Literature Review for Sacramento River Fall Chinook Conservation Objective and Associated S_{MSY} Reference Point

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Basis for current conservation objective and S_{MSY} reference point

As described on p. 21 of the Pacific Coast Salmon Fishery Management Plan for Commercial and Recreational Salmon Fisheries off the Coasts of Washington, Oregon, and California as Revised through Amendment 22 (PFMC 2022a, hereafter "the FMP"), the current conservation objective for Sacramento River Fall Chinook (SRFC) is 122,000-180,000 "adult" spawners returning to natural areas and hatcheries combined in the Sacramento River basin, regardless of origin. When used by the PFMC in reference to SRFC, "adult" is typically interpreted as any spawner of age-3 or older. This objective was derived (PFMC 1984, Section 3.5.2.1, pp. 3-16 to 3-19) as the sum of contributions from spawners in different natural areas and hatcheries, with PFMC (1984) rejecting the idea of formally establishing area-specific goals.

The hatchery contributions were based on "mitigation requirements or hatchery capacities, whichever is higher" and were set equal to 9,000 for the Upper-River hatchery (i.e., Coleman National Fish Hatchery), 5,000 for Feather River Hatchery, and 6,000 for Nimbus Hatchery on the American River[1]. Contributions for natural areas were initially set equal to 99,000 for the Upper-River, 27,000 for the Feather River, 10,000 for the Yuba River, and 24,000 for the American River. "Upper-River" is not explicitly defined in PFMC (1984) although in recent usage in other documents it typically refers to the mainstem and tributaries upstream of Red Bluff Diversion Dam (RBDD, see map on p. 6 of SRFCRT 1994). However, there is also a reference to "upper Sacramento River (above Feather River)" in the description of other run timings (PFMC 1984, p. 3-16). There is no discussion of minor tributaries in the Lower-River, nor the Lower-River mainstem[2].

PFMC (1984, p. 3-19) further states that natural-area escapement of 99,000 to the Upper-River is unlikely to be achieved until "problems caused by the Red Bluff Diversion Dam are rectified"[3] and so establishes an "interim" (p. 3-19) alternative contribution of 50,000 for

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[1] According to PFMC 2022b Table B-1, current fall-run Chinook goals are 12,000 adults for Coleman National Fish Hatchery, 6,000 adults for Feather River Hatchery, and 4,000 adults for Nimbus Hatchery (totaling 22,000 hatchery adults, compared to a total of 20,000 for the goals stated in PFMC [1984]).

[2] According to Azat (2021), the mainstem and tributaries between RBDD and Princeton Ferry (39°24'43.3"N, upstream of Feather River and Butte Creek) have had spawner estimates in the tens of thousands, although estimates from 2006-2020 were all below 10,000. It is unclear whether this area was included in PFMC (1984)'s Upper-River.

[3] The specific problems with RBDD and how they would be rectified are not clearly stated on p. 3-19 of PFMC (1984), although p. 3-18 refers to passage problems. Construction of RBDD was completed in 1964 (https://www.usbr.gov/projects/index.php?id=244). RBDD was decommissioned and its gates were permanently locked in the open position in 2013 (and had been fully open since May 2011), although the structure has not been

natural areas and the hatchery in the Upper-River combined, based on Upper-River fall Chinook runs "fall[ing] from 81,700 to 51,500 adult[s]" from 1979-1983[4] (PFMC 1984, p. 3-19) and an expectation that returns would stabilize at about 50,000. In fact, returns to the Upper-River were much higher than this for the late 1980s and the late 1990s through the early 2000s (Figure 1).

The contributions to the Lower-River sum to 72,000 and thus the lower bound of the conservation objective is set equal to 72,000+50,000 = 122,000 while the upper bound of the conservation objective is set equal to the sum of 72,000 for the combined Lower-River, 9,000 for the Upper-River hatchery, and 99,000 for the Upper-River natural areas = 180,000 total. The S_{MSY} reference point is set equal to the lower bound of the conservation objective at 122,000.

PFMC (1984) states that the natural-area contributions were based on "averages of previous years' run sizes" and initially states that these averages were from 1953-1960 on p. 3-16. However, the description of the Yuba River contribution on p. 3-17 states that it is based on the 1971-1981 average. According to values reported in Azat (2021), in-river escapement to the mainstem Sacramento River and its tributaries above RBDD had a mean of 197,207 for 1953-1960, although this includes jacks as well as adults. However, it seems unlikely that the inclusion of jacks[5] is the sole reason this number is so much larger than the 99,000 reported in PFMC (1984). Additionally, Azat (2021) reports escapements with a mean of 39,640 to the mainstem and tributaries between Princeton Ferry and RBDD (i.e., above the confluence with the Feather River) for 1953-1960, which might need to also be accounted for in the Upper-River total. For the Feather River, the mean of the 1953-1960 in-river fall Chinook escapements reported by Azat (2021) is 51,131. Again, the discrepancy with the 27,000 reported in PFMC (1984) seems larger than could be explained by the inclusion of jacks alone. For the American River, Azat (2021) yields a 1953-1960 mean of 17,267 in-river spawners, once again at odds with the 24,000 reported in PFMC (1984), although lower in this case. For the Yuba River, the 1971-1981 mean escapement from Azat (2021) is 11,023, reasonably close to the stated contribution of 10,000, especially after factoring in likely jack contributions[6]. Changing the period for calculation of the mean to 1971-1981 does not reconcile the numbers for other natural areas with the values reported in Azat (2021), yielding 43,478 for the Upper-River (not

removed and its removal is not planned (Duda 2013). Efforts to improve passage occurred prior to this as well (USBR 2008). Since 1964, natural-area escapements above RBDD exceeded 100,000 in 1965-1966, 1968-1969, 1988, 1995-1997, and 1999-2003 (Azat 2021), and in some additional years escapement to Coleman National Fish Hatchery far exceeded 9,000 and brought total Upper-River escapement above 100,000.

[4] According to PFMC (2022b, Table B-1) adult fall Chinook escapement to the Upper Sacramento was 81,332 for natural areas and 4,766 for Coleman Hatchery in 1979 and 42,570 for natural areas and 5,367 for Coleman Hatchery in 1983, however this is only the Upper Sacramento above RBDD whereas PFMC (1984) may have included more of the watershed.

[5] For 1970-2021, natural area SRFC escapement ranged from 2%-35% jacks with median 13% (PFMC 2022b Table B-1). Note also that Azat (2021) refers to "adult" salmon, but Azat (2021) uses "adult" in the biological sense of sexually mature fish returning to freshwater, rather than denoting age-3+ as in many PFMC documents (confirmed via email exchange with Jason Azat, 19 September 2022).

[6] According to PFMC 2022b Table B-1, 1971-1981 mean adult fall run escapement to the Yuba River was 9,397 and the mean for jacks was 1,625 for a sum of 11,022.

including areas upstream of Princeton Ferry but downstream of RBDD), 43,843 for the Feather River, and 38,167 for the American River.

Consistency with definitions and stated goals in the FMP

The FMP (p. 14) defines S_{MSY} as "The abundance of adult spawners that is expected, on average, to produce MSY." Maximum Sustainable Yield (MSY) is defined on page 13 as "the largest long-term average catch or yield that can be taken from a stock or stock complex under prevailing ecological and environmental conditions and fishery technological characteristics, and distribution of catch among fleets". PFMC (1984) does not attempt to quantify expected yield.

The FMP further states that "Often, data are insufficient to directly estimate S_{MSY}. In these cases, the Council may use MSY proxies derived from more general estimates of productive capacity" (p. 13). The 50,000 contribution toward S_{MSY} assigned to the Upper-River is not based on an estimate of productive capacity. No argument is presented for why the reported average run size over a particular time period in the past (which does not represent current prevailing ecological and environmental conditions) constitutes an estimate of productive capacity for the Lower-River.

The FMP (p. 19) states that "The Council's conservation objectives for natural stocks may (1) be based on estimates for achieving MSY or an MSY proxy, or (2) represent special data gathering or rebuilding strategies to approach MSY and to eventually develop MSY objectives." There is no data gathering or rebuilding strategy built into the conservation objective.

