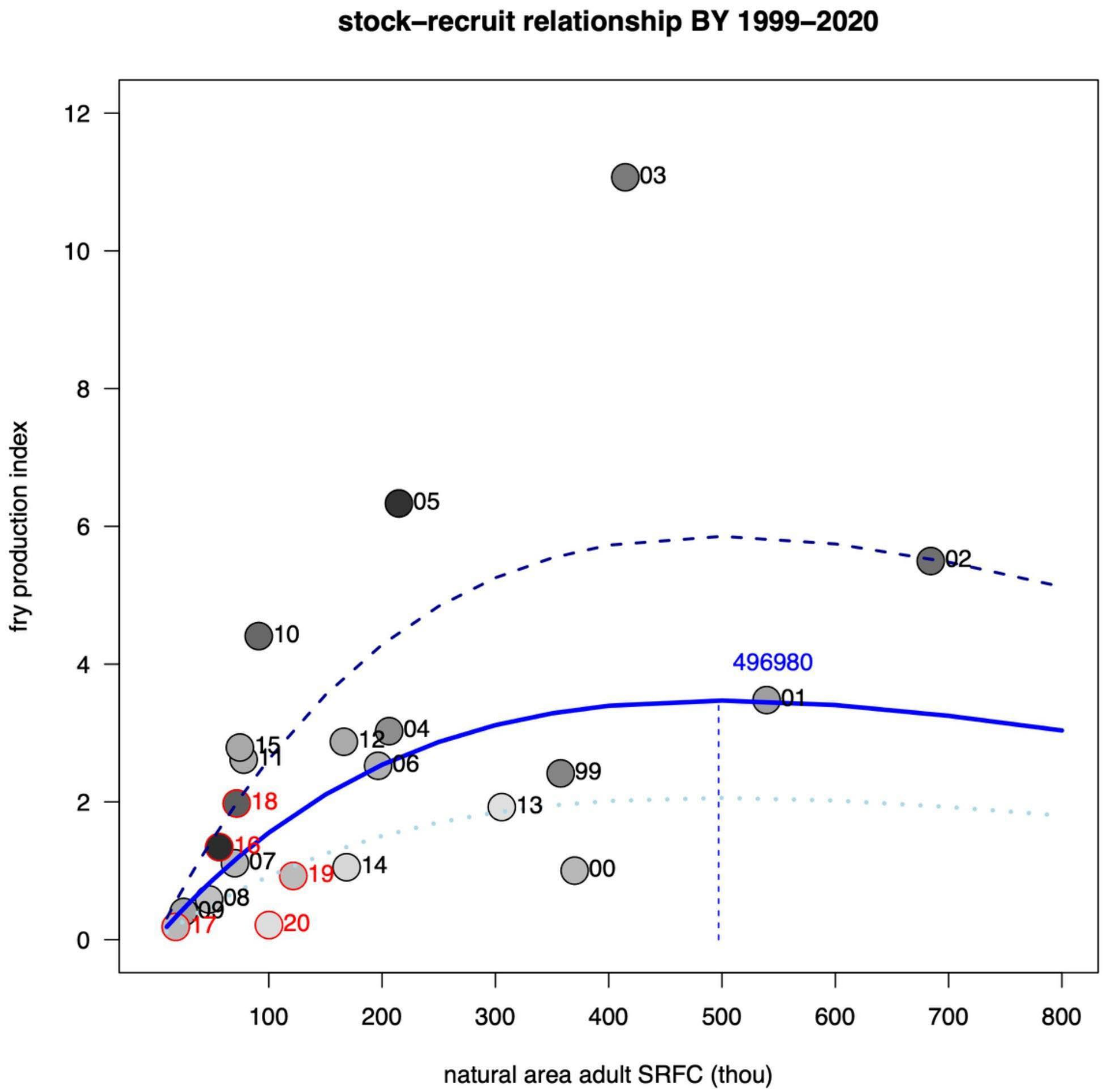
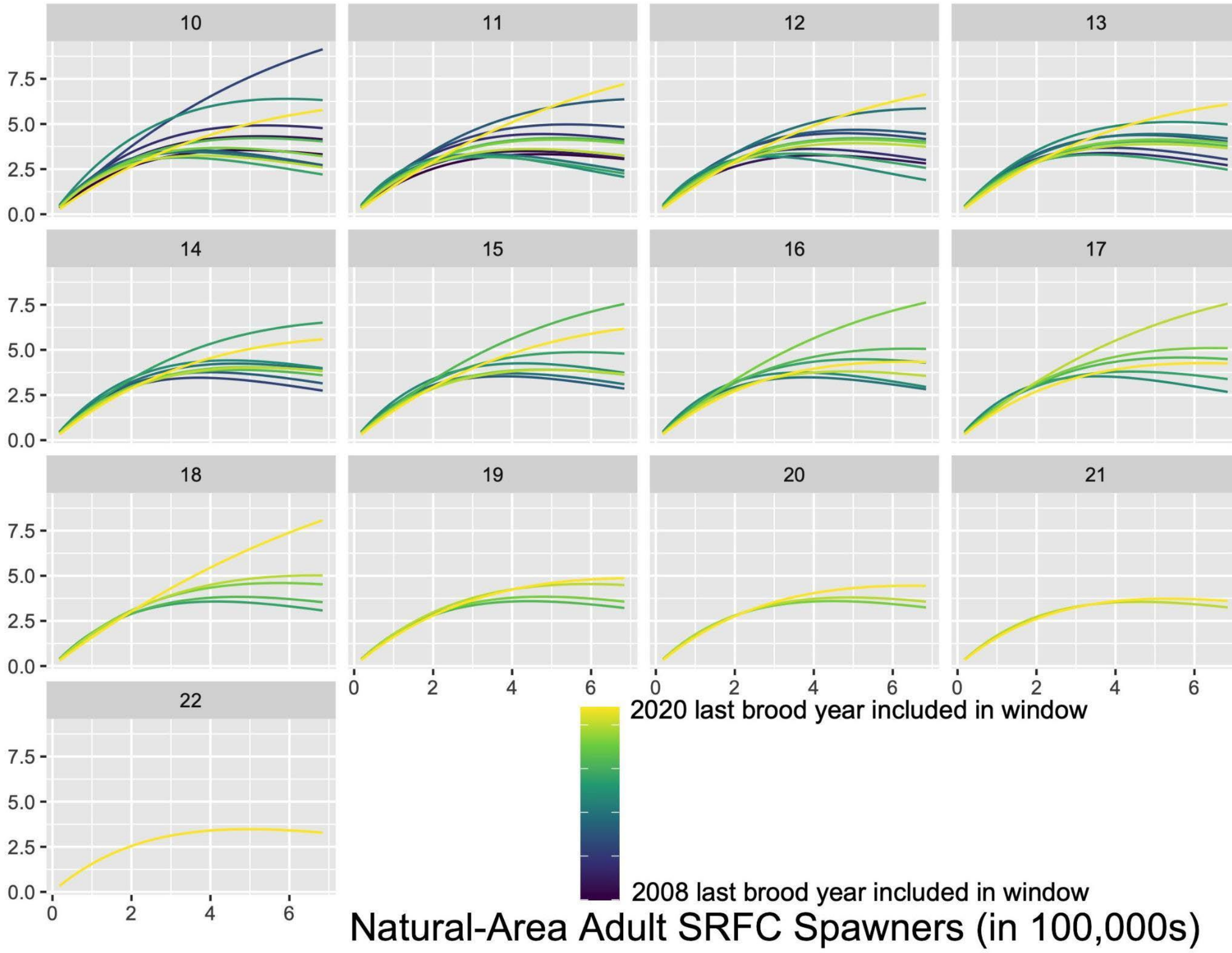


Figure 2. Ricker fits to various moving-window subsets of the data. The title for each panel indicates the number of consecutive brood years included (e.g., the first panel labeled "10" contains all possible 10-year moving windows from within the full brood year 1999-2020 dataset). Curves with colors toward the yellow end of the scale have the most recent end date to the moving window (and thus are the only curves possible for long window lengths), curves toward the purple end of the scale have the oldest end date for the moving window (and thus are only possible for the shorter windows).



Discussion

In addition to structural and statistical uncertainty, the SRWG wishes to highlight two further uncertainties associated with this analysis. Although the SRWG finds the updated Munsch et al. (2020) juvenile production index to be the most useful metric of SRFC natural-origin recruitment currently available (see Appendix B) until a cohort reconstruction is available for more years covering a wider range of conditions, it may not fully predict recruitment of natural-origin fish to the fishery because it is driven by fry-sized migrants (and thus might miss years with unusually high contributions of fish growing to larger sizes before passing the sampling stations), and does not account for density-dependence occurring after passage through the lower river. Although any potential for density-dependence after the fry stage is likely to be highly affected by numerous hatchery releases in this system, it is still possible that the density of natural-origin fish that maximizes recruitment to the lower river is not the same as the density that maximizes recruitment to the ocean sizes and ages available to the fishery, and so the S_{MP} estimated on the basis of recruits to the fishery may be lower than the S_{MP} estimated on the basis of juvenile fry. This index also does not account for variation in survival during the early ocean stage, nor variation in maturation rates or natural mortality later in ocean residency, although a long-term estimate of MSY might most appropriately average over variation in those conditions anyway.

The cohort reconstruction (Chen et al. 2024) addresses many of these challenges, but is not currently available for a sufficient number of years covering a sufficient range of conditions (see main text, particularly Figure 2). The SRWG recommends periodically re-assessing the sufficiency of years covered by a cohort reconstruction, and re-evaluating S_{MSY} when sufficiently informative new data have accumulated.

