Temperature and Discharge Dependent Mortality of Juvenile Spring-Run Chinook Salmon in Clear Creek

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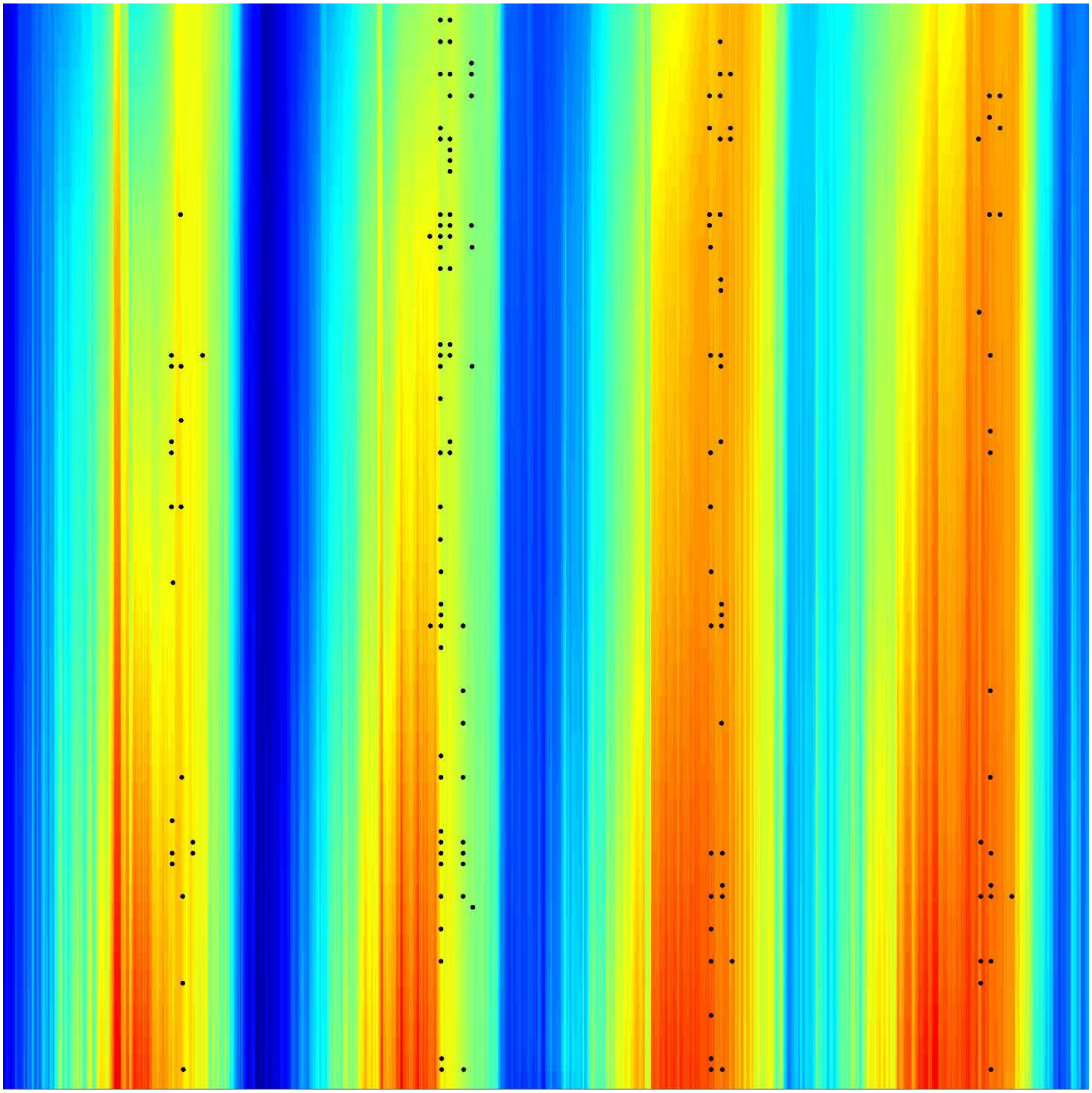

Table of Contents

Introduction

Central Valley Chinook Salmon (*Oncorhynchus tshawytscha*) have significant economic, social, and ecological impacts (NMFS 2015; Michael 1998). Unfortunately, the total number of salmon returning to the Central Valley has declined significantly over the past two decades due to anthropogenic alterations including dam construction (Angillet 2008), economic and population growth (Lackey 2005), and climatic change (Crozier 2007). Efforts to support and enhance salmon populations began in the 1850s with the development of salmon hatcheries by the Federal Government in the 1870s. Since the early 1850s, substantial research and monitoring has been performed by federal, state and private agencies to "recover" salmon populations. However, despite several billions of dollars of expenditure and the efforts of thousands of scientists and other experts, the long term downward trend in populations continues (Lackey 2017).

Long term datasets and improved statistical analyses may offer some insight and management directions to address this downward trend of salmon populations. This paper will explore the relationship between juvenile spring run Chinook egg-to-fry survival and temperature and discharge conditions during their development period as eggs and alevin in redd. An empirical model will be fit to abiotic and brood year survival estimates collected on Clear Creek, Redding CA from 2003 to 2017. The objective of this analysis is to investigate the utility of this modeling approach for guiding management decisions and, if appropriate, to offer management recommendations based on the findings.

Study Area

Clear Creek is a west side tributary of the Sacramento River (Figure 1). This 80-kilometer-long creek has headwaters in the Trinity Mountains west of Shasta Lake (Redding, CA). In 1963, Construction of Whiskeytown Dam was completed at river kilometer 30.9 (rkm; origin of measurement at the confluence with the Sacramento River). The dam reduced the free-flowing watershed above the USGS gaging station near Igo CA (11372000), located at rkm 17.9, from 591 km^2 to 73.8 km^2 (Matthews 2013). All water does not flow directly from upper Clear Creek to lower Clear Creek. Some water from the Trinity River can be transported to Whiskeytown Reservoir by the Clear Creek Tunnel, and water from Whiskeytown Reservoir can be transported to the Keswick reservoir (above Keswick Dam on the Sacramento River) by the Spring Tunnel. This impoundment and diversion at Whiskeytown influences flow and thermal regimes and eliminates sediment transport into lower Clear Creek. To address the latter issue, gravel injections began on Clear Creek soon after the completion of Whiskeytown Dam. Since 1996, over 191 thousand tons of spawning gravel has been added to Clear Creek. Additionally, from 1962-2001 a second dam, Saeltzer Dam, blocked fish passage at rkm 10.5. This dam was removed in 2002 to allow upstream fish passage and access to 20.4 rkm of habitat. Since 2010, three fires have occurred within the Clear Creek Watershed. In the summers of 2012 and 2013, respectively, the Dale Fire and Clover Fire burned in the catchment Reach 5, the lowest extent of Spring Run Chinook Salmon spawning habitat. In 2015, the Happy Valley Fire burned near the upstream limits of Reach 7, downstream of Spring Run Chinook Salmon spawning habitat. Following fires in a watershed a stream may see increases in fine sediment and turbidity (Miller 2011); and increases in fine sediments can reduce in-redd survival of salmonids (Levasseur 2006). Anecdotal evidence suggests the prevalence of fine sediment and turbidity events increased downstream of these fire locations. Major fishery restoration management actions on Clear Creek have included establishing base flows and temperature criteria, channel and floodplain restoration, gravel injection, and dam removal (Provins 2018).