The FMP (p. 21) states that the SRFC conservation objective "is intended to provide adequate escapement of natural and hatchery production", but "adequate" is not defined. PFMC (1984) rejected the idea of formally establishing area-specific subgoals. However, if the individual hatchery and natural area contributions identified are considered to represent adequate[7] levels of spawners in the respective areas, total escapement equal to their sum is exceedingly unlikely to lead to adequate escapement to all areas, since some level of variation is expected in the proportion of escapement returning to each area, and there is no reason to expect the proportions escaping to different areas to exactly equal their proportional contributions to the total objective. Table 1 reports annual total adult escapement as well as adult escapements to the individual areas described in PFMC (1984), using values from PFMC (2022b, Table B-1), and assuming that Upper-River signifies above RBDD (since PFMC 2022b does not report escapements to the mainstem downstream of RBDD). Out of 52 years 1970-2021, only 11 years had all area-specific escapement estimates above their respective

[7] Presumably, "adequate" hatchery performance entails meeting the mitigation requirement. However, "adequate" escapement might be less than the optimal spawning escapement in a given natural area, with the idea that successful management would sometimes miss the optimum above and sometimes below. However, the contributions reported in PFMC (1984) are far below the levels estimated to maximize production or yield, as described in the review of other literature later in this report. Nevertheless, it might make sense to assess the probability of all subareas being above some percentage of their optimal contribution, similar to setting MSST equal to 75% of S_{MSY}.

contributions to the low end of the conservation objective[8]. In 7/11 of those years the Upper-River natural-area adult escapement estimate was above 99,000, and in two more of those years it was close (96,716 in 2005 and 90,119 in 2013). For the 7 years above the full contributions to the current conservation objective, estimated total adult escapement ranged from 239,307 to 769,868 with median 417,537. Expanding to include the 4 years where estimated Upper-River natural-area escapement was below 99,000 but estimated combined Upper-River escapement was above 50,000 reduced the minimum to 164,641 and the median to 399,830.

A logistic regression modeling the probability of meeting or exceeding all contributions as a function of total adult escapement suggested that a total escapement of at least 312,000 (lower end of Upper-River contribution) or 386,000 (upper end) adults would be required for at least a 50% probability of meeting or exceeding all contributions (Figure 2). The logistic regression model requires several unrealistic assumptions and a more sophisticated model may be more appropriate (e.g., Appendix D of PFMC 2007, DFO 2022).

Page 51 of the FMP states that "With respect to California stocks, ocean commercial and recreational fisheries operating in this area[9] are managed to maximize natural production consistent with meeting the U.S. obligation to Indian tribes with federally recognized fishing rights, and recreational needs in inland areas." However, the current SRFC conservation objective does not include any quantification of production, and it does not distinguish natural- from hatchery-origin fish, nor does it distinguish fish spawning in hatcheries versus natural areas.

PFMC (1984, p. 3-19) rejected the idea of separate hatchery and natural[10] objectives. Part of the argument states "The only major tributary with a truly natural run is the Yuba River. Runs in this river have been remarkably stable from 1971-1981, averaging about 10,000 adults. The run increased sharply in 1982 to 23,000. The stability of the Yuba River escapement suggests that present and past management practices have not reduced the productivity of natural stocks." However, it is not clear why stable run size necessarily represents management actions stabilizing run size at the escapement that would maximize yield or production. In addition, while "remarkably stable" is a qualitative judgment that cannot be quantitatively validated or refuted, examination of Yuba River escapement estimates reported by Azat (2021) reveals substantial variation, including periods of substantially higher escapement but also escapements as low as 1,600 with multiple years below 4,000 (Figure 3). In addition, the assertion that the Yuba River has a "truly natural run" is incorrect. Synthesis of Coded Wire Tag

[8] Note however that three years (1986, 1995, and 1997) only missed the established Nimbus Hatchery goal of 6,000 (PFMC 1984) but met the updated Nimbus Hatchery goal of 4,000 (PFMC 2022b Table B-1) while meeting all other contributions including the high end of the Upper-River contribution. These years had estimated total adult escapements of 239,307, 344,841, and 301,663, respectively.

[9] This quote is from a section titled "South of latitude 40°10' N" and similar wording appears in the section describing fisheries in the rest of California.

[10] The terms "natural" and "wild" appear somewhat interchangeably throughout the FMP, with no specific definition provided for either, although each term appears more often in association with some stocks than others. "Natural" is typically used in association with California stocks. In this document, no special significance should be attributed to the use of "natural" versus "wild".

Recovery Reports (Kormos et al. 2012, Palmer-Zwhalen and Kormos 2013, 2015, and 2020; Palmer-Zwhalen et al. 2018 and 2019a,b, Letvin et al. 2020 and 2021a,b) indicates that escapement to the Yuba River in 2010-2019 (Figure 4) ranged from 37%-87% hatchery-origin with median 58%. In comparison, natural-area spawning in the Sacramento River above RBDD was 5%-68% hatchery-origin with median 37% for the same time period; so the Yuba River is not even the part of the system closest to being mainly natural. However, it is possible that hatchery strays made up a smaller proportion of Yuba River escapement at the time PFMC (1984) was written, since there was less downstream transport of hatchery production and thus probably less straying prior to the mid-1980s (Sturrock et al. 2019).

PFMC (1984, p. 3-19) further states that "the distinction between hatchery and natural fish has become lost in these parts of the river" (apparently intending to exclude the Yuba from "these parts", though this is not entirely clear). Williamson and May (2005) documented extensive hybridization and homogenization among Central Valley fall Chinook at the seven microsatellite loci they examined, which they attributed to extensive hatchery straying and introgression with fish spawning in natural areas. However, Meek et al. (2020) performed a broader genomic study and found greater population structure than previously documented, including evidence for differentiation and adaptation. A comprehensive review of comparisons between hatchery- and natural-origin fish in genetic and phenotypic aspects is beyond the scope of this paper, but the articles cited in the previous sentence may provide good entry points to the literature, along with CA HSRG (2012).

Additionally, PFMC (1984) argued that hatcheries on the Feather and American Rivers close their ladders once capacity is reached and additional fish that would have returned to the hatchery remain in the river and are counted as natural spawners. However, in reality spawners collected at individual hatcheries have often been far above capacity (see Table 1) and following the practice described in PFMC (1984) could have unintended consequences like inadvertent selection on return timing or even age at return.

Other documents relevant to the SRFC conservation objective cited in the FMP

The FMP (p. 21) cites four other documents in association with the SRFC conservation objective (ASETF 1979, SRFCRT 1994, Hallock 1977, and Reisenbichler 1986), and these are discussed in turn.

ASETF (1979) discusses Sacramento River Chinook abundances and goals on pp. 5-7. It states that "Estimates of the number of salmon spawning in the Sacramento River drainage are not based on solid data. The average annual escapement might have been 300,000 to 500,000 chinook [sic] salmon, and an escapement of 400,000 adults is used in this report." This refers to all run timings combined. ASETF (1979) goes on to state "a catch-to-escapement ratio (C/E) of 1.17/1.0 was used to estimate the proportion of the [harvested] fish originating from the Sacramento system prior to water developments", although the basis of the 1.17 value is not stated. A C/E ratio of 1.17 along with escapement of 400,000 adults implies a total catch of 468,000 and total production of 868,000. ASETF (1979) goes on to state "the goal for the Sacramento River system is 935,000 adult salmon" although no clear basis for this goal is given. Table 1 of ASETF (1979) describes this number as representing "with enhancement". At the assumed C/E ratio of 1.17, this would require escapement of 400,000*935,000/868,000 = 431,000 adults of all run timings combined. ASETF also states “The present (1972-1976) spawning escapement in the Sacramento River system has averaged 254,000[11] fish annually, with a goal of 340,000 when the problems in the upper river are solved.” The basis for the 340,000 goal is not provided[12], while loss of spawning gravel, heavy metal contamination, fish passage at RBDD, and streamflow manipulations are listed as problems with the upper river. Table 1 of (ASETF) lists 340,000 under “Fill present habitat”, suggesting it may reflect an estimate of habitat capacity, which could serve as a proxy for S_{MSY} under the alternative definition on p. 13 of the FMP. It would need to be adjusted to represent fall run rather than all run timings combined, which might be done based on proportional run sizes (Azat 2021, PFMC 2022b) or ratios among goals proposed for the different run timings by Hallock (1977, 1978, see below).

