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RESEARCH

An Approach to Defining a Sacramento River Fall Chinook Escapement Objective Considering Natural Production, Hatcheries, and Risk Tolerance

William H. Satterthwaite[1]

ABSTRACT

The escapement objective used to manage fisheries for Sacramento River Fall Chinook (SRFC) Salmon was established in 1984. Despite substantial changes to the system and multiple calls to re-evaluate the objective, data and analytical limitations have slowed progress. Synthesizing the available information is further complicated by the different measurement scales employed by relevant studies. Here, I offer a modeling framework for integrating consideration of established hatchery spawning goals, natural-area production or habitat capacities measured at varying spatial scales, and policy decisions about what fraction of potential natural production is desired along with risk tolerance. The model allows evaluating how likely a potential escapement goal (measured at the currently-used scale of fall-run adults returning to both hatcheries and natural areas throughout the Sacramento River basin) is both to meet hatchery goals and to produce at least a specified fraction of potential natural production. The framework also incorporates consideration of forecasting and ocean harvest planning error into identifying a pre-season planning target and its probability of resulting in escapement at least as high as the goal. The model indicates that the low end of the current escapement goal range of 122,000 to 180,000 adults, if achieved, would be more likely than not to achieve hatchery goals while achieving around 50% of potential natural production. Realized escapement equal to the high end is modeled to be very likely to achieve hatchery goals, and likely to achieve around 75% of potential basin-wide natural production or around 60% of upper Sacramento River potential production. The model indicates diminishing returns from total adult SRFC escapements higher than about 300,000 adults. However, past performance of forecast and harvest-planning models suggest that a pre-season target higher than the ultimate escapement goal is needed to have even a 50% chance of achieving the escapement goal.

KEY WORDS

Chinook Salmon, escapement, target, goal, risk tolerance, yield, fishery, harvest, management, *Oncorhynchus tshawytscha*

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* Corresponding author: will.satterthwaite@noaa.gov

1 Fisheries Ecology Division
Southwest Fisheries Science Center
National Marine Fisheries Service
National Oceanic and Atmospheric Administration
Santa Cruz, CA 95060 USA

INTRODUCTION

Chinook Salmon are an iconic species of great ecological (Garman 1992; Chasco et al. 2017), cultural (Yoshiyama and Fisher 2001; Montgomery 2003), and economic (PFMC 2022a) significance, and a major provider of ecosystem services, including nutrient transport (Merz and Moyle 2006) and prey provision to endangered charismatic megafauna (Ford et al. 2016). Central Valley Chinook Salmon are the southernmost native population of Chinook Salmon. The Central Valley supports a diversity of adult return timings (fall, late-fall, winter, and spring), leading to its unique distinction as the only basin where adult Chinook Salmon are present year-round (Fisher et al. 1991). It is likely that the late-fall and winter runs were always lower in abundance than fall and spring runs, and spring-run numbers have also been substantially reduced (Yoshiyama et al. 1998). Central Valley Fall Chinook (CVFC) Salmon have also been greatly affected by habitat changes and harvest (Munsch et al. 2022), with signs of both recent decline (Lindley et al. 2009) and reduced stability (Carlson and Satterthwaite 2011; Satterthwaite and Carlson 2015), especially in the San Joaquin River. Nevertheless, Sacramento River Fall Chinook (SRFC) Salmon are still relatively abundant (PFMC 2022b) and support extensive commercial (38.7 to 248.6 thousand fish annually from 2017 to 2021) and recreational (31.9 to 74.4 thousand fish annually from 2017 to 2021) ocean fisheries along with a substantial recreational river fishery (10.8 to 22.1 thousand fish annually from 2017 to 2021). Larger harvests were obtained in the past, with over a million fish harvested in 1988 and 1995 (PFMC 2022c).

Since 1984 the Pacific Fishery Management Council (PFMC) manages fisheries on SRFC with a goal in most years of 122,000 to 180,000 “adults” (age-3 or older) returning to spawn in hatcheries and natural areas combined (PFMC 2022a). This goal is formally referred to as the “conservation objective” (PFMC 2022a). The upper end of this goal was established as the sum of hatchery goals and average escapements reported for various natural areas during a reference period in the 1950s and 1970s (PFMC 1984); the lower end represents an “interim” reduction based on a lower estimate of capacity for the upper Sacramento River “until such times as the problems with Red Bluff Diversion Dam are rectified” (PFMC 1984). Figure 1 displays the location of Red Bluff Diversion Dam (RBDD) and other significant geographic reference points. The basis for the particular reference periods identified in PFMC (1984) is not clear, not all of the reported averages can be reproduced (Satterthwaite 2022), and the gates of RBDD have been fully open since 2011 (Duda 2013), presumably substantially improving passage even if not solving all the problems of the upper watershed. Other historical and ongoing changes in water management and hydrology (e.g., Munsch et al. 2022) along with restoration actions (e.g., Peterson and Duarte 2020) likely have also changed—and will continue to change—habitat capacity in the system.

The PFMC’s salmon Fishery Management Plan (FMP; PFMC 2022a) states that the intent of the goal is to “provide adequate escapement of natural and hatchery production for Sacramento and San Joaquin fall and late-fall stocks based on habitat conditions and average run-sizes,” although it also states (p. 51) that fisheries for California stocks are managed to maximize natural production. The references to the San Joaquin and late-fall runs reflect SRFC serving as an “indicator stock” for a larger “stock complex.” The conflicting wording regarding maximizing natural production vs. “adequacy” for both natural and hatchery production may reflect an underlying tension between appropriate or sustainable harvest levels for hatchery vs. natural stocks (Kope 1992; California HSRG 2012) and a common perception of SRFC as a hatchery-dominated stock (PFMC 1984; PFMC 2022a). However, recent analyses made possible by the constant fractional marking program (Buttars 2010) suggest a higher natural-origin contribution to SRFC escapement than commonly assumed (median 25% with range 16% to 40% from 2010 to 2019; Letvin et al. 2021 and associated references as described in Appendix A). Although PFMC (1984) argued that the distinction between hatchery and natural fish in the system has been lost, and genetic studies have found evidence for substantial introgression

