

# **Sacramento River winter Chinook management strategy evaluation: methods supplement**

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## **1 Introduction**

This is a companion report to “Preliminary evaluation of Sacramento River winter Chinook salmon control rules” (O'Farrell 2017) providing methods and parameter estimates for the management strategy evaluation (MSE) simulations. Much of the content of this report is taken directly from Winship et al. (2012), which can be accessed at [http://www.pcouncil.org/wp-content/uploads/SRWC\\_MSE\\_2012\\_02\\_28.pdf](http://www.pcouncil.org/wp-content/uploads/SRWC_MSE_2012_02_28.pdf). However, notable additions to this report include (1) a description of the environmental covariate in the egg-to-fry relationship and (2) a description of the abundance forecasting method.

## **2 Methods**

### **2.1 Operating model**

The MSE operating model was structured by origin (natural and hatchery), sex and age and had a time step of one year. The model tracked the number of fish on 1 March. Spawning adults, symbolized by  $S$ , were assumed to enter the river on the last day of February. Their offspring (fry),  $J$ , along with hatchery-produced juveniles (pre-smolts),  $P$ , migrated back down the river during

the following fall and winter and were assumed to enter the ocean on the last day of February one year later. Fish in the ocean were symbolized by  $O$  with fish being referred to as age-2 during their first year in the ocean and their age advancing 1 year every 1 March. Fish of age  $a$  that returned to the river to spawn were referred to as age- $a$  even though spawning occurred during the summer following river entry.

For fish in the ocean on 1 March, the first modelled event each biological year was fishery impacts:

$$I_{osat} \sim \text{Binomial}(O_{osat}, i_{at}) \quad \text{for } 2 < a \leq A \quad (1)$$

where  $I_{osat}$  is the number of fish of origin  $o$ , sex  $s$  and age  $a$  that died during the fishing season following time  $t$  due to interactions with fisheries (harvest, release and drop-off mortality),  $O_{osat}$  is the number of fish of origin  $o$ , sex  $s$  and age  $a$  in the ocean at time  $t$ ,  $i_{at}$  is the fishery impact rate on fish of age  $a$  during the fishing season following time  $t$ , and  $A$  is maximum age. The notation  $x = \text{Binomial}(n, p)$  indicates that  $x$  is binomially distributed with sample size  $n$  and probability  $p$ . The term  $x$  represents the number of successes in  $n$  Bernoulli trials (two possible outcomes) with a probability of success of  $p$ . The number of successes will vary among sets of trials of size  $n$  by chance. The binomial distribution describes the distribution of the numbers of successes across sets of trials. In the case of Eq. 1, the number of fishery impacts  $I_{osat}$  represents the number of successes, the number of fish in the ocean  $O_{osat}$  represents the sample size, and the fishery impact rate  $i_{at}$  represents the probability of success.

Natural mortality was assumed to occur over winter after fishery impacts followed by sexual maturity completing the biological year:

$$[O_{os(a+1)(t+1)}, S_{osa(t+1)}] \sim \text{Multinomial}[O_{osat} - I_{osat}, n_a(1 - m_{sa}), n_a m_{sa}] \quad \text{for } 2 < a < A \quad (2)$$

$$S_{osa(t+1)} \sim \text{Binomial}(O_{osat} - I_{osat}, n_a) \quad \text{for } a = A \quad (3)$$

where  $S_{osat}$  is the number of fish of origin  $o$ , sex  $s$  and age  $a$  returning to the river at time  $t$ ,  $n_a$  is the overwinter natural survival rate of fish of age  $a$ , and  $m_{sa}$  is the probability that a fish of sex

$s$  and age  $a$  will mature into a spawner. The model assumed that the earliest age at which a fish could spawn was 2 years and that all fish matured by the maximum age. Fisheries were assumed to impact only fish of age 3 or older. It was also assumed that fishery impact rates, natural survival rates and maturation rates were identical between natural-origin and hatchery-origin fish.