SRFCRT (1994) had the goal of “determin[ing] why the escapement goal for [SRFC] was not met in 1990-1992, and to recommend actions to assure future productivity of the stock”, where “the escapement goal” refers to the conservation objective established by PFMC (1984). SRFCRT (1994) did not explore alternative conservation objectives nor did it examine the basis of the current objective.

Hallock (1977) is no longer publicly available, but a copy from Chuck Tracy’s (retired PFMC) personal archive was obtained and compared to the publicly available Hallock (1978) and judged to be substantially equivalent with respect to information and arguments relevant to the SRFC conservation objective. Hallock (1978, p. 3) states that “Defining spawning levels to serve as management goals is a difficult and largely subjective process” and goes on to recommend “an ‘average’ escapement goal, which is a desirable level around which escapement will fluctuate” (p. 4). Hallock (1977 his Table 4, 1978 his Table 1) suggested SRFC escapement goals of 150,000 for the Upper Sacramento (which he defines as the mainstem and tributaries above the confluence with the Feather River), 40,000 for the Feather River, 25,000 for the Yuba River[13], and 30,000 for the American River, totaling 245,000 spawners (the FMP reports 240,000 as the basin capacity identified by Hallock 1977, but both Hallock 1977 and Hallock 1978 actually report 245,000). The basis for these goals is not clear. The goals for the Upper Sacramento and Yuba River are higher than the 1967-1976 averages reported by Hallock (1977, 1978), while the Feather River and American River goals are lower. Hallock (1977, 1978) does not state whether these goals are for adults only or include jacks, however his area-specific reported averages for 1967-1976 closely (within 1,000 fish) match means calculated for

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[11] Values reported in Azat (2021) yield a mean Sacramento Chinook (all run timings and all ages) escapement of 260,468 for this period, a fairly close match (and the adult-only number would be expected to be slightly lower).

[12] However, while this may be coincidence, Hallock (1977, p. S-13-Cs) reports a 1953-1960 average escapement of 340,00 “fall-spawning” Sacramento Chinook, where “fall-spawning” refers to both fall and spring run timings (Hallock [1977] uses “spring-spawning” to refer to late-fall and winter runs). Hallock (1977, p. S-12-Cs) also suggests a goal of 340,000 for all run timings combined, although its derivation is not clear, see discussion of Hallock (1977) below.

[13] Hallock (1977, p. S-21-Cs; 1978, p. 9) refers to “A combination of hatchery production and improvements in spawning and nursery habitat” being planned for the Yuba River, but there is no Chinook hatchery located on the Yuba (although numerous hatchery fish, largely from Feather River Hatchery, do spawn there [Figure 4]).

the same period from Azat (2021) using combined jack plus adult escapement and including hatchery returns. As with PFMC (1984), setting a total goal equal to the sum of goals for individual areas makes it unlikely that all goals will be met simultaneously, although Hallock (1977, 1978) seems to accept this possibility since he states that fluctuations around the goals are expected. As these values are not linked to projections of yield or production, and not explicitly linked to capacity, it is not clear that they would satisfy any of the definitions or goals in the FMP for use as conservation objectives or S_{MSY}, although they might be regarded as implicit estimates of capacity.

Reisenbichler (1986) is a PhD thesis that does not seem to be available online, but a hard copy was located in the SWFSC Salmon Assessment Team archives. Resienbichler (1986) estimated Ricker stock-recruit relationships for Chinook salmon on several rivers in California, including fall Chinook in most but not all of the Sacramento River basin. Reisenbichler (1986) attempted to avoid confounding from hatchery-origin fish by excluding Battle Creek (the site of Coleman National Fish Hatchery) from most[14] of his analyses of the Upper Sacramento (which looked at various time periods between 1950 and 1979[15]), and analyzed data from the Feather River (1953[16]-1966) and American River (1945-1955) prior to the establishment of their major rim dams and hatcheries. Reisenbichler (1986) does not specifically discuss the Yuba River[17] or other tributaries in the main text. The FMP (p. 21) states that Reisenbichler (1986) found that 118,000 natural-area spawners would maximize production, but it is not clear how this number was extracted from Reisenbichler (1986); nor how it could have been given that Reisenbichler (1986) did not consider the entire Sacramento Basin and used different time periods for the parts he did consider. However, the stock-recruit parameters reported by Reisenbichler (1986) for the Upper Sacramento for 1954-1963 do imply an S_{MSY} (so maximizing yield rather than production) for just the Upper Sacramento River of approximately 118,000 natural-area spawners if it is assumed that there is a typo in Table 6 of Reisenbichler (1986) such that it reports Beta x 1000 rather than Beta x 100 as stated (see below).

Combining the separate stock-recruit relationships estimated by Reisenbichler (1986) into an implied total SRFC escapement goal is challenging, if not impossible, because they cover different time periods, differ in whether they include jacks, and omit part of the system. In addition, Resienbichler (1986) excluded putative “outlier” years (p. 42), depends on questionable inferences about ocean harvest (p. 46) along with limited information on age structure (p. 49), and noted simulations showing that estimates of stock-recruit parameters are

[14] Resienbichler (1986, p. 37) but see Resienbichler, (1986 pp. 69-70).

[15] There is some inconsistency among different table and figure legends in Resienbichler (1986) as to whether the last year included in analyses for the Upper Sacramento is 1978 or 1979.

[16] The current Feather River Hatchery was established in 1967 (although the earliest stages of Oroville Dam construction began in 1961), but a Feather River Hatchery on another site operated from 1924-1953, potentially contributing to spawner returns for the first few years of this period. https://wildlife.ca.gov/Fishing/Hatcheries/Feather-River/History

[17] The Yuba River downstream of Englebright Dam is depicted (with no label) in Reisenbichler’s Figure 3, and his Appendix A gives the date of Englebright Dam’s establishment while labeling the Yuba as a tributary to the Feather, but it is not explicitly stated whether escapement on the Yuba was included in his estimates of Feather River escapement.

"imprecise (have large standard deviations) and often highly biased" (p. 82). Nevertheless, because Reisenbichler (1986) reported the parameters of his fitted Ricker stock-recruit relationships, values for S_{MSY} for subsets of the basin for particular time periods can be calculated using the approach described in Scheuerell (2016), as reported in Table 2. However, the values resulting from the reported parameter estimates seem implausibly small, and are inconsistent with the values displayed in the figures in Reisenbichler (1986), unless it is assumed that Reisenbichler (1986) reported Beta x 1000 rather than Beta x 100 in his Table 6.

To provide information relevant to the goal stated on page 51 of the FMP, Table 3 reports the natural-area escapements predicted to maximize production (S_{MSP}, calculated as 1/Beta, Quinn 2013) for each of the area-year combinations reported by Reisenbichler (1986), assuming that Reisenbichler (1986) reported Beta x 1000 rather than Beta x 100.

Other documents relevant to the SRFC conservation objective not cited in the FMP

This document is not meant to represent a comprehensive review of all recent literature potentially relevant to the SRFC conservation objective. Adkison (2022) provides a wealth of general guidance on the fitting of spawner-recruit relationships and how they can inform management, but not all of the approaches from that document can be applied given currently-available data for SRFC. For SRFC in particular, there are two highly relevant documents that have been seen by the Council and/or its advisory bodies in other contexts.