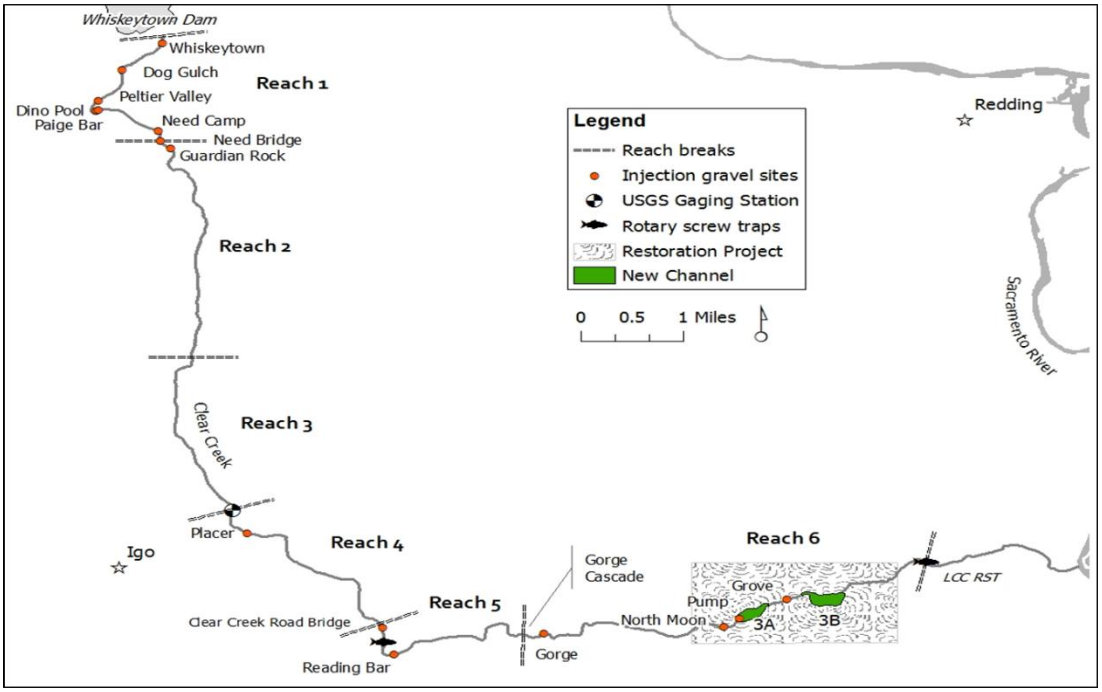

Figure 1. Map of Lower Clear Creek, Redding Ca.

Spring Chinook Developmental Physiology

Four runs of Chinook Salmon return to the California Central Valley: fall, late fall, winter and spring run. Of the four runs of Chinook Salmon that return to California's Central Valley, spring run Chinook Salmon have seen the largest decline. Spring run was probably the largest run returning to the California Central Valley historically (NMFS 2014). Over the last 5 years, approximately 5% of the salmon returning to the Central Valley have been spring run (CDFW 2017).

The life history of Spring Run Chinook Salmon makes them particularly susceptible to habitat fragmentation that may result from impoundment, diversion and land use changes. Spawning adults return to freshwater in spring, after 1-5 years in the ocean. Adults hold in cool upstream reaches through spring and early summer before spawning in late summer (NMFS 2014; Yoshiyama 1998). In general, water temperatures in higher order streams peak during this holding period (Maheu et al. 2015), and decline through the spawning and incubation period. Prior to the installation of the valley rim dams, it may have been possible for spawning adults to continue upstream to higher elevation, and cooler water temperatures (Moyle 2002). Thermal and bioenergetic stressors interact with individual fecundity and physiology to shape Chinook Salmon distribution and abundance. However, these allostatic load tradeoffs require access to diverse habitat (Schreck 2010; Baldock et al. 2016). Due to the thermal habitat fragmentation and restriction resulting from impoundment and diversion and land use practices, spring run Chinook Salmon may require purposeful management of spawning stream temperature to persist as a species.

Many factors affect the successful development of Chinook Salmon pre-emergent embryos and larvae including dissolved oxygen. Some of the key factors contributing to the total dissolved oxygen delivered to eggs include: water temperature, ambient river dissolved oxygen (DO), local water velocity/vector, and hydraulic conductivity. The interaction between these factors is complex. Each fertilized egg has a dissolved oxygen uptake rate. The rate of DO uptake and the developmental necessity of fully meeting this DO rate vary between fertilization and emergence (Ciuhandu 2007). Dissolved Oxygen at the boundary layer of each embryo (before hatching) and larvae (after hatching), is maintained by hyporheic water movement across the boundary layer. The velocity of this boundary water is dictated by local bathymetry, local water column velocity and hydraulic conductivity from the water column to the egg mass. Hydraulic conductivity through a redd is the product of many factors including redd structure and sediment composition (Tonina 2009). Stream discharge has been used as an analog for velocity at the boundary layer (Levasseur 2006), fluctuations in hydraulic conductivity through the development period was associated with the transportation of different size sediment. Water column DO is modified before reaching the egg mass by groundwater diffusion and microbial respiration (Youngson 2004; Bloomer 2016). Because cold water readily holds more oxygen than warm water (all other conditions equal), more oxygen reaches the boundary layer of the embryo or larvae when the water column temperature is colder. While a full understanding of in-redd survival would include an investigation of DO, hydraulic conductivity, and boundary layer velocity, water column temperature alone has been used to describe upwards of 60% of Chinook Salmon survival to fry (Martin 2016a,b).

Many published works have proposed thermally-based mortality rates for Chinook Salmon during egg incubation. These estimates range widely and may not be directly comparable due to different Chinook Salmon runs, methods, and means of classifying mortality. For example, Moyle (2002) provides temperatures for maximum survival and Seymour (1956) reports a management threshold. Mortality rates associated with specific temperatures may have greater management utility. Some studies have found that temperature based mortality is variable throughout incubation, with specific tolerances at fertilization, hatching and emergence. One study that focused on mortality that is related to temperature variation found that incubation mortality is high when embryos are exposed to very cold temperatures (<2.8 C) immediately following spawning (6 days-3 weeks). However, if the embryo is initially incubated at a higher temperature (5.9-12.8ºC/6 days-3 weeks), the tolerance for cold temperature was greatly improved (McCullough 1999). Murray and Beacham (1987) found that water temperature up through the completion of epiboly (first third of incubation) was a better indicator of overall survival than temperature after this developmental point, though it should be noted that the three incubation temperatures explored by this study: 4, 8, and 12 ºC may not be relevant to the likely thermal stress experienced by wild Central Valley fish. Ciuhandu (2007) explored the DO boundary of embryos and larvae and reported that DO demand may increase as the embryo approaches hatching. Overall, a decreasing temperature regime that simulates natural incubation conditions results in high survival and yields larger alevins and fry than increasing temperature regimes (McCollough 1999; Murray and Beacham 1987).

Empirical Modeling

In 2016, Ben Martin and others developed an empirical model that estimated winter run Chinook Salmon mortality. This model specifically investigated the relationship between stream temperature at identified redd locations and survival of juveniles from fertilization to downstream fry movement. The primary input to the model was the thermal experience of each winter run redd. Information used to estimate the annual survival of winter run juveniles included estimates of the number of redds and fry captured at a downstream screw trap. The relationship between thermal experiences and brood year survival was hypothesized through three parameters: the temperature above which mortality begins, the influence on survival for of each degree above the critical mortality temperature, and the baseline or temperature independent mortality. A non-linear optimization algorithm estimated model parameters with the objective of minimizing the logit sum of squares between a temperature dependent mortality model and juvenile survival as estimated from an ongoing rotary screw trapping effort. Martin also explored density dependent factors by including a parameter that represented the effect of number of spawning adult females estimated each year on survival. For the density independent and dependent models, the coefficients of determination of these models were 0.66 and 0.77, respectively. This level of fit suggests that the models have strong management utility; however replication of this analysis with other species and data may have additional value for managers.

Input Datasets

Redd Location, Stream Temperature and Juvenile Outmigrants

The U.S. Fish and Wildlife Service (USFWS) has been collecting redd location, stream temperature and juvenile outmigration data on spring run Chinook Salmon in Clear Creek since 2003. Redd location data was collected by snorkel survey. This survey was completed every two weeks through the duration of the spring run spawning period (approximately 2 months, from August to early November). Coordinates of each identified spring run Chinook Salmon redd were determined using a handheld GPS. Stream temperature data has been recorded (c. 3 rkm resolution) with a temperature logger (onset Hobo logger) from 2003 to the present (Figure 2). Finally, salmonid juvenile out migration from Clear Creek was estimated using a 5-foot rotary screw trap (EG Solutions, Corvallis OR) deployed in the thalwag. Capture efficiency of the trap was estimated using mark recapture. A known number of outmigrating juvenile Chinook Salmon were marked and released upstream. The trapping efficiency then was estimated as proportion of marked fish recaptured to the total number released. The total number of spring run Chinook Salmon leaving the watershed were estimated by dividing the number of fish captured by rotary screw trap captured in a period and the associated estimated capture efficiency for that period. Survival proportion for spring run was calculated by multiplying the number of redds above the screw trap by an average fecundity of spring run female, and dividing this value by the screw trap passage estimate.

