Agenda Item D.1.a
Attachment 2
November 2008

The Sacramento Index

Michael R. O'Farrell[1]

Michael S. Mohr[1]

Melodie L. Palmer-Zwahlen[2]

Allen M. Grover[2]

[1]National Marine Fisheries Service
Southwest Fisheries Science Center
Fisheries Ecology Division
110 Shaffer Road, Santa Cruz, CA 95060

[2]California Department of Fish and Game
Marine Region
Ocean Salmon Project
475 Aviation Boulevard, Suite 130
Santa Rosa, CA 95403

October 7, 2008

1 Introduction

Sacramento River fall Chinook (SRFC) have been the largest contributor to ocean salmon harvest off California and Oregon for several decades. At present, however, the stock appears to have collapsed as indicated by the 2006 and 2007 jack (estimated age-two) spawning escapement being the lowest on record (since 1970), and the 2007 adult (estimated age $\geq$ 3) escapement of 88,000 being the second lowest on record. Adding to the concern, the 2008 forecast escapement was 59,100 adults assuming all ocean salmon fisheries south of Cape Falcon, Oregon, and Sacramento River Basin fisheries impacting SRFC were closed in 2008. Given the stock's current status, and its 2008 forecast abundance, the U.S. Secretary of Commerce took the unprecedented step of closing all 2008 ocean Chinook fisheries south of Cape Falcon, and the California Fish and Game Commission took the equally unprecedented step of closing all 2008 Sacramento River Basin fisheries impacting SRFC. This report describes the data and methods used in 2008 to develop a historical index of SRFC adult ocean abundance and the forecast of this index abundance in 2008, which led to the forecast escapement of 59,100 adults. We begin with a brief synopsis of the methods used prior to 2008, and follow with a description of the methods proposed for use in 2009 and beyond.

1.1 Pre-2008 methods: Central Valley Index

In years prior to 2008, SRFC escapement projections were derived from forecasts of the Central Valley Index (*CVI*), which served as an index of abundance for the combined stocks of Central Valley Chinook, including SRFC, Sacramento River winter Chinook, Sacramento River late-fall Chinook, Central Valley spring Chinook, and San Joaquin River fall Chinook. The *CVI* is an annual index defined as the calendar year sum of Central Valley Chinook adult escapement (E_{CV}) and the ocean catch of Chinook (all stocks, including non-Central Valley) between Point Arena, California, and the U.S./Mexico border (C_{AM})

$$CVI = E_{CV} + C_{\mathsf{AM}}. \tag{1}$$

Linear regression of the *CVI* in year *t* against Central Valley Chinook jack spawning escapement in year *t-1*, with *t* = 1990–forward, was used to forecast the current year *CVI* based on the previous year's jack escapement (e.g., see PFMC 2007, Figure II-1).

SRFC adult escapement (E) was then forecast using the projected *CVI*, the anticipated *CVI* ocean harvest rate index ($h_{CVI} = C_{\mathsf{AM}}/CVI$), and the anticipated proportion (π) of E_{CV} that would be SRFC as

$$E = CVI \times (1 - h_{CVI}) \times \pi, \tag{2}$$

allowing for a pre-season evaluation of E relative to the SRFC escapement goal. In the most recent use of this model for forecasting purposes (2007), the previous year's h_{CVI} estimate, and the mean of the previous five years of π estimates, were used for these quantities in equation (2). Prior to 2008, stocks other than SRFC constrained ocean fisheries and a model more sophisticated than equation (2) was unnecessary for SRFC assessment.

1.2 2008 methods: Sacramento Index

There are several shortcomings to using the *CVI* to forecast SRFC escapement, including (1) the index itself is not SRFC-specific, (2) the index is calculated on a calendar year basis rather than on a biological year (between annual spawning events) basis, (3) ocean harvest north of Point Arena is not accounted for, and (4) river harvest is not accounted for. These shortcomings coupled with the critical status of SRFC in 2008 hastened the development of a new SRFC-specific abundance index (the *Sacramento Index*, *SI*) and a new SRFC-specific harvest model (the *Sacramento Harvest Model*, *SHM*).

The *SI* was similar in structure to the *CVI*:

$$SI = H_{o,S} + E, \tag{3}$$

where $H_{o,S}$ is the Sept. 1 through Aug. 31 (biological year) ocean harvest of SRFC south of Cape Falcon, and E is the SRFC adult escapement. Methods developed in 2008 provided estimates of SRFC ocean harvest in all time-area-fisheries south of Cape Falcon; a significant improvement in the extent, resolution, and specificity of SRFC ocean harvest information compared to that previously available. Like the *CVI* however, the *SI* defined in equation (3) does not include river harvest (although E implicitly depends on this harvest).

Based on a forecast of the *SI* and of the SRFC harvest expected in the ocean and river fisheries, the *SHM* provides a forecast of the current year SRFC adult escapement. The 2008 *SHM* did this by deducting the projected SRFC ocean harvest (a function of the *SI* and ocean fishery management measures) from the *SI* which yielded a forecast of SRFC adult escapement assuming a "typical" (largely unconstrained) SRFC river fishery (the type of fishery that generated the data from which the 2008 *SI* was constructed). To forecast the expected escapement under a constrained river fishery, the 2008 *SHM* first projected the SRFC adult river run abundance by dividing the projected escapement under a typical river fishery by (1 - average river harvest rate), and then multiplied this by (1 - constrained river harvest rate). For a complete description of the *SHM* see Mohr and O'Farrell (2008).

1.3 Post-2008 methods: Sacramento Index

As defined in 2008, the *SI* is an incomplete representation of SRFC adult ocean abundance, in part because it does not explicitly include the harvest of SRFC adults by the Sacramento River Basin recreational fishery. River harvest was not included in the 2008 formulation of the *SI* because of gaps in the historical time series of river harvest estimates. However, further analysis of the existing SRFC river harvest estimates derived from California Department of Fish and Game (CDFG) angler creel surveys, coupled with the methods described in this report, now allow for the hindcasting of river harvest for years in which survey estimates are unavailable, and this allows for a re-definition of the *SI* to explicitly include SRFC adult river harvest (H_r):

$$SI = H_{o,S} + H_r + E. \tag{4}$$

The addition of H_r to the *SI* also permits a more straightforward formulation of SRFC river harvest and escapement within the *SHM*.

This report describes in detail our assessment of the individual components of the *SI* as defined by equation (4). Section 2 documents how the $H_{o,S}$ estimates were derived. Section 3 details how the CDFG angler survey estimates, and hindcasts of H_r, were developed. Section 4 describes the escapement survey methods used to generate E. Section 5 presents the *SI* time series. Finally, Section 6 documents how the *SI* is annually forecast for use in the *SHM*.

2 Ocean Harvest

The ocean harvest of SRFC, $H_{o,S}$, is a key component of the *SI*, and for the purposes of the *SI*, is defined as the Sept. 1 through Aug. 31 SRFC ocean harvest south of Cape Falcon. Some SRFC have been harvested north of Cape Falcon, but this harvest was determined to be a small percentage of the SRFC overall ocean harvest (Appendix A). For years 1986–2007, the average proportion of the SRFC overall ocean harvest landed north of Cape Falcon was approximately two percent.

The *SI* is intended to be an index of SRFC *adult* ocean abundance. While direct measures are taken to ensure that only adults are included in the H_r and E estimates, directly restricting $H_{o,S}$ to include only age 3–5 SRFC is not possible given the limitations of available ocean harvest age composition data. However, few age-two Chinook are vulnerable to ocean fishing gear, and age-two Chinook are generally smaller than the minimum size-limits in ocean fisheries. For these reasons, the contribution of age-two fish to the ocean harvest is small. We thus consider the *SI* to be an index of SRFC adult ocean abundance, yet acknowledge that a small number of age-two fish may be harvested in ocean fisheries and therefore contribute to the index.

Estimation of $H_{o,S}$ from the mixed-stock ocean harvest presents challenges due to the limitations of the available data. In particular, the lack of age-specific SRFC harvest and escapement data precludes using cohort reconstruction methods to estimate SRFC ocean harvest (as is done, for example, with Klamath River fall Chinook, KRFC). The only data currently available for estimation of $H_{o,S}$ are the coded-wire tags recovered in ocean fisheries. We used these tag recoveries from ocean fisheries south of Cape Falcon, and the historical dominance of SRFC in the ocean harvest south of Point Arena, to estimate $H_{o,S}$ for all time-area-fisheries south of Cape Falcon. The remainder of Section 2 describes the details of this estimation methodology.

Table 1. Description of management areas south of Cape Falcon, Oregon. KMZ denotes the Klamath Management Zone which extends from Humbug Mountain, Oregon to Horse Mountain, California. "Falcon-to-Arena" is the region extending from Cape Falcon, Oregon to Point Arena, California, consisting of the {NO, CO, KO, KC, FB} areas. "Arena-to-Mexico" is the region extending from Point Arena, California, to the U.S./Mexico border, consisting of the {SF, MO} areas.

Area	*Abbreviation*	*Northern border*	*Major Ports*
Northern Oregon	NO	Cape Falcon, OR	Newport, Tillamook
Central Oregon	CO	Florence South Jetty, OR	Coos Bay
Oregon KMZ	KO	Humbug Mountain, OR	Brookings
California KMZ	KC	OR/CA border	Eureka, Crescent City
Fort Bragg	FB	Horse Mountain, CA	Fort Bragg
Falcon-to-Arena	FA		
San Francisco	SF	Point Arena, CA	San Francisco
Monterey	MO	Pigeon Point, CA	Monterey
Arena-to-Mexico	AM		

2.1 Data

Total Chinook (mixed-stock) harvest is estimated annually by management area $a \in \{\text{NO, CO, KO, KC, FB, SF, MO}\}$ (here confined to the areas south of Cape Falcon, see Table 1), month m, and fishery $x \in \{\text{Commercial, Recreational}\}$. Summaries of this harvest can be found in PFMC (2008b, Appendix A). To obtain an estimate of $H_{o,S}$ from this mixed-stock harvest, two additional sources of information were required.

The first additional source of information required to derive $H_{o,S}$ was the estimated ocean harvest of KRFC in all time-area-fisheries south of Cape Falcon. These estimates were provided by the KRFC cohort reconstruction results which are available for brood years 1979–forward. The databases and methods used for KRFC cohort reconstruction are described in detail by Goldwasser et al. (2001) and Mohr (2006).