PFMC (2019) was adopted by the Council and includes a Ricker stock-recruit relationship fitted to fry-equivalent juvenile production as a function of natural-area female spawners in the Upper Sacramento (above RBDD) for brood years 2002-2015 (pp. 24-25). This analysis indicated that maximum production would occur for an escapement of approximately 80,000 females to natural areas above RBDD, or approximately 160,000 spawners assuming a 50:50 sex ratio[18]. This could be scaled to a basin-wide target based on typical proportions escaping to different parts of the system (Azat 2021), or a model could be developed identifying the probability of meeting or exceeding an Upper Sacramento natural-area spawner goal defined from this stock-recruit relationship at different levels of total escapement to the system. The number could be refined further to provide a total adult spawner goal given typical age structures for males versus females. This would not meet the FMP's stated definition of S_{MSY} but could inform the stated goal of maximizing natural production. An estimate of escapement maximizing natural production (S_{MSP}) might be scaled to an estimate of escapement maximizing natural yield (i.e., meeting the definition of S_{MSY}) based on meta-analysis of ratios between escapement levels maximizing production and maximizing yield for suitably-estimated salmon stock-recruit relationships. For example, S_{MSY}/S_{MSP} ratios for the Ricker relationships fitted to SRFC populations by Reisenbicher (1986) ranged from 0.73 to 0.83 with median 0.79. Applying such a multiplier would implicitly assume the absence of compensatory or over-compensatory density dependence after the fry stage, which could be reasonable given that natural-origin juveniles

[18] Note that PFMC 2019 does not specify whether the numbers refer to total female natural-area spawners, or total adult female natural-area spawners. Because the number reported is females, it is likely to be largely adults. However, a 50:50 sex ratio may not be appropriate for extrapolating to total adults but may be closer to appropriate for total spawners.

constitute only a fraction of ocean abundance, and potentially less mechanistic basis to assume strong density dependence in less physically constrained habitats.

While PFMC (1984) stated that it would be difficult to meet an Upper-River goal without over-escapement to the Lower-River, there is considerable variability in the proportion of total escapement (including escapement to hatcheries) which occurs to natural areas of the Upper-River (Table 1), ranging from 3% to 64% with median 38% for the years reported in Table 1. In addition, the proportion of total escapement returning to the Upper-River would be expected to be higher on average if production there was higher, as would be expected in response to higher Upper-River escapements.

Munsch et al. (2020) has been described in presentations to the Council under various NMFS Science Center Reports, and was included in background materials on the Central Valley Fall Chinook Indicator reviewed by the SSC Ecosystem Subcommittee. However, it has never been reviewed by the Council's other technical advisory bodies nor adopted by the Council. Munsch et al. (2020) modeled a Chinook fry production index for the Sacramento River basin as a function of flow and natural-area spawners, using data from outmigration years 1999-2016. Due to the size and timing cutoffs in the fry production index, Munsch et al. (2020) argued that the analysis largely excludes hatchery-origin fish and the late-fall life history, but includes fall, spring, and winter run timings. Thus Munsch et al. (2020) considered the natural-area escapement of these three run timings combined, although fall-run predominates by a very large margin (Azat 2021). Munsch et al. (2020) found that fry production was maximized at a natural-area escapement of around 400,000[19] spawners. This analysis has an advantage over tributary-specific studies in that Munsch et al. (2020) examined basin-wide escapement that was actually achieved given historical variation in how spawners were distributed across the landscape, implicitly incorporating the effects of expected proportional over-escapement to some areas relative to others and finding the optimal expected tradeoff.

While Munsch et al. (2020) found strong effects of flow, they also found that even at the lowest flow levels included in the study, fry production tended to increase with increases in natural-area spawner abundance well above 200,000 (Figure 5). The natural-area spawning escapement of fall, winter, and spring runs combined found by Munsch et al. (2020) to maximize natural production could be converted to a natural-area S_{MSP} for SRFC alone based on typical ratios among run sizes reported in Azat (2021) or PFMC (2022b) or the ratios among run timings in escapement goals developed by Hallock (1978); and if needed could be converted from total spawners to adults based on typical jack contributions. This would not meet the FMP's stated definition of S_{MSY} but could inform the stated goal of maximizing natural production. Additionally, an estimate of escapement maximizing natural production might be scaled to an estimate of escapement maximizing natural yield (i.e., meeting the definition of S_{MSY}) based on meta-analysis of ratios between escapement levels maximizing production and maximizing yield, as described previously for PFMC (2019).

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[19] According to Stu Munsch, the GAMs fitted in Munsch et al. (2020) indicate production is maximized at 459,863 natural-area spawners (excluding late-fall) and the best-fit Ricker Beta implies maximum production at 449,663 natural-area spawners (excluding late-fall). Because Munsch et al. (2020) used fry rather than adults as the measure of recruits, the fitted Alpha value is not suitable for estimating S_{MSY}.

Other components of the Central Valley Fall Chinook Stock Complex

SRFC are the indicator stock for the Central Valley Fall Chinook Stock Complex, which also includes San Joaquin Fall Chinook and Sacramento Late Fall Chinook. Sacramento Late Fall Chinook are not mentioned in PFMC (1984), aside from an acknowledgment of their existence on p. 3-16. For San Joaquin Fall Chinook, p. 3-16 of PFMC (1984) states that in 1977 a goal was established based on 1972-1977[20] run sizes, but neither the run sizes nor the goal are reported. PFMC (1984, page 3-19) states, without further explanation, that "management for Sacramento River chinook [sic] within the escapement range adopted will provide adequate escapement of San Joaquin stocks to achieve spawning requirements".

For 1970-2021, the correlation between Sacramento River Fall Chinook adult escapement and San Joaquin Fall Chinook adult escapement was 0.38 (PFMC 2022b, Tables B-1 and B-2). For 1971-2021, the correlation between Sacramento River Fall Chinook adult escapement and Sacramento Late Fall Chinook adult escapement was 0.41 (PFMC 2022b, Tables B-1 and B-3).

ASETF (1979) listed an escapement of 11,000 San Joaquin Chinook under "fill present habitat" and refers to a goal of 15,000 fish. It is not clear whether these numbers include jacks and/or hatchery spawners. Estimated adult San Joaquin spawners in natural areas exceeded 11,000 in 1/11 years 2011-2021 and never exceeded 15,000 during that period; while including adults returning to hatcheries boosted returns above 15,000 in 4/11 years and above 11,000 in 7/11 years (PFMC 2022b, Table B-2). Total (including jacks) San Joaquin Fall Chinook spawners in natural areas and hatcheries combined exceeded 15,000 in 9/11 years 2011-2021 and exceeded 11,000 in one more year, but were well below 11,000 in the other year (PFMC 2022b, Table B-2).

Hallock (1977, 1978) proposed a Sacramento Late Fall Chinook escapement goal of 25,000, although it is unclear whether this includes jacks and/or hatchery returns. Total estimated returns of Sacramento Late Fall Chinook (adults and jacks, to natural areas and hatcheries combined) last exceeded 25,000 in 2002 and were below 10,000 in 9/11 years 2011-2021 (PFMC 2022b, Table B-3).

Comparability Among Different Sources in the Literature

Although there is considerable literature relevant to S_{MSY} and the conservation objective for SRFC, the different documents vary in the currency used (e.g. adults versus total spawners, fall run versus multiple run timings, treatment of hatchery spawners) and in the basis of any stated or implied goal (e.g. maximizing yield, maximizing production, filling available habitat, or "adequacy"). They also differ widely in the age, quantity, and quality of data included. Nevertheless, with some simplifying assumptions, it is possible to convert values from the

[20] It seems unlikely that an estimate of 1977 run size would be available in time to inform the choice of a goal in 1977, but this is what it is reported.

different documents to something like a common currency for a coarse comparison[21] (Table 4), although these comparisons rely on several assumptions and simplifications.

The current S_{MSY} reference point of 122,000 includes fish returning to both hatcheries and natural areas. In recent years (2012-2021), a median 69% of total adult SRFC spawners returned to natural areas (PFMC 2022b Table B-1), suggesting this reference point is roughly equivalent to a goal of 84,000 natural-area spawning adults in practice. For 1970-2021, a median 82% of SRFC adults spawned in natural areas (PFMC 2022b Table B-1), such that the S_{MSY} reference point would roughly correspond to 100,000 natural-area adult SRFC spawners.