Discharge

Discharge in Clear Creek was measured at rkm 17.9 at USGS gage (11372000) in 30-minute intervals. This data was summarized by calculating daily mean discharge for each day in the study period. Discharge (Mean 7.7 CMS) was not strongly correlated with water temperature (Mean 9.9 °C) during the spring run Chinook Salmon incubation period on Clear Creek (Pearson r=-0.002), nor are these datasets strongly predictive of each other (coefficient of determination, R^2 0.024; Figure 3).

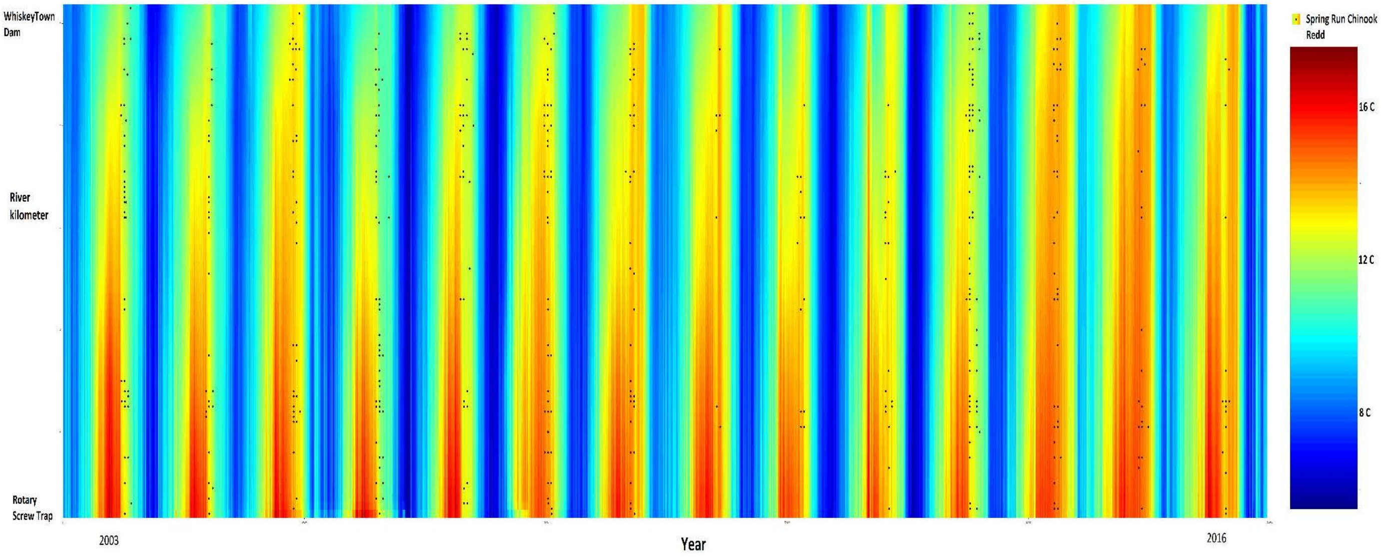

Figure 3. Plot of temperatures in Clear Creek by river kilometer, from 2003 to 2017. Black markers (dots) represent the location (y-axis) and timing (x-axis) of spring run Chinook Salmon redds with each vertical bar representing a day. Colors indicate estimated temperatures along the length of the study reach.

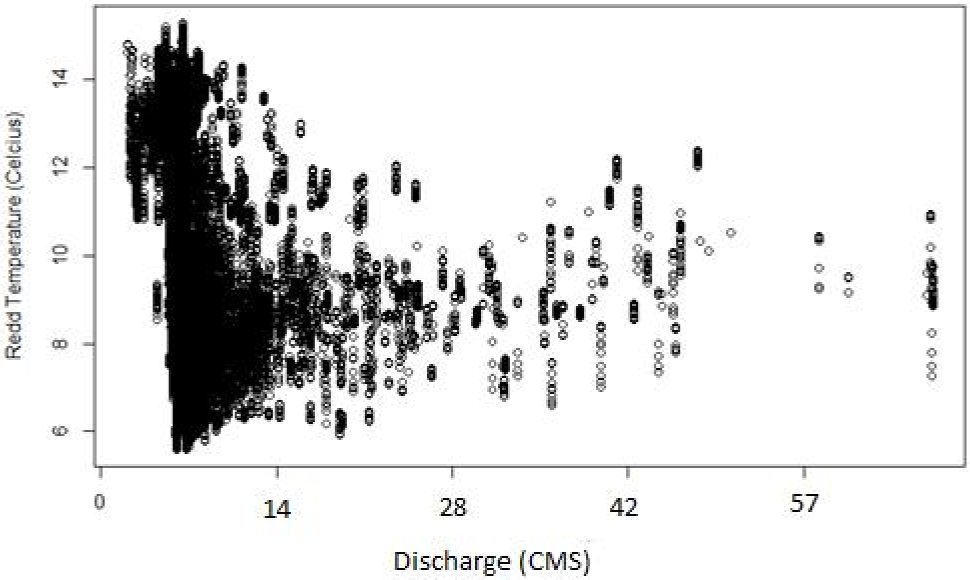

Figure 3. Mean daily discharge (cubic meters per second) at USGS gage (11372000) and temperature at the redd site, for the first 150 days of incubation at spring run Chinook Salmon redds identified on Clear Creek.

Input Datasets – best practice/method undefined

Eggs per Redd

To estimate egg-to-fry survival, it was necessary to estimate the number of eggs deposited in each redd. The number of eggs deposited in each redd can vary widely among individual females and years (Moyle 2002). This variation has been attributed to multiple factors and is documented to be positively related to fish length (Kaufman 2009). Moyle (2002) reported that Chinook fecundity ranges from 2,000 to 17,000, with average spring run fecundity at 4,895 (Fisher 1994). Three approaches were considered to estimate the number of eggs deposited in each redd: allocate a uniform average fecundity to all redds, apply annual spring run Chinook fecundities reported from returned spawning females at Feather River Hatchery, and estimate annual egg number by average fork length of collected carcasses on Clear Creek based on fork-length relationships to fecundity from Kaufman et al 2009 (Figure 4). Each of these methods suggests a different number of eggs for each year (Figure 5). The first method makes the assumption that all redds initially contain the same number of eggs. Each year Feather River Hatchery (Oroville CA) calculates the average number of eggs per spring run Chinook salmon female returning to the hatchery. Both the Feather River and Clear Creek are tributaries to the Sacramento River, and genetic and coded wire tag analysis suggest that Feather River strays contribute significantly to Clear Creek spring run ((Gallagher *Personal communication* USFWS).Clear Creek fecundity tracks annually with fecundity at Feather River Hatchery. The third method would use spring run carcass recoveries on Clear Creek to suggest an average fork length for a given year (Figure 4). The average fork length would be used in an established fork length to egg count relationship to calculate an annual number of eggs per redd (Kaufman et al 2009). This approach would assume that the carcasses recovered are representative of those who successfully spawned in the creek. Due to the extreme low number of carcass recoveries, this approach is compromised by low carcass sample size. For the analysis in this report, a fixed number of eggs (4,895) from Fisher (1994) will be allocated to each redd. An investigation of the model sensitivity to egg number per redd will be presented later.

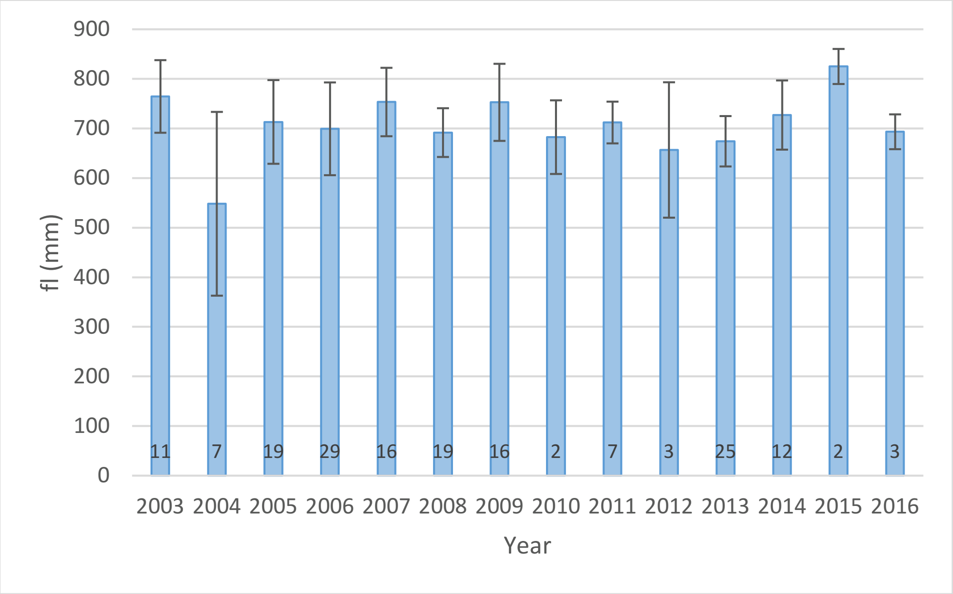

Figure 4. Fork length (fl) of spring run Chinook Salmon carcasses recovered on Clear Creek, Redding Ca. Number or carcass recoveries indicated by number at the base of each bar. Error bars indicate +/- one standard deviation for each year.