The second additional source of information required to derive $H_{o,S}$ was the coded-wire tag recovery data from all Chinook stocks other than KRFC in all time-area-fisheries south of Cape Falcon (obtained from the Regional Mark Processing Center, http://www.rmpc.org). Coded-wire tags recovered in both commercial and recreational fisheries were expanded for the non-exhaustive sampling of ocean harvest to produce stock-specific estimates of the total number of coded-wire tagged fish harvested in all time-area-fisheries. These sample-expanded estimates were then further expanded to account for the hatchery mark-rate (tagged versus untagged) in order to estimate hatchery-specific ocean harvest by time-area-fishery. An exception to this procedure was used in the case of SRFC, where it was not feasible to expand for the hatchery mark-rate because of the low and variable tagging rates historically employed at SRFC-producing hatcheries. SRFC coded-wire tags were therefore only expanded for sampling.

2.2 Methods

Estimation of $H_{o,S}$ is performed by means of a two-part process that exploits the fact that SRFC dominate ocean Chinook harvest in the AM region. For each biological year t ($m =$ Sept. 1, *t-1* through Aug. 31, t), for the areas south of Point Arena, $a \in \{\mathsf{SF}, \mathsf{MO}\}$, and in both the commercial and recreational fisheries, the time-area-fishery-specific ocean harvest of SRFC ($H_{o,S,a,m,x}$) was estimated by subtracting from the respective total Chinook harvest ($H_{o,T,a,m,x}$) the estimated harvest of all other stock groups that could be accounted for:

$$H_{o,S,a,m,x} = H_{o,T,a,m,x} - \sum_{g=K,V,N} H_{o,g,a,m,x}\,, \qquad \text{for} \quad a \in \{\mathsf{SF}, \mathsf{MO}\}. \tag{5}$$

$H_{o,K,a,m,x}$ is the estimated harvest of KRFC, hatchery- and natural-origin, derived from the KRFC cohort reconstruction. $H_{o,V,a,m,x}$ is the estimated harvest of all Central Valley hatchery-origin Chinook other than SRFC (including Sacramento River late-fall Chinook, Sacramento River winter Chinook, Central Valley spring Chinook, and San Joaquin River fall Chinook), as well as age-two SRFC coded-wire tagged groups (expanded for sampling only). $H_{o,N,a,m,x}$ is the estimated harvest of all non-Central Valley hatchery-origin Chinook stocks (excluding KRFC).

The summation term in equation (5) represents the best estimate of all known Chinook harvest in the SF and MO areas, other than age 3–5 SRFC. This expression omits the harvest of stocks without a coded-wire tagged hatchery component (e.g. some California Coastal Chinook), natural-origin fish from stocks with hatchery components (except for KRFC), and age-two SRFC natural- and untagged hatchery-origin fish. These omissions likely constitute a very small proportion of the total harvest in these southern areas.

To derive estimates of $H_{o,S,a,m,x}$ for the time-area-fisheries between Cape Falcon and Point Arena, we applied the ratio of SRFC harvest per SRFC coded-wire tag[1] observed south of Point Arena to the number of SRFC coded-wire tags recovered in the areas between Cape Falcon and Point Arena on a biological year basis as follows. Yearly SRFC ocean harvest in the region between Point Arena and the U.S./Mexico border (AM) was determined by summing $H_{o,S,a,m,x}$ over the SF and MO areas, over all months (Sept. 1 through Aug. 31), and over both fisheries:

$$H_{o,S,\mathsf{AM}} = \sum_{a=\mathsf{SF},\mathsf{MO}} \sum_{m,x} H_{o,S,a,m,x} \,. \tag{6}$$

The number of SRFC sample-expanded coded-wire tags recovered over this same subset of the harvest, $Z_{o,S,\mathsf{AM}}$, led to the ratio

$$\lambda = \frac{H_{o,S,\mathsf{AM}}}{Z_{o,S,\mathsf{AM}}}, \tag{7}$$

which represents the expected number of SRFC (hatchery- and natural-origin) harvested per SRFC coded-wire tag in the harvest, independent of month and fishery. For the time-area-fisheries between Cape Falcon and Point Arena, λ was then applied to the number of SRFC sample-expanded coded-wire tag recoveries, $Z_{o,S,a,m,x}$, to estimate the respective SRFC ocean harvest:

$$H_{o,S,a,m,x} = Z_{o,S,a,m,x} \times \lambda, \qquad \text{for} \quad a \in \{\mathsf{NO}, \mathsf{CO}, \mathsf{KO}, \mathsf{KC}, \mathsf{FB}\}. \tag{8}$$

With this two-part (north and south of Point Arena) method, the SRFC ocean harvest for each time-area-fishery south of Cape Falcon was estimated, and then aggregated for the SRFC overall ocean harvest,

$$H_{o,S} = \sum_{a,m,x} H_{o,S,a,m,x} \,. \tag{9}$$

The procedures described above parse each time-area-fishery Chinook total (T) harvest into two stocks (S and K) and two stock groupings (V and N). For the areas south of Point Arena, the sum of these four components, by construction, equaled the total harvest. However, for the

---

[1] In an attempt to constrain the estimate of $H_{o,S,a,m,x}$ to age 3–5 fish, we limited the coded-wire tag recoveries of SRFC used to estimate $H_{o,S,a,m,x}$ to age 3–5 fish. Hereafter, reference to "SRFC coded-wire tag" implies SRFC coded-wire tags from age 3–5 fish.

areas north of Point Arena, the estimated harvest of S, K, V, and N did not always sum to the total harvest. In these cases, the estimated component harvests were adjusted so that they did sum to the total harvest, using the methods described in Appendix B.

2.3 Results

For the region south of Point Arena, Table 2 displays the estimated SRFC ocean harvest, the number of age 3–5 SRFC sample-expanded coded-wire tags recovered, and their ratio for each biological year. Factors likely contributing to the observed annual variation in λ include variable SRFC natural-origin production, and variable tagging rates at SRFC-producing hatcheries. For example, while production levels at Coleman National Fish Hatchery have remained steady, the number of fish coded-wire tagged decreased sharply beginning with brood year 2002. It is likely that this reduction in tagging rate post-2002 at least partially accounts for the high λ values observed in 2005–2007.

Figure 1 displays total Chinook and SRFC ocean harvest estimates for the seven management areas south of Cape Falcon, 1983–2008. The proportion of total Chinook harvest attributed to SRFC is substantial for all areas, particularly in the south.

3 River Harvest

River harvest was not included in the 2008 formulation of the *SI* because of gaps in the historical time series of river harvest estimates. As a consequence, the *SHM's* 2008 escapement forecast was a function of the *SI* forecast, the $H_{o,S}$ forecast, and the average river harvest rate observed in past years compared to that expected in 2008 (PFMC 2008a, Appendix D). The approach used in the 2008 assessment to estimate this average river harvest rate is presented in this section, as well as an alternative river harvest rate model which depends nonlinearly on river run abundance.

The derived river harvest rate models are also used to hindcast the river harvest in years when angler surveys were not conducted based on (1) the escapement in that year, and (2) the river harvest rate expected at that level of escapement. These hindcast river harvest estimates for the

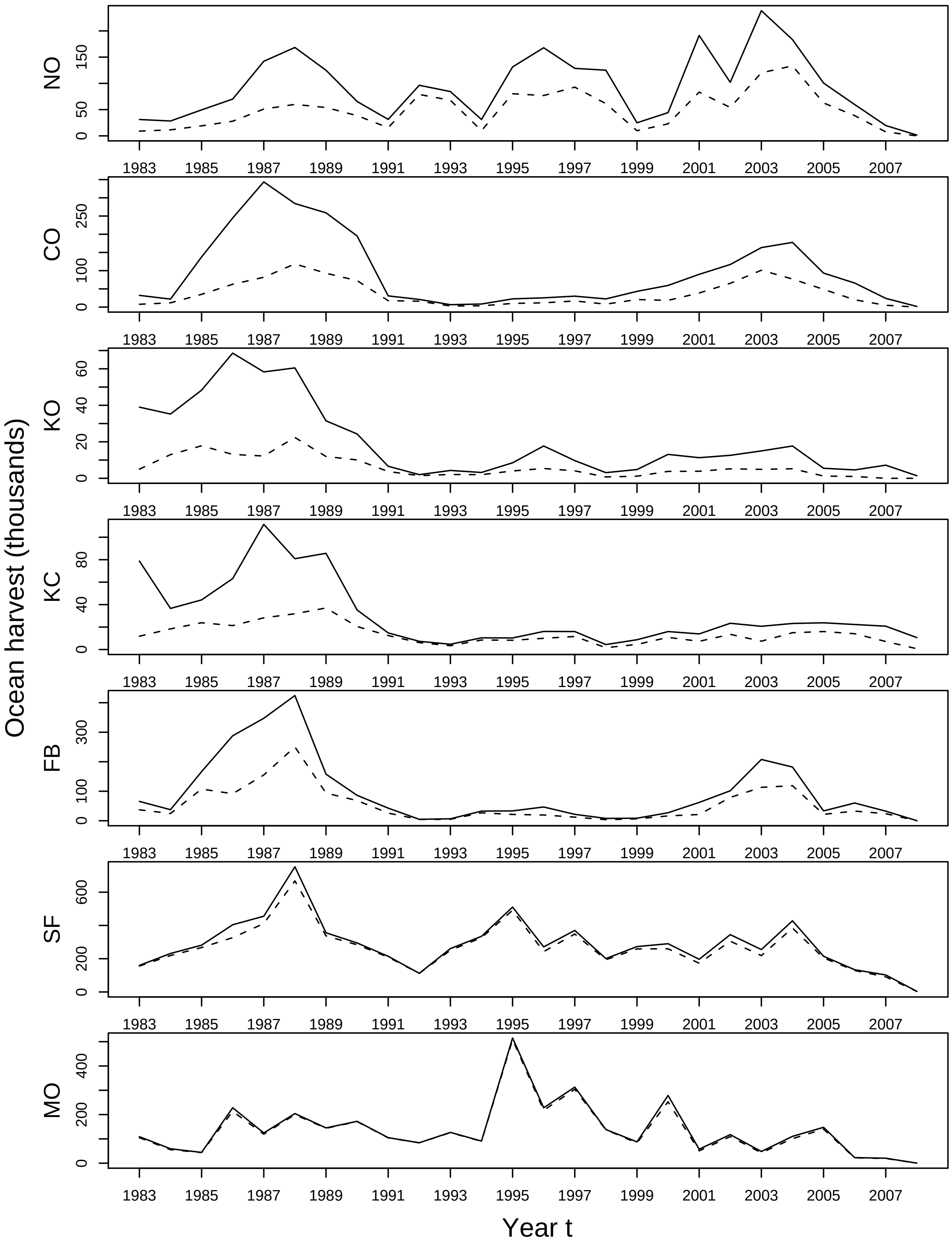

Figure 1. Estimated total Chinook (solid lines) and Sacramento River fall Chinook (dashed lines) ocean harvest for areas south of Cape Falcon, Oregon, for the Sept. 1, *t-1* through Aug. 31, *t* period, 1983–2008. Note that the y-axis scale differs for each management area.