It has been suggested that the Sacramento Basin may have experienced a "regime shift" that has permanently lowered the productivity and/or capacity of the system for fall Chinook, relative to the earlier years included in the fry recruitment index, which extends back to brood year 1999 in this analysis. While it seems plausible that productivity may be persistently lower now than it was prior to the return year 2008-2009 "collapse" (Lindley et al. 2009), this generally lower productivity in recent years may largely be the result of poor flow-dependent downstream migrant survival (Michel 2019) that should be reflected in the flow covariate's effect on productivity. It is unclear whether any of the recent changes hypothesized to reduce productivity would have reduced capacity as well (i.e., there is still a lot of habitat available when flow and temperature conditions allow its full use), and simulations have demonstrated that attempting to model time-dependent capacity is extremely challenging (Wor et al. 2025). There are examples of past declarations of permanently lower capacity that have not borne out in this system (e.g., based on then-recent declines PFMC [1984] predicted returns to the Upper Sacramento would stabilize around 50,000 adults after the mid-1980s but instead averaged just over 150,000 for 1985-2005 [Satterthwaite 2022]) and other systems (e.g., Terceiro 2011). In a Ricker model, if capacity remains constant but productivity decreases, both S_{MSY} and F_{MSY} would be predicted to decrease. In other words, a small S_{MSY} in relation to S_{MP} also implies a low F_{MSY}, potentially incompatible with the current F_{MSY} proxy based on Klamath and Rogue fall Chinook. Thus, the SRWG continues to recommend periodically revisiting both reference points.

This document contains additional appendices that more fully describe the Munsch et al. (2020) recruitment index and how it was updated with more recent data. It also includes multiple appendices showing the results of spawner-recruit analyses based on different recruitment datasets. The SRWG emphasizes that analyses restricted to the more recent time period informing the cohort reconstruction or natural-adjusted Sacramento Index do not cover an adequate range of escapements and environmental conditions. These supplemental analyses are intended as sensitivities and presented in the interest of transparency, but are not recommended for use in deriving reference points.

References for Appendix A

Chen, E. K., W. H. Satterthwaite, M. R. O'Farrell, and S. M. Carlson. 2024. Cohort reconstruction for Sacramento River Fall Chinook salmon and comparison with the Sacramento Index. Report to Pacific Fishery Management Council. https://www.pcouncil.org/documents/2024/09/cohort-reconstruction-for-sacramento-fall-chinook-salmon-and-comparison-with-the-sacramento-index.pdf/

Confer, T. and M. Falcy. 2014. Conservation Objective for Southern Oregon Coastal Chinook. Report to Pacific Fishery Management Council. Available from: https://www.pcouncil.org/documents/2014/11/f-salmon-management-november-2014.pdf/#page=123

Huber, E., and S. M. Carlson. 2015. Trends in hatchery releases of fall-run Chinook salmon in California's Central Valley. San Francisco Estuary and Watershed Science 13(2):3. Available from: https://doi.org/10.15447/sfews.2015v13iss2art3

Lindley, S. T., C. B. Grimes, M. S. Mohr, W. Peterson, J. Stein, J. T. Anderson, L. W. Botsford, D. L. Bottom, C. A. Busack, T. K. Collier, et al. 2009. What caused the Sacramento River fall Chinook stock collapse? US Department of Commerce. NOAA Technical Memorandum NOAA-TM-NMFS-SWFSC-447. Available from: https://repository.library.noaa.gov/view/noaa/3664/noaa_3664_DS1.pdf

Michel, C. J. 2019. Decoupling outmigration from marine survival indicates outsized influence of streamflow on cohort success for California's Chinook salmon populations. Canadian Journal of Fisheries and Aquatic Sciences 76:1398–1410. Available from: dx.doi.org/10.1139/cjfas-2018-0140

Munsch, S. H., C. M. Greene, R. C. Johnson, W. H. Satterthwaite, H. Imaki, P. L. Brandes, and M. R. O'Farrell. 2020. Science for integrative management of a diadromous fish stock: interdependencies of fisheries, flow, and habitat restoration. Canadian Journal of Fisheries and Aquatic Sciences 77:1487-1504. Available from: https://doi.org/10.1139/cjfas-2020-0075

Ogle, D. H., J. C. Doll, A. P. Wheeler, and A. Dinno. FSA: Simple Fisheries Stock Assessment Methods. R package version 0.9.5. Available from: https://CRAN.R-project.org/package=FSA

PFMC (Pacific Fishery Management Council), 1984. Framework amendment for managing the ocean salmon fisheries off the coasts of Washington, Oregon and California commencing in 1985. Pacific Fishery Management Council, 7700 NE Ambassador Place, Suite 101, Portland, Oregon 97220-1384. Available from: https://www.pcouncil.org/documents/1995/10/final-framework-amendment-for-managing-the-ocean-salmon-fisheries-off-the-coasts-of-washington-oregon-and-california-commencing-in-1985.pdf/

R Core Team. 2023. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. Available from: https://www.R-project.org/

Satterthwaite, W. 2022. Literature review for Sacramento River Fall Chinook conservation objective and associated S_{MSY} reference point. Report to Pacific Fishery Management Council. Available from: https://www.pcouncil.org/documents/2022/10/d-2-attachment-1-methodology-review-materials-electronic-only.pdf/#page=50

SSC [Scientific and Statistical Committee of the Pacific Fishery Management Council]. 2024. Scientific and Statistical Committee report on Sacramento River fall Chinook workgroup - progress report. Available from: https://www.pcouncil.org/documents/2024/06/e-1-b-supplemental-ssc-report-1.pdf/

STT [Salmon Technical Team of the Pacific Fishery Management Council]. 2005. Klamath River Fall Chinook Stock-Recruitment Analysis. Report to PFMC. Available from: https://www.pcouncil.org/documents/2005/09/klamath-river-fall-chinook-stock-recruitment-analysis.pdf/

STT [Salmon Technical Team of the Pacific Fishery Management Council]. 2024. Salmon Technical Team report on Sacramento River fall Chinook workgroup progress report. Available from: https://www.pcouncil.org/documents/2024/06/e-1-b-supplemental-stt-report-1.pdf/

Terceiro, M. 2011. The summer flounder chronicles II: new science, new controversy, 2001-2010. Reviews in Fish Biology and Fisheries 21:681-712. Available from: https://www.researchgate.net/publication/251269270_The_summer_flounder_chronicles_II_New_science_new_controversy_2001-2010

Wor, C. D. A. Greenberg, C. A. Holt, B. Connors, M. L. Feddern, C. Freshwater, G. I. Britten, and M. Mazur. Recommendations for estimating and detecting time-varying spawner-recruit dynamics in fish populations. Ecological Modelling 507:11159. Available from: https://doi.org/10.1016/j.ecolmodel.2025.111159 .

Appendix B. Description and updating of Munsch et al. (2020) juvenile production index and associated flow covariate

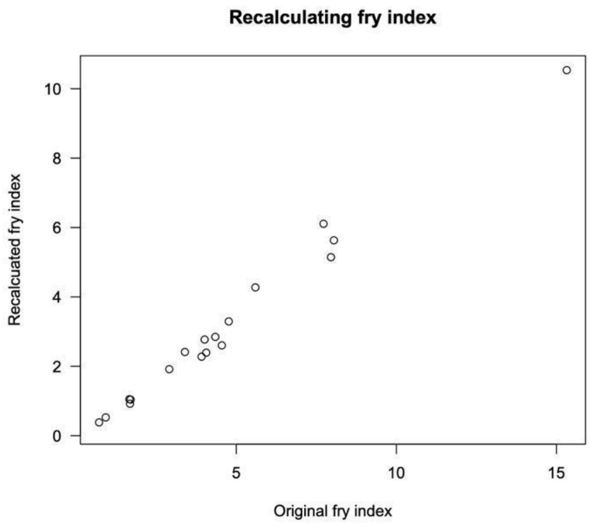
Original juvenile production index

Munsch et al. (2020) developed a set of statistical models of fry (<55mm) Chinook catches in the lower Sacramento between December and May during beach seining conducted by the US Fish and Wildlife Service's Juvenile Fish Monitoring Program (Mahardja et al. 2019). The size cutoff was meant to exclude hatchery-origin fish (which were released almost exclusively at larger sizes for release years 1999-2021), so that the index reflected natural-origin juvenile abundance (Munsch et al. 2020, p. 1497). To develop the annual index used in the spawner-recruit analysis, the capture rates of fry during this time period were modeled using a negative binomial hurdle model accounting for year, date within the year, and site effects for locations in the Sacramento River (Munsch et al. 2020, pp. 1497-1501). Thus, the annual value represents the expected number of fry encountered on a typical day of the year and in a typical location within the landscape.

Updating and extending the juvenile production index

To update the juvenile production index, we first obtained beach seining data from more recent years (https://portal.edirepository.org/nis/mapbrowse?scope=edi&identifier=244&revision=12, downloaded July 2, 2024). While processing those data, we detected an error in the scripts used in the initial analysis that led to the exclusion of seining events where Chinook were present, but all were above the 55mm cutoff. These seining events were effectively treated as missing data, but should have been treated as observations of zero fry. Correcting this error scaled the fry index downward, but had very little effect on the relative value across years (r=0.99, Figure B1), and therefore had very little effect on the estimated location of the peak in a Ricker spawner-recruit relationship.

Figure B1. Original versus recalculated fry production index for brood years 1998-2015 (outmigration years 1999-2016).



The original Munsch et al. (2020) paper used data for brood years 1998-2015 (outmigration and years 1999-2016). The ending brood year of 2015 was based on the latest data available at the time it was written. The brood year 1998 (outmigration or hatchery release year 1999) start date was based on hatcheries nearly discontinuing the release of fry-sized fish that year (Munsch et al. 2020, p. 1497). It is difficult to precisely define a cutoff year for when hatchery releases of fry essentially "stopped" (and after publication of the paper, release of unmarked hatchery fry resumed in brood year 2021 at Coleman National Fish Hatchery and more broadly in subsequent brood years). Given concern about the impact of these unmarked fry releases on sampling efforts in recent years and into the future, we re-examined past fry release practices (Huber and Carlson [2015], their Figure 5). Fry releases in 1999 were considerably lower than 1998 and most earlier years, but still numbered close to 1 million, of similar magnitude to recent unmarked fry pilot studies. To avoid confounding with hatchery-origin fish, we excluded brood years 1998, 2021, and 2022 from the analysis used to inform the spawner-recruit relationship.