The numbers of natural-origin and hatchery-origin fish returning to spawn at age 2 and remaining in the ocean at age 3 were assumed to be functions of natural and hatchery production:

$$\begin{aligned} & \left[ O_{(\text{natural})(\text{male})3(t+1)}, O_{(\text{natural})(\text{female})3(t+1)}, S_{(\text{natural})(\text{male})2(t+1)}, S_{(\text{natural})(\text{female})2(t+1)} \right] \sim \\ & \text{Multinomial} \left[ J_t, 0.5n_{2t} (1 - m_{(\text{male})2}), 0.5n_{2t} (1 - m_{(\text{female})2}), 0.5n_{2t}m_{(\text{male})2}, 0.5n_{2t}m_{(\text{female})2} \right] \end{aligned} \quad (4)$$

$$\begin{aligned} & \left[ O_{(\text{hatchery})(\text{male})3(t+1)}, O_{(\text{hatchery})(\text{female})3(t+1)}, S_{(\text{hatchery})(\text{male})2(t+1)}, S_{(\text{hatchery})(\text{female})2(t+1)} \right] \sim \\ & \text{Multinomial} \left[ P_t, 0.5hn_{2t} (1 - m_{(\text{male})2}), 0.5hn_{2t} (1 - m_{(\text{female})2}), 0.5hn_{2t}m_{(\text{male})2}, 0.5hn_{2t}m_{(\text{female})2} \right] \end{aligned} \quad (5)$$

where  $J_t$  is the number of fry produced in natural spawning areas by spawners who entered the river at time  $t - 1$ ,  $n_{2t}$  is the juvenile survival rate of natural-origin fry from time  $t$  to time  $t + 1$  (freshwater outmigration and their first year in the ocean),  $P_t$  is the number of pre-smolts released into the river by the hatchery, and  $h$  is the juvenile survival rate of hatchery-origin pre-smolts as a multiple of the survival rate of natural-origin fry. A juvenile sex ratio of 1:1 was assumed. Eqs. 4-5 incorporated demographic stochasticity in the sex ratio, maturation rate and survival rate of juveniles.

The effect of variation in environmental conditions on juvenile survival was included by allowing the juvenile survival rate to vary over time according to a first-order autoregressive process whose marginal distribution was a beta distribution (McKenzie 1985):

$$n_{2t} = 1 - U_t [1 - W_t n_{2(t-1)}] \quad (6)$$

where

$$U_t \sim \text{Beta}(\beta_{n_2}, \alpha_{n_2} - p_{n_2}) \quad (7)$$

$$W_t \sim \text{Beta}(p_{n_2}, \alpha_{n_2} - p_{n_2}) \quad (8)$$

for  $0 < p_{n_2} < \alpha_{n_2}$ . Note that  $U_t$  and  $W_t$  were independent of each other and  $n_{2(t-1)}$ . Eqs. 6-8 allow for positive autocorrelation in  $n_{2t}$  over time. The parameters of these beta distributions ( $\alpha_{n_2}$ ,  $\beta_{n_2}$ ,  $p_{n_2}$ ) were determined by specifying the mean, CV and autocorrelation of  $n_{2t}$  ( $\mu_{n_2}$ ,  $CV_{n_2}$ ,  $\rho_{n_2}$ ) and using the following relationships:

$$\alpha_{n_2} = \frac{1 - \mu_{n_2} (1 + CV_{n_2}^2)}{CV_{n_2}^2} \quad (9)$$

$$\beta_{n_2} = \frac{\frac{1}{\mu_{n_2}} - 2 + \mu_{n_2} + (\mu_{n_2} - 1) CV_{n_2}^2}{CV_{n_2}^2} \quad (10)$$

$$p = \frac{\alpha_{n_2} + \beta_{n_2}}{1 + \frac{\beta_{n_2}}{\rho_{n_2} \alpha_{n_2}}} \quad (11)$$

where  $0 < \rho_{n_2} < 1$ . Eq. 11 was derived based on McKenzie (1985). The sequence of juvenile survival rates was initialized by setting  $n_{21} = \mu_{n_2}$ . Autocorrelation in juvenile survival rates over time was intended to reflect autocorrelation in environmental conditions over time (e.g., sequences of consecutive good or bad years). Demographic stochasticity in juvenile survival rates was modelled (Eqs. 4-5) in addition to the stochasticity described here (Eqs. 6-8). The value used for  $CV_{n_2}$  was estimated from data at escapement levels of hundreds or thousands of spawners so additional variance in realized juvenile survival rates was allowed at very small population sizes.