Table 2. For the area south of Point Arena, estimated SRFC ocean harvest ($H_{o,S,\mathrm{AM}}$), number of SRFC age 3–5 sample-expanded coded-wire tags recovered ($Z_{o,S,\mathrm{AM}}$), and their ratio (λ, equation (7)), for the Sept. 1, *t-1* through Aug. 31, *t* period.

Year (t)	$H_{o,S,\mathrm{AM}}$	$Z_{o,S,\mathrm{AM}}$	λ
1983	260623	7981	32.66
1984	274200	5318	51.57
1985	311040	3314	93.90
1986	539879	8364	64.56
1987	530790	7192	73.80
1988	867888	15752	55.10
1989	480937	8077	59.56
1990	454626	8637	52.63
1991	313661	4771	65.75
1992	195500	1156	169.21
1993	376387	2903	129.70
1994	416422	2913	142.86
1995	999708	10256	97.47
1996	460311	13090	35.16
1997	652541	19004	34.34
1998	331319	17060	19.42
1999	342166	13258	25.81
2000	512112	4896	104.60
2001	223494	7565	29.54
2002	414641	10506	39.46
2003	261342	13156	19.86
2004	485356	16271	29.83
2005	344530	4212	81.83
2006	151140	1508	100.20
2007	110046	498	221.24

survey “gap” years, presented for the first time in this report, together with the harvest estimates for the survey years, provide a complete time series of H_r estimates, and it is this set of estimates that will be used for constructing the *SI* (equation (4)) in post-2008 assessments.

3.1 Data

Summary estimates of harvest and fishing effort, derived from the Sacramento River Basin angler surveys conducted by the California Department of Fish and Game (CDFG), were obtained from Dr. Robert G. Titus (CDFG, personal communication). SRFC river harvest and angler effort estimates exist for 1991–1994, 1998–2000, 2002, and 2007[2]. The proportion of jacks in samples of creel-surveyed fish in conjunction with the river harvest estimates allowed us to infer the adult harvest. The creel surveys were performed on eight sections of the Sacramento River, three sections of the American River, and three sections of the Feather River. Some additional surveys were conducted on the Yuba River, but survey effort there was much lower and estimated harvest (when surveys were conducted) was very low relative to the other surveyed rivers. For this reason, harvest and effort estimates from the Yuba River surveys were not included in the assessment. The estimated number of caught-and-released Chinook are available for the survey years, but were not used in the assessment.

In some years survey data were lacking for a particular month-stream-section, hence no estimates of harvest or effort were available. The methods employed to interpolate for these missing estimates are described in Appendix C. The effect of this interpolation was minor; the percent difference in the resulting river harvest estimate using the interpolated and non-interpolated datasets was less than four percent for all years.

3.2 Methods

For the surveyed years, Sacramento River Basin total annual river harvest of SRFC adults, H_r, was estimated as the sum of the estimated overall harvest (including jacks), H'_r, from each section k of streams $s \in \{\textsf{Sacramento, American, Feather}\}$, for months $m \in \{\textsf{Jun.}, \ldots, \textsf{Dec.}\}$, multiplied by

---

[2] Limited survey data exist for 2001 but these data were not used in the assessment since survey coverage in time and space was greatly reduced relative to the other years.

one minus the estimated proportion of jacks, p_J:

$$H_r = (1 - p_J) \sum_{m,s,k} H'_{r,m,s,k}. \tag{10}$$

All Chinook caught in these streams between the months of June and December were assumed to be SRFC. Adding H_r to the SRFC adult escapement estimate E yielded an estimate of the SRFC adult river run abundance,

$$R = H_r + E, \tag{11}$$

and in turn an estimate of the SRFC adult river harvest rate,

$$h_r = H_r / R. \tag{12}$$

For the 2008 SRFC assessment, the harvest in the largely unconstrained river fishery for previous years was modeled as being proportional to the river run abundance with an additive error term. The proportionality constant in this model is the mean harvest rate, $h_{r,mean}$:

$$H_r = h_{r,mean} R + \varepsilon. \tag{13}$$

The mean harvest rate was then estimated from the survey data using the ratio estimator

$$\hat{h}_{r,mean} = \bar{H}_r / \bar{R}, \tag{14}$$

where $\bar{H}_r$ and $\bar{R}$ denote the arithmetic mean of H_r and R over the survey years, respectively. The ratio estimator is the optimal estimator of the mean harvest rate under model (13) if the variance of ε increases in proportion to R (Thompson 2002).

For this report, we also consider an alternative model for the river harvest rate based on

$$h = f \times q, \tag{15}$$

where f is fishing effort in the Sacramento River Basin and q is the catchability coefficient. Equation (15) closely approximates the standard Type I fishery harvest rate model $h = 1 - e^{-qf}$ (Ricker 1975) for $h \leq 0.25$. We modeled f and q themselves as power functions of R:

$$\begin{aligned} f &= \alpha_f R^{\beta_f} e^{\theta_f}, \qquad & \theta_f &\sim N(0, \sigma_f^2), \\ q &= \alpha_q R^{\beta_q} e^{\theta_q}, \qquad & \theta_q &\sim N(0, \sigma_q^2), \end{aligned} \tag{16}$$

allowing these quantities to vary nonlinearly with river run abundance, which is appropriate for many fishery scenarios (Hilborn and Walters 1992). Equations (15) and (16) together imply that the harvest rate itself is a power function of R

$$h_r = \alpha_h R^{\beta_h} e^{\theta_h}, \qquad \theta_h \sim N(0, \sigma_h^2), \tag{17}$$

with $\alpha_h = \alpha_f \times \alpha_q$, $\beta_h = \beta_f + \beta_q$, and $\sigma_h^2 = \sigma_f^2 + \sigma_q^2$.

The parameters (α_f, β_f) and (α_q, β_q) were estimated using log-log ordinary least-squares regression (LL-OLS) on $\{f, R\}$ and $\{q, R\}$, respectively, for the survey years. The catchability coefficient was computed as $q = h_r/f$. Similarly, LL-OLS was used on $\{h_r, R\}$ to directly estimate (α_h, β_h), resulting in the fitted model

$$\hat{h}_{r,power} = \hat{\alpha}_h R^{\hat{\beta}_h}. \tag{18}$$

The fitted river harvest rate models were used to hindcast the SRFC adult river harvest for years in which angler surveys were not conducted, based on the relationship

$$\hat{H}_r = \hat{R} \times \hat{h}_r = (\hat{H}_r + E) \times \hat{h}_r, \tag{19}$$

noting that E is available for years 1970–forward. For the mean harvest rate model, solving (19) for $\hat{H}_r$ is straightforward. After changing the subscripts in (19) to reflect the mean model, we obtain

$$\hat{H}_{r,mean} = \frac{E \times \hat{h}_{r,mean}}{1 - \hat{h}_{r,mean}}. \tag{20}$$

For the power function harvest rate model, substitution of equation (18) into equation (19) yields

$$\hat{H}_{r,power} = \hat{\alpha}_h (\hat{H}_{r,power} + E)^{\hat{\beta}_h + 1}. \tag{21}$$

$\hat{H}_{r,power}$ cannot be solved for analytically in (21), however the unique value of $\hat{H}_{r,power}$ which satisfies the equality in (21) can be determined numerically (e.g., by minimizing the squared difference of the left and right hand sides of equation (21) subject to the constraint $\hat{H}_{r,power} \geq 0$).

Finally, in an attempt to reasonably bracket the river harvest hindcast estimates detailed above, the minimum and maximum harvest rates estimated over the survey years were substituted in place of $\hat{h}_{r,mean}$ in equation (20) to compute a minimum and maximum hindcast river harvest, respectively.

3.3 Results

The survey-derived f, H_r, R, and h_r are listed in Table 3. In addition, several model-derived harvest hindcasts for years with and without angler survey data, from 1970–2007, are listed in Table 3. Hindcast harvest estimates prior to 1991 assume that pre-1991 fisheries resembled post-1991 fisheries in terms of effort capacity, effort response to abundance, etc.

Figure 2 demonstrates the mean and power function models fitted to the harvest rate estimates derived from the survey. The solid line depicts the fitted mean model, which assumes that h_r is insensitive to river run abundance. The dashed line depicts the fitted power function model, which suggests that the river harvest rate may not be constant over the observed run sizes, but rather is higher (relative to the mean harvest rate) at low run sizes and lower at high run sizes. The power function estimated coefficient $\hat{\beta}_h$ is not significantly less than zero ($p = 0.122$). However, the residual pattern is more balanced for the power function model. At low river run abundance, the mean model residuals are nearly all positive, whereas the power function model residuals are both positive and negative, and the magnitude of the residuals is smaller for the harvest rate at the two highest levels of river run abundance.

Figure 3 provides additional support for the power function harvest rate model. The effort estimates derived from the angler survey appear to flatten somewhat at high run sizes, suggesting that there may be some limit to the effort capacity of the fishery. Conversely, the catchability coefficient appears to increase at an increasing rate as the river run abundance decreases, consistent with fishermen targeting a highly clumped abundance in areas where salmon are known to aggregate. The estimated power coefficients ($\hat{\beta}_f, \hat{\beta}_q$) were significantly greater than and less than zero, respectively ($p < 0.001$). The combination of the two relationships in Figure 3 results in the Figure 2 dashed line.