Original flow index

The original Munsch et al. (2020, p. 1501) analysis developed an annual flow index based on the median flow for the period of December – May (corresponding to rearing and outmigration) starting in December of the brood year. Median flow for each year was log-transformed to reflect the diminishing returns of increasing flow at higher levels (see Munsch et al. [2020], their Figure 3), then the annual values were z-score transformed to standardize them to have mean 0 and standard deviation 1. Flows were measured at USGS gage 11447650 at Freeport.

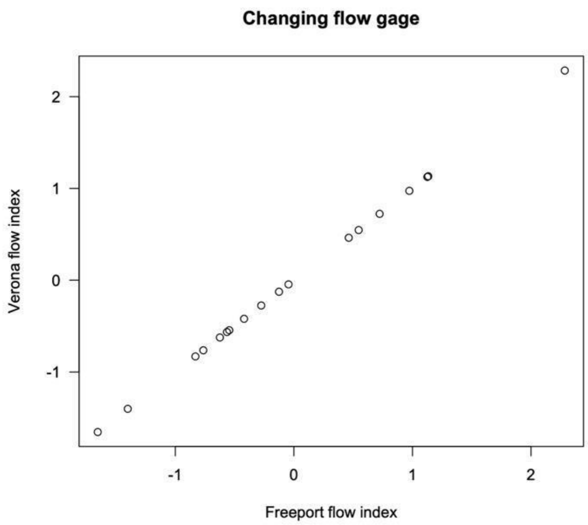
Updating and extending flow index

When we attempted to update the flow index with additional years of data, we were no longer able to download the Freeport gage data in the same format as previously. However, we were able to download gage data in the required format from the nearby gage 11425500 at

Verona, so we calculated a flow metric based on the calculations described previously using data from that gage. Although Verona is above the confluence with the American River, because flows on the American are correlated with flows throughout the Sacramento, the Verona gage still does a good job of capturing annual variation in total flow through the system.

The change in flow gage locations had almost no effect on the z-scored value of the flow index (r=0.99 for common years, Figure B2).

Figure B2. z-score standardized logged annual median December-May flow at Freeport versus Verona, for brood years 1998-2015 (water years 1999-2016).



References for Appendix B

Huber, E., and S. M. Carlson. 2015. Trends in hatchery releases of fall-run Chinook salmon in California's Central Valley. San Francisco Estuary and Watershed Science 13(2):3. Available from: https://doi.org/10.15447/sfews.2015v13iss2art3

Mahardja, B., Nanninga A., and Barnard, D. 2019. Interagency Ecological Program: Over four decades of juvenile fish monitoring data from the San Francisco Estuary, collected by the Delta Juvenile Fish Monitoring Program, 1976–2018. Environmental Data Initiative. Available from: https://dx.doi.org/10.6073/pasta/87dda12bed2271ce3d91abdb7864c50c

Munsch, S. H., C. M. Greene, R. C. Johnson, W. H. Satterthwaite, H. Imaki, P. L. Brandes, and M. R. O'Farrell. 2020. Science for integrative management of a diadromous fish stock: interdependencies of fisheries, flow, and habitat restoration. Canadian Journal of Fisheries and Aquatic Sciences 77:1487-1504. Available from: https://doi.org/10.1139/cjfas-2020-0075

Appendix C. R Code for natural-area SRFC S_{MSY} based on updated Munsch et al fry index

Data and code to reproduce these analyses are available at https://dx.doi.org/10.17632/2cr59gtpv4.1.

1976-2023_DJFMP_beach_seine_fish_and_water_quality_data.csv contains the seining data used to generate the juvenile production index

SRFC_SmsyCode.R generates the annual values of the juvenile production index using the negative binomial hurdle model described in Munsch et al. 2020. Code within this file also downloads the flow data, calculates the annual flow metric, and fits a variety of spawner-recruit functions and displays (but does not save) a variety of diagnostic plots. It saves the key inputs to the spawner-recruit analysis as "SRfitting_data.csv". Note that because the fry index model is fit using a Bayesian model, it yields slightly different values of the annual recruitment index at each iteration (with CVs of 0.11% to 0.18% at the current chain lengths), so the particular run creating the figure in the main document was saved to the code archive and is used to generate the figure and specific values in the text of the document. As a final step, the code outputs the spawner-recruit figure used in the main document.

dummydatSR.csv is basically a spaceholder used for plotting purposes.

values_from_Munsch_2020.csv is used to document the effects of updating the index calculation compared to the Munsch et al. 2020 paper.

Other files in this directory are outputs of the main R code file, using the aforementioned input files.

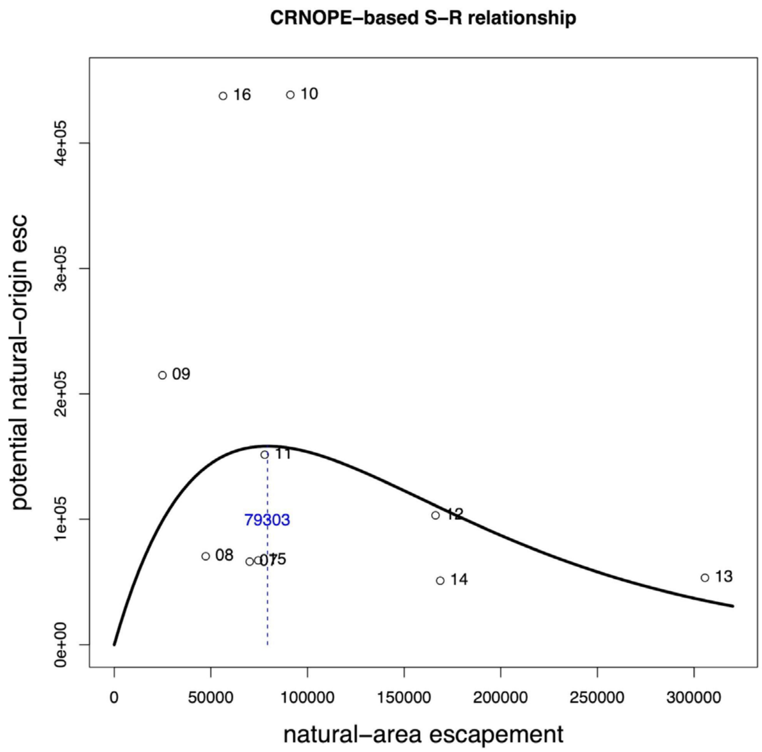
Appendix D. Sensitivity analysis: Spawner-recruit analysis based on cohort reconstruction estimate of potential natural-origin adult escapement in the absence of fishing

It is the SRWG's position that at the current time, the SRFC cohort reconstruction (Chen et al. 2024) does not cover a sufficient range of parent escapements over a sufficient range of environmental conditions (see Figure 2 in main text) to inform estimation of reference points from a spawner-recruit relationship. It also does not meet the minimum sample size of at least 15 year classes recommended by the Chinook Technical Committee (CTC) of the Pacific Salmon Commission (CTC 1999). Estimated natural-area adult escapement for the currently included brood years of 2007-2016 ranged from a low of 24,948 in 2009 to 305,635 in 2013. This is greater than the minimum 8x range recommended by the CTC (CTC 1999), however it is notable that the highest escapement occurred at the lowest value of the flow covariate (see Figure 2 in the main body of the progress report). With that year excluded, the escapement range covers only 24,948-168,667, a range of 6.7x, less than the minimum recommended by the CTC. Even with the low-flow 2013 escapement included, the range of escapements covered is still small relative to the historical range (PFMC 2025, their Table B-1) and does not include values greater than, or even closely approaching, the estimated S_{MP} from the juvenile index of nearly 500,000 spawners. While it seems plausible that productivity may be persistently lower now than it was prior to the 2008-2009 "collapse" (Lindley et al. 2009), it still seems problematic to analyze a spawner-recruit curve over such a narrow range of escapements, and it is unclear whether any of the recent changes hypothesized to reduce productivity would have reduced capacity as well (i.e. there is still a lot of habitat available when flow and temperature conditions allow its full use).

Nevertheless, in the interest of transparency, we fit spawner-recruit relationships to data for brood years 2007-2016 where escapement was natural-area adult spawners and recruits were potential natural-origin adult (age-3+) escapement in the absence of fishing as estimated from the cohort reconstruction (Chen et al. 2024). Potential escapement was estimated in the absence of any fishing (not just terminal-year fishing) and estimated pre-fishing abundance included the effects of harvest north of Cape Falcon. The general approach of relating natural-area escapement of parent spawners to potential natural-origin escapement of recruits is closely parallel to the approach used for deriving the current reference points for Klamath River Fall Chinook (KRFC, STT 2005), including the use of an influential covariate explaining productivity: flow in the case of SRFC, an early-life survival estimate from tagged hatchery-origin fish for KRFC.