Livingston Stone National Fish Hatchery obtains new broodstock each year by capturing returning natural-origin spawners (in few cases, hatchery-origin SRWC have been used for broodstock) in the Keswick Dam fish trap. Thus, not all natural-origin fish returning to the river contribute to natural production. The numbers of fish that spawned in the river were calculated as

follows:

$$R_{osat} = \begin{cases} S_{osat} & \text{for } o = \text{hatchery} \\ S_{osat} - B_{sat} & \text{for } o = \text{natural} \end{cases} \quad (12)$$

where  $R_{osat}$  is the number of fish of origin  $o$ , sex  $s$  and age  $a$  that returned to the river at time  $t$  and subsequently spawned in the river and  $B_{sat}$  is the number of natural-origin fish of sex  $s$  and age  $a$  that returned to the river at time  $t$  and were subsequently removed from the river for broodstock.

The model assumed targeted total broodstock for each sex,  $B^{\text{target}}$ , but that the total broodstock for each sex actually taken in a given year,  $B_t^{\text{sex}}$ , was constrained by the number of returning natural-origin spawners. It was also assumed that at most 20% of returning natural-origin spawners were taken as broodstock:

$$B_t^{\text{sex}} = \min \left\{ B^{\text{target}}, \text{round} \left[ 0.2 \sum_{a=2}^A S_{(\text{natural})(\text{female})at} \right], \text{round} \left[ 0.2 \sum_{a=2}^A S_{(\text{natural})(\text{male})at} \right] \right\} \quad (13)$$

Eq. 13 assumed that the numbers of broodstock taken were determined by the sex with the fewest returning spawners. It is possible that the hatchery would be unable to obtain 20% of returning natural-origin spawners if abundance was low and  $< 20\%$  of spawners entered the trap. If this was the case, the number of broodstock taken (and subsequent hatchery production) would be lower than specified by Eq. 13.

The total male broodstock was assumed to be equal to the female broodstock, and broodstock was partitioned stochastically among ages according the age composition of returning fish:

$$[B_{s2t}, \dots, B_{sAt}] \sim \text{Multinomial} \left[ B_t^{\text{sex}}, \frac{S_{(\text{natural})s2t}}{\sum_{a=2}^A S_{(\text{natural})sat}}, \dots, \frac{S_{(\text{natural})sAt}}{\sum_{a=2}^A S_{(\text{natural})sat}} \right]. \quad (14)$$

The expected number of fry produced in the wild was assumed to be a density-dependent function of the number of eggs produced following the Beverton-Holt stock-recruitment relationship

(Beverton and Holt 1957)

$$J_t = \frac{\theta_1 g F_t}{1 + \theta_2 g F_t}, \quad (15)$$

where  $F_t$  is the total number of natural-origin and hatchery-origin females who entered the river at time  $t$  and subsequently spawned in the river,  $g$  is the number of eggs per female,  $\theta_1$  is the maximum rate of successful egg deposition, incubation, hatching and survival to the fry stage, and  $\theta_2$  is a parameter specifying the strength of density dependence.

The egg-to-fry model was further modified by the addition of an environmental covariate shown to affect egg survival for SRWC (Martin et al. 2017). The  $\theta_1$  parameter in Eq. 15 was formulated as a function of a temperature covariate ( $X_t$ ) defined as the number of degree days above a critical temperature threshold of 12°C (O'Farrell et al. 2016),

$$\text{logit}(\theta_{1,t}) = \gamma_0 + \gamma_1 X_t, \quad (16)$$

where  $\text{logit}(\theta_1) = \log[\theta_1/(1 - \theta_1)]$ . Figure 1 display the relationship between  $\theta_1$  and the temperature covariate, given the estimated  $\gamma$  parameters.