Hindcasted harvests derived from the mean and power function models, as well as minimum and maximum hindcast harvest brackets are plotted in Figure 4. Comparison of the model-derived harvest hindcasts to the survey-derived harvest estimates provides an indication of the accuracy of the river harvest hindcast method for the non-survey years. In general, the mean and power function models yield very similar results. In particular, the hindcasts from both models are very

Table 3. Sacramento River fall Chinook adult river return summary statistics and estimates, 1970–2007: escapement (E), angler effort (f), river run abundance (R), fishery harvest (H_r,$\hat{H}_{r,*}$), and harvest rate (h_r). Escapement estimates are sourced from PFMC (2008b, Tables B-1 and B-2); remaining estimates were developed as described in this report, with $\hat{H}_{r,min}$, $\hat{H}_{r,max}$, and $\hat{H}_{r,mean}$ derived from equation (20), and $\hat{H}_{r,power}$ derived from equation (21).

		Angler survey				*Model-estimated harvest*			
Year	E	f	H_r	R	h_r	$\hat{H}_{r,min}$	$\hat{H}_{r,mean}$	$\hat{H}_{r,power}$	$\hat{H}_{r,max}$
1970	157152	—	—	—	—	18291	26692	29941	47756
1971	154882	—	—	—	—	18027	26306	29572	47066
1972	92156	—	—	—	—	10726	15653	19010	28004
1973	220060	—	—	—	—	25613	37377	39894	66872
1974	202017	—	—	—	—	23513	34312	37087	61389
1975	155621	—	—	—	—	18113	26432	29692	47290
1976	167865	—	—	—	—	19538	28512	31672	51011
1977	164010	—	—	—	—	19089	27857	31051	49840
1978	126948	—	—	—	—	14775	21562	24965	38577
1979	169444	—	—	—	—	19722	28780	31925	51491
1980	142028	—	—	—	—	16531	24123	27469	43160
1981	174891	—	—	—	—	20355	29705	32798	53146
1982	163959	—	—	—	—	19083	27848	31043	49824
1983	109386	—	—	—	—	12731	18579	21994	33240
1984	158230	—	—	—	—	18416	26875	30116	48083
1985	238704	—	—	—	—	27783	40543	42760	72538
1986	238157	—	—	—	—	27719	40450	42676	72371
1987	194623	—	—	—	—	22652	33056	35927	59142
1988	224724	—	—	—	—	26156	38169	40614	68289
1989	151625	—	—	—	—	17648	25753	29042	46076
1990	104946	—	—	—	—	12215	17825	21232	31891
1991	117432	757901	26362	143794	0.183	13668	19946	23363	35685
1992	81145	440046	13876	95021	0.146	9444	13782	17061	24658
1993	135182	658570	28380	163562	0.174	15734	22960	26337	41079
1994	163631	870741	29548	193179	0.153	19045	27792	30990	49724
1995	295034	—	—	—	—	34339	50111	51234	89655
1996	299589	—	—	—	—	34869	50885	51908	91040
1997	342875	—	—	—	—	39907	58237	58249	104193
1998	238060	1375750	72342	310402	0.233	27708	40434	42661	72342
1999	395942	1491350	71115	467057	0.152	46084	67250	65868	120319
2000	416789	1433272	62005	478794	0.130	48510	70791	68821	126654
2001	546056	—	—	—	—	63555	92746	86700	165936
2002	775499	1866041	90260	865759	0.104	90260	131717	117053	235660
2003	521636	—	—	—	—	60713	88599	83374	158515
2004	283554	—	—	—	—	33003	48161	49527	86167
2005	394007	—	—	—	—	45858	66921	65593	119731
2006	267908	—	—	—	—	31182	45504	47185	81412
2007	87966	713323	15725	103691	0.152	10238	14941	18273	26731

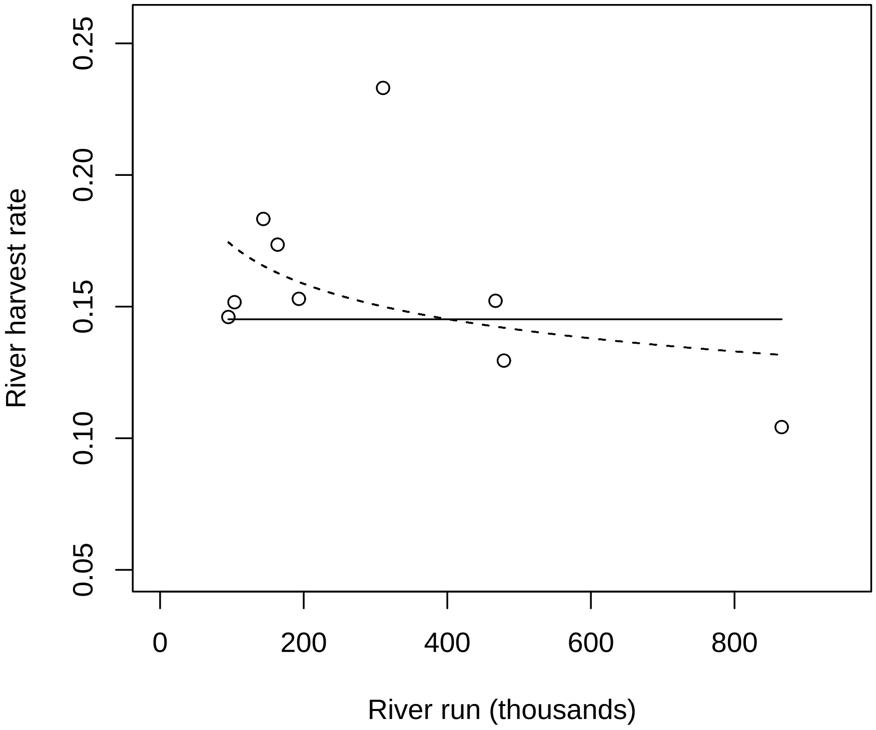

Figure 2. Estimated Sacramento River fall Chinook adult river harvest rate plotted as a function of the adult river run abundance. The solid line represents the fitted mean model, equation (14), with $\hat{h}_{r,mean} = 0.1452$. The dashed line represents the fitted power function model, equation (18), with $(\hat{\alpha}_h, \hat{\beta}_h) = (0.7515, -0.1274)$.

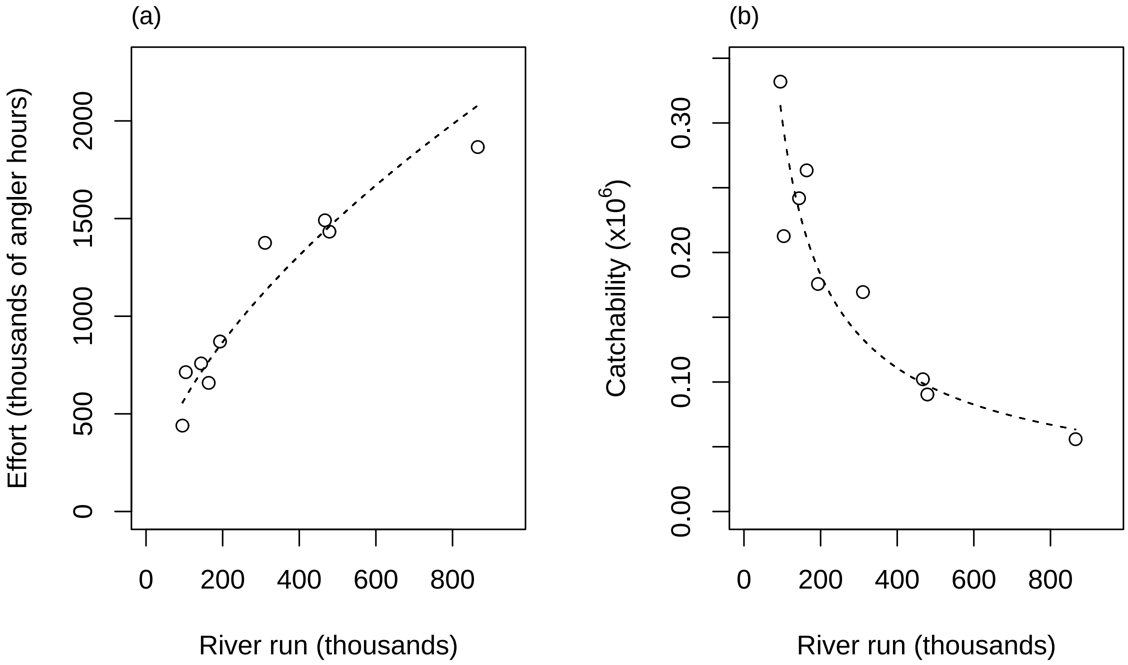

Figure 3. The relationships between adult river run abundance and (a) fishing effort (f) and (b) the catchability coefficient (q). Open circles are the survey-derived estimates; dashed lines depict the fitted models in (16) with $(\hat{\alpha}_f, \hat{\beta}_f) = (598.5711, 0.5963)$ and $(\hat{\alpha}_q, \hat{\beta}_q) = (0.0013, -0.7237)$.