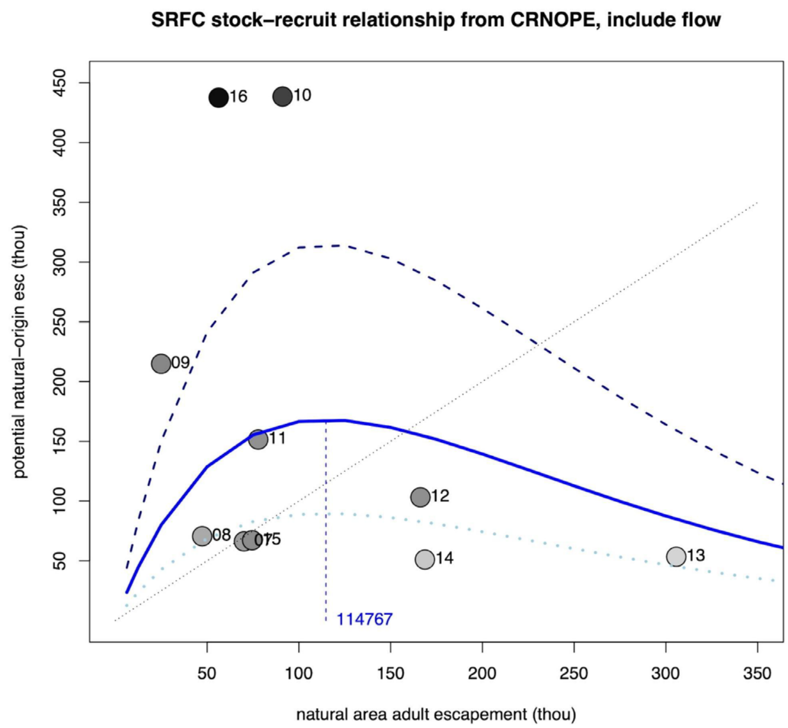
With no flow covariate, the fit was very poor (R^2=0.04) and the model estimated that natural production was maximized at S_{MP} = 79,303 natural-area adults (Figure D1).

Figure D1. SRFC spawner-recruit relationship (Ricker) where spawners are natural-area adults and recruits are potential natural-origin adult escapement in the absence of fishing from the cohort reconstruction. Points are labeled by brood year.



Adding the same flow covariate as used in the main text substantially increased R^2 to 0.72, and increased the estimate of S_{MP} to 114,767 natural-area adults (Figure D2). Approximate profile-based 95% confidence intervals on β calculated using the *confint* command in R corresponded to S_{MP} values ranging from 66,219-430,067.

Figure D2. SRFC spawner-recruit relationship (Ricker) where spawners are natural-area adults and recruits are potential natural-origin adult escapement in the absence of fishing as estimated from the cohort reconstruction, with a flow covariate describing flow during rearing and outmigration (see main text and Appendix B for further detail). Points are labeled by brood year, and the darkness of the fill indicates the value of the flow covariate. The solid curve represents predicted recruitment when the flow covariate is at its mean value, the dashed curve represents predicted recruitment when the flow covariate is 1 SD above the mean, and the dotted curve represents predicted recruitment when the flow covariate is 1 SD below the mean. The diagonal dotted line indicates where natural-origin recruits equal natural-area spawners.



The S_{MP} found by the analysis including the flow covariate and using the cohort reconstruction to estimate recruitment would correspond to $S_{MSY} = F_{MSY} \times S_{MP} = 0.58 \times 114{,}767 = 66{,}565$ natural-area adults. Following the example set for KRFC (STT 2005), one could also attempt to estimate MSY for the natural component of the stock directly (using the formulae in Scheuerell [2016]) from a spawner-recruit relationship like this relating potential natural-origin escapement in the future to the current number of natural-area spawners. This leads to a slightly smaller S_{MSY} of 64,278 natural-area adults, accompanied by a lower F_{MSY} of 0.56, consistent with the smaller ratio between S_{MSY} and S_{MP} than implied by the F_{MSY} proxy. These values correspond to a flow index value of 0.0, the mean of brood years 1999-2020 used in the main analysis. The brood years 2007-2016 used in the cohort reconstruction analysis had a mean flow index value of -0.18, corresponding to F_{MSY}=0.55 and S_{MSY}=63,260.

However, the SRWG highlights serious concerns with these numbers. Most crucially, they come from a limited data set covering only a limited range of escapements and environmental conditions, and the only observation at escapement substantially higher than the S_{MP} estimate came from the lowest flow year included in the dataset. In addition, given the 2011-2024 median ratio of SRFC natural-area adult escapement to total adult escapement (PFMC

2025, their Table B-1) of 0.68, the proxy S_{MSY} of 66,565 natural-area adults based on the F_{MSY} proxy would correspond to a total adult escapement of around 99,000. This level of total escapement would have only a modest probability of meeting the currently-defined (PFMC 2025, their Table B-1) hatchery escapement goals (Satterthwaite 2023, his Figure 4), while the lower direct estimate of S_{MSY} would further reduce the probability of meeting hatchery goals. Targeting escapement this low would also reduce expected river harvests compared to the status quo targeting of at least 122,000 total adults.

Attempting to estimate MSY directly from the fitted spawner-recruit relationship is also confounded by hatchery strays and a mismatch between the units of spawners (natural-area) versus recruits (natural-origin). Although this approach has precedent in the Klamath basin (STT 2005), the contribution of hatchery-origin fish to natural-area spawners in that system is much lower than in the Sacramento. To be consistent with how MSY is derived and the required assumption that population dynamics are independent of hatchery influence (STT 2005), the implied S_{MSY} of 64,278 adults spawning in natural areas might be better stated as 64,278 natural-origin adults spawning in natural areas.

References for Appendix D

Chen, E. K., W. H. Satterthwaite, M. R. O'Farrell, and S. M. Carlson. 2024. Cohort Reconstruction for Sacramento River Fall Chinook salmon and Comparison with the Sacramento Index. Report to Pacific Fishery Management Council. Available from: https://www.pcouncil.org/documents/2024/09/cohort-reconstruction-for-sacramento-fall-chinook-salmon-and-comparison-with-the-sacramento-index.pdf/

CTC [Chinook Technical Committee of the Pacific Salmon Commission]. 1999. Maximum sustained yield or biologically based escapement goals for selected chinook salmon stocks used by the Pacific Salmon Commission's Chinook Technical Committee for escapement assessment. Pacific Salmon Commission, Joint Chinook Technical Committee Report TCCHINOOK (99)-3, Vancouver. Available from: https://www.psc.org/download/35/chinook-technical-committee/2172/tcchinook99-3.pdf

Lindley, S. T., C. B. Grimes, M. S. Mohr, W. Peterson, J. Stein, J. T. Anderson, L. W. Botsford, D. L. Bottom, C. A. Busack, T. K. Collier, et al. 2009. What caused the Sacramento River fall Chinook stock collapse? US Department of Commerce. NOAA Technical Memorandum NOAA-TM-NMFS-SWFSC-447. Available from: https://repository.library.noaa.gov/view/noaa/3664/noaa_3664_DS1.pdf

PFMC [Pacific Fishery Management Council]. 2025. Review of 2024 ocean salmon fisheries: stock assessment and fishery evaluation document for the Pacific Coast Salmon Fishery Management Plan. Available from: https://www.pcouncil.org/documents/2025/02/review-of-2024-ocean-salmon-fisheries.pdf/

Satterthwaite, W. H. 2023. An approach to defining a Sacramento River Fall Chinook escapement objective considering natural production, hatcheries, and risk tolerance. San Francisco Estuary and Watershed Science 21(3):3. Available from: https://doi.org/10.15447/sfews.2023v21iss3art3

Scheuerell, M. D. 2016. An explicit solution for calculating optimum spawning stock size from Ricker's stock recruitment model. PeerJ 4:e1623. Available from: https://doi.org/10.7717/peerj.1623

STT [Salmon Technical Team of the Pacific Fishery Management Council]. 2005. Klamath River Fall Chinook Stock-Recruitment Analysis. Report to PFMC. Available from: https://www.pcouncil.org/documents/2005/09/klamath-river-fall-chinook-stock-recruitment-analysis.pdf/