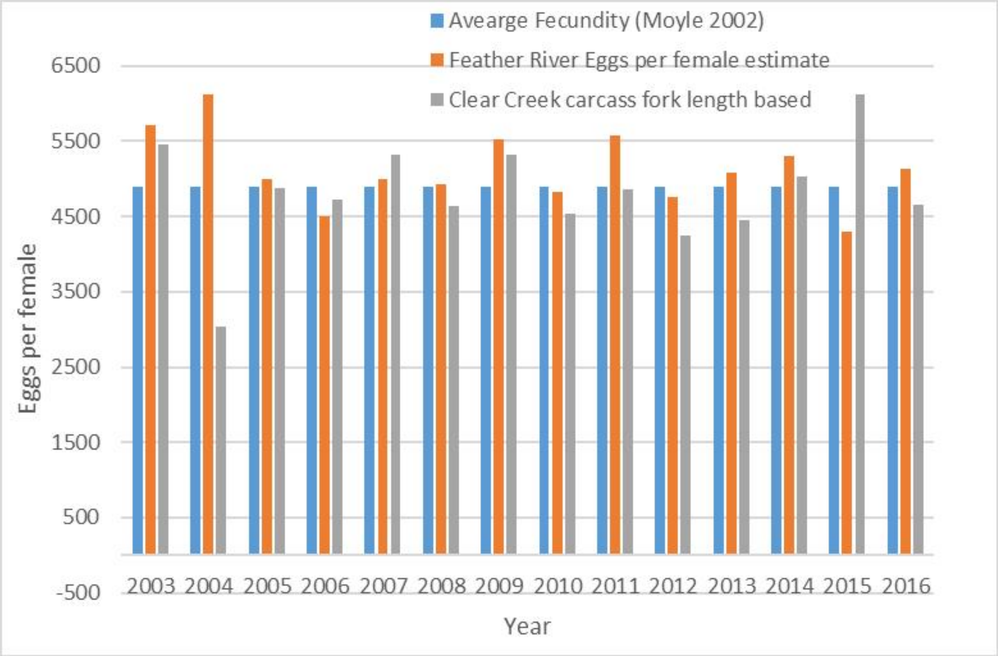

Figure 5. Number of eggs per female suggested by three different method of analysis.

Emergence Models

Many different models exist for estimating the number of days from fertilization to emergence (Schraml and Earley In progress). Martin (2014) employed the temperature dependent model presented in Zueg et al. (2009) as cited by Martin (2016), wherein emergence occurs when the relative development state (*D*) exceeds 1 in the equation:

$$D = D_i + ((.00058 * MDT_i) - .018),$$

where D_i is D calculated for the previous day of incubation. This variable serves as a counter of progress towards emergence. MDT is the mean daily temperature (in F°) at incubation site on day *i*.

Egg-to-Migration Survival Models

Four egg-to-fry survival models were structured to assess the relationship between abiotic parameters and empirical measures of juvenile survival (measured as the passage of juvenile spring Chinook estimated at the trap, divided by the number of spring Chinook eggs estimated to have been deposited in redds upstream). Each model was an attempt to describe annual empirical brood year survival using alternative sets of parameters (Table 1). Similar to most empirical model fitting, optimization was used to estimate parameter values that minimized the difference between the empirical brood year survival and model predicted brood year survival. Each parameter set represented a set of hypotheses that best describe the data within the relationship proposed by the model and are described below. The support for each hypothesis was evaluated by comparing the estimates of survival based on the parameterized model to the brood year survival estimated from rotary screw trap captures.

Model A - Fixed temperature dependent mortality model

This model was structured with the assumption that temperature dependent egg-to-fry mortality begins to occur when the mean daily temperature at a redd reaches a certain critical temperature, and that daily mortality increases linearly above that temperature. Total survival of fish from a redd to passage at our trap site is the product of daily survival through emigration, and a baseline mortality. The model tests hypotheses about the existence and value of this critical temperature (*Tcrit)*, temperature dependent mortality rate (*bT)*, and baseline mortality rate independent of temperature (*U)*.

Model B - Discharge dependent mortality

This model was structured with the assumption that discharge dependent egg-to-fry mortality begins to occur when the mean daily discharge reaches a certain threshold value or is below another threshold value, and that daily mortality increases linearly once the flow was above or below the threshold values. Total survival of a redd was the product of daily survivals through emergence, and a baseline mortality. The model evaluates the hypotheses about the value of this high critical flow (*HFlow_Crit)*, and a mortality above it (*HFlow_bT),* a low critical flow (*LFlow_Crit*), and a mortality below it (*LFlow_bT),* and baseline mortality rate independent of discharge (*U)*.

Model C - Variable temperature dependent mortality model

This model was structured with the assumption that egg-to-fry mortality occurs when the mean daily temperature at a redd exceeds a critical temperature, and that daily mortality increases linearly above that temperature. The additional key assumption of this model is that the threshold temperature varies linearly between two values from the day of identification to predicted emergence; with a single threshold value shared by the day of observation and the day of predicted emergence and another value that defines the temperature threshold halfway through development. Total survival of a redd is the product of daily survival through emergence, and a baseline mortality. The model tested hypotheses about the value of the critical temperature (*Tcrit)*, the critical temperature half-way through development (Tmid), the mortality rate (*bT*), and baseline mortality rate independent of temperature (*U)*.

Model D - Variable temperature and discharge dependent mortality model

This model combined the assumptions of B and C above and tested a combination of the parameters. The validity of each hypothesis was tested by comparing the estimates of survival based on the temperature at each redd location and discharge measurements during the incubation period to the brood year survival estimated from rotary screw trap captures.

Table 1. Parameters and Data Inputs used by each Model.

Models	***Description***	***Parameters***
A	Fixed temperature dependent mortality model	*U, Tcrit, bT*
B	Discharge dependent mortality	*U, Hflow Crit, Hflow_bT, Lflow_Crit, Lflow_bT*
C	Variable temperature dependent mortality model	*U, Tcrit, T mid, bT*
D	Variable temperature and discharge dependent mortality model	*U, Tcrit, bT, Hflow Crit, Hflow_bT, Lflow_Crit, Lflow_bT*
Data inputs		***Model Use***
Empirical brood year survival	Rotary Screw Trap annual survival estimates	A,B,C,D
Redd number	The number of redds identified each year in the study area	A,B,C,D
Thermal Exposure	Mean daily temperature at each redd location (0.16 river kilometer resolution), starting with the day of observation of each redd.	A,C,D
Discharge exposure	Mean daily flow at USGS gaging station (rkm 17.9), starting with the day of observation of each redd.	B,D
Model Parameters:		**Model Use**
Tcrit	Temperature at which temperature dependent mortality rate begins	A,B,C,D
bT	Temperature dependent daily mortality for each degree above Tcrit.	A,B,C,D
U	Survival rate independent of model terms	A,B,C,D
Tmid	For models C and D, *Tmid* is the Tcrit value at the middle of development. In these models, *Tcrit* is the value at the beginning and end.	C,D
Hflow_Crit	Discharge above which mortality occurs	B,D
Hflow_b	Rate mortality occurs above *Hflow_Crit*,	B,D
LFlow_Crit	Discharge below which mortality occurs	B,D
Lflow_b	Rate mortality occurs below *LFlow_Crit,*	B,D

Methods

Egg-to-Migration Survival Models

The general structure for calculating brood year survival was shared between the four models. For each redd, river kilometer specific temperature and discharge data were summarized for each day from field identification of redds to estimated emergence. Daily survival, from 0% to 100%, was calculated for each day and redd using an equation that represented each hypothesis (Table 2). The fractional survival for each redd was the product of daily survivals through emergence and the model term independent survival, *U (equation 2).* Model brood year survival was calculated as the average of individual redd survival within the year (equation 3). Empirical brood year survival was calculated by dividing the rotary screw trap passage index by the product of the number of redds identified and the number of eggs per redd (equation 4). Each model brood year survival and empirical brood year survival were logit transformed (as in Martin 2014, Wharton and Hui 2011) and a sum of squares analysis was calculated (equation 5). Parameter estimation was conducted using R statistical software with the *Optim* function with the objective of minimizing the the logit transformed sum of squares. The result of this process was a parameter set that best described the empirical brood year survival estimates, given the structure proposed by the model. The product of each annual model brood year survival estimate, and the estimated initial egg count was used to produce a model passage (or abundance) estimate. Standard error of each parameter estimate was derived from the hessian matrix output of the *Optim* function 0.95 confidence limits on parameter estimation were calculated as in Jorgensen (1998).