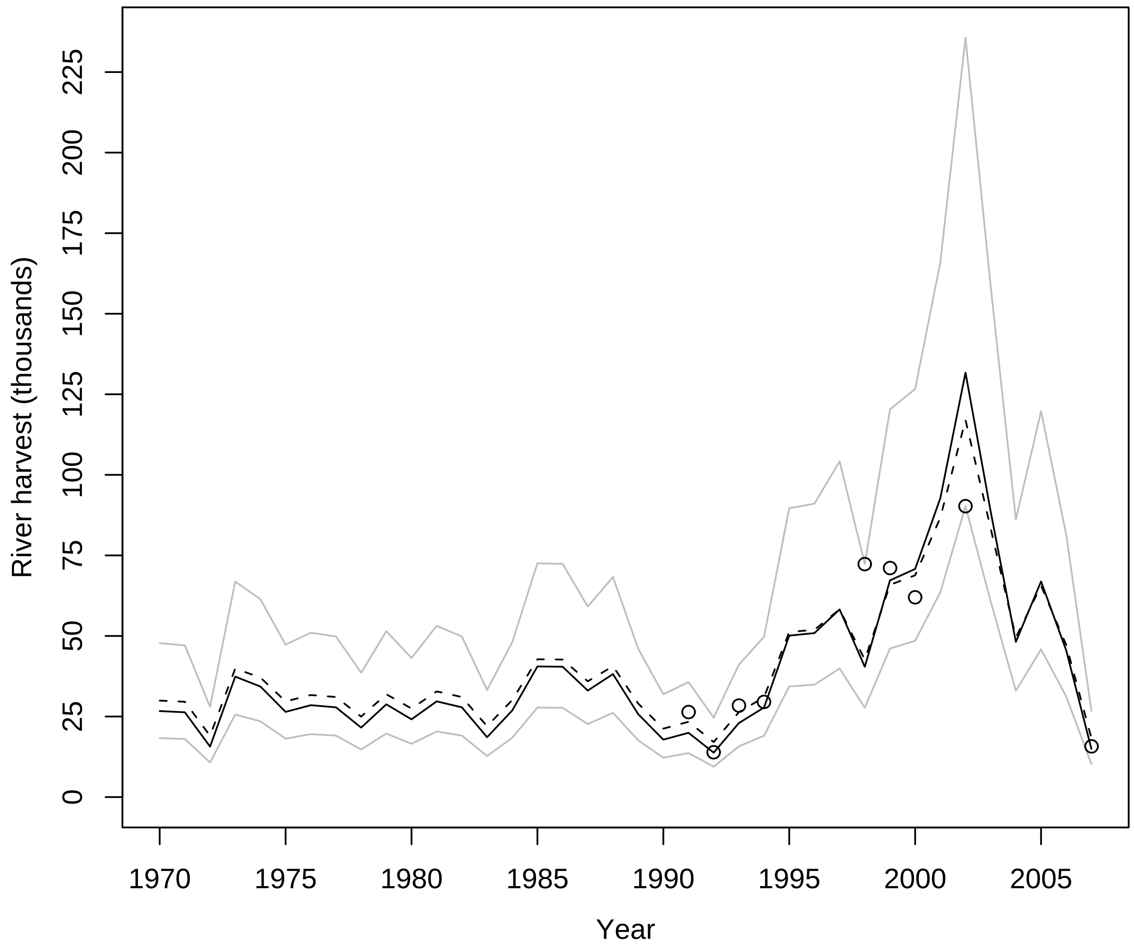

Figure 4. Estimated and hindcast river harvest of Sacramento River fall Chinook adults, 1970–2007. Circles are survey-derived estimates. The solid black line is the hindcasted harvest using the fitted mean harvest rate model. The dashed black line is the hindcasted harvest using the fitted power function harvest rate model. Solid grey lines depict the minimum and maximum hindcasted harvest, using the minimum and maximum harvest rates estimated over the nine survey years, respectively.

similar for years 1990–forward when angler surveys were not conducted (the "gap" years). Years 1990–forward are the years used for the SI forecast model (see Section 6). Further analysis (not shown) suggests that the choice between the power function harvest rate model-generated H_r and the mean harvest rate model-generated H_r has a negligible effect on the SI and the forecast of the SI. For this reason, and the simplicity of assuming a one parameter harvest rate model, the hindcasted H_r used in the remainder of this report and for post-2008 assessments will be $\hat{H}_{r,mean}$.

4 Escapement

SRFC escapement estimates are compiled annually from hatcheries and natural-area spawning surveys in the Sacramento River Basin. Tables B-1 and B-2 in PFMC (2008b) report natural-area and hatchery escapement, respectively, for Central Valley fall Chinook. The combined natural-area and hatchery escapement, both jacks and adults, for SRFC can be computed from these tables by summing the Sacramento River total adult (jack) escapement (located in Table B-1) and the total adult (jack) escapement from Sacramento hatcheries (located in Table B-2). In this report, Table 3 displays the combined natural-area and hatchery adult escapement of SRFC used for the construction of the *SI* (equation (4)).

Sacramento River Basin hatcheries, which include Coleman National Fish Hatchery (Battle Creek), Feather River Hatchery (Feather River) and Nimbus Hatchery (American River), enumerate jacks and adults separately as they enter the hatchery based on an established fork-length (FL) "cut-off" value (jack: FL $<$ cut-off; adult: FL $\geq$ cut-off). Since 1990, Coleman National Fish Hatchery has used a jack cut-off length of 65 cm and Nimbus Hatchery has used a 61 cm cut-off. At Feather River Hatchery, the jack cut-off was 61 cm from 1990–2005, and 65 cm thereafter.

Natural-area escapement estimates have been made using various means, including carcass surveys, aerial redd counts, ladder counts, weir counts and video monitoring (Table 4; also see CDFG (2007) for more information on the individual sampling programs). Jack and adult proportions are determined by a survey-specific fork-length cut-off value. For natural-area escapement surveys, this cut-off value has varied from 61–70 cm (Table 4). In some instances, the cut-off value has been arrived at empirically based on analysis of that year's length frequency distribution. More often, the cut-off value has been treated as a fixed constant across a series of years. For 1990–2007, all natural-area surveys in the American, Yuba, and Feather Rivers were carcass surveys employing mark-recapture estimation methods. The upper mainstem Sacramento River natural-area escapement estimates are a combination of individual survey-derived estimates performed on the Sacramento River mainstem, Battle Creek, Clear Creek, and other minor tributaries. Sampling in the minor tributaries (Deer, Mill, Butte, and Cottonwood Creeks) has been sporadic. However,

Table 4. Sacramento River fall Chinook natural-area escapement survey methods employed from 1990–2007. Cut-off: fork-length (FL) value used to distinguish a jack (FL $<$ cut-off) from an adult (FL $\geq$ cut-off). R: Red Bluff Diversion Dam passage, May 15–Sept. 15 (upstream tributary escapements subtracted from passage to estimate mainstem escapement); S: carcass survey; V: video monitoring; C: carcass count; CDFG: California Department of Fish and Game; USFWS: United States Fish and Wildlife Service; DWR: Department of Water Resources.

			Jack Proportion		
System	*Years*	*Escapement Survey*	*Survey*	*Cut-off (cm)*	*Agency*
Mainstem Sacramento River	1990–2000	R	R	61	CDFG/USFWS
	2001–2005	S	S	61	CDFG
	2006	S	S	68	CDFG
	2007	S	S	67.5	CDFG
Clear Creek	1990–2007	S	S	61	CDFG
Battle Creek	1990–2005	S	S	61	CDFG/USFWS
	2006–2007	V	C	61	CDFG/USFWS
Deer Creek	1993–1994	S	S	61	CDFG
	1997–1998	S	S	61	CDFG
	2004–2007	S	S	61	CDFG
Mill Creek	1992–1994	S	S	61	CDFG
	1997–1998	S	S	61	CDFG
	2002–2007	S	S	61	CDFG
Butte Creek	1995–1998	S	S	61	CDFG
	2001–2005	S	S	61	CDFG
	2006–2007	S	S	65	CDFG
Yuba River	1990–2007	S	S	61	CDFG
Feather River	1990–1999	S	S	61	CDFG
	2000–2005	S	S	68	DWR
	2006–2007	S	S	65	DWR
American River	1990–2007	S	S	67–70	CDFG

since 2004, surveys have been conducted without interruption on Deer, Mill, and Butte Creeks, and sampling is expected to continue on these tributaries into the future. The 2004–2007 average annual escapement of these three tributaries was approximately six percent of the total natural-area escapement in the upper Sacramento River. Escapement to these minor tributaries represents a small fraction of the overall SRFC escapement.

5 *SI* Time Series

The resulting *SI* time series and its components are listed in Table 5 and displayed graphically in Figure 5 for the period 1983–2007. Both the *SI* and the relative contribution of its components have varied over this time period. The lowest level of the *SI*, by a significant margin, occurred in 2007, but the *SI* was also relatively low in 1983–1984 and in the early 1990s. Similarly, the high *SI* levels that occurred during the 2000–2005 period are comparable to the levels of the late 1980s, although the relative contribution of the *SI* components in these two periods differs (a shift in the relative contributions occurred in the mid- to late-1990s). Prior to 1998, the fraction of the *SI* taken as ocean harvest averaged about 0.74, whereas since then it has averaged about 0.51. The escapement fraction averaged about 0.22 prior to 1998, and about 0.41 since that time. The contribution of river harvest to the *SI* has been consistently small relative to the ocean harvest and escapement components. The contrast between the time series of SRFC abundance (as indexed by the *SI*) and the time series of SRFC escapement is striking. In particular, the anomalously high escapement levels in years 1999–2003 were due, at least in part, to the reduced ocean harvest fraction over this period. High levels of the *SI* in the mid- to late-1980s did not translate into comparable high levels of escapement due to the relatively high fraction of fish removed by ocean fisheries during this period.

The *SI* is plotted against the *CVI* in Figure 6). The two indices of abundance are highly correlated ($R^2 = 0.93$). This is not surprising given the dominance of SRFC relative to other Central Valley Chinook stocks in both escapement and ocean harvest in the AM region over the 1983–2007 period. The 1:1 line plotted in Figure 6 highlights the fact that the *SI* exceeded the *CVI* in all years

Table 5. Sacramento River fall Chinook ocean harvest ($H_{o,S}$), river harvest (H_r), escapement (E), and the Sacramento Index (SI) as defined in equation (4), 1983–2007. $H_{o,S}$ is for the Sept. 1, $t-1$ through Aug. 31, t period.

	$H_{o,S}$					
Year (t)	*Commercial*	*Recreational*	*Total*	H_r	E	SI
1983	245156	86149	331305	18579	109386	459270
1984	266162	86978	353140	26875	158230	538245
1985	355388	158895	514283	40543	238704	793530
1986	618726	137543	756269	40450	238157	1034876
1987	686093	173155	859248	33056	194623	1086927
1988	1162584	188275	1350859	38169	224724	1613752
1989	611420	159180	770600	25753	151625	947978
1990	514202	150520	664722	17825	104946	787493
1991	298804	90161	388965	26362	117432	532759
1992	232456	70143	302599	13876	81145	397620
1993	342422	115345	457767	28380	135182	621329
1994	302329	164730	467059	29548	163631	660238
1995	735704	387895	1123598	50111	295034	1468743
1996	426719	156978	583696	50885	299589	934170
1997	579731	210240	789971	58237	342875	1191083
1998	292840	113886	406726	72342	238060	717128
1999	308096	76600	384696	71115	395942	851753
2000	431354	153174	584528	62005	416789	1063322
2001	284414	93450	377864	92746	546056	1016666
2002	447624	184062	631686	90260	775499	1497445
2003	501864	106456	608319	88599	521636	1218554
2004	621935	212601	834536	48161	283554	1166251
2005	367740	127065	494805	66921	394007	955733
2006	149910	107653	257562	45504	267908	570974
2007	120953	32821	153774	15725	87966	257465

over this period (except 2000), due primarily to the inclusion of FA-region ocean harvest and river harvest in the *SI*.