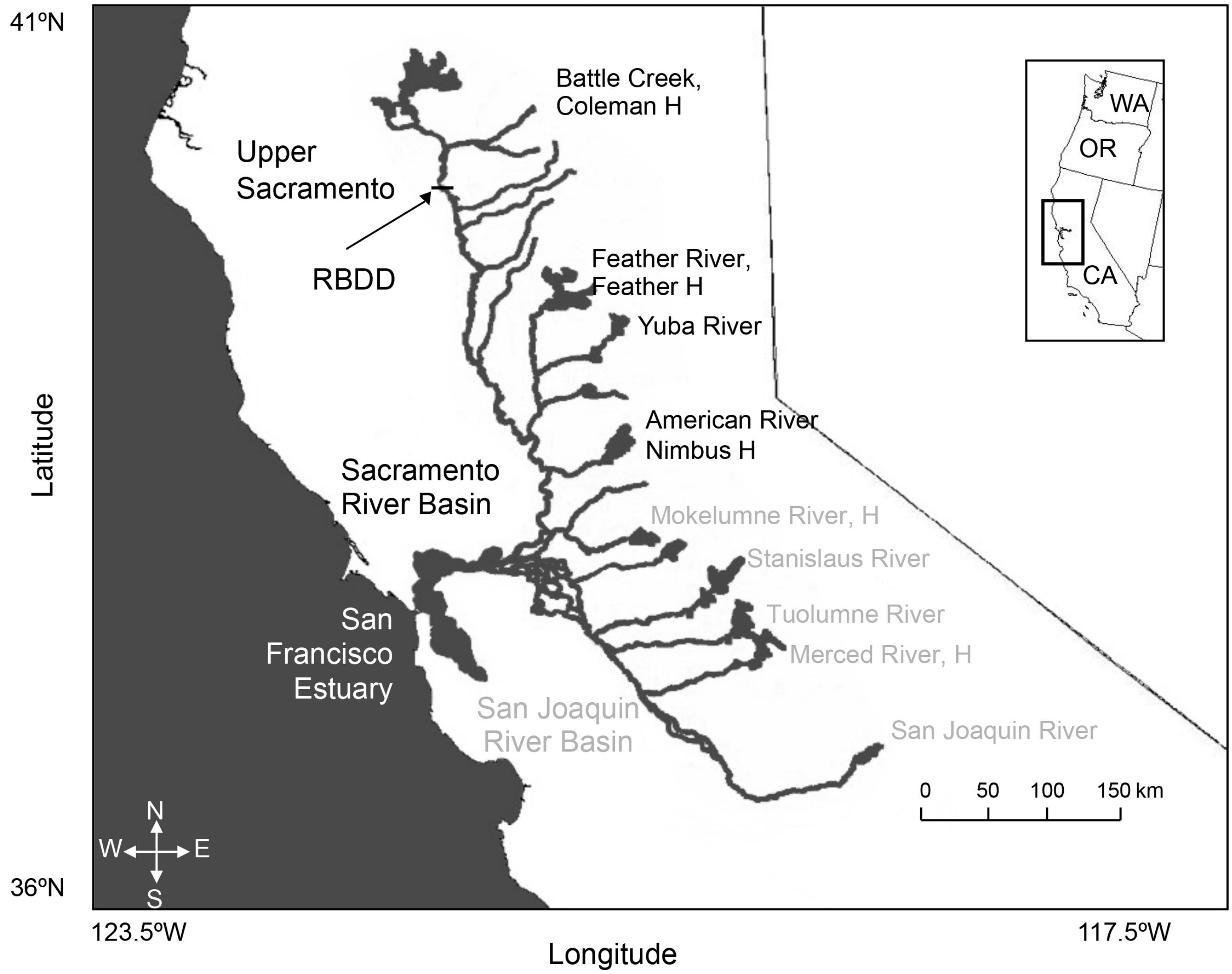

Figure 1 Map of Central Valley rivers with major fall-run Chinook Salmon populations, hatcheries, and significant landmarks referred to in the text. The portion of the Sacramento River basin above Red Bluff Diversion Dam (RBDD) is considered the "upper Sacramento." Fall-run Chinook Salmon spawning in the San Joaquin basin are not counted toward the SRFC escapement objective.

and homogenization (Williamson and May 2005), recent, more detailed genomic studies suggest some that degree of differentiation and local adaptation remains (Meek et al. 2020).

For these and other reasons, numerous advisory bodies both external to (Lindley et al. 2009; California HSRG 2012) and within (PFMC 2019; STT 2020; SRKWWG 2020; SSC 2022) the PFMC have recommended revisiting the SRFC escapement objective, often including the suggestion to develop a goal specifically for natural fish, which could foster a more robust portfolio effect and increase resilience (Lindley et al. 2009; Carlson and Satterthwaite 2011). Additionally, there have been repeated calls (Pawson 2006; Wainwright 2021; Satterthwaite and Shelton 2023) to account for forecast error and other sources of uncertainty when fisheries are planned to achieve a particular escapement level. However, incorporating these factors into the existing management framework has been difficult. The pre-season abundance forecast (Winship et al. 2015) and ocean-harvest planning models (Mohr and O'Farrell 2014) both provide point estimates of combined hatchery plus natural escapement, and so modifications to both those models would be needed to plan for an explicit natural-areas spawning escapement goal.

Additionally, identifying an escapement goal relevant to optimizing natural production or yield is challenging because of a lack of suitable data. To date, no estimates have been made of pre-fishing ocean abundance that separate natural- from hatchery-origin fish, precluding the fitting of typical spawner–recruit relationships as is routinely done for other Chinook Salmon stocks such as Klamath River Fall Chinook (KRFC; STT 2005). The PFMC's FMP states that, when possible, escapement objectives should be related to attaining maximum sustainable yield (PFMC 2022a), typically estimated from a spawner–recruit curve where recruits are measured as recruits to the fishery. Reisenbichler (1986) attempted analyses along these lines for select rivers within and outside the Central Valley but used very dated information (mostly from before the 1970s) and had to make dubious assumptions about harvest while excluding putative "outliers" and noting that simulations suggested his results could be both biased and highly imprecise. More recently, PFMC (2019) fit a spawner–recruitment relationship to natural juvenile production in just the upper Sacramento River above RBDD and used female spawners rather than all adults as the measure of spawners. However, we lack comparable estimates of juvenile production for other natural areas in the watershed, and using juveniles rather than recruits to the fishery precludes direct estimation of fishery reference points from this relationship, even for the portion of the stock that it covers. Munsch et al. (2020) developed an index of natural juvenile production meant to represent combined fall, spring, and winter runs throughout the Sacramento basin, and related this production to flow and to the number of natural-area spawners (including jacks) of all three runs combined. Again, the analysis does not measure spawners at a scale compatible with the existing fishery planning models, and recruits are not measured as recruits to the fishery.

To accommodate these potentially conflicting management goals (i.e., focus on natural-origin fish vs. the hatchery-natural composite, objectives relating to yield or production or "adequacy"), along with the different measurement units required for different purposes and available in different data sets, I offer a modular framework for deriving an escapement objective that considers established hatchery spawner goals, data on natural production as available, and policy-makers' decisions on the degree of natural production desired as well as risk tolerance (i.e., tolerated probability of failing to achieve the stated ultimate goals in the face of biological and management uncertainty). I discuss two separate but related quantities for escapement planning: the goal is the amount of escapement desired under successful management, and the target is used to inform the pre-season planning process. If forecasts and harvest planning models are unbiased, if costs associated with over- or under-forecasting are symmetric, and if managers want to take a risk-neutral approach, the target and goal could be set equal. If pre-season planning models had known bias and/or if managers wished to take a precautionary approach, the target might be set higher than the goal (or lower in the case of abundance forecast models that were biased low or harvest planning models that over-predicted harvest rates). An example of a precautionary approach in existing PFMC management is that to buffer against scientific uncertainty the PFMC sets Acceptable Biological Catch (ABC) limits lower than Overfishing Limits (OFLs) for both groundfish (PFMC 2020) and coastal pelagic species (PFMC 2021a).

This approach separates the science and data analyses from policy decisions, while still ensuring that scientific products will be available in a form that can be merged with policy decisions. The modular form of the approach (outlined in Figure 2, with more detail provided in the subsequent sections) will, I hope, allow for easy modification if and when improved data sources or modeling tools for individual components of the analysis are developed. Although I make no explicit recommendations for a revised escapement objective, for illustrative