Appendix E. R Code for the spawner-recruit analysis based on cohort reconstruction estimate of potential natural-origin adult escapement in the absence of fishing.

```
#use Ogle's FSA package to fit S-R relationships
library(FSA)
dat.crnpe=read.csv("CRNPEdatSR.csv")
year.labs=c("07","08","09","10","11","12","13","14","15","16")


#fit a Ricker, ignoring flow
r3 <- srFuns("Ricker",param=3)
r3s <- srStarts(recruits~spawners,data=dat.crnpe,type="Ricker",param=3)
fit2 <- nls(log(recruits)~log(r3(spawners,a,Rp)),data=dat.crnpe,start=r3s)
summary(fit2,correlation=TRUE)
#plot the S-R curve and some reference points
pdf("CRNOPEbasedSR.pdf",height=8,width=8)
plot(dat.crnpe$spawners,dat.crnpe$recruits,xlab="natural-area
escapement",ylab="potential natural-origin esc",main="CRNOPE-based S-R
relationship",xlim=c(0,320000),ylim=c(0,450000),cex.lab=1.5)
curve(r3(x,a=coef(fit2)[1],Rp=coef(fit2)[2]),from=0,to=320000,lwd=3,add=TRUE)
#calculate and plot maximum production
a=coef(fit2)[1]
Ricker.alpha=log(a)
Rp=coef(fit2)[2]
Smp=Rp*exp(1)/a
#79302.87
Ricker.beta=1/Smp
MP=r3(Smp,a=coef(fit2)[1],Rp=coef(fit2)[2])
lines(x=c(Smp,Smp),y=c(0,MP),col="blue",lty=2)
text(x=Smp,y=1.4*Smp,round(Smp),pos=1,col="blue")
text(x=dat.crnpe$spawners,y=dat.crnpe$recruits,year.labs,pos=4)
dev.off()
recruits.observed=dat.crnpe$recruits
recruits.predicted=r3(dat.crnpe$spawners,a=coef(fit2)[1],Rp=coef(fit2)[2])
SS.mean=sum((recruits.observed-mean(recruits.observed))^2)
SS.pred=sum((recruits.observed-recruits.predicted)^2)
Rsquared=1-SS.pred/SS.mean
#0.04070565

#fit a Ricker, including flow
dat=read.csv("CRNPEdatSR.csv")
r_starters <- srStarts(recruits ~ spawners, data = dat, type = "Ricker")
#add a starting value for flow covariate (used same starting value as Stu)
r_f_starters_list <- list(a = r_starters$a, b = r_starters$b, f = 0.2)
r_f_z <- nls(log(recruits)~log((a * spawners) * exp(-b * spawners)) + f * flow, data =
dat, start = r_f_starters_list)
dummy_data <- read.csv("dummydatSR.csv")
dummy_data$recruit_prediction <- predict(r_f_z, newdata = dummy_data)
dummy_range=dummy_data$spawners[dummy_data$flow==0]
dummy_predict_mean=exp(dummy_data$recruit_prediction[dummy_data$flow==0])
dummy_predict_hi=exp(dummy_data$recruit_prediction[dummy_data$flow==1])
dummy_predict_lo=exp(dummy_data$recruit_prediction[dummy_data$flow==-1])
pdf("CRNOPEbasedSR-WithFlow.pdf",height=7.5,width=8)
plot(dat$spawners,dat$recruits,cex=2.5,xlab="natural area adult escapement
(thou)",ylab="potential natural-origin esc (thou)",main="SRFC stock-recruit
relationship from CRNOPE, include
flow",xaxt="n",yaxt="n",xlim=c(0,350000),ylim=c(0,450000))
axis(side=1,at=c(50000,100000,150000,200000,250000,300000,350000),labels=c(50,100,150,
200,250,300,350))
axis(side=2,at=c(50000,100000,150000,200000,250000,300000,350000,400000,450000),labels
=c(50,100,150,200,250,300,350,400,450))
points(x=dat$spawners,y=dat$recruits,pch=21,cex=2.5,bg=grey(1-(dat$flow+2)/4.5))
```

```
lines(dummy_range,dummy_predict_mean,lwd=3,col="blue")
lines(dummy_range,dummy_predict_hi,lwd=2,lty=2,col="dark blue")
lines(dummy_range,dummy_predict_lo,lwd=3,lty=3,col="light blue")
lines(x=c(0,350000),y=c(0,350000),lty=3)
Smp_flow=1/coef(r_f_z)[2]
#114766.7
a=coef(r_f_z)[1]
b=coef(r_f_z)[2]
f=coef(r_f_z)[3]
MP_flow_mean=exp(log((a*Smp_flow)*exp(-b*Smp_flow))+f*0)
MP_flow_hi=exp(log((a*Smp_flow)*exp(-b*Smp_flow))+f*1)
MP_flow_lo=exp(log((a*Smp_flow)*exp(-b*Smp_flow))+f*(-1))
lines(x=c(Smp_flow,Smp_flow),y=c(0,MP_flow_mean),lty=2,col="blue")
text(x=Smp_flow,y=0,round(Smp_flow),pos=4,col="blue")
text(x=dat.crnpe$spawners,y=dat.crnpe$recruits,year.labs,pos=4)
dev.off()
#calculate arithmetic-scale Rsquare
SS=sum((dat.crnpe$recruits-mean(dat.crnpe$recruits))^2)
SS_r_f_z=sum((exp(predict(r_f_z))-dat.crnpe$recruits)^2)
Rsquare_r_f_z=1-SS_r_f_z/SS
#[1] 0.72417

#go with Klamath-style assumption we could use this to estimate MSY directly
#code based on Scheuerell (2016) - https://dx.doi.org/10.7717/peerj.1623
library(gsl)
alpha=a
beta=b
lambert_in=exp(1-log(alpha))
lambert_out=lambert_W0(lambert_in)
Smsy=(1-lambert_out)/beta
# 64278.31
Smp=1/beta
Rmsy=alpha*Smsy*exp(-beta*Smsy)
Rmp=alpha*Smp*exp(-beta*Smp)
Ymsy=Rmsy-Smsy
Ymp=Rmp-Smp
Fmsy=Ymsy/(Ymsy+Smsy)
# 0.5600782

#put confidence intervals on Smp
Smp.upper=1/confint(r_f_z)[2,1]
#430067.1
Smp.lower=1/confint(r_f_z)[2,2]
#66218.83
```

Appendix F. Input files for spawner-recruit analysis based on cohort reconstruction estimate of potential natural-origin adult escapement in the absence of fishing.

Save the below to a .csv file named "CRNPEdatSR.csv" in the working directory for the code in Appendix E:

```
Year,spawners,flow,recruits
2007,70072,-0.5456973,66237.81301
2008,47316,-0.7515642,70527.22988
2009,24948,-0.2010693,214843.1128
2010,91126,1.028593,438514.8194
2011,77854,-0.3551712,151460.1945
2012,166233,-0.3232398,103140.5817
2013,305635,-1.374569,53366.51214
2014,168667,-1.193305,51024.65126
2015,74504,-0.2794978,67208.66237
2016,56297,2.218739,437579.9501
```

Save the below to a .csv file named "dummydatSR.csv" in the working directory for the code in Appendix E:

```
spawners,flow
6250,-1
12500,-1
25000,-1
50000,-1
75000,-1
100000,-1
125000,-1
150000,-1
175000,-1
200000,-1
225000,-1
250000,-1
275000,-1
300000,-1
325000,-1
350000,-1
375000,-1
400000,-1
6250,0
12500,0
25000,0
50000,0
75000,0
100000,0
125000,0
150000,0
175000,0
200000,0
225000,0
250000,0
275000,0
300000,0
325000,0
350000,0
375000,0
```

```
400000,0
6250,1
12500,1
25000,1
50000,1
75000,1
100000,1
125000,1
150000,1
175000,1
200000,1
225000,1
250000,1
275000,1
300000,1
325000,1
350000,1
375000,1
400000,1
```

Appendix G. Sensitivity analysis: Spawner-recruit analysis based on Sacramento Index and proportion natural-origin escapement

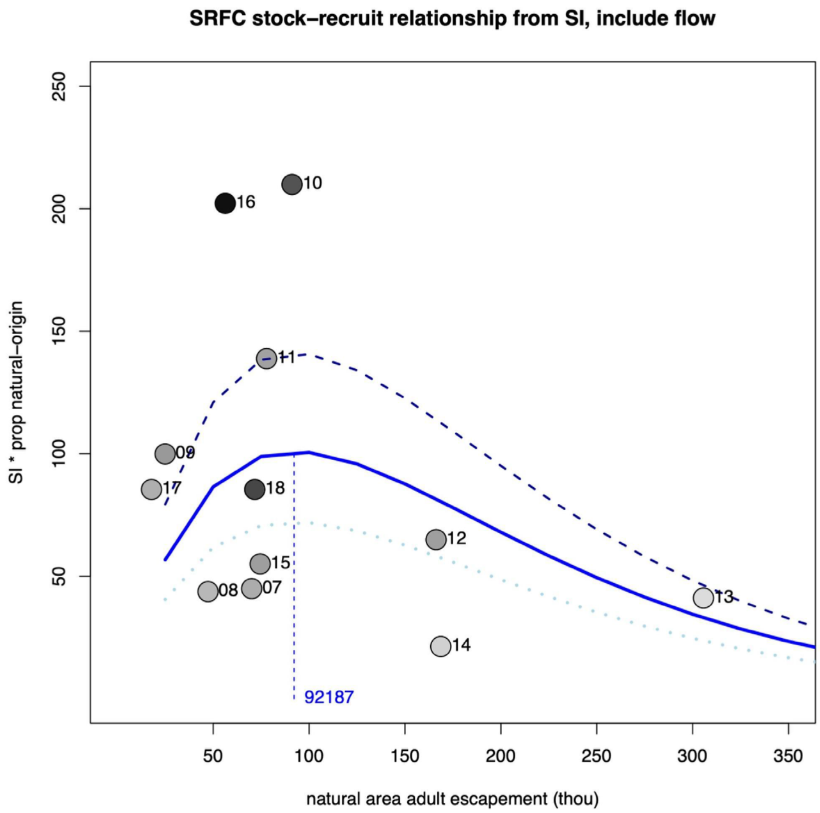
It is the SRWG's position that the Sacramento Index (SI, O'Farrell et al. 2013) is a less useful index of SRFC recruitment or potential escapement in the absence of fishing than the cohort reconstruction (Chen et al. 2024), a position that is shared by the Council's scientific and technical advisory bodies (SSC 2024, STT 2024). At the current time, neither the SRFC cohort reconstruction (Chen et al. 2024) nor years for which the SI can be adjusted by the proportion of escapement that is natural-origin cover a sufficient range of parent escapements over a sufficient range of environmental conditions (see Figure 2 in main text). Since the publication of White et al. (2025) there are now two more years for which we can estimate a natural-adjusted SI (i.e., SI times the proportion of escapement estimated to be natural-origin) compared to how many years we can perform a natural-origin cohort reconstruction for (which requires scale age data and observing complete cohorts, versus the SI for a cohort being calculated at the time of age-3 returns). Given the high correlation between the natural-adjusted SI and the cohort reconstruction (see main text), the larger sample size might justify use of the natural-adjusted SI in the near-term.

Estimated natural-area adult escapement for the brood years with natural-origin escapement estimates available three years later (2007-2018) ranged from a low of 17,851 in 2017 to 305,635 in 2013. This is greater than the minimum 8x range recommended by the Chinook Technical Committee of the Pacific Salmon Commission (CTC 1999), however it is notable that the highest escapement occurred at the lowest value of the flow covariate (see Figure 2 in the main body of the progress report). With that year excluded, the escapement range covers 17,851-168,667, a range of 9.4x, greater than the minimum recommended by the CTC. However, even with the low-flow 2013 escapement included, the range of escapements covered is still small relative to the historical range (PFMC 2025, their Table B-1) and does not include values greater than, or even closely approaching, the estimated S_{MP} from the juvenile index of nearly 500,000 spawners. While it seems plausible that productivity may be persistently lower now than it was prior to the 2008-2009 "collapse" (Lindley et al. 2009), it still seems problematic to analyze a spawner-recruit curve over such a narrow range of escapements, and it is unclear whether any of the recent changes hypothesized to reduce productivity would have reduced capacity as well (i.e. there is still a lot of habitat available when flow and temperature conditions allow its full use).