Stochasticity in the number of natural-origin fry was incorporated using a bias-corrected log-normal distribution. The following equation describes the production of natural-origin fry in the model:

$$J_{t+1} \sim \text{round} \left\{ \text{Lognormal} \left[ \log(J_t) - 0.5\sigma_{\log J}^2, \sigma_{\log J}^2 \right] \right\} \quad (17)$$

where  $\text{Lognormal}(\mu, \sigma^2)$  is a lognormal distribution with mean  $\mu$  and variance  $\sigma^2$  on the log-scale. It was assumed that the number of male spawners did not limit the number of fry produced. The CV of natural production ( $CV_J$ ) was specified and the variance on the log scale was calculated as

$$\sigma_{\log J}^2 = \log(1 + CV_J^2). \quad (18)$$

Hatchery production was modelled by assuming that all females taken for broodstock were spawned and that each of these females ultimately produced 3000 hatchery-origin pre-smolts for

release into the river:

$$P_{t+1} = \text{round}[3000B_t^{\text{sex}}] \quad (19)$$

The number of pre-smolts released per broodstock female was estimated from the numbers of female spawners taken as broodstock between 2006-2009 and the corresponding numbers of hatchery-origin pre-smolts released from those brood years.

Fishery impact rates were modelled as follows:

$$i_{at} = 1 - e^{\log[1-(c_t+\delta)]v_a} \quad (20)$$

where  $c_t$  is the realized impact rate south of Point Arena following time  $t$ ,  $\delta$  is the additional fishery impact rate north of Point Arena, and  $v_a$  is the relative instantaneous impact rate on age  $a$ . The realized impact rate was assumed to be distributed according to a beta distribution whose mean was the impact rate specified by the impact control rule (the maximum allowable impact rate):

$$c_t \sim \text{Beta}(\alpha_{c_t}, \beta_{c_t}) \quad (21)$$

where

$$\alpha_{c_t} = \frac{1 - \mu_{c_t} (1 + CV_c^2)}{CV_c^2} \quad (22)$$

$$\beta_{c_t} = \frac{\frac{1}{\mu_{c_t}} - 2 + \mu_{c_t} + (\mu_{c_t} - 1) CV_c^2}{CV_c^2}, \quad (23)$$

$\mu_{c_t}$  was the impact rate specified by the control rule at time  $t$  and  $CV_c$  was the coefficient of variation of the realized impact rate relative to the maximum allowable impact rate. The deviations of the realized impact rate from that specified by the control rule were intended to capture the unpredictable complexities of the real process of trying to design fishery controls to achieve a specific maximum allowable impact rate. For some simulation scenarios  $c_t$  was restricted to be  $\leq 0.35$  to prevent unrealistic realized impact rates. This constraint was implemented by truncating the beta

distribution in Eq. 21 (i.e., discarding values higher than 0.35 and resampling until a permissible value was obtained). Demographic stochasticity in the realized impact rate was modelled (Eq. 1) in addition to the stochasticity described here (Eq. 21). As with  $CV_{n_2}$ , the value used for  $CV_c$  was estimated from data at escapement levels of hundreds or thousands of fish so additional variance in realized impact rates was allowed at very small population sizes.

## Parameterization

Model parameter values are presented in Table 1.

The target hatchery broodstock ( $B_0^{\text{sex}}$  and  $B^{\text{target}}$ , respectively) was set to 50 females and 50 males. This broodstock was assumed to produce 150,000 pre-smolts following the assumption of 3000 pre-smolts per female. This assumed hatchery production reflected the average hatchery production over time, though it does not reflect the recent increases in hatchery production in response to drought conditions.