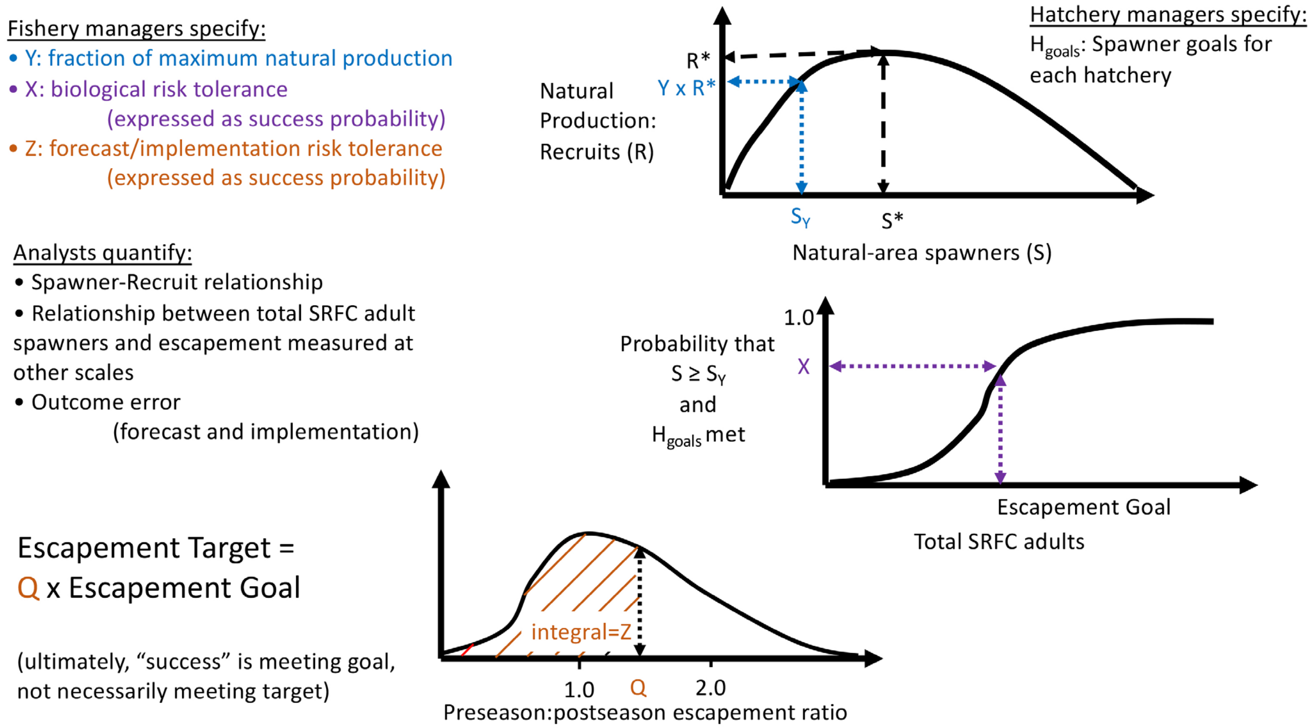

Figure 2 Proposed approach to determining total adult SRFC escapement goal and target levels. External to this process, hatchery managers identify the number of spawners returning to each hatchery desired to meet production, genetic, and other goals. Fishery managers state the fraction of maximum potential natural production (*Y*) they want to achieve, and how confident they want to be (*X*) that achieving the escapement goal for total SRFC adults would be sufficient to achieve that level of natural production while also meeting the hatchery goals. Analysts fit a spawner–recruit relationship that identifies S^*, the natural-area spawning escapement that produces maximum natural production (R^*) along with S_Y, the lowest natural-area spawning escapement predicted to produce at least fraction *Y* of R^*. Analysts also model the past relationship between total SRFC adult escapement and the probability of simultaneously meeting all hatchery goals and achieving natural-area escapement of at least S_Y. The escapement goal is set equal to the lowest total SRFC adult escapement that is modeled to have at least *X* probability of success. Then, based on the past relationship between pre-season expectations of escapement vs. post-season estimates, a multiplier *Q* is found such that there is at least a *Z* probability of achieving a post-season estimated escapement equal to the escapement goal, if the escapement target used to plan fishing regulations is found by multiplying the goal by *Q*.

purposes I do provide worked examples based on currently available data and a range of ultimate goals as implied in the FMP.

MATERIALS AND METHODS

Spawning Escapement

I obtained estimates of adult SRFC escapement to individual hatcheries and natural areas for 1970 to 2021 from PFMC (2022b, Table B-1), obtaining individual-year values for early years from the spreadsheet version of this table available at the PFMC's website[1]. I obtained estimates of female spawners in natural areas above RBDD from 2002 through 2020 from Voss and Poytress (2022), an updated version of the data used in PFMC (2019). I obtained estimates of Sacramento basin-wide spawning escapement (including age-2 "jacks") of fall-, winter-, and spring-run Chinook Salmon from 1998 through 2015 (to match out-migration years from 1999 through 2016 in Munsch et al. 2020; see "Hatchery Goals") from Azat (2022).

Hatchery Goals

The current SRFC escapement objective is based on hatchery goals as found in PFMC (1984). However, PFMC (2022b) lists updated objectives of 12,000 adult spawners for Coleman National Fish

a. *https://www.pcouncil.org/salmon-management-documents/#historical-data-(%22blue-book%22)-toc-9c03886c-0462-4ea2-8017-7cda6c2c907f*

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Hatchery on Battle Creek, 6,000 for the Feather River Hatchery, and 4,000 for Nimbus Hatchery on the American River. In all cases, these goals refer to the number of spawners returning to the hatcheries, regardless of their origin. I used these updated goals for all the analyses in this paper, although the goals used in future applications of this approach could easily be updated further based on the most current guidance from each hatchery.

Natural Production

I obtained estimates of fry-equivalent, juvenile fall-run, natural production above RBDD for brood years 2002 through 2020 (out-migration years 2003 through 2021) from Voss and Poytress (2022). Munsch et al. (2020) developed a natural juvenile production index for fall, spring, and winter runs combined throughout the Sacramento basin. I did not use this production index directly but did obtain (2022 email between S. Munsch and WHS, unreferenced, see "Notes") the parameter estimates for the Ricker stock–recruit curve that Munsch et al. (2020) fit to their juvenile production index, using the same fall-, spring-, and winter-run escapements as reported in Azat (2022) for 1998–2015.

Outcome Error

"Outcome error" refers to the discrepancy between the outcome managers expect based on the management package they adopt, and the post-season estimate of the outcome achieved. Outcome error can be driven by abundance forecasting error (documented for SRFC in Satterthwaite and Shelton [2023]) and "implementation error" where regulations do not achieve the expected harvest amount or rate (not formally tracked for SRFC but see NMFS [2022]). Rather than attempt to model each of these components of outcome error independently, I modeled the overall outcome error by comparing the total adult SRFC escapement expected at the end of the pre-season planning process (obtained from annual versions of Pre-III for 2001 through 2021, e.g., PFMC 2021b) to the post-season estimate of adult SRFC escapement (PFMC 2022b), covering return years 2001 through 2021.

Estimating Spawner–Recruit Relationships

I assumed that the relationship between spawners and recruits (in this case, juvenile production) was described by a Ricker (1975) spawner–recruit relationship:

$$R = e^{\alpha} S e^{-\beta S} \tag{1}$$

Where R denotes recruits and S denotes the spawners giving rise to those recruits, α describes how rapidly the population increases at low abundance (and is commonly referred to as the "productivity" term), and β describes the strength of density dependence. Maximum recruitment occurs for a spawning escapement of $1/\beta$. If recruits are measured at the scale of recruits to the fishery, the spawning escapement that maximizes yield can be approximated or calculated in several ways of varying computational complexity and speed (Scheuerell 2016), but these approaches do not apply when recruits are measured as juveniles, rather than as adults available to the fishery. I fit the parameters of the Ricker model for fall-run Chinook Salmon in the upper Sacramento assuming multiplicative errors using the R package FSA (Ogle et al. 2022), as Munsch et al. (2020) did for fall-, spring-, and winter-run throughout the Sacramento basin.

Determining Escapement Needed for Varying Levels of Production

Assuming that the parameters of the Ricker model are constant, it is simple to determine the spawning escapement S^* that produces maximum recruitment R^*, and then Equation 1 can easily be solved for the smallest S that produces at least fraction Y of R^*. Assuming that environmental variability primarily acts on productivity (α) rather than the strength of density dependence (β), or as a multiplicative error term (additive on the log scale commonly employed in fitting the Ricker), the same escapement will produce fraction Y of the potential maximum production in any given year, scaling the whole stock–recruit curve up or down proportionately, but not changing the location of the escapement that produces the maximum or fractions thereof. Assuming that environmental variation acts through α or a multiplicative error term while holding β constant is a common approach (Peterman et al. 2000) that Munsch et al. (2020) also took; they did not find evidence that their Sacramento Chinook Salmon data set supported an alternative approach.

Estimating Probability of Achieving Hatchery Goals

I classified each return year from 2002 through 2021 as a "success" if escapements to all three hatcheries were above the respective hatchery goals, or a failure otherwise. I then used logistic regression (implemented in Program R, R Core Team 2022) to model the probability of "success" as a function of total SRFC adult escapement. I used these return years to match the years for which the upper Sacramento natural-area/natural-origin spawner–recruit relationship was estimated (i.e., those available in Voss and Poytress 2022), and to reflect that hatchery goals have changed over time (PFMC 1984 vs. PFMC 2022b) such that earlier years may be less representative.