Table 2. Daily survival equation for each model.

Model	*Equation 1*
A	$S_i = e^{-b_T max(T_i - T_{crit},0)}$
B	$S_i = e^{-HFlow_b max(MeanFlow-HFlow\_Crit,0)} * e^{-LFlow_b\, max(MeanFlow-LFlow\_Crit,0)}$
C	$S_i = \sum_{i=0}^{i=.5} e^{-b_T max\left(T_i-((T_{crit-}\left(\frac{Tcrit-Tmid}{.5}\right)*i),0\right)}$, $\sum_{i=.5}^{i=1} e^{-b_T max\left(T_i-((T_{mid+}\left(\frac{Tcrit-Tmid}{.5}\right)*i),0\right)}$
D	$S_i = \sum_{i=0}^{i=.5} e^{-b_T max\left(T_i-((T_{crit-}\left(\frac{Tcrit-Tmid}{.5}\right)*i),0\right)} * (S_i = e^{-HFlow_b max(MeanFlow-HFlow_{Crit},0)}) * (e^{-LFlow_b\, max(MeanFlow-LFlow_{Crit},0)})$, $,\sum_{i=.5}^{i=1} e^{-b_T max\left(T_i-((T_{mid+}\left(\frac{Tcrit-Tmid}{.5}\right)*i),0\right)} * (S_i = e^{-HFlow_b max(MeanFlow-HFlow_{Crit},0)}) * (e^{-LFlow_b\, max(MeanFlow-LFlow_{Crit},0)})$

Table 3. Equations used to build egg to migration models.

Number	Equation	
2	$S_r = \mathrm{U} * \prod_{i=1}^{z} S_i$	S_r=Fractional Survival to emergence for a single redd U= Model term independent Survival z=Number of days from identification to emergence Si=Daily survival
3	$\mathrm{S}_{ma} = \frac{\sum S_r}{R_a}$	S_{ma}=Annual brood year fractional survival model estimate where S_r= Fractional Survival to emergence for a single redd R_a= is the number of redds identified in a particular year.
4	$\mathrm{S}_{ea} = \frac{P_i}{R_a * E_r}$	S_{ea}=Annual brood year fractional survival *empirical* estimate P_i =is the rotary screw trap passage estimate R_a = The number of redds identified in a particular year. $E_{r =}$ is the number of eggs per redd.
5	$SSQ(\emptyset) = \sum_{i=1}^{n} ((log(\frac{S_{ma}}{1 - S_{ma}}) - (log(\frac{S_{ea}}{1 - S_{ea}}))\hat{}2$	SSQ = Logit sum of squares between model brood year survival estimate and empirical survival estimate S_{ea}=Annual brood year fractional survival *empirical* estimate S_{ma}=Annual brood year fractional survival model estimate where

Model selection and evaluation

Sensitivity to uncertainty

The best model was identified by estimating uncertainty in annual measurements and comparing parametric bootstrap confidence limits of the coefficient of determination (R^2).

Uncertainty evaluation

Incorporating measurement error into parameter estimates

To incorporate likely error in the outmigrant and redds on the parameter estimates of the best fitting model, I calculated parametric bootstrap confidence intervals using multiple sources of uncertainty. One source of error in this modeling effort was the measurement of brood year survival by rotary screw trap. The accuracy and precision of estimating fish passage by rotary screw trap can vary with stream conditions, weather conditions, and fish populations (Schraml and Earley in progress). The uncertainty in estimating brood year survival was reported by the USFWS as confidence intervals (CI) on the annual abundance estimate. To approximate this uncertainty, a normal distribution was fit to these reported confidence intervals with the mean equal to the reported estimate and standard deviation that resulted in quantiles that equaled the upper and lower limits.

Another source of error in the modeling effort was the estimated number of redds. No well-established estimate for redd count uncertainty exists for Clear Creek spring run and the local USFWS methods. Based on local expert consultation, annual redd count error was estimated as +/- 20% (.95 CI) (Gallagher *Personal communication* USFWS, Red Bluff CA, Bottaro *Personal Communication* USFWS, Red Bluff CA). I evaluated the sensitivity of the model estimates to this source of error assuming a normal distribution with mean equal to the estimated number of redds for each year and coefficient of variation for the estimate of 20%.

The uncertainty in rotary screw trap passage estimate and redd enumeration were introduced following the procedures detailed in Martin (2016 A). The number of redds and outmigrating juveniles was randomly sampled from their respective distributions 200 times, generating 200 paired simulations of passage estimate and redd count. The best fitting model was re-run with each new dataset; keeping all other inputs (e.g., temperature, discharge) at their observed values. The ninety five percent bootstrap confidence interval for each parameter was estimated by the 0.025 and 0.975 percentiles for each parameter.

Error introduced by estimating the number of eggs per redd.

A major assumption of this modeling effort is that all redds initially contain the same number of live eggs. The best fitting model was run with possible eggs-per-redd numbers suggested by literature (Moyle 2002); other data was held constant. Model D was run 14 times with different values for the shared number of eggs per redd. Test values ranged from a minimum of 4000 eggs to a maximum of 17000 eggs in increments of 1000.

Sensitivity analysis

Sensitivity to yearly measurement error

A sensitivity analysis was completed to explore response of the best fitting model parameter estimates to variations in individual inputs. Juvenile passage estimates and redd count numbers were varied for each year according to the degree of uncertainty quantified above. For each input value, test values were generated 2 standard deviations (SD) above the mean, 1 SD above the mean, 1 unit above the mean, 1 unit below the mean, 1 SD below the mean and 2 SD below the mean (Figure 6, 7). The response of each model parameter to the perturbation of individual inputs was explored graphically.

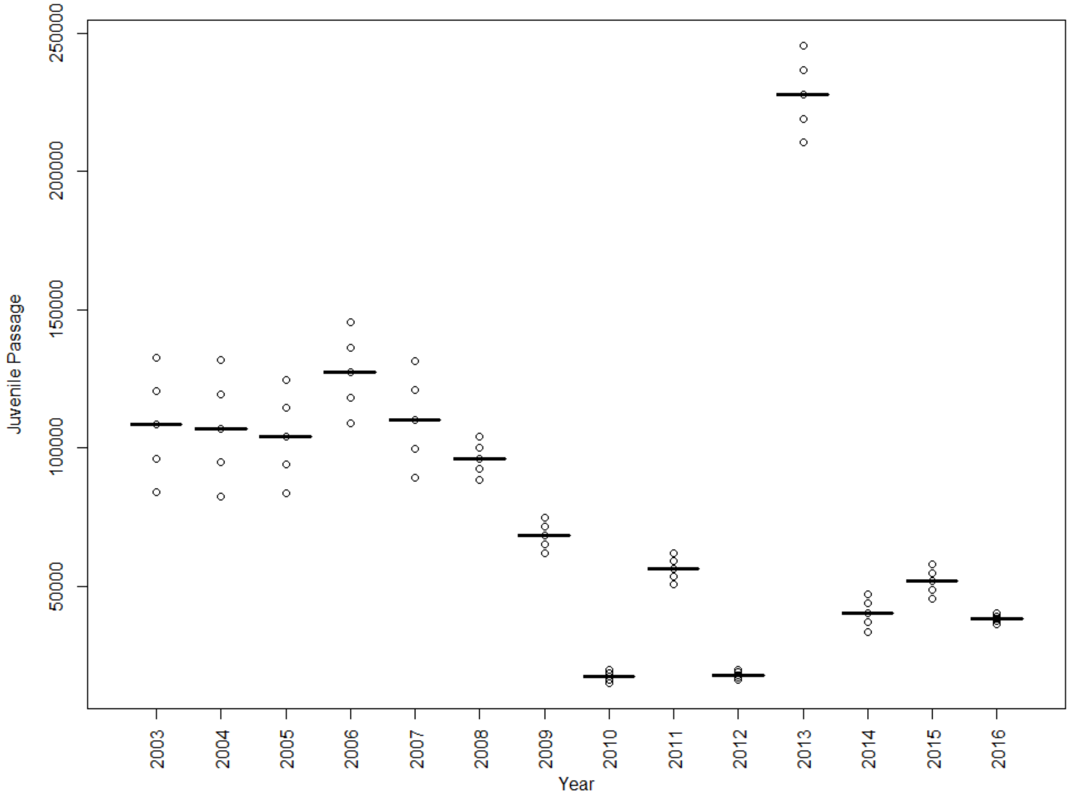

Figure 6. Juvenile passage test values used for sensitivity and elasticity analyses. For each year, a juvenile passage number was prepared, 2 standard deviations (SD) above the mean, 1 SD above the mean, 1 unit above the mean, 1 unit below the mean, 1 SD below the mean and 2 SD below the mean.