As written, PFMC (1984) implies an upper-end natural-area adult fall run escapement "goal" (i.e., the sum of natural area contributions to the defined overall goal) of 160,000 adults (99,000 for the Upper-River, 27,000 for the Feather River, 10,000 for the Yuba River, and 24,000 for the American River, where the Yuba River contribution is based on mean 1971-1981 escapement and the other contributions are said to be based on mean 1953-1960 escapements but cannot be reproduced). Using numbers reported by Azat (2021) (which include jacks) for the stated periods yields contributions of 197,207 (excluding areas downstream of RBDD but upstream of Princeton Ferry), 51,131, 11,023, and 17,267, respectively; for an implied natural-area fall run escapement goal (including jacks) of about 277,000 at the upper end, or approximately 316,000 spawners after accounting for spawners between RBDD and Princeton Ferry. If the Upper-River contribution to the lower end is arbitrarily lowered to 50,000 (for comparability, this number should be slightly larger to include jacks, but might need to be reduced to reflect Coleman Hatchery's inclusion in the 50,000 low-end contribution), this would yield an implied lower end natural-area spawner goal of about 126,000 spawners. Including updated hatchery goals would increase all of these goals by a further 22,000.

Hallock (1977) stated a goal of 245,000 fall run spawners. Hallock (1977) is not explicit about whether this goal is for total spawners or natural-area spawners, nor about whether this includes jacks. However, average escapements reported by Hallock (1977) for various reference periods could be closely reproduced using escapement estimates from Azat (2021) including jacks and hatchery returns, so it likely includes both. For 1970-2021, 40%-94% with median 82% of total SRFC adult escapement was to natural areas (PFMC 2022b Table B-1), although this proportion has been lower in recent years. For 2012-2021, a median 69% of total SRFC adult spawners were in natural areas. Thus, the 245,000 spawner goal identified by Hallock (1977) might equate to about 200,000 or 169,000 natural-area SRFC spawners.

Various parts of ASETF (1979) imply goals of 340,000 to 431,000 adults of all runs combined. For 1971-2021 (PFMC 2021 Tables B-1 and B-3) adult SRFC natural-area spawners made up a median 69% of all adult Chinook spawners (jacks included in spring run tributary estimates) in the Sacramento Basin (including hatchery spawners). This could imply SRFC natural-area adult goals of 235,00 to 298,000 for each of the all-run goals stated previously. For 1970-2021 (PFMC 2022b Table B-1), natural area SRFC escapement ranged from 2%-35% jacks with median 13%, implying total natural-area SRFC spawner goals of 272,000 to 344,000.

[21] The calculations that follow were carried out at full precision, and so products may not exactly match the products of the rounded intermediate values reported here.

Reisenbichler (1986) analyzed multiple areas over multiple time periods. However, the 1954-1963 analysis of the Upper Sacramento uses a time period similar to the stated basis of PFMC (1984), and seems to be the source of the S_{MSY} value that appears (mislabeled as the basin-wide natural-area escapement maximizing production) in the FMP, although Resienbichler (1986) included everything above the confluence with the Feather River compared to recent practice typically referring to the Upper Sacramento above RBDD. Reisenbichler's (1986) implied S_{MSY} for the Upper Sacramento of 118,247 natural-area spawners (including jacks) implies a Sacramento basin-wide S_{MSY} of about 163,000 natural-area spawners based on a median of 72% of SRFC natural-area escapement occurring to the Upper Sacramento mainstem and tributaries above Princeton Ferry for 1954-1963 according to Azat (2021). Reisenbichler's (1986) implied S_{MSP} for the Upper Sacramento of 161,290 spawners implies an escapement of about 223,000 fall Chinook (including jacks) to natural areas for the Sacramento Basin as a whole would maximize production.

PFMC (2019) found that Upper Sacramento natural fall Chinook production was maximized at approximately 80,000 female spawners based on data from the 1998-2015 spawner years. 80,000 females implies about 160,000 spawners (which, to be consistent with assuming a 50:50 sex ratio would likely include jacks) in natural areas to maximize production, or about 126,000 Upper Sacramento fall run spawners to maximize yield given typical S_{MSY}/S_{MSP} ratios (S_{MSY}/S_{MSP} ratios for the Ricker relationships fitted to SRFC populations by Reisenbicher [1986] ranged from 0.73-0.83 with median 0.79). For the 1998-2015 spawning years used in PFMC (2019), a median 45%[22] of natural-area SRFC escapement was to the Upper Sacramento (calculated from PFMC 2022 Table B-1), implying that maximum production could be achieved with about 359,000 natural-area fall-run spawners and maximum sustainable yield for SRFC could be achieved with Sacramento Basin natural-area fall run spawning escapement (including jacks) of around 283,000, close to the level implied by Munsch et al. 2020

Munsch et al. (2020) found that a natural-area Sacramento Basin spawning escapement of around 400,000[23] fall/spring/winter runs combined would maximize production, and this number includes jacks[24]. For 1998-2015 (matching outmigration years 1999-2016 used in Munsch et al. 2020), fall run made up 76%-98% of combined fall/spring/winter run escapement to natural areas in the Sacramento Basin with median 93% (calculated from PFMC 2022 Tables B-1 and B-3, using adults only when possible), implying maximum production at 371,000 fall-run spawners. Given typical S_{MSY}/S_{MSP} ratios, this could imply an S_{MSY} of about 400,000 x 0.93 x 0.79 = about 293,000 natural-area SRFC spawners (including jacks). Despite using different measures of juvenile production, different measures of spawners, and different modeling methods, the

[22] However, this proportion is exceedingly variable, ranging from 26%-76% for 1998-2015 and from 9% to 77% for 1970-2021.

[23] According to Stu Munsch, the GAMs fitted in Munsch et al. (2020) indicate production is maximized at 459,863 natural-area spawners (excluding late-fall) and the best-fit Ricker Beta implies maximum production at 449,663 natural-area spawners (excluding late-fall).

[24] Despite some references to "spawning adults" in Munsch et al. 2020 – the intent there was to simply distinguish reproductively mature returning spawners from sexually immature juveniles in freshwater. Munsch et al. (2020) used spawner numbers from GrandTab, an earlier iteration of Azat (2021).

natural-area SRFC spawners corresponding to S_{MSY} implied by PFMC (2019) and Munsch et al. (2020) are remarkably similar[25].

Note that these calculations of MSY are based on yield of natural-origin fish (consistent with the approach employed for Klamath River Fall Chinook). Setting reference points for composite hatchery- and natural-origin stocks has long been recognized as a challenging task that risks over-harvesting the natural-origin component (Kope 1992, CA HSRG 2012 [their section 2.3]).

Errors in the FMP

Based on this literature review, several errors were identified in the FMP's description of the SRFC conservation objective and S_{MSY} derivation in Table 3-1. Suggested corrections to result in factual accuracy (assuming no changes to current management practices) are provided below in track-changes form (deletions in ~~strikethrough~~, additions in underline):

> 122,000-180,000 natural and hatchery adult spawners (122,00 is the MSY proxy adopted 1984). ~~This~~ The upper end of this objective is intended to provide adequate escapement of natural and hatchery production based on the sum of previous hatchery goals and reports of average fall Chinook escapements for various parts of the Sacramento Basin (which are inconsistent with current estimates for those years) during various reference periods (PFMC 1984). The lower end of the objective and S_{MSY} are based on a reduction from the average Upper Sacramento escapement, meant to be used until "problems caused by the Red Bluff Diversion Dam are rectified".~~ for Sacramento and San Joaquin fall and late-fall stocks based on habitat conditions and average run-sizes as follows: Sacramento River 1953-1960; San Joaquin River 1972-1977 (ASETF 1979; PFMC 1984; SRFCRT 1994).~~ The objective is less than ~~the~~ an estimated basin capacity of 24~~0~~5,000 fall-run spawners (Hallock 1977), but greater than the 118,000 spawners for maximum ~~production~~ yield estimated for natural areas in the Upper Sacramento alone, based on data from 1954-1963~~ on a basin by basin basis before Oroville and Nimbus Dams~~ (Reisenbichler 1986).