Estimating Probability of Achieving Natural-Origin Production Goals

Given a target fraction Y of maximum potential natural production in any given year, I used Equation 1 to determine the escapement required (either of females above RBDD, or fall-, spring-, and winter-run spawners throughout the Sacramento basin, depending on the production scenario) to achieve at least Y fraction of the maximum possible natural production. I then characterized years with sufficient natural-area escapement at the required scale (females above RBDD, or total fall-, spring-, and winter-run Chinook Salmon in the basin) as a "success," and modeled the probability of success as a function of total adult SRFC escapement using logistic regression. Note that this approach was based on exceeding the minimum escapement required to achieve Y fraction of natural production. It did not consider reductions in production at escapements far above the escapement level that maximized production, in part because escapements that high were very rarely observed in recent data, and in part because of a lack of support in the SRFC data that the Ricker function described the spawner–recruit relationship for Sacramento Chinook Salmon better than a Beverton–Holt relationship in which production never decreases with increased escapement (Munsch et al. 2020).

Estimating Probability of Simultaneously Achieving Hatchery and Natural-Production Goals

Similarly, I classified years where all hatchery goals were met and there is sufficient natural-area escapement at the relevant scale (females above RBDD, or total fall-, spring-, and winter-run Chinook Salmon in the basin) to achieve at least fraction Y of potential natural production as "success," then used a logistic regression model to fit the probability of success as a function of total adult SRFC escapement. I did this analysis using the stock–recruit curve estimated for either natural production of fall run in the upper Sacramento above RBDD or for natural production of fall-, spring-, and winter-run combined, and looked at success in reaching hatchery goals only in the years included in the corresponding spawner–recruit analysis.

Illustrating Management Consequences for Decision-Makers

To visualize the expected consequences of different levels of total SRFC escapement, I plotted the logistic regression results that illustrated the modeled probability of meeting hatchery goals at different levels of total escapement, and created a contour plot that showed the probability X of achieving at least Y fraction of potential natural production, given different levels of total SRFC adult escapement. I created separate contour plots that showed the probability of simultaneously achieving at least Y fraction of potential natural production and meeting all hatchery goals.

Incorporating the Effects of Outcome Error

Following the approach of Satterthwaite and Shelton (2023), I assumed that the ratio between the pre-season *expectation* and the post-season *estimate* of escapement followed a lognormal distribution with log-scale mean μ and log-scale standard deviation σ, corresponding to an arithmetic-scale median ratio e^{μ}. This implies that to have a 50% chance that the post-season escapement estimate will be above or below the goal, a pre-season target should be set equal to the goal multiplied by e^{μ}. To have a probability Z of achieving the escapement goal, the pre-season planning target should be set by multiplying the goal by the Z quantile of the lognormal distribution.

Assuming independence, X (the probability that achieving the goal escapement will provide at least the desired fraction of potential natural production) and Z (the probability that planning for a pre-season escapement target will achieve escapement at least as high as the goal) should be chosen so that their product (which reflects the modeled probability of achieving objectives, given a pre-season expectation of total adult SRFC escapement coming out of the forecast and harvest models) matches the managers' desired level of risk tolerance.

Reproducible Science

All data and code required to reproduce the results of this paper are available from *https://doi.org/10.17632/fm5kh4svg7*.

RESULTS

Stock-Recruit Relationship

In the upper Sacramento above RBDD (Figure 3A), fry-equivalent, natural-origin, juvenile production as a function of female escapement was best described by:

$$R = e^{6.68} S e^{-0.0000109S} \tag{2}$$

while for the Sacramento basin as a whole (Figure 3B), the natural-origin, juvenile production for fall-, spring-, and winter-run Chinook Salmon combined as a function of the total (jack and adult) natural area escapement of those three runs at mean flow was best described by:

$$R = e^{1.14} (S/100000) e^{-0.222(S/100000)} \tag{3}$$

where use of $S/100000$ reflects Munsch et al. (2020) using units of hundreds of thousands of spawners. Munsch et al. (2020) additionally

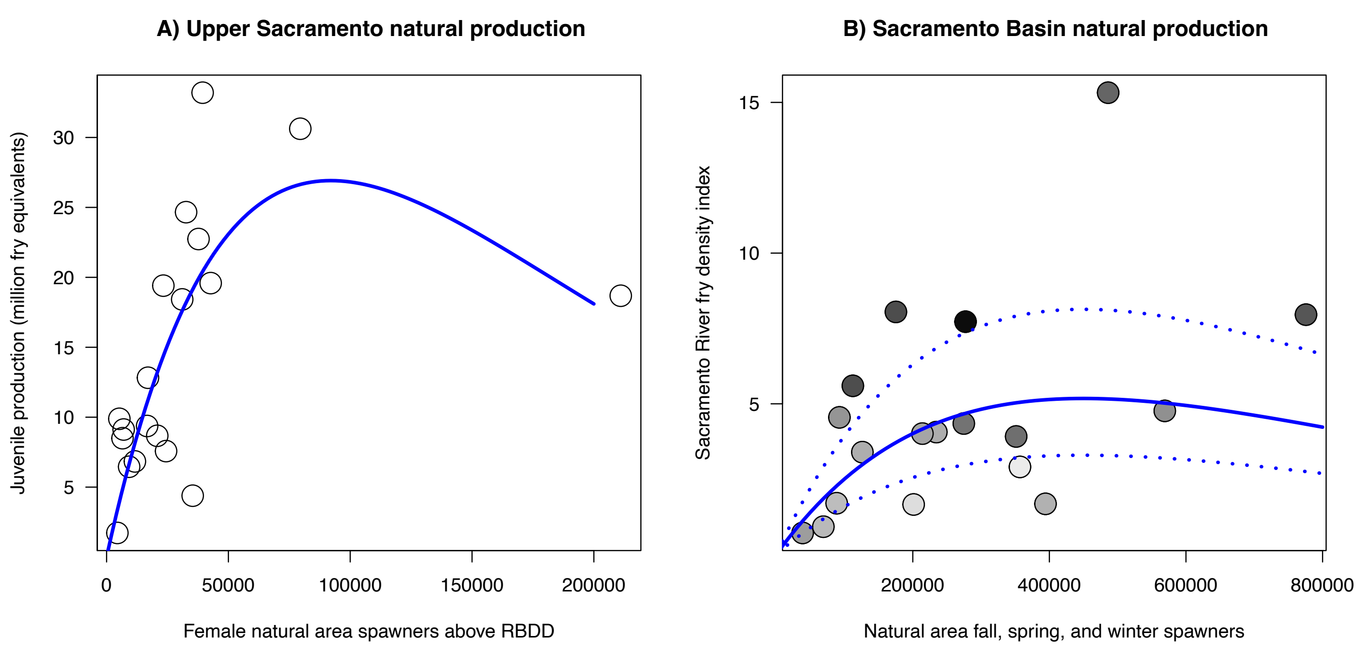

Figure 3 Juvenile production in natural areas as a function of escapement for fall Chinook above Red Bluff Diversion Dam (**A**) or fall-, spring-, and winter-run Chinook Salmon throughout the Sacramento Basin (**B**). Panel (**B**) also incorporates an effect of flow as described in Munsch et al. (2020) but note that the peak production is estimated to occur at the same escapement regardless of flow. The *solid line* indicates modeled production at mean flow, with the *dashed lines* indicating flow levels one standard deviation above (*upper*) or below (*lower*) the mean flow. The *darkness of the filled circles* indicates the flow index for each year (darker = higher flow, see Munsch et al. [2020] for details).

incorporated a flow covariate F that represented z-score transformed (i.e., scaled with mean = 0 and standard deviation = 1) log flow (see Munsch et al. 2020 for details of the flow metric):

$$R = e^{1.14+0.452F}(S/100000)e^{-0.222(S/100000)} \tag{4}$$

Note that Equation 4 reduces to Equation 3 at mean flow (F = 0) and represents a multiplicative arithmetic-scale effect of flow on productivity.

The fitted Ricker curve implies that maximum production of natural-origin SRFC juveniles in the upper Sacramento River would occur for an escapement of about 92,000 females to natural areas above RBDD (a slight update from PFMC [2019], which estimated that production was maximized at about 80,000 females) or 449,000 spawners (both sexes, including jacks) of fall-, spring-, and winter-run Chinook Salmon in natural areas throughout the Sacramento River basin (Munsch et al. [2020] reported this as about 400,000).