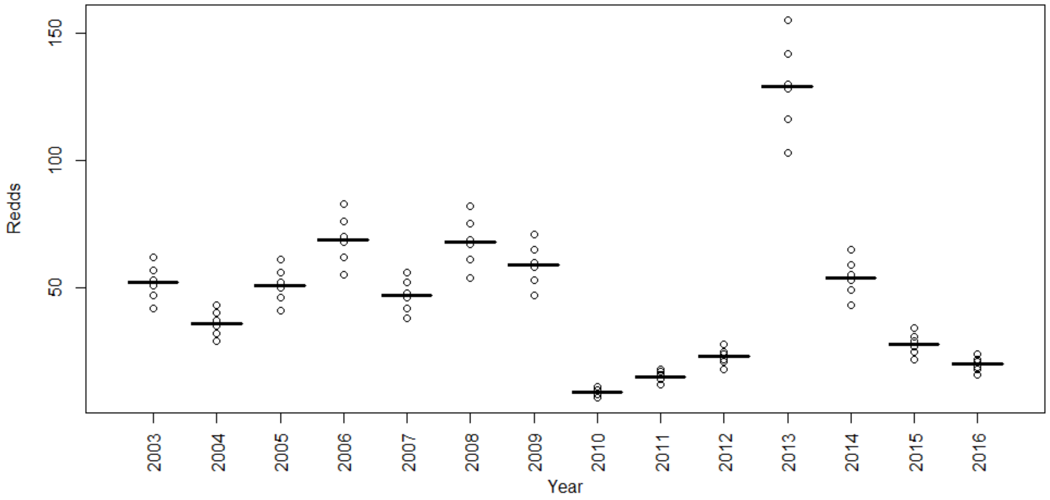

Figure 7. Redd count test values used for sensitivity and elasticity analysis. For each year, redd count numbers were prepared, 2 standard deviations (SD) above the mean, 1 SD above the mean, 1 unit above the mean, 1 unit below the mean, 1 SD below the mean and 2 SD below the mean.

Sensitivity to Systematic Error

The best fitting model was run to simulate systematic bias in the juvenile passage estimates and redd counts. The model was run eight times to explore the potential influence of systematic bias, four run where all juvenile passage estimates were varied and four runs where all redd counts were varied. The degree of systematic bias tested was based on the measurement uncertainty quantified above, each data set was modified: two standard deviations lower than the mean, one standard deviation lower than the mean, 1 standard deviation higher than the mean, 2 standard deviations higher than the mean.

Elasticity

An elasticity analysis was completed for the best fitting model to explore the relative influence of data input error upon model solution parameters. The test value set of juvenile passage and redd count was reduced from the sensitivity analysis; including only 2 standard deviations (SD) above the mean, 1 SD above the mean1 SD below the mean and 2 SD below the mean. For each test value, elasticity was calculated as:

$$Elasticity(x, y) = \frac{\Delta y}{\Delta x} * \frac{x}{y},$$

where x is the mean of the value being perturbed, y is the solution parameter calculated with mean estimated inputs. Δy and Δx are the degree of perturbation, and change in parameter solution respectively. For each pair of inputs and output, the four test values were averaged.

Sensitivity to temperature data source

The best fitting model was run with daily redd incubation temperature data from a fixed location, IGO gaging station rkm 17.9, rather than the temperature estimated from the temperature loggers closest to the redd. Results were compared to the base model.

Results and Discussion

Egg-to-Migration survival models

Discussion of parameter application

The nature of the model results presented here may require some interpretation for clarity. The four “critical” values (Tcrit, Tmid, Hflow_Crit and Lflow_Crit) can be interpreted directly, any mean daily measurement above (or below in the case of Lflow_Crit) these values is associated with an increase in daily mortality probability (or rate). The associated mortality rate terms (bT, Hflow_b, Lflow_b) require some more careful application. Mortality for a given day (given for each model in Table 2) is calculated as the exponential function of the -1 * the rate term * the degree beyond the critical value. For example, in Model A, if the *Tcrit* value was calculated to be 9.71 Celsius and *bT* was .0034. A daily mean temperature of 10.71 Celsius would indicate a daily survival probability of 0.9966 ($e^{(-1*0.0034*1)}$). If the temperature remained constant for the entire incubation period (50 days @ 10.71 C), the total survival due to temperature would be 0.9971^{50} or 0.844. Usefully, the quantity of measure beyond the critical value is linear; if on the first 5 days of incubation the critical temperature was exceeded by 10 degrees Celsius, and then the temperature dropped below the critical temperature for the remainder of incubation, total survival due to temperature would be 0.844, the same as the example above. The final parameter estimate in these models is *U*, model term independent survival; *U* may be best thought of as background survival from egg deposition to emigration passage.

Model A- Fixed temperature dependent mortality model

The fit of model A to empirical egg to migration survival estimates was the poorest, with a coiefficient of determination of 0.213 (Table 4). Model A results suggest that temperature dependent egg-to-fry mortality occurs at mean daily incubation temperatures above 9.7 C° , and the best fit hypothesis for the egg to migration background survival *U* was 64.84% (Table 5). The model parameters were substantially different than the parameters found in a similar analysis of winter run Chinook Salmon in a nearby system (Tcrit: 12.1, bT: 0.05905, U: 0.347; Martin et al. 2016 A). Compared with this study, our results suggest that thermal mortality begins at a lower temperature, that thermal mortality increases less per degree above this temperature and that more mortality can be explained by thermal exposure. It is important to note that the fit of our model of temperature dependent mortality for spring run Chinook Salmon on Clear Creek had a lower measure of fit (coefficient of determination 0.21; Figure 9) than the winter run Chinook Salmon model for the Sacramento River (coefficient of determination 0.66).

The parameters for this model do not reflect the literature values. A common threshold for in-redd temperature mortality used in aquaculture and fisheries management is 13.3 C°. Based on Model A results, a redd held at 13.3 C° from fertilization to emergence would experience significant temperature dependent mortality. Over 52% of the eggs in the redd would die due to temperature impacts. The large amount of evidence in published literature that indicates that thermal mortality occurs at a higher temperature than estimated by model A suggests that the estimate from model A is probably unreliable and should not be used for management.

Table 4. Model fitting statistics for the four alternative models of redd to outmigrant survival. R^2 is the coefficient of determination calculated between survival as predicted by the indicated Model and estimated by rotary screw trap. SSQ is the logit sum of squares, and was minimized in the optimization routine. K is the number of parameters estimated.

	Model			
Fit Statistics	**A**	**B**	**C**	**D**
R^2	0.213	0.332	0.323	0.738
SSQ	5.732	4.437	4.962	1.83
K	3	5	4	8

Table 5. Parameter estimates, standard errors (in parenthesis), and 95% confidence limits [in brackets] estimated for the four alternative models of redd to out-migrant survival. Parameters are defined in Table 1 above. A dash indicates that standard error could not be calculated for the corresponding parameter and NA indicates that the parameter was not included in model.