6 *SI* Forecast

The *SHM* forecast of SRFC harvest and escapement is based on that year's *SI* forecast. The *SI* forecast in turn is based on the previous year's jack (*J*) spawning escapement using a statistical model relating *J* in year *t-1* to the *SI* in year *t*. *SI* estimates from 1990–forward are used to fit the

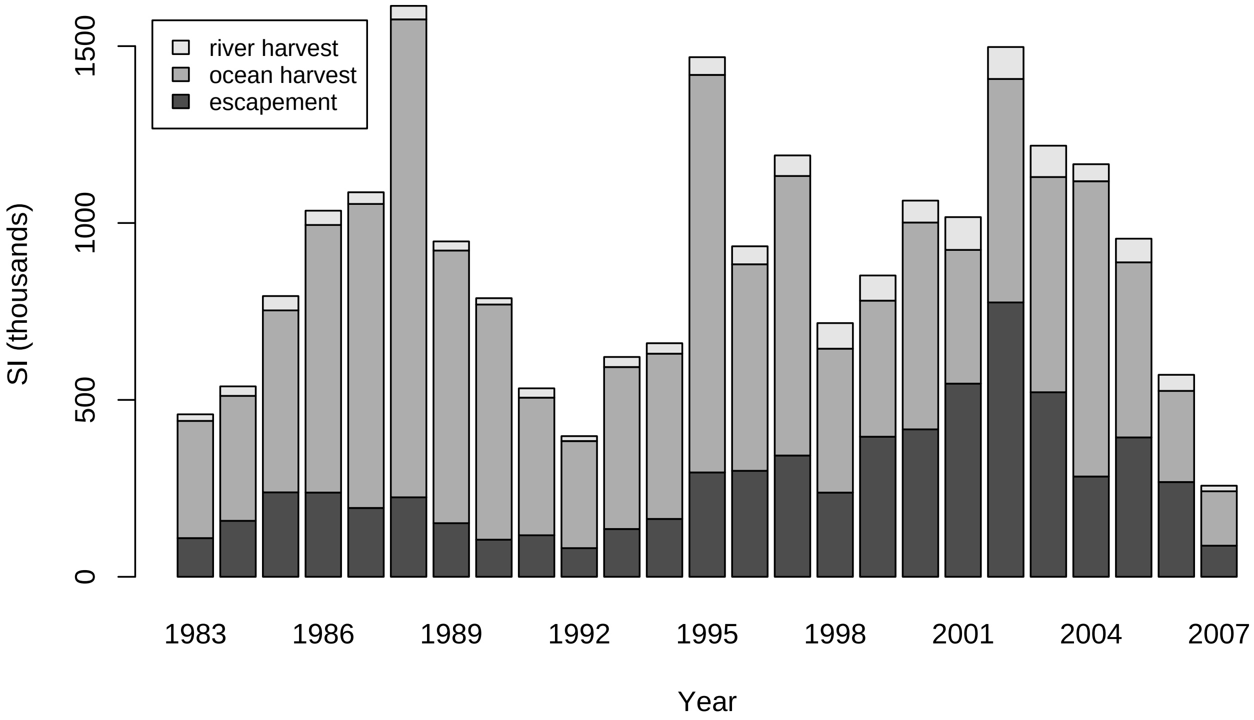

Figure 5. The Sacramento Index (SI) and the relative levels of its components, 1983–2007.

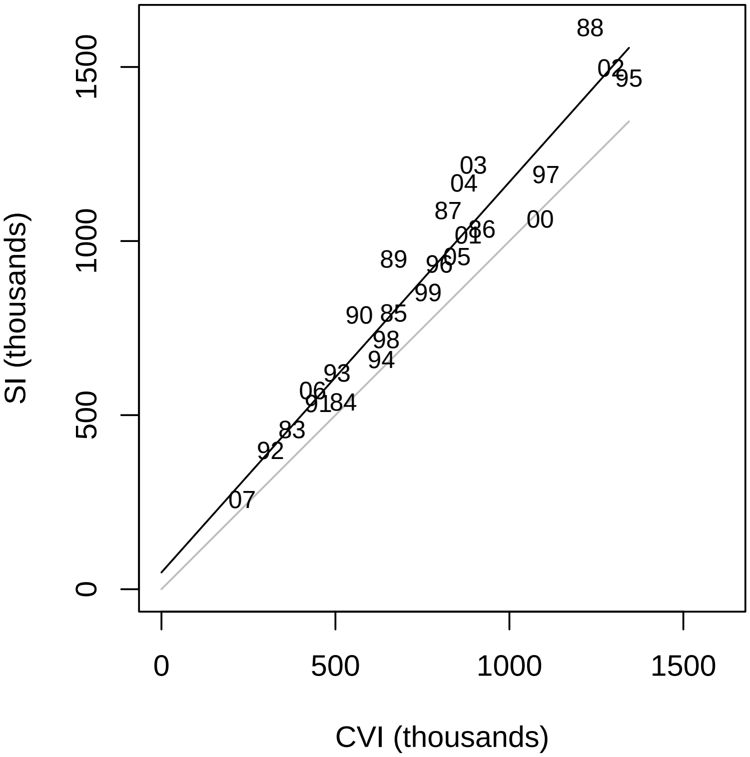

Figure 6. The Sacramento Index (*SI*) and the Central Valley Index (*CVI*) from 1983–2007 plotted on equal scales. The black line is the least-squares regression line for the *SI* and *CVI* ($R^2 = 0.93$). The grey line is the 1:1 line (*SI* = *CVI*).

model, even though estimates of the *SI* are available back to 1983. Use of this particular range of years is consistent with the range of years used to fit the *CVI* forecast model in the pre-2008 SRFC assessments. For both the *CVI* and the *SI*, their relationship to the previous year's jack escapement is markedly different before and after 1990. While the mechanism underlying this shift in the relationship is not known, limiting the data to the 1990–forward period improves the performance of these forecast models under current conditions.

For the 2008 assessment, with the *SI* defined as in equation (3), a variety of statistical models relating the *SI* in year *t* to *J* in year *t-1* were examined (see PFMC 2008a, Appendix C). Ultimately, a linear model with zero-intercept and additive errors was most strongly supported

$$SI = \beta_{SI} J + \varepsilon, \tag{22}$$

and the ratio estimator

$$\hat{\beta}_{SI} = \bar{SI}/\bar{J} \tag{23}$$

was judged to be the optimal estimator of β_{SI}. Figure 7 displays the fitted model with slope $\hat{\beta}_{SI} =$ 28.766, and the forecasted *SI* value used for the 2008 SRFC assessment. Use of the zero-intercept model for the 2008 assessment was particularly justified given the very low jack escapement in 2006 and the very low levels of $H_{o,S}$ and E in 2007, all indicating a particularly weak 2004 year class that would contribute little 4-year-old carryover to the *SI* in 2008. The 2005 data point was excluded from the fitting of the model because it was uninformative with respect to forecasting the 2008 *SI* given the record low 2007 jack escapement, and because of its excessive leverage on the overall fit of the model (PFMC 2008a, Appendix C).

Figure 8 shows the zero-intercept linear model fitted to the reformulated *SI* (equation (4)) data. Including the river harvest in the *SI* results in an increased slope estimate ($\hat{\beta}_{SI} = 30.525$) and thus a higher *SI* forecast, relative to the *SI* definition that did not include river harvest, but no change is evident in the displayed pattern of the data points. The data, estimates, and models used for the SRFC annual assessment are carefully evaluated each year and modifications to the methods of assessment are proposed as warranted. We emphasize that the reformulated *SI*, and the fitted model displayed in Figure 8, were not used for the 2008 SRFC assessment.

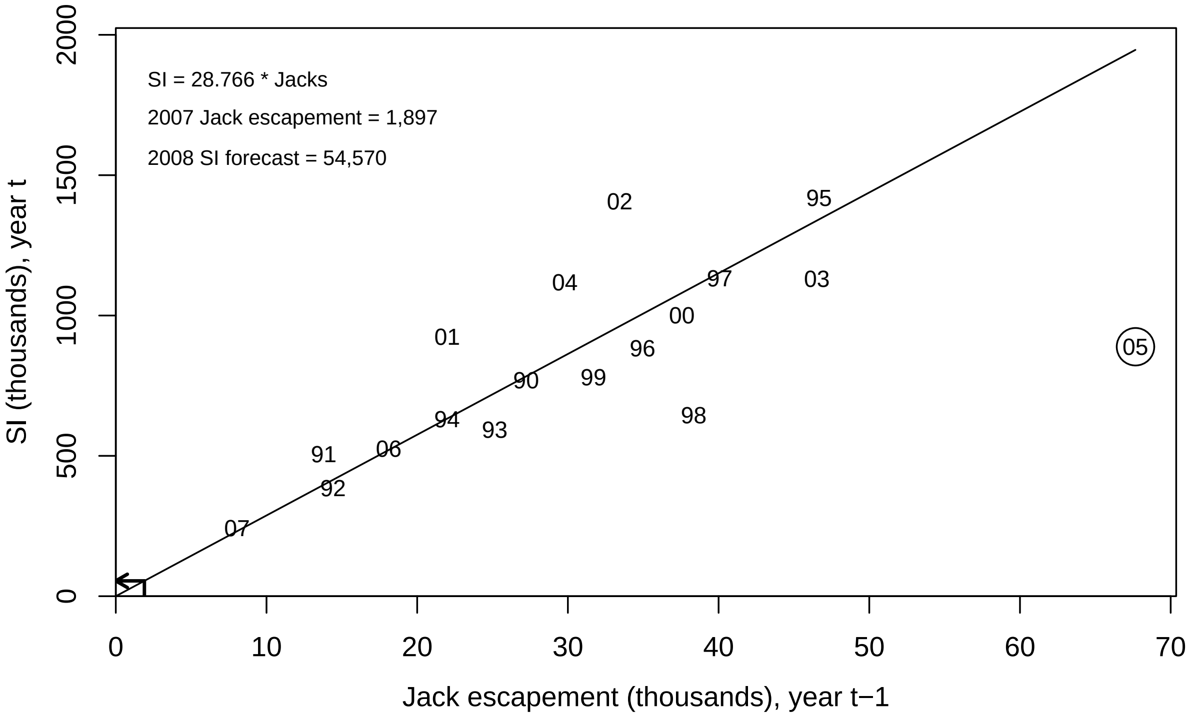

Figure 7. The Sacramento Index (*SI*) forecast model in the 2008 assessment. Arrow traces the 2007 jack escapement to the forecast *SI* for 2008.