Probability of Achieving Hatchery Goals

The modeled probability of meeting all hatchery goals based on observations from 2002 through 2021 is very low (≤ 0.05) for total SRFC adult escapements below about 80,000; first exceeds $p = 0.50$ for escapements above about 111,000 adults; is reasonably probable ($p = 0.74$) for 122,000 adults; and very high ($p \geq 0.95$) for total adult escapements above about 143,000 adults (Figure 4). There is a limited range of escapements in the data for which a mix of successes and failures was observed, which prevented reliable estimation of parameter uncertainty, and so confidence intervals are not shown. In the data analyzed, the minimum total adult escapement at which all hatchery goals were met was 104,483, and the highest total adult escapement at which not all hatchery goals were met was 124,276.

Probability of Achieving Natural Production Goal

Figure 5 illustrates the minimum total adult SRFC escapement needed (thousands) to achieve at least X probability of at least Y fraction of maximum potential natural production. Panel A (left) describes this relationship for natural

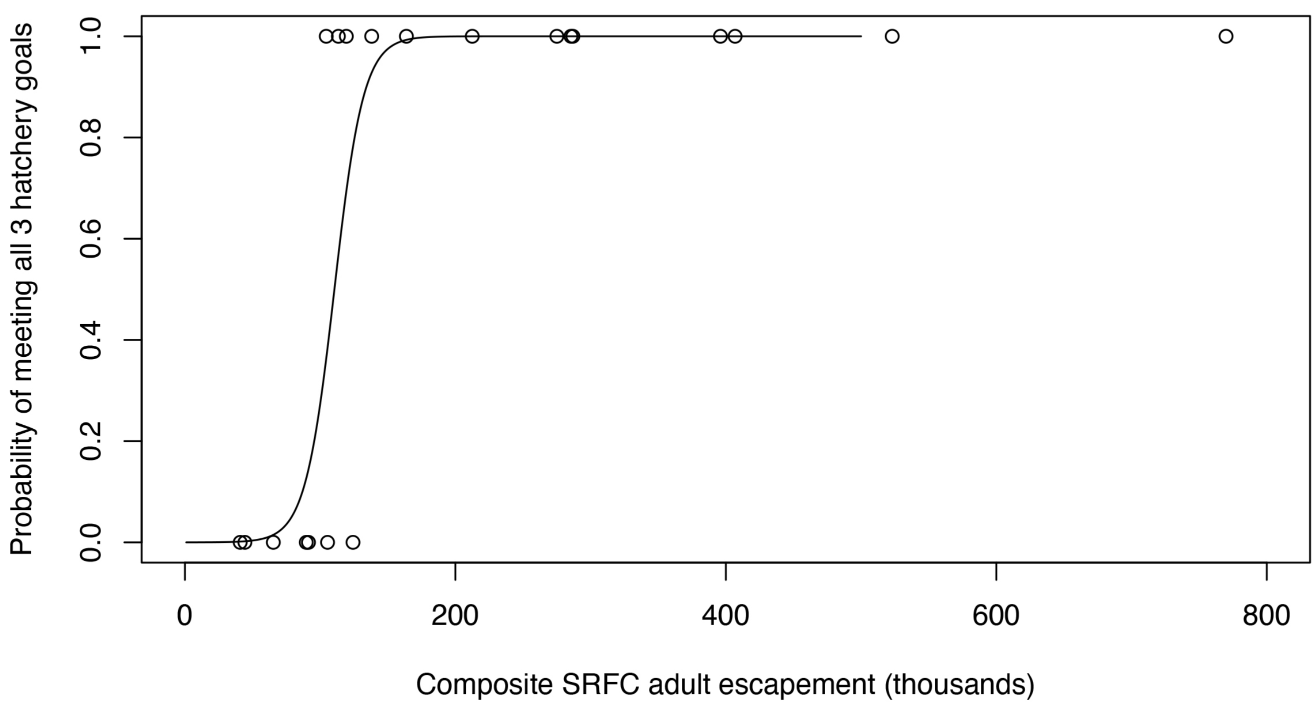

Figure 4 Modeled probability of meeting all hatchery goals (12,000 adults to Coleman National Fish Hatchery, 6,000 adults to Feather River Hatchery, and 4,000 adults to Nimbus Hatchery) as a function of total SRFC adult escapement, based on returns observed for 2002–2021.

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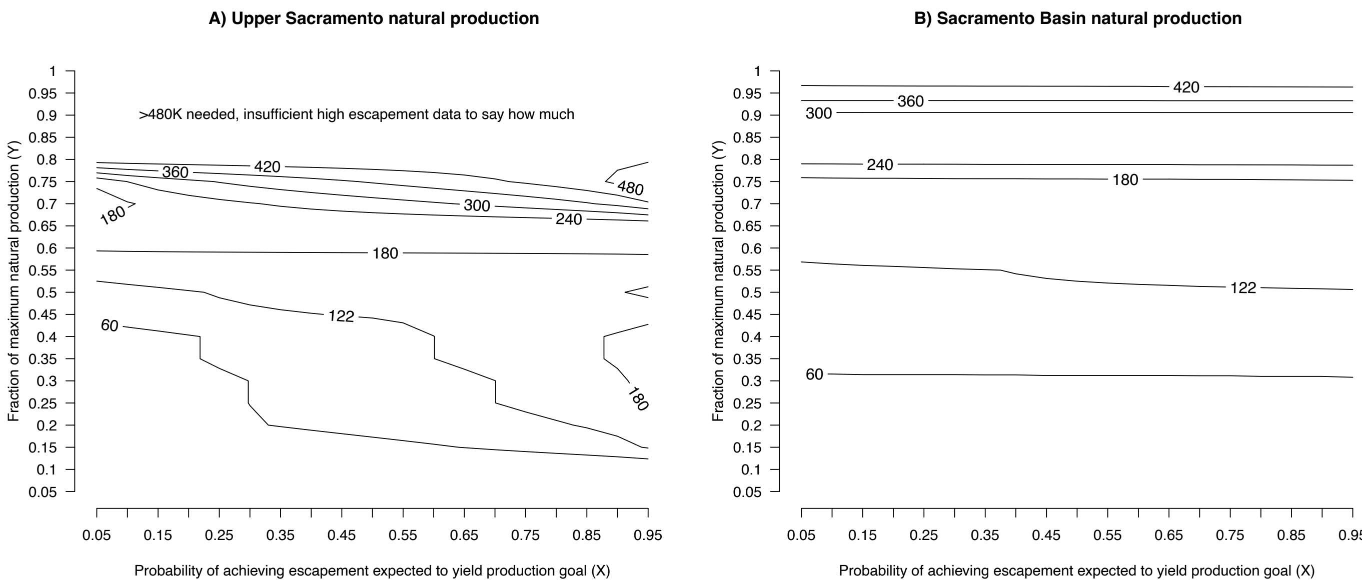

Figure 5 Contour plot of the total adult SRFC escapement (*in thousands*) needed to achieve at least *X* probability of at least *Y* fraction of maximum potential natural production above RBDD (**A**) or for the Sacramento basin as a whole (**B**). *Contour lines* are interpolated on a grid, so locations are approximate.

production above RBDD; panel B (right) reflects the same relationship for the Sacramento River basin as a whole. For example, if one wanted to achieve a fraction of 0.75 (y-axis) of natural spawning potential above RBDD (Figure 5A), with at least a p=0.5 probability (*x*-axis), the total adult SRFC escapement necessary would be 300,000 to 360,000. If a high (e.g., >50% to 60%) fraction of potential production were desired, the escapement required was relatively *more* sensitive to the *fraction of production* (*y*-axis, Figure 5A) and *less* sensitive to the *desired probability* (*x*-axis, Figure 5B). The model indicates that escapement of 122,000 total adult SRFC spawners is unlikely to achieve more than about 50% of potential natural production above RBDD, and only has a high (>75%) probability of achieving more than about 25% of potential natural production above RBDD. The model suggests that a total SRFC adult escapement of 180,000 is likely to achieve about 60% of potential natural production above RBDD and suggests diminishing returns for escapements above 240,000 total adult SRFC. It also suggests that much higher escapements are required to achieve more than 80% of potential natural production above RBDD. But the model is substantially uncertain, especially at high escapement, given limited observations from years with very high escapement.