Nevertheless, in the interest of transparency, we fit spawner-recruit relationships to data for brood years 2007-2018 where escapement was natural-area adult spawners and recruits were calculated as the SI times the proportion of escapement that was of natural origin three years later. Note that the natural-origin recruitment estimates using this method are generally lower than potential natural-origin escapement in the absence of fishing from the cohort reconstruction, suggesting that the assumptions noted for this method in the main body of the progress report are violated. The degree of difference likely depends on annual variation in age-3 maturation rates, the strength of consecutive brood years, and the potential contribution of fish that would have been predicted to spawn at age-4 if they escaped fishing.

With no flow covariate, the fit was poor (R^2=0.11) and the model estimated that natural production was maximized at S_{MP} = 78,746 natural-area adults. Adding the same flow covariate as used in the main text increased R^2 to 0.52, and increased the estimate of S_{MP} to 92,187 natural-area adults (Figure G1). Approximate 95% confidence intervals on β calculated using the *confint* command in R corresponded to S_{MP} values ranging from 58,787-213,471.

Figure G1. SRFC spawner-recruit relationship (Ricker) where spawners are natural-area adults and recruits are the SI times the proportion of escapement estimated to be natural-origin, with a flow covariate describing flow during rearing and outmigration (see main text and Appendix B for further detail). Points are labeled by brood year, and the darkness of the fill indicates the value of the flow covariate. The solid curve represents predicted recruitment when the flow covariate is at its mean value, the dashed curve represents predicted recruitment when the flow covariate is 1 SD above the mean, and the dotted curve represents predicted recruitment when the flow covariate is 1 SD below the mean.



The S_{MP} estimated by the analysis including the flow covariate and using the natural-adjusted SI to estimate recruitment would correspond to $S_{MSY} = F_{MSY} \times S_{MP} = 0.58 \times 92{,}187 = 53{,}468$ natural-area adults. To the extent the SI captures potential escapement in the absence of fishing, and subject to all the caveats raised in discussion of the SI-based metric in the main body of the progress report, this could be viewed as a spawner-recruit analysis where spawners are natural-area spawners and recruits are potential natural-origin spawners in the absence of fishing. One might therefore be tempted to estimate MSY-related quantities directly from the parameters of the fitted spawner-recruit relationship, even though the units of spawners and recruits do not fully match (natural-area versus natural-origin). Such an approach was taken for Klamath River Fall Chinook (STT 2005), although the contribution of hatchery-origin strays spawning in natural areas is substantially less in that system. Estimating MSY quantities directly from this spawner-recruit relationship (using the formulae in Scheuerell [2016]) leads to an even lower estimate of S_{MSY}=42,854 natural-area adults accompanied by a lower F_{MSY}=0.46.

However, the SRWG highlights serious concerns with these numbers. Most crucially, they come from a limited data set covering only a limited range of escapements and environmental conditions, and the only observation at escapement substantially higher than the S_{MP} estimate came from the lowest flow year included in the dataset. Targeting escapement this low would also reduce expected river harvests compared to the status quo targeting of at least 122,000.

Attempting to estimate MSY directly from the fitted spawner-recruit relationship is also confounded by hatchery strays and a mismatch between the units of spawners (natural-area) versus recruits (natural-origin). Although this approach has precedent in the Klamath basin (STT 2005), the contribution of hatchery-origin fish to natural-area spawners in that system is much lower than in the Sacramento. In addition, given the 2011-2024 median ratio of SRFC natural-area adult escapement to total adult escapement (PFMC 2025, their Table B-1) of 0.68, these natural area escapements would correspond to a total adult escapements that have only a modest probability of meeting the currently-defined (PFMC 2025, their Table B-1) hatchery escapement goals (Satterthwaite 2023, his Figure 4). To be consistent with how MSY is derived and the required assumption that population dynamics are independent of hatchery influence (STT 2005), the implied S_{MSY} of 42,854 adults spawning in natural areas might be better stated as 42,854 natural-origin adults spawning in natural areas.

References for Appendix G

Chen, E. K., W. H. Satterthwaite, M. R. O'Farrell, and S. M. Carlson. 2024. Cohort Reconstruction for Sacramento River Fall Chinook salmon and Comparison with the Sacramento Index. Report to Pacific Fishery Management Council. Available from: https://www.pcouncil.org/documents/2024/09/cohort-reconstruction-for-sacramento-fall-chinook-salmon-and-comparison-with-the-sacramento-index.pdf/

CTC [Chinook Technical Committee of the Pacific Salmon Commission]. 1999. Maximum sustained yield or biologically based escapement goals for selected chinook salmon stocks used by the Pacific Salmon Commission's Chinook Technical Committee for escapement assessment. Pacific Salmon Commission, Joint Chinook Technical Committee Report TCCHINOOK (99)-3, Vancouver. Available from: https://www.psc.org/download/35/chinook-technical-committee/2172/tcchinook99-3.pdf

Lindley, S. T., C. B. Grimes, M. S. Mohr, W. Peterson, J. Stein, J. T. Anderson, L. W. Botsford, D. L. Bottom, C. A. Busack, T. K. Collier, et al. 2009. What caused the Sacramento River fall Chinook stock collapse? US Department of Commerce. NOAA Technical Memorandum NOAA-TM-NMFS-SWFSC-447. Available from: https://repository.library.noaa.gov/view/noaa/3664/noaa_3664_DS1.pdf

O'Farrell, M. R., M. S. Mohr, M. L. Palmer-Zwahlen, and A. M. Grover. 2013. The Sacramento Index (SI). NOAA-TM-NMFS-SWFSC-512:1–41. Available from: https://swfsc-publications.fisheries.noaa.gov/publications/TM/SWFSC/NOAA-TM-NMFS-SWFSC-512.pdf

PFMC [Pacific Fishery Management Council]. 2025. Review of 2024 ocean salmon fisheries: stock assessment and fishery evaluation document for the Pacific Coast Salmon Fishery Management Plan. Available from: https://www.pcouncil.org/documents/2025/02/review-of-2024-ocean-salmon-fisheries.pdf/

Satterthwaite, W. H. 2023. An approach to defining a Sacramento River Fall Chinook escapement objective considering natural production, hatcheries, and risk tolerance. San Francisco Estuary and Watershed Science 21(3):3. Available from: https://doi.org/10.15447/sfews.2023v21iss3art3

Scheuerell, M. D. 2016. An explicit solution for calculating optimum spawning stock size from Ricker's stock recruitment model. PeerJ 4:e1623. Available from: https://doi.org/10.7717/peerj.1623

SSC [Scientific and Statistical Committee of the Pacific Fishery Management Council]. 2024. Scientific and Statistical Committee Report on Final Methodology Review Results. Available from: https://www.pcouncil.org/documents/2024/11/f-2-a-supplemental-ssc-report-1-ssc-report-on-final-methodology-review-results.pdf/

STT [Salmon Technical Team of the Pacific Fishery Management Council]. 2005. Klamath River Fall Chinook Stock-Recruitment Analysis. Report to PFMC. Available from: https://www.pcouncil.org/documents/2005/09/klamath-river-fall-chinook-stock-recruitment-analysis.pdf/

STT [Salmon Technical Team of the Pacific Fishery Management Council]. 2024. Salmon Technical Team Report on 2025 [sic] Salmon Methodology Review. Available from: https://www.pcouncil.org/documents/2024/11/f-2-a-supplemental-stt-report-1-stt-report-on-2025-salmon-methodology-review.pdf/

White, S., C. Lindley, and I. Pritchard. 2025. Recovery of Coded-Wire Tags from Chinook Salmon in California's Central Valley Escapement, Inland Harvest, and Ocean Harvest in 2021. Report funded by the U.S. Bureau of Reclamation, East Bay Municipal Utilities District, and the California Department of Water Resources contracts with the Pacific States Marine Fisheries Commission (PSMFC). Available from: https://www.calfish.org/Portals/2/Programs/CentralValley/CFM/docs/2021_CFM_CWT_Report.pdf