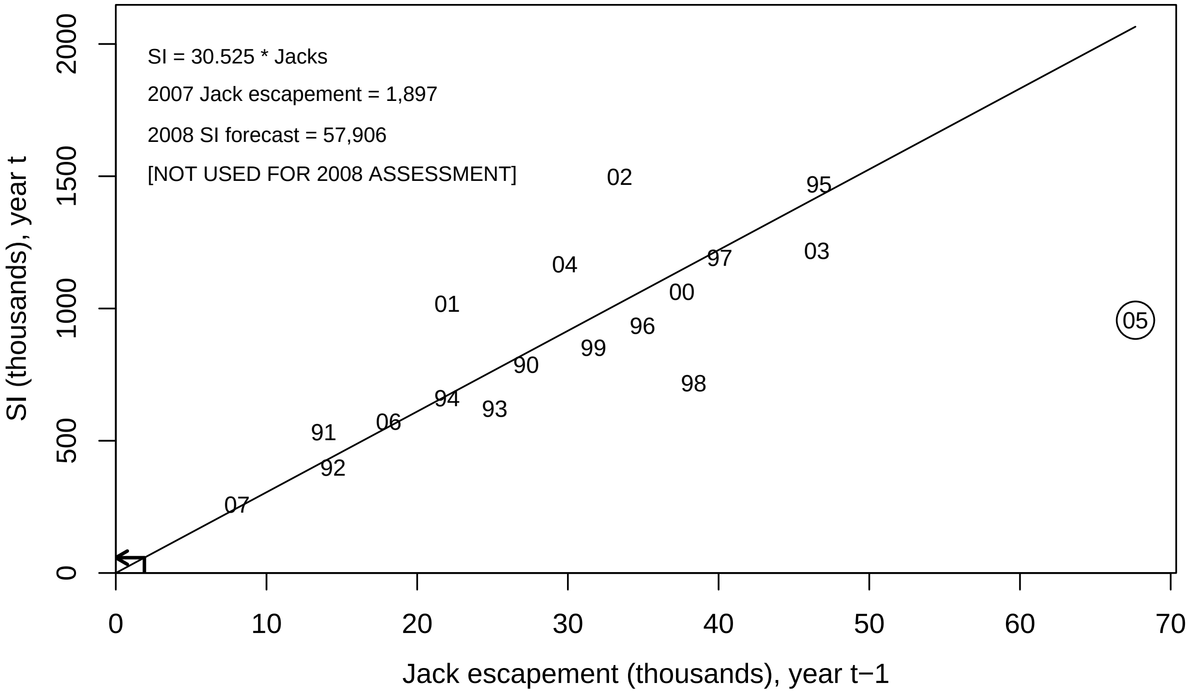

Figure 8. The Sacramento Index (*SI*) forecast model for the reformulated *SI* that includes river harvest, equation (4). Arrow traces the 2007 jack escapement to the forecast *SI* for 2008 under the equation (4) definition of the *SI*. This forecast was not used for the 2008 SRFC assessment.

7 Conclusions

Novel methods were required for the development of the *SI*, particularly for the estimation of SRFC ocean harvest in all time-area-fisheries south of Cape Falcon. Inclusion of SRFC river harvest in the *SI* has provided a more complete index of SRFC adult ocean abundance, and has resulted in a more straightforward formulation of SRFC river harvest and escapement within the *SHM* (Mohr and O'Farrell 2008). Together, the *SI* and *SHM* have significantly advanced the extent, resolution, and specificity of the SRFC assessment framework. It is now possible to directly evaluate the effects of proposed fishery management measures on SRFC expected ocean harvest by time-area-fishery, river harvest, and spawning escapement. This was not possible within the previous *CVI*-based assessment framework.

We recommend that the *SI* be reported in place of the *CVI* in all Pacific Fishery Management Council (PFMC) salmon reports issued in the future, at least in so far as the *CVI* has been used to represent and evaluate the status of the SRFC stock. In particular, we recommend that Table 5 of this report, which lists the *SI* time series and that of its components, replace PFMC Preseason Report I (PFMC 2008a) Table II-1 (analogous listing of the *CVI* and its components). We also recommend that Figure 5 of this report, a graphical presentation of the *SI* time series and that of its components, replace PFMC Preseason Report I Figure II-2 (time-series of SRFC spawning escapement). Finally, we recommend that Figure 8 of this report, a graphical depiction of the *SI* forecast model, replace PFMC Preseason Report I Figure II-1 (*CVI* forecast model).

8 Acknowledgements

We thank Rob Titus, CDFG Anadromous Resource Assessment Unit, for providing us access to the Sacramento River Basin angler survey data, and his willingness to discuss with us the particulars of the survey design, data, and estimates. We also thank all of those responsible for the ocean harvest, river harvest, and escapement monitoring programs that produced the data used in this report.

References

CDFG (California Department of Fish and Game) (2007). Existing program summary: Central Valley salmon and steelhead monitoring programs. Edited by A. Low. California Deparment of Fish and Game, Sacramento, CA.

Goldwasser, L., M. S. Mohr, A. M. Grover, and M. L. Palmer-Zwahlen (2001). The supporting databases and biological analyses for the revision of the Klamath Ocean Harvest Model. Unpublished report. National Marine Fisheries Service, Santa Cruz, CA.

Hilborn, R. and C. J. Walters (1992). *Quantitative Fisheries Stock Assessment*. Boston: Kluwer.

Mohr, M. S. (2006). The cohort reconstruction model for Klamath River fall Chinook salmon. Unpublished report. National Marine Fisheries Service, Santa Cruz, CA.

Mohr, M. S. and M. R. O'Farrell (2008). The Sacramento Harvest Model. Report in preparation. National Marine Fisheries Service, Santa Cruz, CA.

PFMC (Pacific Fishery Management Council) (2007). Preseason report I: Stock abundance analysis for 2007 ocean salmon fisheries. Pacific Fishery Management Council, 7700 NE Ambassador Place, Suite 101, Portland, Oregon 97220-1384.

PFMC (Pacific Fishery Management Council) (2008a). Preseason report II: Analysis of proposed regulatory options for 2008 ocean salmon fisheries. Pacific Fishery Management Council, 7700 NE Ambassador Place, Suite 101, Portland, Oregon 97220-1384.

PFMC (Pacific Fishery Management Council) (2008b). Review of 2007 ocean salmon fisheries. Pacific Fishery Management Council, 7700 NE Ambassador Place, Suite 101, Portland, Oregon 97220-1384.

Ricker, W. E. (1975). *Computation and Interpretation of Biological Statistics of Fish Populations*. Bulletin of the Fisheries Research Board of Canada, Number 191.

Thompson, S. K. (2002). *Sampling, 2nd edition*. New York: Wiley.

Appendix A   Harvest North of Cape Falcon

The ocean harvest component of the *SI* includes SRFC harvest from Cape Falcon to the U.S./Mexico border, but not SRFC harvest north of Cape Falcon (NF). The proportion of the SRFC overall ocean harvest landed in the NF region was previously estimated and published in PFMC (2008a, Appendix B). In that document, the mean proportion of the SRFC overall ocean harvest landed in the NF region was estimated to be approximately one half of one percent over the 1986–2007 period. Subsequent to publication of PFMC (2008a), further analysis indicated that this estimate was likely too low.

For this report, SRFC harvest in the NF region was estimated following the same methods that were used in the FA region. SRFC coded-wire tags recovered in the NF region were expanded for sampling and multiplied by λ to estimate the SRFC harvest, as in equation (8). The Sept. 1 through Aug. 31 SRFC harvest for the NF region was then divided by the Sept. 1 through Aug. 31 SRFC overall ocean harvest to obtain the proportion of SRFC overall ocean harvest landed in the NF region. Figure 9 displays this proportion for the years 1986–2007. The proportion was less than or equal to five percent in all but one year (2005), and averaged 2.37 percent over this time period.

Appendix B   Ocean Harvest Estimate Adjustment Methods

For the Cape Falcon to Point Arena region (FA), the time-area-fishery estimated harvest of the four components (S, K, V, N) did not always sum to the total harvest, likely due to a combination of factors such as sampling error, incomplete data for all stocks that contribute to the harvest in these areas, and variation in the distribution of untagged stocks that contribute to the λ expansion factors. For notational simplicity, we omit all harvest (H) subscripts in this Appendix other than those denoting the stock components (S, K, V, N) and total (T), noting that these methods are applied at the year-time-area-fishery level of stratification. For the FA region, over the period 1983–2007, there were a total of 1446 year-time-area-fishery strata. The sum of the component groups' harvest was less than the total harvest in 875 of these strata, and greater than the total