	Model			
Parameter	**A**	**B**	**C**	**D**
Tcrit	9.71 (0.477) [8.77-10.64]	*NA*	10.26 (0.970) [8.36-12.16]	8.46 (0.825) [6.84-10.08]
bT	0.003 (0.001) [0.001 -0.005]	*NA*	0.008 (0.003) [0.004-0.013]	0.007 (0.002) [0.002-0.011]
U	0.648 (0.074) [0.503-0.793]	0.499 (0.0561) [0.389-0.609]	0.543 (0.061) [0.423-0.663]	0.782 (0.084) [0.617-0.947]
Tmid	*NA*	*NA*	9.82 (.818) [8.22-11.42]	11.45 (0.973) [0.617-0.947]
Hflow_Crit	*NA*	31.15 (-)	*NA*	29 (-)
Hflow_b	*NA*	24.28 (-)	*NA*	16.35 (-)
Lflow_Crit	*NA*	6.15 (0.157) [5.84-6.46]	*NA*	6.64 (0.165) [6.31-6.96]
Lflow_b	*NA*	0.011 (0.004) [6.31-6.96]	*NA*	0.018 (0.018) [0.0-0.036]

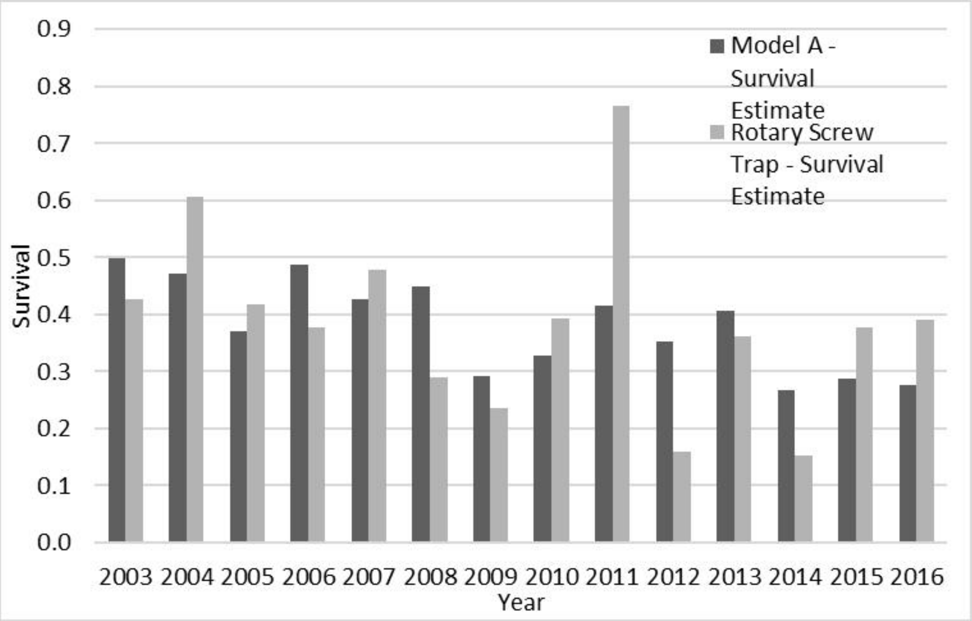

Figure 8. Brood year survival as predicted by Model A and estimated by Rotary Screw Trap.

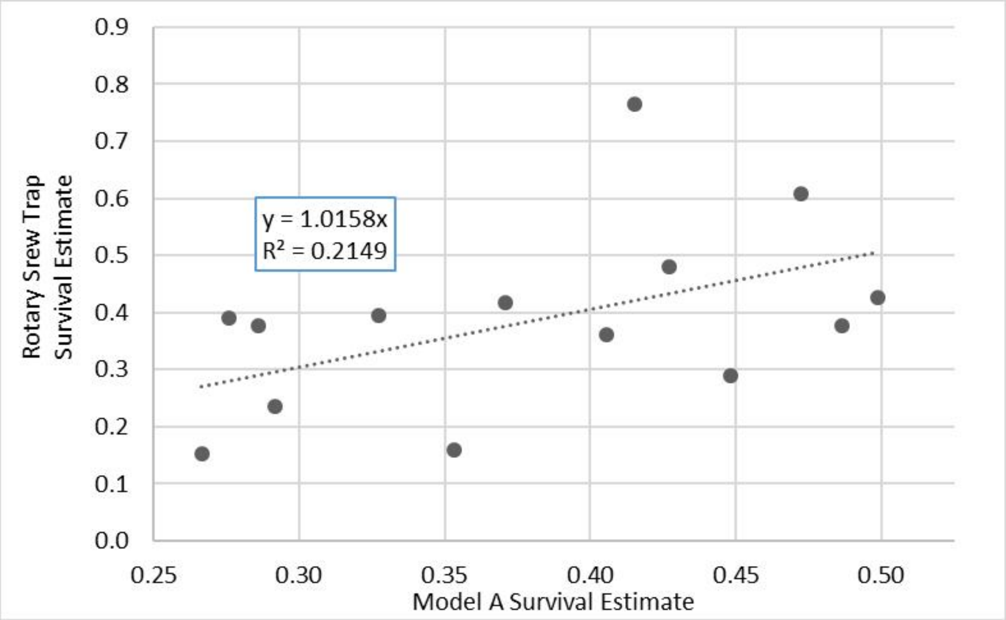

Figure 9. Simple linear regression of brood year survival as predicted by Model A and estimated by Rotary Screw Trap (broken line) and observed values (points). Regression assumes intercept is fixed at zero.

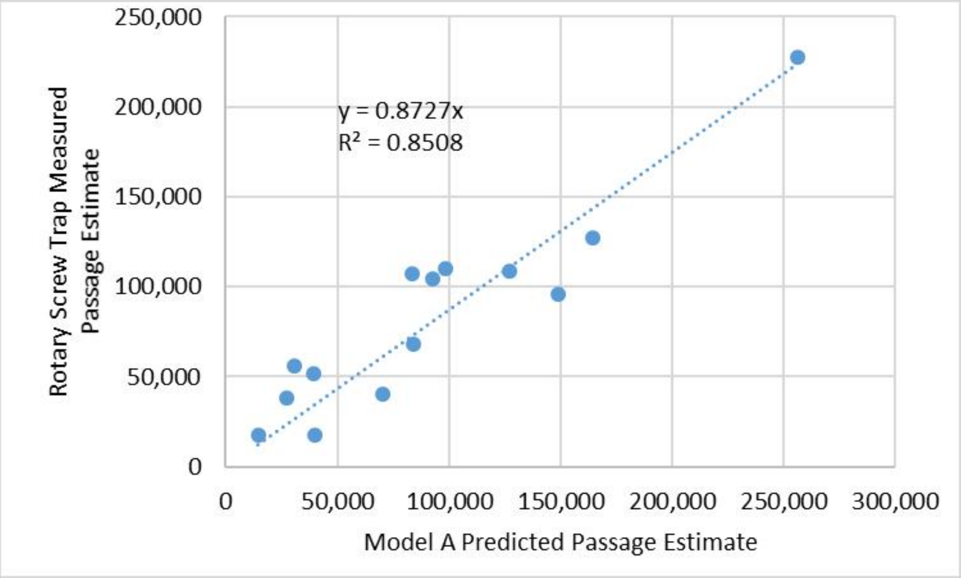

Figure 10. Simple regression of juvenile Spring Run Chinook Salmon Passage as predicted by Model A and estimated by Rotary Screw Trap (broken line) and observed values (points). Regression assumes intercept is fixed at zero.

Model B-Discharge dependent mortality

Discharge dependent mortality, as represented in model B, explained nearly 34% of the variation in measured brood year survival (Table 4 and Figure 12). The daily mean discharge above which mortality is predicted to occur was estimated as 31.12 cubic meters per second (CMS) and may indicate mortality as a result of redd scour (Table 5). According to anecdotal evidence from stream surveys in the survey area, redds are often flattened after a discharge event of this magnitude. The survival penalty for a discharge above 31.12, is very high. This value is best interpreted as catastrophically reduced survival in redds when flow exceeds the critical value; the parameters suggest less than 1 percent daily survival for a 0.2 CMS increase in mean daily discharge. Parameter estimates of survival reduction due to low flow suggest a modest reduction in survival, for a relativity low discharge in the dataset (Figure 3). Discharge appears to describe some of the mortality observed in redds. However, the results of the model may be misleading due to the spread of the input data. A mean daily discharge of 31.12 CMS is a sizeable storm event on Clear Creek and in most cases, the instantaneous peak discharge within a day can be a much higher value than the mean daily discharge. This suggests that information about discharge dependent mortality would better be assessed at a smaller time scale than daily, or by maximum daily flow. An investigation of velocity at the redd site also might provide more information than stream wide discharge.