Several of the parameter values used herein were obtained from a statistical model developed for SRWC (Winship et al. 2011; O’Farrell et al. 2016). The structure of the population model in that analysis was similar to the population component of the operating model, thus, the parameters were transferable between models. The parameter values that were taken from the statistical analysis included the stock-recruitment parameters ( $g, \gamma_0, \gamma_1, \theta_2, CV_J$ ), sexual maturation probabilities ( $m_{sa}$ ), juvenile survival probabilities ( $\mu_{n_2}, CV_{n_2}, h$ ) and the  $CV$  of estimates of the number of fry ( $CV_f$ ) and the number of fish spawning in the river ( $CV_{N^{\text{spawn}}}$ ). Median posterior estimates from the statistical model were used because the posterior probability distributions were sometimes heavily skewed and medians are less affected by parameter transformations. The values of  $CV_f$  and  $CV_{N^{\text{spawn}}}$  were set to the mean of annual estimates.

A constant natural annual survival probability of 80% for ages  $\geq 3$  was used, following assumptions in models by CDFG (1989) and O’Farrell et al. (2012). The model assumed that the survival rates of hatchery-origin and natural-origin fish older than age 2 were identical. The average age distributions of hatchery-origin and natural-origin spawners were similar between 2001-2009



(USFWS 2010), which is consistent with similar survival rates conditional on similar maturation rates.

The impact rate specified by the control rule was assumed to be the age-3 impact rate ( $v_3 = 1$ ). Fish were assumed to be invulnerable to fishery-related mortality during their first year in the ocean (i.e.,  $v_2 = 0$ ). Estimated age-4 impact rates have been highly variable and based on small numbers of coded-wire tag recoveries (O’Farrell et al. 2012), therefore it was assumed that the instantaneous age-4 impact rate was twice that of the age-3 impact rate ( $v_4 = 2$ ). The contributions of fishery impacts north of Point Arena to the overall impact rate were also variable, but a constant  $\delta = 0.006$  was assumed, corresponding to the average value between 2000 and 2007. The pre-simulation age-3 impact rate,  $i_{30}$ , was assumed to be 0.2 (O’Farrell et al. 2012). The CV of the realized impact rate relative to that specified by the control rule,  $CV_c$ , was calculated from an analysis of estimated impact rates for SRWC (O’Farrell et al. 2012) and hindcast impact rates from the Winter Run Harvest Model for years 2000-2014.

## **Abundance forecast**

Simulations were performed for nine control rules as described in O’Farrell (2017). Control rules 1–3 specify a constant allowable impact rate regardless of abundance. Control rules 4–7 and 9 specify the allowable age-3 impact rate as a function of the forecasted value of the age-3 escapement absent fishing ( $E_3^0$ ; O’Farrell et al. 2016). Control rule 8 is the current control rule that specifies the allowable impact rate as a function of the geometric mean of estimated escapement for the three prior years, accounting for observation error and the number of fish taken for hatchery broodstock.

With regard to control rules 1–7 and 9, the abundance forecasting approach used within MSE simulations was the *Base* forecast model described in O’Farrell et al. (2016). Forecasts of  $E_3^0$  were implemented in each year of each simulation in the following manner.

The “true” number of natural-origin fry  $J$ , accounting for lognormal process error, was specified by Eq. 17. A distribution of the estimated number of fry, accounting for observation error

associated with estimating fry passage at Red Bluff Diversion Dam, was represented by 200 draws from the bias-corrected lognormal distribution:

$$\hat{J} \sim \text{round} \left[ \text{Lognormal} \left( \log J - 0.5\sigma_{\log \hat{J}}^2, \sigma_{\log \hat{J}}^2 \right) \right] \quad (24)$$

where the *CV* of the fry estimates  $CV_f$  enabled computation of the variance on the log scale as in Eq. 18. Eq. 24 assumed that the true number of fry passing Red Bluff Diversion Dam was the mean of the lognormal distribution.