The references to late-fall and San Joaquin spawners should be removed because they are not considered in PFMC (1984). The year ranges should be removed because they are incorrect for the Yuba River portion of the Sacramento basin and averages for the named

[25] Note however that the Munch et al. (2020) calculation started from the rounded value of 400,000 total spawners and the PFMC (2019) calculator started from the rounded value of 80,000 female spawners in natural areas of the Upper Sacramento, calculations starting from full precision model estimates would be slightly different.

periods could not be even approximately reproduced for the rest of the Sacramento basin, and no run sizes for the San Joaquin were reported or used in PFMC (1984). 240,000 is not the correct number for Hallock 1977, 245,000 fall-run spawners is (the fall-run modifier is suggested because Hallock [1977] also offers numbers for other run timings and their sum). The original description of Resienbichler (1986) was inaccurate in multiple respects (production versus yield, entire basin versus Upper Sacramento) and could either be revised for accuracy, or simply dropped because as corrected it may not be a particularly useful comparison. The reference to SRFCRT (1994) should be dropped because it does not present information or analyses relevant to the choice of a specific value for S_{MSY} or the conservation objective. If the reference to ASETF (1979) is retained, it could be appropriate to point out that various parts of ASETF (1979) imply a Sacramento Basin Chinook escapement goal of 340,000-467,500 adults of all run timings combined.

In addition, p. 51 of the FMP states that salmon fisheries in California are "managed to maximize natural production consistent with meeting the U.S. obligation to Indian tribes with federally recognized fishing rights, and recreational needs in inland areas" but this is incorrect. As described earlier in this document, the current SRFC conservation objective and S_{MSY} reference point are based on an analysis that explicitly rejected an objective for natural fish, and does not attempt to quantify production. For Klamath River Fall Chinook, although natural-area fish are specifically considered, S_{MSY} and the conservation objective are based on maximizing yield, not production. Other salmon stocks in California are either managed under Endangered Species Act requirements or not actively managed.

Data and Code Availability

Grey literature or open access references cited in this report, along with data and code for calculating the summary statistics and other quantitative analyses presented here, are available at https://drive.google.com/drive/folders/1q3yBGqT4RCBZ-Q2xzS7R2_xHBs0LevF3 (access will be granted upon request if needed). Email will.satterthwaite@noaa.gov for help with access options for paywalled journal articles.

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Table 1. Total adult SRFC escapement and escapement to each area contributing to the SRFC conservation objective, relative to their respective contribution to the total objective. Estimates are from Table B-1 of PFMC (2022b) and the qualifiers and caveats provided there apply here as well. For 1971-1986, the reported systemwide total adult escapement was higher than the sum of reported adult escapements to the individual subareas by as much as a few hundred fish, reflecting the inclusion of fish spawning in the since-discontinued Tehama-Colusa Fish Facility. Red cells are below the conservation objective contributions. For Upper-River natural areas, yellow cells meet the 50,000 contribution (though only when combined with Coleman Hatchery in some cases) at the low end of the conservation objective but not the 99,000 natural-area contribution at the high end.

	SRFC Adult Spawners							
		Natural Areas				Hatcheries		
Year	System-Wide	Upper-River	Feather	Yuba	American	Coleman	Feather	Nimbus
GOAL	122,000-180,000	50,000-99,000	27,000	10,000	24,000	9,000	5,000	6,000
1970	156,665	61,160	45,140	11,852	25,238	3,010	2,439	7,827
1971	154,882	67,586	33,582	5,255	35,720	1,503	2,326	8,684
1972	92,157	36,485	27,130	5,555	14,962	1,188	1,414	5,352
1973	220,059	48,948	52,080	22,117	77,225	1,047	7,180	10,830
1974	202,016	66,304	53,558	16,758	51,613	1,305	4,321	7,478
1975	155,621	72,985	34,754	4,699	29,112	1,823	4,170	6,612
1976	167,865	80,263	50,724	3,087	22,163	1,799	4,299	4,313
1977	164,011	60,967	35,672	6,786	39,608	4,741	8,529	6,367
1978	126,948	66,991	29,007	6,363	11,933	1,090	3,864	6,073
1979	172,397	81,332	25,289	10,441	39,523	4,766	3,505	5,900
1980	142,109	45,504	29,077	10,260	32,352	8,800	1,107	13,538
1981	174,958	51,831	40,488	12,047	39,662	4,438	7,255	17,792
1982	164,641	39,694	40,427	23,463	29,391	16,225	6,451	8,097
1983	110,248	42,570	18,441	11,390	19,261	5,367	6,075	6,399
1984	158,972	51,772	35,378	7,104	25,993	18,668	8,842	10,289
1985	239,307	103,698	46,527	10,121	49,707	13,089	5,602	7,784
1986	240,103	113,875	40,566	16,940	46,875	11,283	5,781	4,784
1987	195,065	76,861	51,278	12,352	34,741	9,981	6,510	3,342
1988	227,467	128,725	40,215	7,110	24,646	12,594	6,156	8,021
1989	152,562	67,296	36,487	6,402	17,435	10,212	6,479	8,251
1990	105,090	50,225	25,000	3,500	4,618	13,464	4,258	4,026
1991	118,869	35,259	28,524	11,164	17,892	10,031	9,227	6,772

Year	System-Wide	Upper-River	Feat. R.	Yuba	American	Coleman	Feat. H.	Nimbus
GOAL	122,000-180,000	50,000-99,000	27,000	10,000	24,000	9,000	5,000	6,000
1992	81,545	31,734	19,790	4,517	3,816	6,257	10,324	5,107
1993	137,390	55,144	27,367	5,818	24,435	7,056	10,228	7,342
1994	165,587	66,383	31,013	7,046	30,544	11,585	11,341	7,676
1995	295,313	112,235	56,197	12,998	72,335	24,810	11,566	5,172
1996	301,633	131,268	44,593	23,492	69,761	18,848	6,494	7,177
1997	344,841	167,353	47,009	19,202	48,001	44,590	13,358	5,328
1998	245,907	60,713	39,600	26,737	48,942	42,400	17,567	9,949
1999	399,830	256,629	30,000	18,778	52,199	23,194	12,822	6,207
2000	417,537	152,923	109,924	12,954	94,161	20,793	16,470	10,312
2001	596,775	179,198	169,588	21,567	169,023	23,710	24,001	9,688
2002	769,868	474,812	93,766	18,406	97,242	61,895	17,516	6,231
2003	523,016	164,802	85,578	26,820	137,444	82,882	13,615	11,875
2004	286,885	70,548	48,580	9,260	77,842	52,145	15,769	12,741
2005	396,005	96,716	43,738	16,251	58,155	139,979	20,597	20,569
2006	275,030	89,933	75,545	7,891	23,120	56,819	13,400	8,322
2007	91,374	36,079	21,541	2,523	9,929	11,543	5,169	4,590
2008	65,364	36,274	5,703	3,084	2,255	10,181	5,031	2,836
2009	40,873	12,277	3,950	3,992	4,729	5,433	6,240	4,252
2010	124,276	25,688	40,981	12,074	12,383	8,666	17,215	7,269
2011	119,342	20,466	35,656	6,917	14,815	19,312	15,925	6,251
2012	285,429	67,190	57,507	6,009	35,527	77,318	33,628	8,250
2013	406,846	90,119	145,650	13,830	56,036	67,758	25,152	8,301
2014	212,476	80,407	55,480	9,885	22,895	17,937	18,824	7,048
2015	113,468	40,696	18,069	3,844	11,895	13,861	17,700	7,403
2016	89,699	10,563	34,054	2,143	9,537	8,306	17,594	7,502
2017	44,329	1,526	8,120	1,207	6,998	1,316	16,598	8,564
2018	105,466	18,317	39,210	2,140	12,022	8,207	21,084	4,486
2019	163,767	53,706	43,352	2,677	21,894	13,065	19,731	9,342
2020	138,091	36,447	40,499	3,801	19,422	12,478	20,340	5,104
2021	104,483	52,320	9,203	3,918	7,787	14,555	9,372	7,328

Table 2. Area-specific S_{MSY} values derived from Ricker stock-recruit parameters (arithmetic mean version, excluding grilse [jacks] when available) reported by Reisenbichler (1986) using the analytical solution for S_{MSY} derived by Scheureuell (2016). The values obtained directly from Reisenbichler (1986) seem implausibly small and conflict with his figures, and it seems likely that Reisenbichler's Table 6 reported Beta x 1000 rather than Beta x 100 as stated. The "(fixed)" columns reflect this adjustment.