For natural production of fall-, spring-, and winter-run Chinook Salmon in the Sacramento River basin as a whole (Figure 5B), there was much less sensitivity to the probability desired (*X*), because total SRFC adult escapement predicted total natural-area fall-, spring-, and winter-run Chinook Salmon escapement quite well (r=0.99), such that a given total escapement was modeled to be either very likely—or very unlikely—to be accompanied by sufficient total natural-area escapement. Total adult SRFC escapement of 122,000 was predicted to achieve about 56% of potential maximum production, and adult escapement of 180,000 was predicted to achieve about 73% of potential maximum production. Total adult SRFC escapement above 300,000 was predicted to achieve about 90% of potential maximum production.

Probability of Achieving Hatchery and Natural Production Goals Together

The escapement needed to achieve a specified fraction of natural production (*Y*) above RBDD and meet all hatchery goals with a given

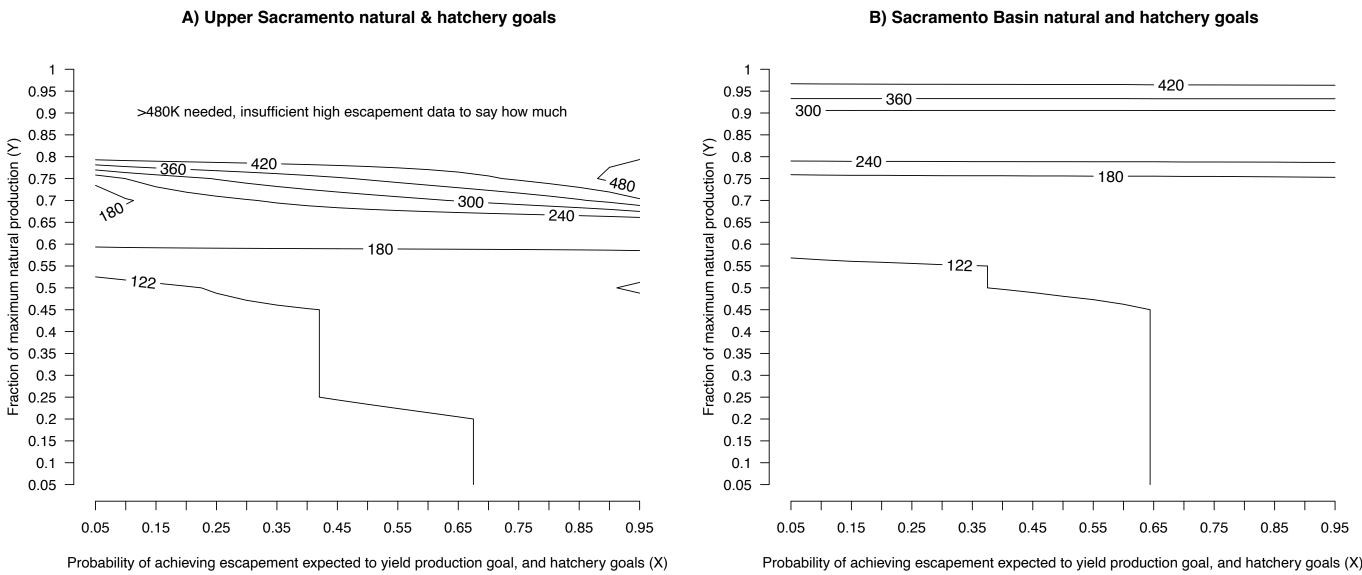

Figure 6 Contour plot of the total adult SRFC escapement (*in thousands*) needed to achieve at least *X* probability of at least *Y* fraction of maximum potential natural production above RBDD and meeting all hatchery goals. *Contour lines* are interpolated on a grid, so locations are approximate.

probability (*X*) was very similar to that for production goals alone at high escapements or high targeted production—where natural production was almost always the limiting factor—but showed more contrast at low escapements or low targeted production where hatchery goals might not be met (Figure 6A). Note that there is no contour at 60,000 in Figure 6A, because a total adult SRFC escapement this low is exceedingly unlikely to meet all the hatchery goals. The contour at 122,000 is changed relative to Figure 5A to reflect that 122,000 total adult spawners is modeled to only have about a 0.74 probability of meeting all the hatchery goals, which is usually the limiting factor when the targeted natural production is very low (< 25%), while both hatchery goals and natural production are limiting when targeting a low level of natural production (25% to 45%). The contours at 180,000 and above are basically identical to the previous case because hatchery goals are almost certain to be met, and only natural production is limiting.

The model considering fall-, spring-, and winter-run Chinook Salmon throughout natural areas of the basin showed a similar pattern of change when considering both natural production and hatchery goals relative to considering just natural production (Figure 6B). Patterns were essentially unchanged at high escapements, where natural production was the limiting factor, but an escapement of 122,000 total adult SRFC had only a moderate probability of meeting the hatchery goals. Note that the different range of input years [1998–2015] led to a modeled 0.66 probability of meeting all hatchery goals at total adult escapement of 122,000 compared to 0.74 for the model based on 2002-2021. An escapement of only 60,000 did not have an appreciable probability of meeting the hatchery goals, regardless of natural production considerations.

Quantification and Incorporation of Outcome Error

For the period of 2014 (when the current SRFC forecast approach was adopted) to 2021, the ratio between the pre-season expectation of adult SRFC escapement and the post-season estimate of this quantity was best fit by a lognormal distribution (Figure 7) with arithmetic-scale median 1.69 (indicating persistent over-forecasting of escapement, corresponding to log-scale mean 0.528) and log-scale SD of 0.39. The median value of the annual ratios was 1.58.

Thus, to expect a 50% probability of achieving an escapement goal *N*, the escapement targeted

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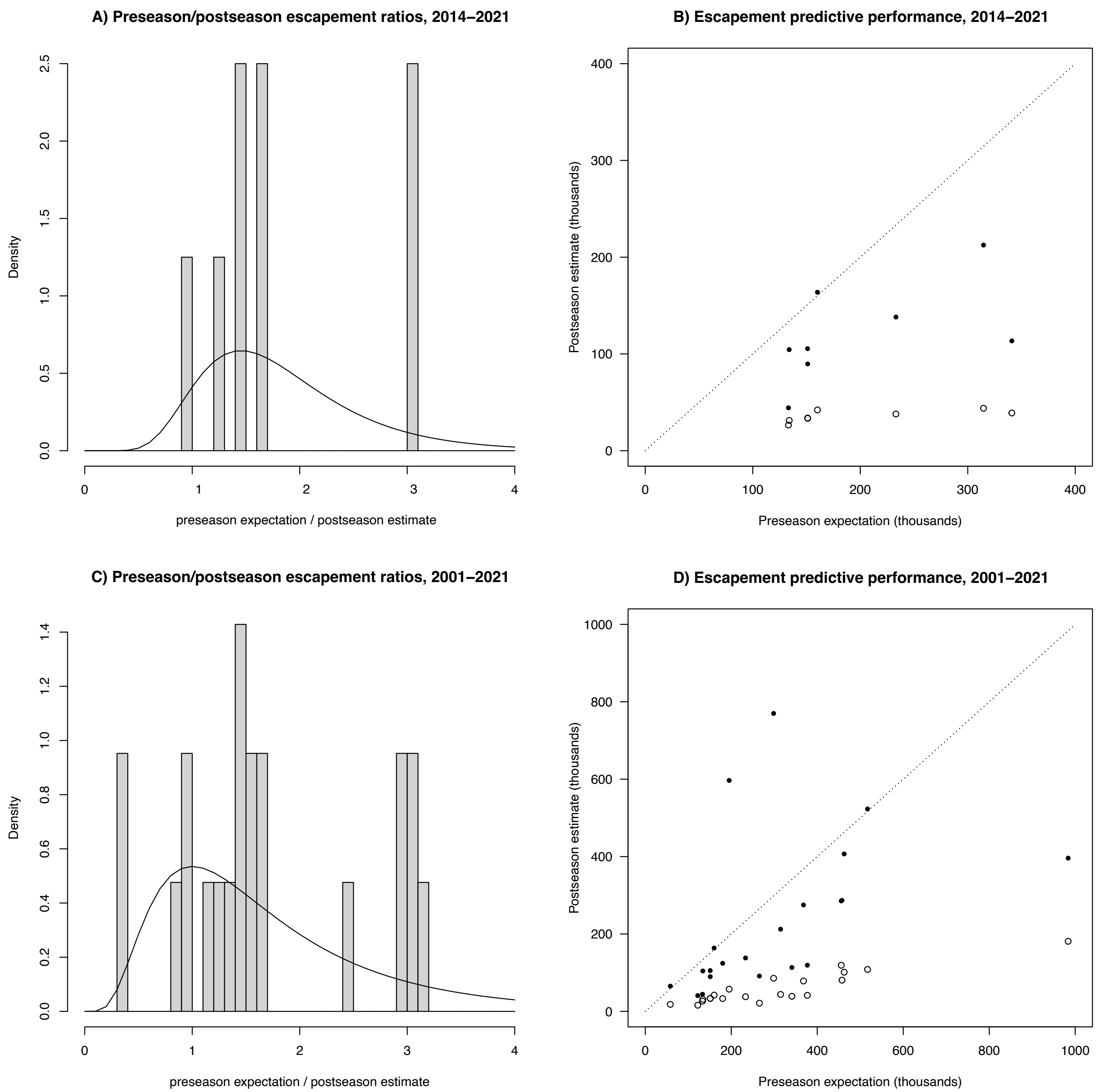