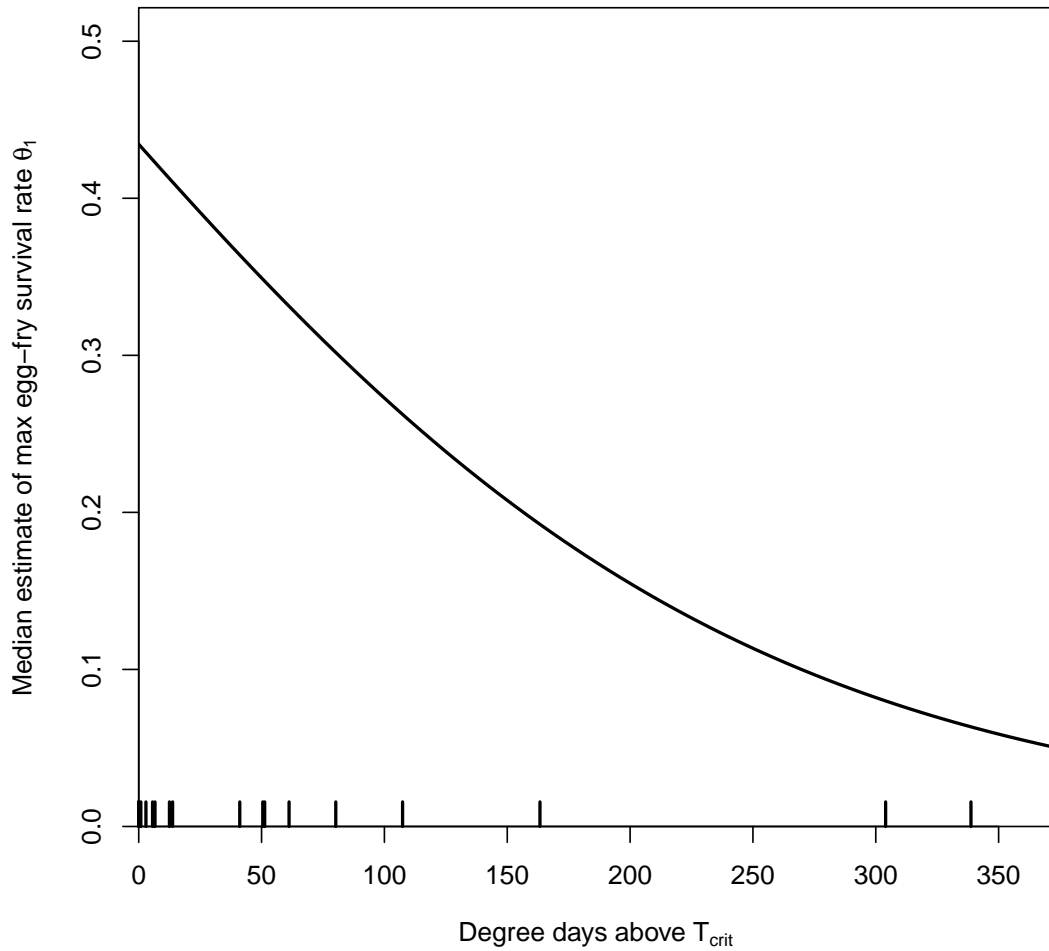
A distribution of the natural-origin juvenile survival rate experienced by the estimated number of fry was represented by 200 draws from a beta distribution, as described in Eqs. 6–11. This distribution represents a sample from the beta distribution fitted to all years of estimated juvenile survival rates (Figure 2). The forecast of  $E_3^0$  is then made by multiplying the number of fry by the juvenile survival rate and accounting for age- and sex-specific maturation rates and the ocean age-3 natural mortality rate as described in O’Farrell et al. (2016).

For hatchery-origin fish, the production of pre-smolts was assumed to be known without error. The juvenile survival rates were modeled by multiplying the 200 draws from the natural-origin juvenile survival rate distribution by  $h$ , the ratio of hatchery-origin to natural-origin juvenile survival rates. Age- and sex-specific maturation rates and the ocean age-3 natural mortality rate were then applied in the same manner as for the natural-origin process described above.