Appendix H. R Code for the spawner-recruit analysis based on the SI.

```
# use Ogle's FSA package to fit S-R relationships
library(FSA)
dat.si=read.csv("SInatdatSR.csv")
year.labs=c("07","08","09","10","11","12","13","14","15","16","17","18")


#fit a Ricker, ignoring flow
r3 <- srFuns("Ricker",param=3)
r3s <- srStarts(recruits~spawners,data=dat.si,type="Ricker",param=3)
fit2 <- nls(log(recruits)~log(r3(spawners,a,Rp)),data=dat.si,start=r3s)
summary(fit2,correlation=TRUE)
#plot the S-R curve and some reference points
pdf("SIbasedSR.pdf",height=8,width=8)
plot(dat.si$spawners,dat.si$recruits,xlab="natural-area escapement",ylab="SI * prop
natrual-orgin",main="SI-based S-R
relationship",xlim=c(0,320000),ylim=c(0,250000),cex.lab=1.5)
curve(r3(x,a=coef(fit2)[1],Rp=coef(fit2)[2]),from=0,to=320000,lwd=3,add=TRUE)
#calculate and plot maximum production
a=coef(fit2)[1]
Ricker.alpha=log(a)
Rp=coef(fit2)[2]
Smp=Rp*exp(1)/a
#78745.52
Ricker.beta=1/Smp
MP=r3(Smp,a=coef(fit2)[1],Rp=coef(fit2)[2])
lines(x=c(Smp,Smp),y=c(0,MP),col="blue",lty=2)
text(x=Smp,y=Smp,round(Smp),pos=1,col="blue")
text(x=dat.si$spawners,y=dat.si$recruits,year.labs,pos=4)
dev.off()
recruits.observed=dat.si$recruits
recruits.predicted=r3(dat.si$spawners,a=coef(fit2)[1],Rp=coef(fit2)[2])
SS.mean=sum((recruits.observed-mean(recruits.observed))^2)
SS.pred=sum((recruits.observed-recruits.predicted)^2)
Rsquared=1-SS.pred/SS.mean
#0.1105386

#fit a Ricker, including flow
dat=read.csv("SInatdatSR.csv")
r_starters <- srStarts(recruits ~ spawners, data = dat, type = "Ricker")
#add a starting value for flow covariate (used same starting value as Stu)
r_f_starters_list <- list(a = r_starters$a, b = r_starters$b, f = 0.2)
r_f_z <- nls(log(recruits)~log((a * spawners) * exp(-b * spawners)) + f * flow, data =
dat, start = r_f_starters_list)
dummy_data <- read.csv("dummydatSR.csv")
dummy_data$recruit_prediction <- predict(r_f_z, newdata = dummy_data)
dummy_range=dummy_data$spawners[dummy_data$flow==0]
dummy_predict_mean=exp(dummy_data$recruit_prediction[dummy_data$flow==0])
dummy_predict_hi=exp(dummy_data$recruit_prediction[dummy_data$flow==1])
dummy_predict_lo=exp(dummy_data$recruit_prediction[dummy_data$flow==-1])
pdf("SIbasedSR-WithFlow.pdf",height=8,width=8)
plot(dat$spawners,dat$recruits,cex=2.5,xlab="natural area adult escapement
(thou)",ylab="SI * prop natural-origin (thou)",main="SRFC stock-recruit relationship
from SI, include flow",xaxt="n",yaxt="n",xlim=c(0,350000),ylim=c(0,250000))
axis(side=1,at=c(50000,100000,150000,200000,250000,300000,350000),labels=c(50,100,150,
200,250,300,350))
axis(side=2,at=c(50000,100000,150000,200000,250000),labels=c(50,100,150,200,250))
points(x=dat$spawners,y=dat$recruits,pch=21,cex=2.5,bg=grey(1-(dat$flow+2)/4.5))
lines(dummy_range,dummy_predict_mean,lwd=3,col="blue")
lines(dummy_range,dummy_predict_hi,lwd=2,lty=2,col="dark blue")
lines(dummy_range,dummy_predict_lo,lwd=3,lty=3,col="light blue")
```

```
Smp_flow=1/coef(r_f_z)[2]
#92187.44
a=coef(r_f_z)[1]
b=coef(r_f_z)[2]
f=coef(r_f_z)[3]
MP_flow_mean=exp(log((a*Smp_flow)*exp(-b*Smp_flow))+f*0)
MP_flow_hi=exp(log((a*Smp_flow)*exp(-b*Smp_flow))+f*1)
MP_flow_lo=exp(log((a*Smp_flow)*exp(-b*Smp_flow))+f*(-1))
lines(x=c(Smp_flow,Smp_flow),y=c(0,MP_flow_mean),lty=2,col="blue")
text(x=Smp_flow,y=0,round(Smp_flow),pos=4,col="blue")
text(x=dat.si$spawners,y=dat.si$recruits,year.labs,pos=4)
dev.off()
#calculate arithmetic-scale Rsquare
SS=sum((dat.si$recruits-mean(dat.si$recruits))^2)
SS_r_f_z=sum((exp(predict(r_f_z))-dat.si$recruits)^2)
Rsquare_r_f_z=1-SS_r_f_z/SS
#[1] 0.5229424

#pretend we could use this to estimate MSY directly
library(gsl)
alpha=a
beta=b
lambert_in=exp(1-log(alpha))
lambert_out=lambert_W0(lambert_in)
Smsy=(1-lambert_out)/beta
# 42854.17
Smp=1/beta
Rmsy=alpha*Smsy*exp(-beta*Smsy)
Rmp=alpha*Smp*exp(-beta*Smp)
Ymsy=Rmsy-Smsy
Ymp=Rmp-Smp
Fmsy=Ymsy/(Ymsy+Smsy)
# 0.4648591

#put confidence intervals on Smp
Smp.upper=1/confint(r_f_z)[2,1]
#213470.6
Smp.lower=1/confint(r_f_z)[2,2]
#58787.41
```

Appendix I. Input files for SI-based spawner-recruit code.

Save the below to a .csv file named "SInatdatSR.csv" in the working directory for the code in Appendix H:

```
Year,spawners,flow,recruits
2007,70072,-0.5456973,44900
2008,47316,-0.7515642,43700
2009,24948,-0.2010693,99900
2010,91126,1.028593,209900
2011,77854,-0.3551712,138800
2012,166233,-0.3232398,64900
2013,305635,-1.374569,41100
2014,168667,-1.193305,21300
2015,74504,-0.2794978,55000
2016,56297,2.218739,202200
2017,17851,-0.6116502,85400
2018,71689,1.223834,85400
```

Save the below to a .csv file named "dummydatSR.csv" in the working directory for the code in Appendix H:

```
spawners,flow
25000,-1
50000,-1
75000,-1
100000,-1
125000,-1
150000,-1
175000,-1
200000,-1
225000,-1
250000,-1
275000,-1
300000,-1
325000,-1
350000,-1
375000,-1
400000,-1
25000,0
50000,0
75000,0
100000,0
125000,0
150000,0
175000,0
200000,0
225000,0
250000,0
275000,0
300000,0
325000,0
350000,0
375000,0
400000,0
25000,1
50000,1
75000,1
100000,1
```

```
125000,1
150000,1
175000,1
200000,1
225000,1
250000,1
275000,1
300000,1
325000,1
350000,1
375000,1
400000,1
```

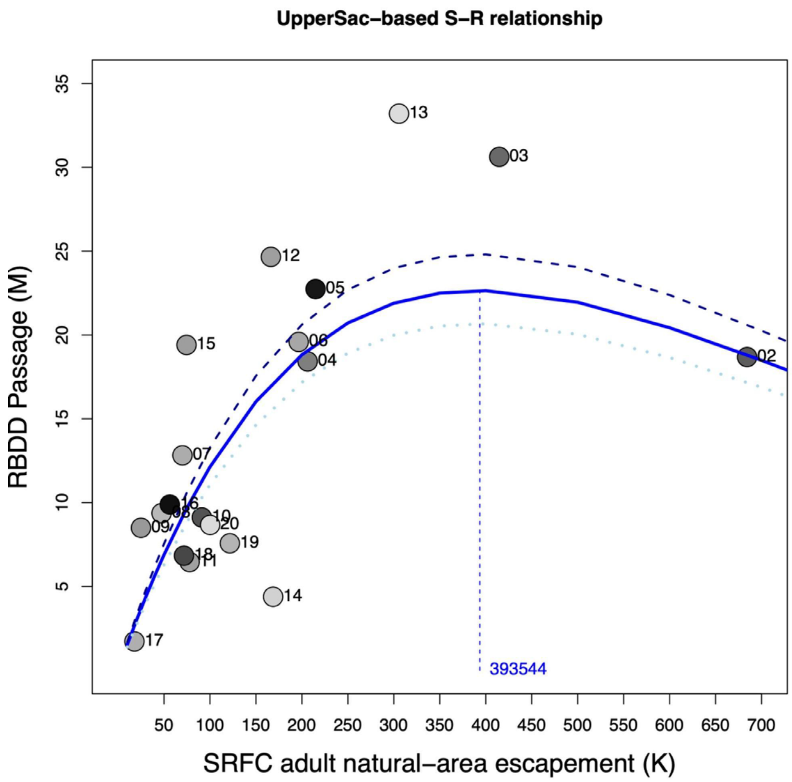
Appendix J. Sensitivity analysis: Spawner-recruit analysis based on RBDD juvenile passage

It is the SRWG's position that the estimated number of fall-run fry equivalents passing downstream of the Red Bluff Diversion Dam (RBDD) rotary screw trap (Voss and Poytress 2022) is a less useful metric of basin-wide natural production than the Munsch et al. (2020) index because it captures production from only the Upper Sacramento rather than the whole basin and because of additional lower river mortality (that might have a density-dependent component) going unmeasured. Nevertheless, for completeness, we performed a sensitivity analysis using the RBDD fall-run juvenile passage as the metric of recruits, while still using total SRFC natural-area spawners as the metric of spawners and using the same lower Sacramento flow index as used in the main analysis. This contrasts with previous analyses of this dataset that considered only females spawning in natural areas above RBDD (PFMC 2019), and one might expect weaker relationships given the geographical mismatches in both spawner and flow metrics. However, this analysis is presented for comparability with the other analyses performed, noting that total natural-area adult SRFC escapement has generally been highly correlated with females spawning in natural areas of the Upper Sacramento (r=0.95 for the spawner years 2002-2020 included here), although there are signs this relationship may be breaking down in recent years (an unusually high 71% of total natural-area adult SRFC escapement was to the Upper Sacramento in 2022, followed by only 6% in 2024 [PFMC 2025]).

With no flow covariate, the fit was reasonable (R^2=0.56) and the model estimated that natural production was maximized at S_{MP} = 409,402 natural-area adults throughout the Sacramento River Basin. Adding the same flow covariate as used in the main text had little effect on R^2 (0.55)[1], or the estimate of S_{MP} (393,544), as shown in Figure J1. Approximate profile-based 95% confidence intervals on β calculated using the *confint* command in R corresponded to S_{MP} values ranging from 236,380-1,174,336. Given the numerous uncertainties associated with these analyses, the SRWG finds these estimates reasonably consistent with those provided by the preferred analysis based on the updated and extended Munsch et al. (2020) index for the same set of years, and highlights the importance of the Upper Sacramento to total natural-origin production in the system.

[1] Although it might be surprising for R^2 to (very slightly) decrease with an additional parameter, note that the Ricker is actually fit in log-space to recruits per spawner, thus the best fit in terms of likelihood may have worse fit in terms of arithmetic-scale differences between predicted and observed recruitment.

Figure J1. SRFC spawner-recruit relationship (Ricker) where spawners are natural-area adults throughout the basin and recruits are fall-run fry equivalents passing Red Bluff Diversion Dam, with a flow covariate describing flow during rearing and outmigration (see main text and Appendix B for further detail). Points are labeled by brood year, and the darkness of the fill indicates the value of the flow covariate. The solid curve represents predicted recruitment when the flow covariate is at its mean value, the dashed curve represents predicted recruitment when the flow covariate is 1 SD above the mean, and the dotted curve represents predicted recruitment when the flow covariate is 1 SD below the mean.