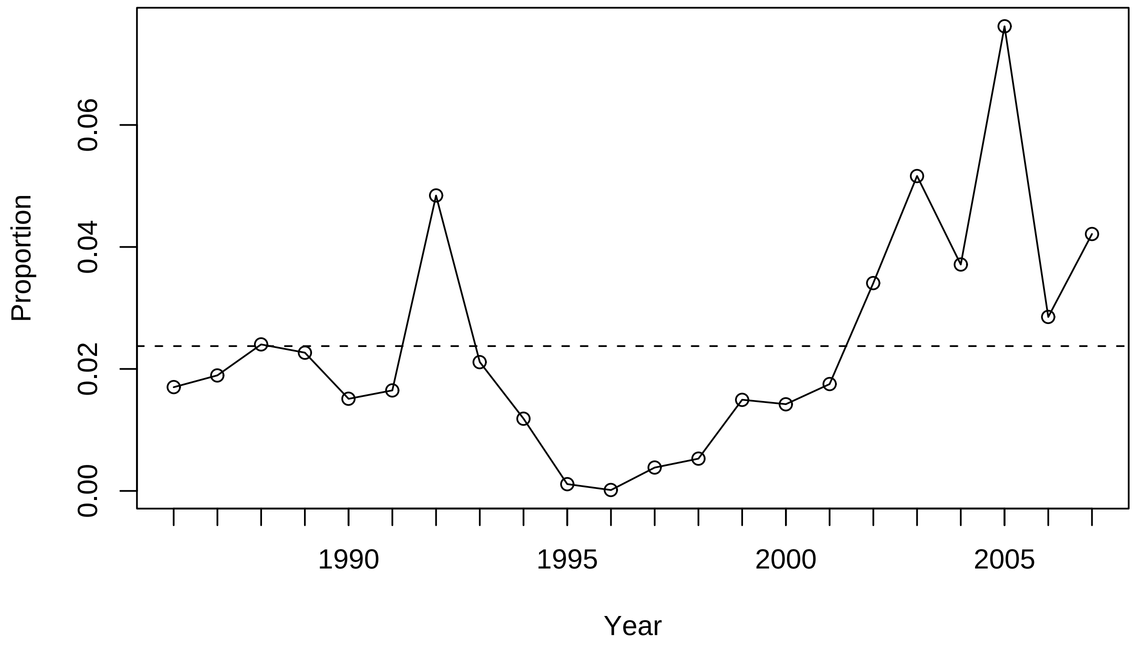

Figure 9. Proportion of Sacramento River fall Chinook overall ocean harvest landed north of Cape Falcon, Oregon, 1986–2007. Dashed line depicts the mean proportion.

harvest in 266 of these strata. For those strata in which there was a difference between the group sum and total harvest, the magnitude of the difference (Δ) was

$$\Delta = |(H_S + H_K + H_V + H_N) - H_T| .$$

The methods used to adjust the component harvests depend on whether their sum was (1) less than or (2) greater than the total harvest, as described below.

B.1 Under-accounted: $H_S + H_K + H_V + H_N < H_T$

The rationale underlying the adjustments in this case was the following. The KRFC harvest estimates are based on expansion of recovered coded-wire tags by well-determined sampling and mark rates, and well-quantified hatchery-to-natural production values, obtained through stock-level cohort analysis. Thus, H_K was not adjusted. H_V and H_N are likely minimum estimates since they do not account for the natural production of these stock groups and were thus adjusted. H_S estimates were not adjusted, and therefore the *SI* is unaffected. The magnitude of the difference, Δ, was prorated to H_V and H_N unless $H_V + H_N = 0$, in which case Δ was allocated to H_N if the area was off Oregon ($a \in \{\mathsf{NO}, \mathsf{CO}, \mathsf{KO}\}$) (harvest of N more likely there), or allocated to H_V if the area was off California ($a \in \{\mathsf{KC}, \mathsf{FB}\}$) (harvest of V more likely there). This set of adjustments is codified below, with $\tilde{H}$ denoting the adjusted harvest:

$$\tilde{H}_K = \quad H_K$$

$$\tilde{H}_S = \quad H_S$$

$$\tilde{H}_V = \begin{cases} H_V + \Delta[H_V/(H_V + H_N)] & : \quad H_V + H_N > 0 \\ \Delta & : \quad H_V + H_N = 0 \quad \text{and} \quad a \in \{\mathsf{KC}, \mathsf{FB}\} \\ 0 & : \quad H_V + H_N = 0 \quad \text{and} \quad a \in \{\mathsf{NO}, \mathsf{CO}, \mathsf{KO}\} \end{cases}$$

$$\tilde{H}_N = \begin{cases} H_N + \Delta[H_N/(H_V + H_N)] & : \quad H_V + H_N > 0 \\ \Delta & : \quad H_V + H_N = 0 \quad \text{and} \quad a \in \{\mathsf{NO}, \mathsf{CO}, \mathsf{KO}\} \\ 0 & : \quad H_V + H_N = 0 \quad \text{and} \quad a \in \{\mathsf{KC}, \mathsf{FB}\}. \end{cases}$$

B.2 Over-accounted: $H_S + H_K + H_V + H_N > H_T$

The rationale underlying the adjustments in this case was the following. The KRFC harvest estimates are based on expansion of recovered coded-wire tags by well-determined sampling and mark rates, and well-quantified hatchery-to-natural production values, obtained through stock-level cohort analysis. Thus, H_K was not adjusted. (In no instance did H_K exceed H_T.) H_V and H_N are likely minimum estimates since they do not account for the natural production of these stock groups, and thus H_S was reduced first to make up for the overage (down to zero if need be). If the H_S adjustment was insufficient to make up for the overage, and the area was off Oregon ($a \in \{\mathsf{NO}, \mathsf{CO}, \mathsf{KO}\}$), then H_V was reduced (down to zero if need be) followed by H_N, if necessary. (The latter ordering reflects the supposition that off Oregon, harvest of N is more likely than V.) If the H_S adjustment was insufficient to make up for the overage, and the area was off California ($a \in \{\mathsf{KC}, \mathsf{FB}\}$), then H_N was reduced (down to zero if need be) followed by H_V, if necessary. (The latter ordering reflects the supposition that off California, harvest of V is more likely than N.) This set of adjustments is codified below, with $\tilde{H}$ denoting the adjusted harvest:

$$\tilde{H}_K = \quad H_K$$

$$\tilde{H}_S = \begin{cases} H_S - \Delta & : \quad \Delta \leq H_S \\ 0 & : \quad \text{otherwise} \end{cases}$$

$$\tilde{H}_V = \begin{cases} H_V & : \quad \Delta \leq H_S \\ H_V - (\Delta - H_S) & : \quad H_S < \Delta \leq H_S + H_V \quad \text{and} \quad a \in \{\mathsf{NO}, \mathsf{CO}, \mathsf{KO}\} \\ H_V - (\Delta - H_S - H_N) & : \quad H_S + H_N < \Delta \leq H_S + H_V + H_N \quad \text{and} \quad a \in \{\mathsf{KC}, \mathsf{FB}\} \\ 0 & : \quad \text{otherwise} \end{cases}$$

$$\tilde{H}_N = \begin{cases} H_N & : \quad \Delta \leq H_S \\ H_N - (\Delta - H_S) & : \quad H_S < \Delta \leq H_S + H_N \quad \text{and} \quad a \in \{\mathsf{KC}, \mathsf{FB}\} \\ H_N - (\Delta - H_S - H_V) & : \quad H_S + H_V < \Delta \leq H_S + H_N + H_V \quad \text{and} \quad a \in \{\mathsf{NO}, \mathsf{CO}, \mathsf{KO}\} \\ 0 & : \quad \text{otherwise} \end{cases}$$

The *SI* was reduced by this set of adjustments since $\tilde{H}_S < H_S$. The unadjusted SRFC harvest ($H_{o,S}$), adjusted SRFC harvest ($\tilde{H}_{o,S}$), and their ratio, are shown in Table 6 for years 1983–2007. In general, the differences between the adjusted and unadjusted harvest estimates were small.

Appendix C River Harvest Data Interpolation Methods

In some years harvest estimates do not exist for a particular stratum (month-stream-section), either because the fishery was closed, or because the fishery was open but it lacked sample coverage. For strata in which the fishery was closed, harvest and angler effort were assumed to be zero. For strata in which the fishery was open but data were lacking, harvest and angler effort were interpolated for using data from the same stratum (month-stream-section) in other years that had a similar level of overall harvest, effort, and escapement.

Table 6. Sacramento River fall Chinook unadjusted ocean harvest ($H_{o,S}$), adjusted ocean harvest ($\tilde{H}_{o,S}$), and their ratio, for the Sept. 1, *t-1* through Aug. 31, *t* period.

Year (t)	$H_{o,S}$	$\tilde{H}_{o,S}$	$\tilde{H}_{o,S}/H_{o,S}$
1983	348120	331305	0.95
1984	356894	353140	0.99
1985	522224	514283	0.98
1986	758670	756269	1.00
1987	879384	859248	0.98
1988	1353463	1350859	1.00
1989	777520	770600	0.99
1990	689658	664722	0.96
1991	397231	388965	0.98
1992	357954	302599	0.85
1993	469881	457767	0.97
1994	480313	467059	0.97
1995	1126329	1123599	1.00
1996	584578	583697	1.00
1997	793131	789971	1.00
1998	406883	406726	1.00
1999	386280	384696	1.00
2000	595698	584528	0.98
2001	380465	377864	0.99
2002	640127	631686	0.99
2003	625738	608320	0.97
2004	894762	834536	0.93
2005	519337	494805	0.95
2006	272500	257563	0.95
2007	186277	153774	0.83

Two “eras” were defined for the purpose of the interpolation. The “low harvest” era consisted of years 1991–1994 and 2007, characterized by relatively low harvest, effort, and escapement. The “high harvest” era consisted of years 1998–2000 and 2002, characterized by relatively high harvest, effort, and escapement.

Interpolation of missing estimates from a particular strata of the angler survey was performed by taking the mean of estimated harvest and effort in the same month-stream-section for the years in the era of the missing estimate. The use of this method may best be illustrated with an example. For September 1999, harvest and effort estimates were unavailable for the Feather River, section 12.1. To interpolate for the missing harvest estimate, we first noted that 1999 was included in the high harvest era. The harvest estimate for this stratum was then computed in the following manner:

$$H'_{r,\mathsf{Sept.,Feather,12.1}} = \frac{1}{3} \times \sum_{t=98,00,02} H'_{r,\mathsf{Sept.,Feather,12.1}}(t), \tag{24}$$

where the years t are denoted by their last two digits. This method takes advantage of the relative similarity in harvests for the two distinct eras.

This interpolation method assumes that run timing and the spatio-temporal allocation of angler effort is consistent across years in the same stream and section. As such, the method is not able to account for year-effects, where harvest and effort levels may vary due to particular circumstances that occur in a given year (e.g., an abundance of good weather in a particular year results in increased harvest and/or effort).

The interpolation method described above differs slightly from the method used for the 2008 assessment. For that assessment, we used a wider variety of interpolation techniques, including nearest neighbor and averaging between sections of a stream within a given year. The differences between the two methods in terms of harvest and effort estimates are minor. In this report, all figures and Table 3 include estimates based on the interpolation methods described above. For comparison, the estimated average harvest rate with these interpolation methods is $\hat{h}_{r,mean} = 0.1452$, while for the 2008 assessment it was $\hat{h}_{r,mean} = 0.1449$. The small difference in these two values is due to the use of the different interpolation methods.