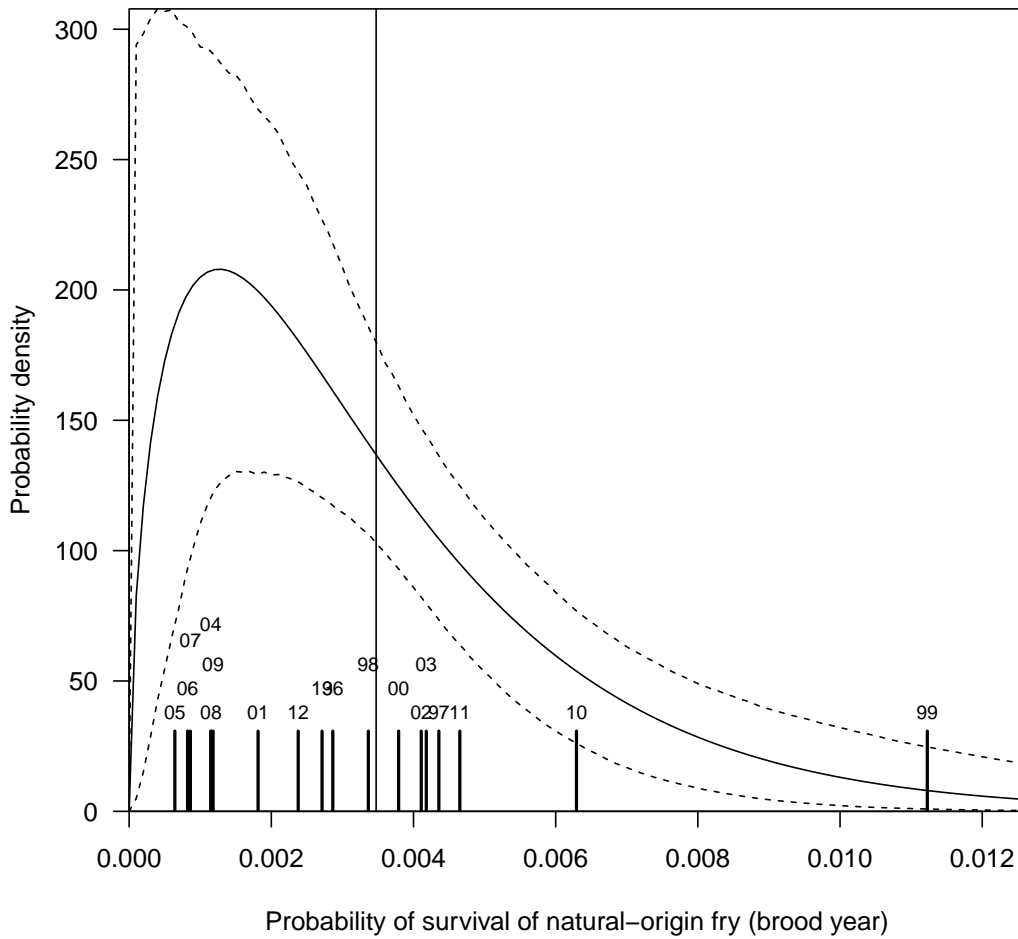
A single value of  $E_3^0$  for each year and simulation was then made by summing the natural-origin and hatchery-origin forecasts and taking the median of the resulting distribution. This median was used with control rules 1–7 and 9 to set the allowable age-3 impact rate within the year/simulation combination.