Figure 7 Outcome error in SRFC escapement projections vs. post-season estimates. Panel (**A**) shows annual ratios between pre-season expectations and post-season estimates of total SRFC adult escapement for 2014–2021, along with a fitted lognormal distribution describing the annual values. Panel (**B**) shows the total adult SRFC escapement projected at the end of the pre-season planning process on the *x* axis and the post-season estimate of total SRFC adult escapement (*solid circles*) or hatchery SRFC adult escapement (*open circles*) on the *y* axis. Panels (**C**) and (**D**) are similar to (**A**) and (**B**), except that they include estimates for 2001–2021. Note that 2014 was the first year that the current abundance forecast model was used, so earlier years may not be as representative of expected future performance as 2014–2021. There is no expectation that the hatchery escapement would match the pre-season expectation of total escapement, and so *open circles* are expected to be below the 1:1 line.

at the end of the pre-season planning process should be 1.69 × *N*, assuming a lognormal distribution is a good fit to the observed ratios, and that the performance of pre-season planning models for 2014 through 2021 represents likely future performance. In general, to have at least *Z* probability of achieving escapement of at least *N*, the escapement targeted at the end of the pre-season planning process should be *Q* × *N*, where *Q* is the *Z* quantile of the lognormal distribution described above. To achieve *Z*=0.55 (i.e., a 55% probability of achieving the goal, loosely analogous to the PFMC's default P*=0.45 or 45% probability of overfishing for groundfish and coastal pelagic species; Satterthwaite and Shelton 2023), obtain the escapement target by multiplying the goal by 1.78 (the 0.55 quantile of the fitted distribution) during the pre-season planning process.

DISCUSSION

Predicted Biological Outcomes of Escapement Goals and Targets

This paper's goal is not to recommend a specific value for the SRFC escapement goal or target. Rather, it is intended to illustrate a means for quantitatively assessing the extent to which various levels of escapement are likely to meet goals for natural production and/or hatchery broodstock, in a way that also allows incorporation of decision-makers' risk tolerance similar to the uncertainty buffers used in the PFMC's management of groundfish and coastal pelagic species. Realized escapement at the lower end of the current escapement objective of 122,000 adult SRFC to hatcheries and natural areas combined appears likely to achieve hatchery spawner goals more often than not, but unlikely to achieve more than half of potential natural production in either the upper Sacramento River above RBDD or for the Sacramento River basin as a whole. Realized escapement at the upper end of the current objective of 180,000 adults is likely to meet hatchery spawner goals and is modeled to be likely to achieve about 60% of potential natural production in the upper Sacramento River and about 75% of natural production in the Sacramento River basin as a whole. Within the range of escapements used to parameterize the model, it appears unlikely to achieve more than about 80% of upper Sacramento natural production with SRFC adult escapement below 500,000; whereas it appears that SRFC adult escapement of around 300,000 could achieve about 90% of potential natural production for the basin as whole, which approaches maximizing production.

However, these calculations reflect *realized* escapement. Actually, achieving these goals may require setting pre-season targets substantially higher, to account for outcome error. Although efforts to improve both pre-season abundance forecast models and pre-season harvest planning models are ongoing, a persistent pattern of under-forecasting harvest rates remains as of this writing, despite multiple model updates (PFMC 2022c). In 2022, the PFMC adopted a change to the SRFC pre-season forecast (using the median rather than mean to convert from logarithmic to arithmetic scales [Satterthwaite 2022]) that should reduce the tendency toward over-forecasting pre-fishing abundance, but even the revised forecast method would have had a mean proportional error of 21% over-forecasting for 2014 through 2021, with a modeled median ratio of 1.08 between the pre-season forecast and post-season estimate of pre-fishing ocean abundance (Satterthwaite 2022), and this does not account for the further effects of errors in achieving planned harvest rates.

The contrasting messages on the feasibility of coming close to maximizing natural productivity based on spawner–recruit relationships for the upper Sacramento River vs. the Sacramento River basin as a whole may reflect challenges and uncertainties in estimating these sorts of relationships (Adkison 2022). Additionally, or alternatively, that contrast could reflect an issue highlighted by PFMC (1984) where achieving sufficient escapement to fully seed the upper Sacramento may often require "over-escapement" to the lower watershed, because of the typical proportion of basin-wide escapement that returns to areas above RBDD. However, the proportion of escapement to areas above RBDD varies

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substantially from year to year (PFMC 2022b), inviting study to identify conditions that could lead to a more efficient allocation of spawners across the landscape. In addition, the low proportional escapement to the upper Sacramento River reflects a system where escapements there are almost always well below the amount predicted to maximize production. Given the relatively large proportion of natural-origin spawners in the upper Sacramento (Appendix A), if more natural production occurred in the upper Sacramento because of higher escapement, a larger proportion of total escapement would return to that area.

Management Considerations

The choice of target fraction of potential natural production (Y) is ultimately a policy decision. Some language in the FMP (PFMC 2022a, p.51) would imply an intent to maximize natural production of California salmon stocks, requiring a goal based on $Y=1$. However, language elsewhere in the FMP (PFMC 2022a, Table 3-1) implies that the escapement objective corresponds to "adequate" production. For Klamath River Fall-run Chinook Salmon (KRFC) and many other stocks in the FMP, escapement objectives are based on consideration of natural-area spawners, but for the purpose of identifying the escapement that maximizes sustainable yield rather than for production. The spawner–recruit relationships available for SRFC measure recruits at a lifestage preceding availability to the fishery, and so cannot be used to calculate yield directly. However, if meta-analyses of suitable stock–recruit relationships for "similar" Chinook Salmon stocks revealed a fairly consistent proportion between production at maximum sustainable yield and maximum production, that same proportion might serve as the basis for choice of Y.

Alternatively, deriving a spawner–recruit relationship for natural-origin SRFC would allow a direct calculation of the spawning escapement that would produce maximum sustainable yield (S_{MSY}), similar to the analysis that serves as the basis of the escapement objective for KRFC (STT 2005). This would require estimates of natural-origin recruits to the fishery, via a cohort reconstruction that estimates natural-origin ocean abundance at the age fish first become susceptible to the fishery (e.g., Mohr 2006; O'Farrell et al. 2012). Numerous advisory bodies to the PFMC have recommended development of a cohort reconstruction for SRFC (PFMC 2019; STT 2020; SRKWWG 2020), but it has not happened to date. In addition to providing information on maximum sustainable yield, developing a cohort reconstruction would likely also improve estimates of harvest rates, and allow for alternative forecasting methods that might be more accurate (Satterthwaite and Shelton 2023). A cohort reconstruction that estimated natural-origin ocean abundance might also allow testing for density-dependence occurring after the juvenile stage used as the metric for production in this analysis.