References for Appendix J

Munsch, S. H., C. M. Greene, R. C. Johnson, W. H. Satterthwaite, H. Imaki, P. L. Brandes, and M. R. O'Farrell. 2020. Science for integrative management of a diadromous fish stock: interdependencies of fisheries, flow, and habitat restoration. Canadian Journal of Fisheries and Aquatic Sciences 77:1487-1504. Available from: https://doi.org/10.1139/cjfas-2020-0075

PFMC [Pacific Fishery Management Council]. 2019. Salmon Rebuilding Plan for Sacramento River Fall Chinook. Pacific Fishery Management Council, 7700 NE Ambassador Place, Suite 101, Portland, Oregon 97220-1384. Available from: https://www.pcouncil.org/documents/2019/07/sacramento-river-fall-chinook-salmon-rebuilding-plan-regulatory-identifier-number-0648-bi04-july-2019.pdf/

PFMC [Pacific Fishery Management Council]. 2025. Review of 2024 ocean salmon fisheries: stock assessment and fishery evaluation document for the Pacific Coast Salmon Fishery Management Plan. Available from: https://www.pcouncil.org/documents/2025/02/review-of-2024-ocean-salmon-fisheries.pdf/

Voss, S. D. and W. R. Poytress. 2022. 2020 Red Bluff Diversion Dam Rotary Trap Juvenile Anadromous Fish Abundance Estimates. Report of U.S. Fish and Wildlife Service to U.S. Bureau of Reclamation, Sacramento, CA. Available from: https://www.researchgate.net/publication/363414690_2020_RED_BLUFF_DIVERSION_DAM_ROTARY_TRAP_JUVENILE_ANADROMOUS_FISH_ABUNDANCE_ESTIMATES

Appendix K. R Code for the spawner-recruit analysis based on the Upper Sacramento (RBDD) juvenile passage index.

```
# use Ogle's FSA package to fit S-R relationships
library(FSA)
dat.UpperSac=read.csv("UpperSacnatdatSR.csv")
year.labs=c("02","03","04","05","06","07","08","09","10","11","12","13","14","15","16"
,"17","18","19","20")


#fit a Ricker, ignoring flow
r3 <- srFuns("Ricker",param=3)
r3s <- srStarts(recruits~spawners,data=dat.UpperSac,type="Ricker",param=3)
fit2 <- nls(log(recruits)~log(r3(spawners,a,Rp)),data=dat.UpperSac,start=r3s)
summary(fit2,correlation=TRUE)
#plot the S-R curve and some reference points
pdf("UpperSacbasedSR.pdf",height=8,width=8)
plot(dat.UpperSac$spawners,dat.UpperSac$recruits,xlab="SRFC adult natural-area
escapement (K)",ylab="RBDD Passage (M)",main="UpperSac-based S-R
relationship",xlim=c(0,700000),ylim=c(0,35000000),cex.lab=1.5,xaxt="n",yaxt="n")
axis(side=1,at=c(50000,100000,150000,200000,250000,300000,350000,400000,450000,500000,
550000,600000,650000,700000),labels=c(50,100,150,200,250,300,350,400,450,500,550,600,6
50,700))
axis(side=2,at=c(5000000,10000000,15000000,20000000,25000000,30000000,35000000),labels
=c(5,10,15,20,25,30,35))
curve(r3(x,a=coef(fit2)[1],Rp=coef(fit2)[2]),from=0,to=700000,lwd=3,add=TRUE)
#calculate and plot maximum production
a=coef(fit2)[1]
Ricker.alpha=log(a)
Rp=coef(fit2)[2]
Smp=Rp*exp(1)/a
#409402
Ricker.beta=1/Smp
MP=r3(Smp,a=coef(fit2)[1],Rp=coef(fit2)[2])
lines(x=c(Smp,Smp),y=c(0,MP),col="blue",lty=2)
text(x=Smp,y=Smp,round(Smp),pos=1,col="blue")
text(x=dat.UpperSac$spawners,y=dat.UpperSac$recruits,year.labs,pos=4)
dev.off()
recruits.observed=dat.UpperSac$recruits
recruits.predicted=r3(dat.UpperSac$spawners,a=coef(fit2)[1],Rp=coef(fit2)[2])
SS.mean=sum((recruits.observed-mean(recruits.observed))^2)
SS.pred=sum((recruits.observed-recruits.predicted)^2)
Rsquared=1-SS.pred/SS.mean
#0.5643677

#fit a Ricker, including flow
dat=read.csv("UpperSacnatdatSR.csv")
r_starters <- srStarts(recruits ~ spawners, data = dat, type = "Ricker")
#add a starting value for flow covariate (used same starting value as Stu)
r_f_starters_list <- list(a = r_starters$a, b = r_starters$b, f = 0.2)
r_f_z <- nls(log(recruits)~log((a * spawners) * exp(-b * spawners)) + f * flow, data =
dat, start = r_f_starters_list)
dummy_data <- read.csv("dummydatSR.csv")
dummy_data$recruit_prediction <- predict(r_f_z, newdata = dummy_data)
dummy_range=dummy_data$spawners[dummy_data$flow==0]
dummy_predict_mean=exp(dummy_data$recruit_prediction[dummy_data$flow==0])
dummy_predict_hi=exp(dummy_data$recruit_prediction[dummy_data$flow==1])
dummy_predict_lo=exp(dummy_data$recruit_prediction[dummy_data$flow==-1])
pdf("UpperSacbasedSR-WithFlow.pdf",height=8,width=8)
plot(dat$spawners,dat$recruits,cex=2.5,xlab="SRFC adult natural-area escapement
(K)",ylab="RBDD Passage (M)",main="UpperSac-based S-R
relationship",xlim=c(0,700000),ylim=c(0,35000000),cex.lab=1.5,xaxt="n",yaxt="n")
```

```
axis(side=1,at=c(50000,100000,150000,200000,250000,300000,350000,400000,450000,500000,
550000,600000,650000,700000),labels=c(50,100,150,200,250,300,350,400,450,500,550,600,6
50,700))
axis(side=2,at=c(5000000,10000000,15000000,20000000,25000000,30000000,35000000),labels
=c(5,10,15,20,25,30,35))
points(x=dat$spawners,y=dat$recruits,pch=21,cex=2.5,bg=grey(1-(dat$flow+2)/4.5))
lines(dummy_range,dummy_predict_mean,lwd=3,col="blue")
lines(dummy_range,dummy_predict_hi,lwd=2,lty=2,col="dark blue")
lines(dummy_range,dummy_predict_lo,lwd=3,lty=3,col="light blue")
Smp_flow=1/coef(r_f_z)[2]
#393543.9
a=coef(r_f_z)[1]
b=coef(r_f_z)[2]
f=coef(r_f_z)[3]
MP_flow_mean=exp(log((a*Smp_flow)*exp(-b*Smp_flow))+f*0)
MP_flow_hi=exp(log((a*Smp_flow)*exp(-b*Smp_flow))+f*1)
MP_flow_lo=exp(log((a*Smp_flow)*exp(-b*Smp_flow))+f*(-1))
lines(x=c(Smp_flow,Smp_flow),y=c(0,MP_flow_mean),lty=2,col="blue")
text(x=Smp_flow,y=0,round(Smp_flow),pos=4,col="blue")
text(x=dat.UpperSac$spawners,y=dat.UpperSac$recruits,year.labs,pos=4)
dev.off()
#calculate arithmetic-scale Rsquare
SS=sum((dat.UpperSac$recruits-mean(dat.UpperSac$recruits))^2)
SS_r_f_z=sum((exp(predict(r_f_z))-dat.UpperSac$recruits)^2)
Rsquare_r_f_z=1-SS_r_f_z/SS
#[1] 0.5504225

#put confidence intervals on Smp
Smp.upper=1/confint(r_f_z)[2,1]
#1174336
Smp.lower=1/confint(r_f_z)[2,2]
#236379.8
```

Appendix L. Input files for RBDD-based spawner-recruit code.

Save the below to a .csv file named "UpperSacnatdatSR.csv" in the working directory for the code in Appendix K:

```
Year,spawners,flow,recruits
2002,684226,0.8542736,18683720
2003,414644,0.6388201,30624209
2004,206230,0.2577683,18421457
2005,214860,2.098677,22739315
2006,196489,-0.4478281,19586600
2007,70072,-0.5456973,12822401
2008,47316,-0.7515642,9371141
2009,24948,-0.2010693,8498417
2010,91126,1.028593,9119714
2011,77854,-0.3551712,6457455
2012,166233,-0.3232398,24659091
2013,305635,-1.374569,33201448
2014,168667,-1.193305,4387348
2015,74504,-0.2794978,19406341
2016,56297,2.218739,9886303
2017,17851,-0.6116502,1723831
2018,71689,1.223834,6837157
2019,121629,-0.6647328,7575182
2020,100169,-1.348141,8670945
```

Save the below to a .csv file named "dummydatSR.csv" in the working directory for the code in Appendix K:

```
spawners,flow
10000,-1
20000,-1
30000,-1
40000,-1
50000,-1
75000,-1
100000,-1
150000,-1
200000,-1
250000,-1
300000,-1
350000,-1
400000,-1
500000,-1
600000,-1
700000,-1
800000,-1
10000,0
20000,0
30000,0
40000,0
50000,0
75000,0
100000,0
150000,0
200000,0
250000,0
300000,0
350000,0
```

```
400000,0
500000,0
600000,0
700000,0
800000,0
10000,1
20000,1
30000,1
40000,1
50000,1
75000,1
100000,1
150000,1
200000,1
250000,1
300000,1
350000,1
400000,1
500000,1
600000,1
700000,1
800000,1
```