**Table 1.** Model parameter values and their descriptions.

Parameter	Description	Dimensions	Value
$A$	max. age		4
$g$	number of eggs per female spawner		4900
$\gamma_0, \gamma_1$	coefficients defining the max. egg-to-fry survival rate as a function of the temperature covariate		$\gamma_0 = -0.26$ $\gamma_1 = -0.0072$
$\theta_2$	strength of density dependence		3.3e-08
$CV_J$	CV of recruitment stochasticity		0.13
$n_a, \mu_{n_2}$	natural survival rate	$a \in \{2, \dots, A\}$	$n_2 = \mu_{n_2} = 0.0035$ $n_{3+} = 0.8$
$CV_{n_2}$	CV of juvenile survival rate		0.79
$\rho_{n_2}$	autocorrelation in juvenile survival rate		0, 0.5
$h$	ratio of hatchery-origin to natural-origin juvenile survival rates		1.9
$m_{sa}$	maturation rate	$s \in \{\text{male, female}\}$ $a \in \{2, \dots, A-1\}$	$m_{(\text{male})2} = 0.14$ $m_{(\text{male})3} = 0.90$ $m_{(\text{female})2} = 0.00063$ $m_{(\text{female})3} = 0.96$
$B_0^{\text{sex}}, B^{\text{target}}$	broodstock	$t \in \{1, 2, \dots, T-1\}$	50
$v_a$	relative impact rate	$a \in \{3, \dots, A\}$	$v_3 = 1$ $v_4 = 2$
$CV_c$	CV of realized impact rate		0.37
$i_{30}$	pre-simulation age-3 impact rate		0.2
$CV_{\hat{N}^{\text{spawn}}}$	CV of observation error for spawners		0.08
$CV_f$	CV of observation error for fry		0.21



**Figure 1.** Relationship between the temperature covariate ( $X$ , the number of degree days above the critical temperature level of  $12^{\circ}\text{C}$ ) and the maximum egg-to-fry survival rate ( $\theta_1$ ) given the estimated  $\gamma_0$  and  $\gamma_1$  parameters.



**Figure 2.** Estimated juvenile survival rate of natural-origin fry. The short vertical bars represent the median estimated survival rates for each brood year. The tall vertical bar represents the posterior median estimate of the mean survival rate. The curved solid line represents the beta distribution fitted to the juvenile survival rates. The dashed lines represent the 95 percent interval of posterior probability for the distribution of survival rates.

## References

- Beverton, R. J. H. and S. J. Holt (1957). *On the dynamics of exploited fish populations, Volume 11. Fish and Fisheries*. Chapman and Hall.
- CDFG (1989). Description of winter Chinook ocean harvest model 1. Ocean Salmon Project Report, CDFG, Sacramento, California.
- Martin, B. T., A. Pike, S. N. John, N. Hamda, J. Roberts, S. T. Lindley, and E. M. Danner (2017). Phenomenological vs. biophysical models of thermal stress in aquatic eggs. *Ecology Letters* 20, 50–59.
- McKenzie, E. (1985). An autoregressive process for beta random variables. *Management Science* 31, 988–997.
- O’Farrell, M., N. Hendrix, and M. Mohr (2016). An evaluation of preseason abundance forecasts for Sacramento River winter Chinook salmon. Report prepared for the 2016 PFMC Salmon Methodology Review.
- O’Farrell, M. R. (2017). Preliminary evaluation of alternative Sacramento River winter Chinook salmon control rules. Report to the Pacific Fishery Management Council. April 2017.
- O’Farrell, M. R., M. S. Mohr, A. M. Grover, and W. H. Satterthwaite (2012). Sacramento River winter Chinook cohort reconstruction: analysis of ocean fishery impacts. U.S. Dept. Commer., NOAA Tech. Memo. NOAA-TM-NMFS-SWFSC-491, 68p.
- USFWS (2010). Upper Sacramento River winter Chinook salmon carcass survey 2009 annual report. USFWS, Red Bluff, California. Available from <http://www.fws.gov/redbluff/getReport.aspx?id=89>.
- Winship, A. J., M. R. O’Farrell, and M. S. Mohr (2011). Estimation of parameter for the Sacramento River winter Chinook management strategy evaluation. Report to the Southwest Region, NMFS.
- Winship, A. J., M. R. O’Farrell, and M. S. Mohr (2012). Management Strategy Evaluation for Sacramento River winter Chinook salmon. Report to the Southwest Region, NMFS.