Spawning Area	Years	includes jacks?	alpha	beta	beta (fixed)	S_{MSY}	S_{MSY} (fixed)
American River	1945-1955	yes	10.7	0.00071	0.000071	1,117	11,174
Feather River	1953-1966	yes	10.6	0.00025	0.000025	3,167	31,671
Feather River	1955-1966	no	13.2	0.00034	0.000034	2,432	24,318
Upper Sacramento	1950-1953	yes	12.5	0.000054	0.0000054	15,159	151,595
Upper Sacramento	1954-1963	yes	7.8	0.000062	0.0000062	11,825	118,247
Upper Sacramento*	1955-1963	no	10.4	0.000086	0.0000086	9,168	91,681
Upper Sacramento*	1955-1965	no	8.3	0.000076	0.0000076	9,815	98,153
Upper Sacramento*	1967-1979	no	10.4	0.00017	0.000017	4,638	46,380

*Excludes Battle Creek.

Table 3. Natural-area spawning escapement to maximize production (1/Beta, Quinn 2012) in areas within the Sacramento Basin based on Ricker parameters estimated by Reisenbichler (1986), assuming that the reported values were Beta x 1000 rather than Beta x 100. Estimates of Beta excluding grilse were used when available.

Spawning Area	Years	includes jacks?	Natural-area escapement to maximize production
American River	1945-1955	yes	14,085
Feather River	1953-1966	yes	40,000
Feather River	1955-1966	no	29,412
Upper Sacramento	1950-1953	yes	185,185
Upper Sacramento	1954-1963	yes	161,290
Upper Sacramento*	1955-1963	no	116,279
Upper Sacramento*	1955-1965	no	131,579
Upper Sacramento*	1967-1979	no	58,824

*Excludes Battle Creek.

Table 4. Stated (bold text) or implied levels of SRFC spawning escapement to achieve various potential objectives, based on the different documents discussed in the main text. Derivations and caveats are described in the main text. For Reisenbichler (1986), the Upper Sacramento stock-recruit relationship estimated for 1954-1963 was used because it appears to be the analysis that yielded the 118,000 figure cited in the FMP. The low end of the PFMC (1984) objective after updating it based on new goals for hatcheries and using estimated mean escapements from Azat (2021) for the years specified in PFMC (1984) is shaded because the conditions for this "interim" adjustment may no longer apply (see main text).

	goals based on unstated or ambiguous criteria				max. production	maximize yield
	adults - hat. & nat.	spawners - hat. & nat.	adults - natural	spawners - natural	spawners - natural	spawners - natural
PFMC 1984 - low end	**122,000**		84,000-100,000			
PFMC 1984 - high end	**180,000**		160,000			
PFMC 1984 - low (updated)		*148,000*		*126,000*		
PFMC 1984 - high (updated)		299,000-339,000		277,000-316,000		
Hallock 1977		**245,000**		169,000-200,000		
ASETF 1979			235,000-298,000	272,000-344,000		
Reisenbichler 1986					223,000	163,000
PFMC 2019					359,000	283,000
Munsch et al 2020					371,000	293,000

Figure 1. Escapement to the Upper Sacramento River above Red Bluff Diversion Dam, including returns to Coleman National Fish Hatchery (PFMC 2022b, Table B-1). The 1979-1983 period referred to in PFMC (1984) is highlighted, as well as the 50,000 level they expected returns to stabilize around.

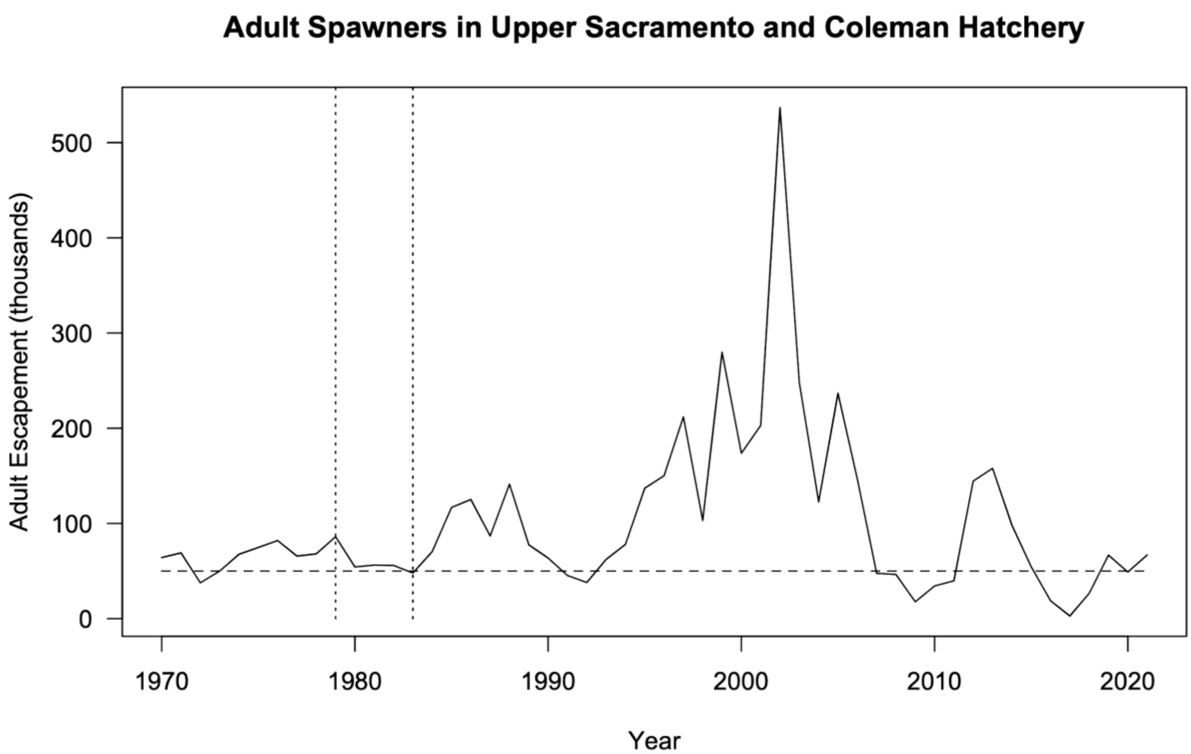

Figure 2. Logistic regression modeled probability of exceeding all areas' contributions to the SRFC conservation objective as a function of total escapement. In the top panel, the Upper-River (natural areas and hatchery combined) has a contribution of 50,000; in the bottom panel the Upper-River natural areas have a contribution of 99,000 and Coleman National Fish Hatchery has a contribution of 9,000. The line is a fitted logistic regression, circles at y=0 indicate years that did not achieve all contributions to the conservation objective, and circles at y=1 indicate years that did.