However, developing a cohort reconstruction for natural-origin SRFC may be substantially more challenging than for natural-origin KRFC because of the generally smaller proportion of natural-origin SRFC and fractional marking/tagging of hatchery-origin SRFC. These two factors make it challenging to estimate natural-origin escapement at age by subtracting out assumed hatchery contributions from escapement-at-age of untagged fish that might be hatchery- or natural-origin, although alternative marking and/or tagging strategies could allow natural-origin escapement to be estimated more precisely (Mohr et al. 2017). In addition, a SRFC cohort reconstruction would likely be limited to brood years 2006 and later, following initiation of the constant fractional marking program (Buttars 2010). Unless or until some additional high-escapement years occur, this means a SRFC stock–recruit analysis based on cohort reconstructions would not be able to explore the range of spawner abundances associated with the higher natural-production years analyzed here.

The desired probability of achieving a successful management outcome (i.e., the product of X and Z) is also a policy decision. Guidelines on implementing the Magnuson Stevens Act indicate that the "probability of overfishing"

(P*, Shertzer et al. 2008) used in buffering catch limits against uncertainty should be no higher than 50% (Methot et al. 2014), perhaps implying a minimum desired probability of 0.50. The PFMC's historical choices of P* for groundfish and coastal pelagic species have ranged from 0.40 to 0.45 with some consideration of 0.35 (2022 email between J. DeVore and WHS, unreferenced, see "Notes"), implying desired probabilities of success of 0.55 to 0.65. The management framework used by ICES (2021) for Atlantic Salmon calls for an expected 0.75 probability of meeting conservation criteria. Note that in many cases targeting at least 60% of potential natural production, there was little change in the escapement needed for large *X* vs. small *X*, at least given the simple logistic regression models applied to the currently limited data on how escapement is distributed across the landscape at high abundance. This may reflect the tendency for escapement to hatcheries to vary less than total escapement (Figure 7D), at least for the years analyzed here. As a result, it may be sensible to choose a value of *X* near 1.0, and focus on *Z*, the level of risk tolerance for outcome error that results from forecast and harvest implementation uncertainty. Outcome uncertainty may require setting a pre-season target escapement higher than the goal for escapement actually achieved, and so it may be appropriate to account for outcome uncertainty in setting pre-season targets and conservation objectives, but not the reference points like S_{MSY} used to determine status or evaluate post-season management success (PFMC 2022a).

Caveats

Data limitations, uncertainties, and a desire for relatively easy communication of statistical models to managers meant that I made numerous simplifying assumptions in this modeling approach. Some assumptions might be relaxed or improved upon in the future as additional data become available, or with more sophisticated but less straightforward modeling approaches.

As mentioned earlier, the metric of recruits used in the stock–recruit relationships fitted here is juveniles, rather than recruits to the fishery. This precludes calculating yield directly, but I assumed stock–recruit curves based on juvenile recruits could still be used to identify the escapement that corresponded to maximum production. As long as there is not fully- or over-compensatory density dependence (Rose et al. 2001) operating at stages between juveniles (measured as fry equivalents here) and recruitment to the fishery, the escapement that maximizes juvenile production should also maximize recruits. It may be reasonable to doubt whether strongly compensatory density dependence could operate (and operate only among natural-origin fish) early in ocean residency as fish move to a much larger habitat. However, even under-compensatory density dependence could change how rapidly recruitment declines as escapement diverges from the level that maximizes production.

Even with recruits measured at the desired scale, numerous challenges in fitting a stock–recruit relationship (in this and other systems), can be very demanding of the data (Adkison 2022). Both spawners and recruits are measured with error, and this can affect parameter estimates if not accounted for, but errors in the escapement estimates and in the basin-wide juvenile production index are not quantified for this system. The best functional form of the spawner–recruit relationship is unknown, and rarely do the data provide enough information to reliably distinguish among them (and even the best model will only partially capture the underlying processes). Relationships may vary over time, but even if the model parameters are assumed to be constant over time, the time-series nature of the data presents additional complications.

On top of these usual challenges to estimating stock–recruit relationships, the approach I used here necessitated a layer of logistic regressions to predict the probability of sufficient escapement at one scale of measurement as a function of escapement measured at a different scale. I borrowed this approach from an idea the Department of Fisheries and Oceans Canada considered (DFO 2022) for establishing escapement reference points for aggregate units that are acceptably likely to yield satisfactory conservation outcomes at finer scales. The

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DFO (2022) cautions that the logistic regression model's assumptions rarely match real-world scenarios, and establishing reference points at a finer scale is generally preferable when possible. Developing a more sophisticated statistical model that leverages the covariance structure among subcomponents of the aggregate escapement may provide more reliable inferences (DFO 2022), but such models still need to be developed and tested. The limited amount of data from high-escapement years, especially from recent years, is particularly challenging when modeling how spawners are likely to be distributed across the landscape at high abundance.

Choosing the temporal range of input data to this and similar models is inherently challenging. Longer time-series will provide larger sample sizes and increase statistical confidence but may be misleading if older data are less representative of current conditions. This could be the case either from changes in habitat conditions or biological characteristics of the stock that change its productivity and/or carrying capacity over time, or from changes in the management models made in hopes of reducing outcome error. When management models are changed, it may be difficult to robustly estimate the level of outcome error to anticipate in the future. Even when the structure of management models is held constant, past performance may not strongly indicate how the same model is likely to perform under changed conditions in the future.

CONCLUSIONS

The current escapement objective for SRFC of 122,000 to 180,000 adult spawners in hatcheries and natural areas combined, if achieved, appears reasonably likely to meet hatchery goals, but the low end (122,000) appears unlikely to realize more than about half of potential natural production, while the high end is likely to achieve 60% to 70% of potential natural production. Substantial error in both pre-season abundance forecasts and harvest rate implementation means that, to have a high probability of meeting the goal, a pre-season target higher than the goal is needed. The approach developed here offers a way to evaluate the likelihood of the different levels of escapement needed to likely achieve natural SRFC production goals for the Sacramento River basin or subsets of it and allows uncertainty and risk tolerance to be incorporated when pre-season targets likely to achieve ultimate goals are developed.

The modular nature of this approach allows individual components to be updated as warranted. As (1) hatchery goals are updated, (2) existing stock–recruit relationships are refined, and/or (3) defensible capacity estimates are developed for additional natural areas in the system (Peterson and Duarte 2020), this framework could be extended to model the probability of meeting revised or additional goals. Habitat capacity estimates might be derived using approaches similar to those currently developed for Sacramento River Winter Chinook Salmon (Hendrix et al. 2014; Dudley 2019). Similarly, the model could be expanded to consider the probability of various levels of SRFC escapement that correspond to meeting goals for the Sacramento Late Fall or San Joaquin Fall Chinook Salmon stocks for which SRFC serve as an indicator stock (PFMC 2022a), if and when such goals were established. The independent variable that drives these probabilities could still be total SRFC adult escapement, allowing sub-area goals or related stocks to be considered more directly, without requiring new forecast and planning models specific to them to be developed. Being able to evaluate proposed harvest regulations on the basis of their likelihood of producing adequate escapement to (1) support natural production throughout spatially diverse areas that experience asynchronous environmental variation (Carlson and Satterthwaite 2011) and (2) support diverse life-history strategies that experience the environment differently (Greene et al. 2010; Cordoleani et al. 2021) would be important for considering strategies that bolster the portfolio effect in Central Valley salmon. This would lead to a more resilient biological and fishery system as it faces an increasingly variable environment (Lindley et al. 2009; Sturrock et al. 2019; Munsch et al. 2022).

As verified improvements to the forecast and/or harvest model are made, the buffer required between the goal and the target required to achieve a particular risk-tolerance for management error (Z) could be recalculated, allowing for less precautionary management as data streams and models are improved over time. Alternatively, irreducible uncertainties (Wainwright 2021) in the processes involved in managing the Central Valley Chinook Salmon fishery (meaning the freshwater production system and especially the ocean harvest) may require more precautionary management approaches (e.g., ICES 2021; Satterthwaite and Shelton 2023) to improve management outcomes for both harvest and conservation objectives.

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