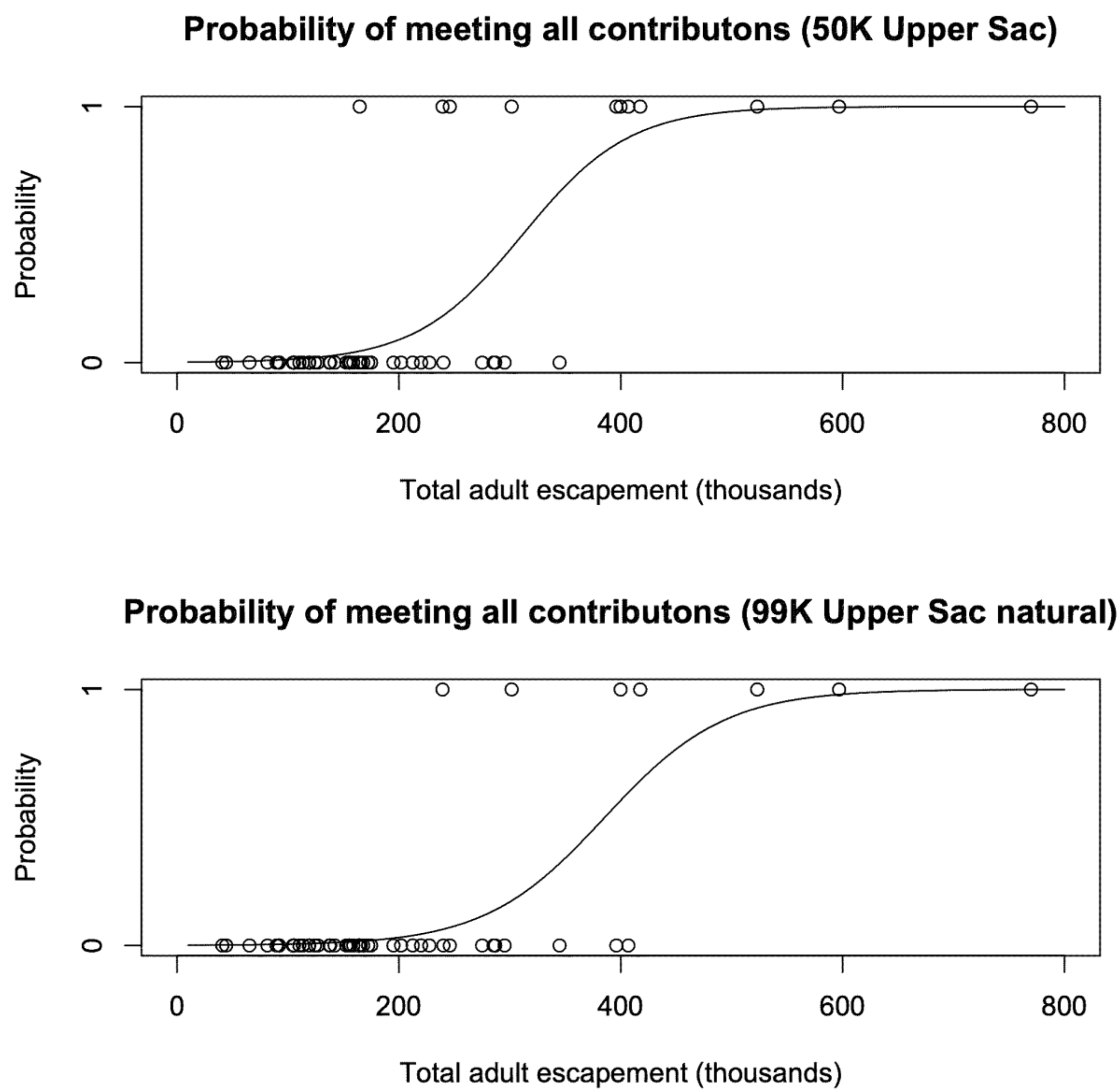

Figure 3. Fall run spawners escaping to the Yuba River (from Azat 2021). The horizontal dashed line represents the 10,000 spawners that PFMC (1984) reports escapement was "remarkably stable" around from 1971-1981, years that are highlighted with vertical dashed lines.

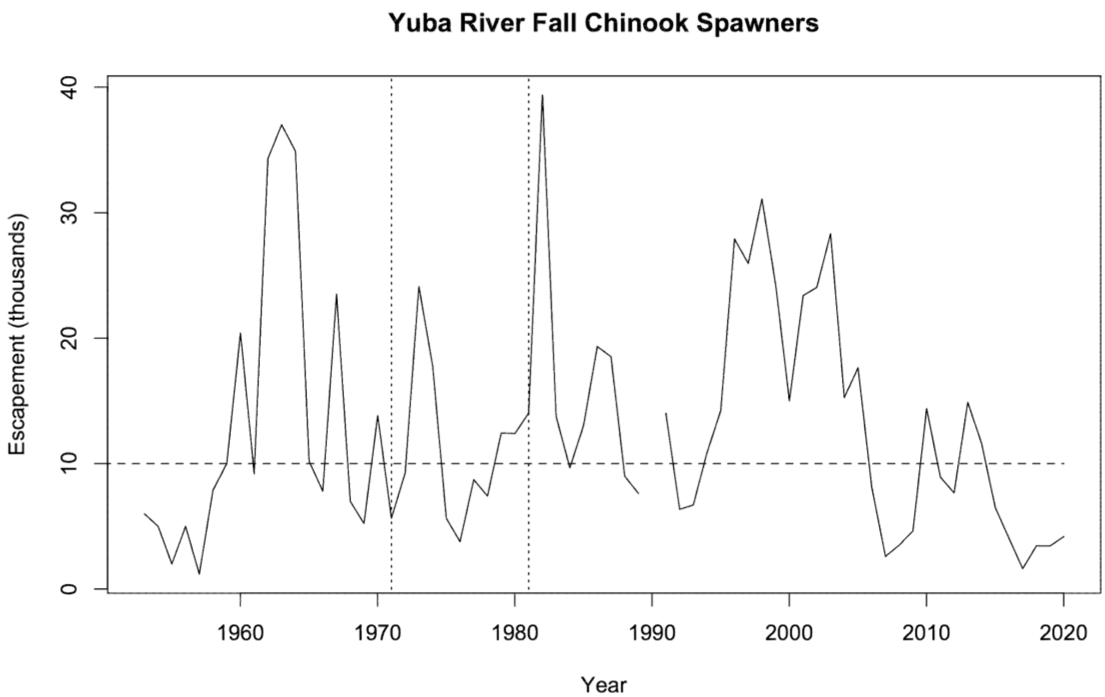

Figure 4. Composition (hatchery-origin versus natural-origin) and abundance of fall run Chinook salmon spawning in the Yuba River according to Coded-Wire Tag Recovery Reports (see citations in main text).

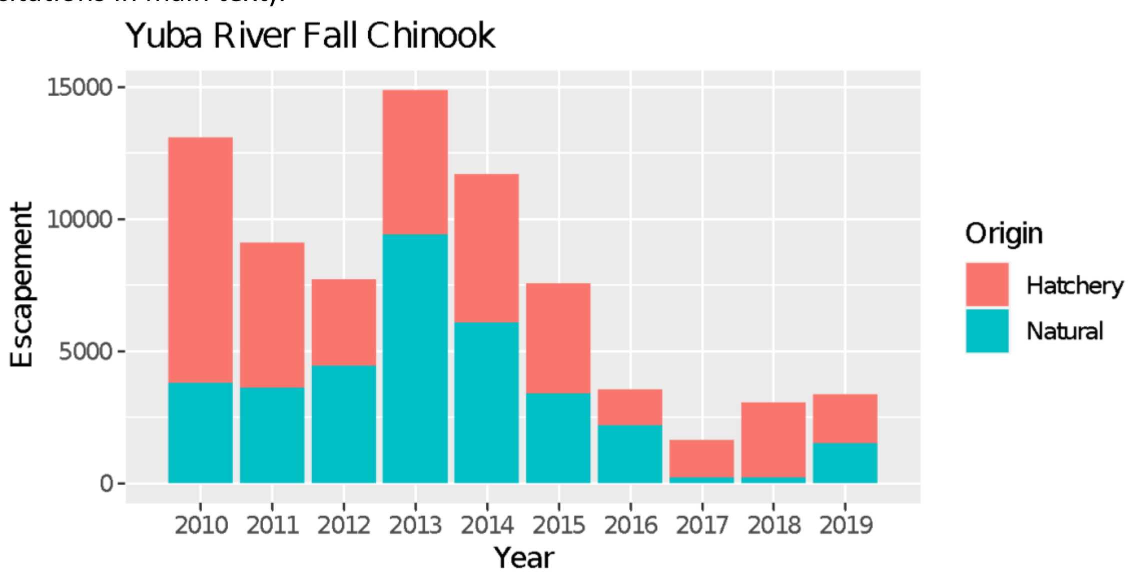

Figure 5. Annual fry density index compared with spawner abundances and flow (median flow between December and May measured at USGS flow gages 11447650 on the Sacramento River and 11303500 on the San Joaquin [two gages summed]) overlaid with predictions from the model describing the relationship among these variables. These models are parameterized by a Beverton–Holt and Ricker stock–recruitment relationships and a linear effect of log-transformed flow. The thick, solid line indicates the median value of median log-transformed flow across all years. Predictions from these top two models were shown because AIC values indicated they fit the data similarly well. Other flow metrics yielded broadly similar results, see Munsch et al. (2020) for details. Reproduced from Munsch et al. (2020) in compliance with the Creative Commons Attribution 4.0 International License (CC BY 4.0), which permits unrestricted use, distribution, and reproduction in any medium, provided the original author(s) and source are credited.