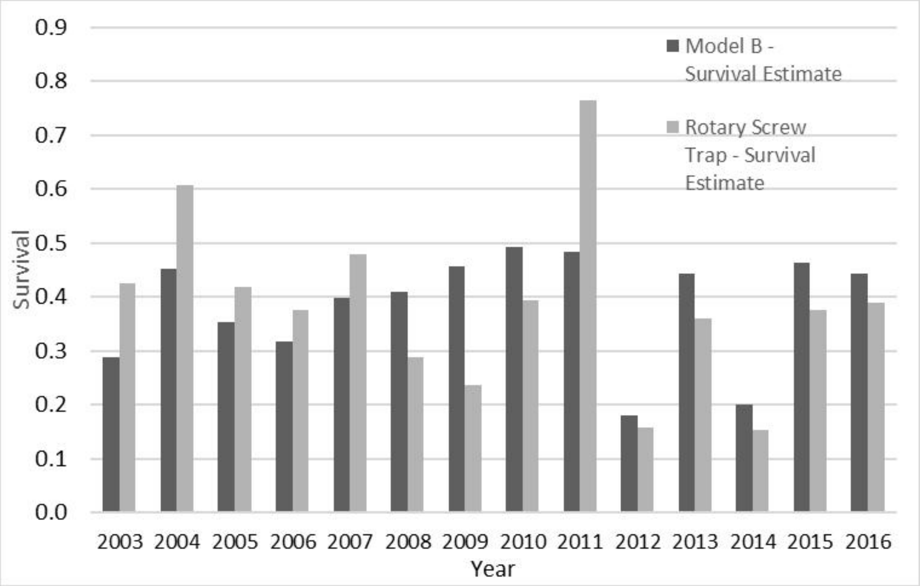

Figure 11. Brood year survival as predicted by Model B and Rotary Screw Trap

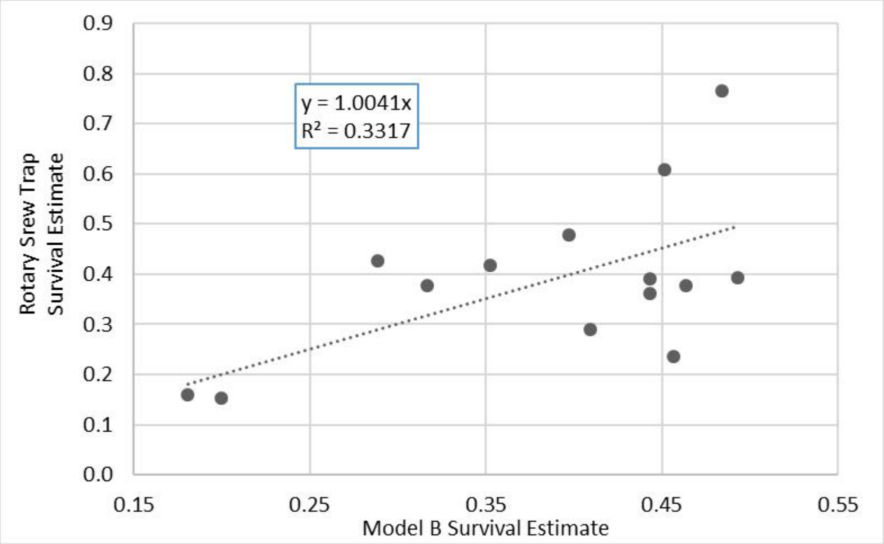

Figure 12. Simple linear regression of brood year survival as predicted by Model B and estimated by Rotary Screw Trap (broken line) and observed values (points). Regression assumes intercept is fixed at zero.

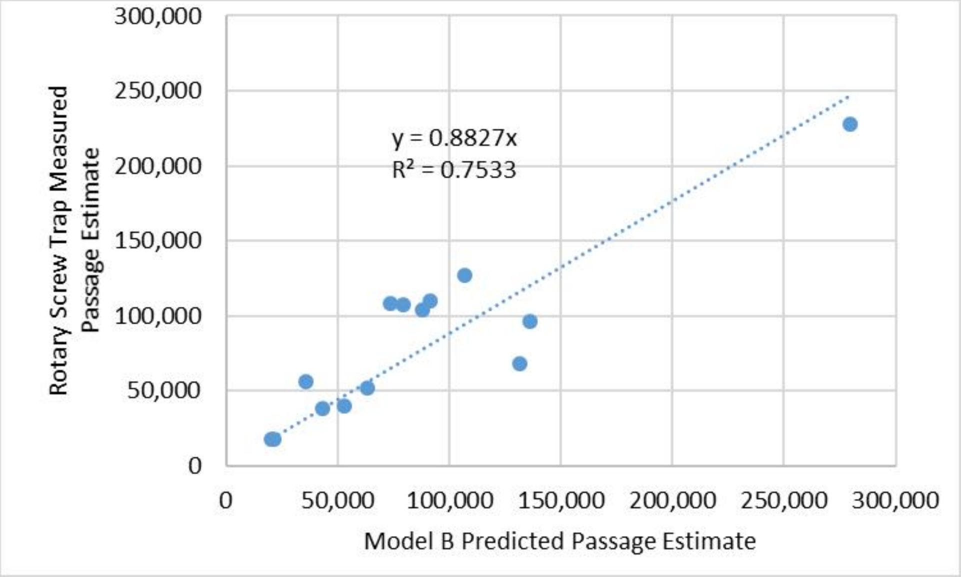

Figure 13. Simple regression of juvenile Spring Run Chinook Salmon Passage as predicted by Model B and estimated by Rotary Screw Trap (broken line) and observed values (points). Regression assumes intercept is fixed at zero.

Model C-Variable temperature dependent mortality model

Variable temperature dependent mortality, as structured in model C, explained less than a third of the variation in measured brood year survival (Table 4, Figure 15). Both the high and low temperature mortality thresholds suggested by this model were greater than the mortality threshold temperature suggested by the fixed temperature dependent model (Table 5). The survival penalty for each degree above the threshold temperature was also greater. Finally, the temperature independent survival was slightly lower for this model than the fixed temperature dependent mortality model, which suggests this model attributed less mortality to temperature than Model A. While the threshold temperatures were still far lower than reported in the literature, the slight increase in temperature sensitivity before hatching is supported by lab findings (Ciuhandu 2007).

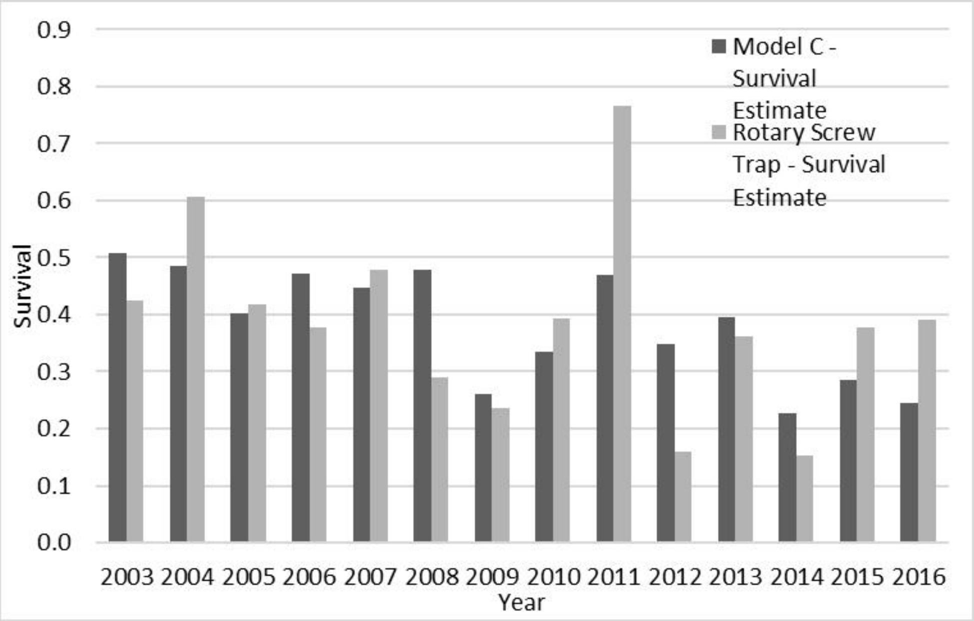

Figure 14. Brood year survival as predicted by Model C and Rotary Screw Trap

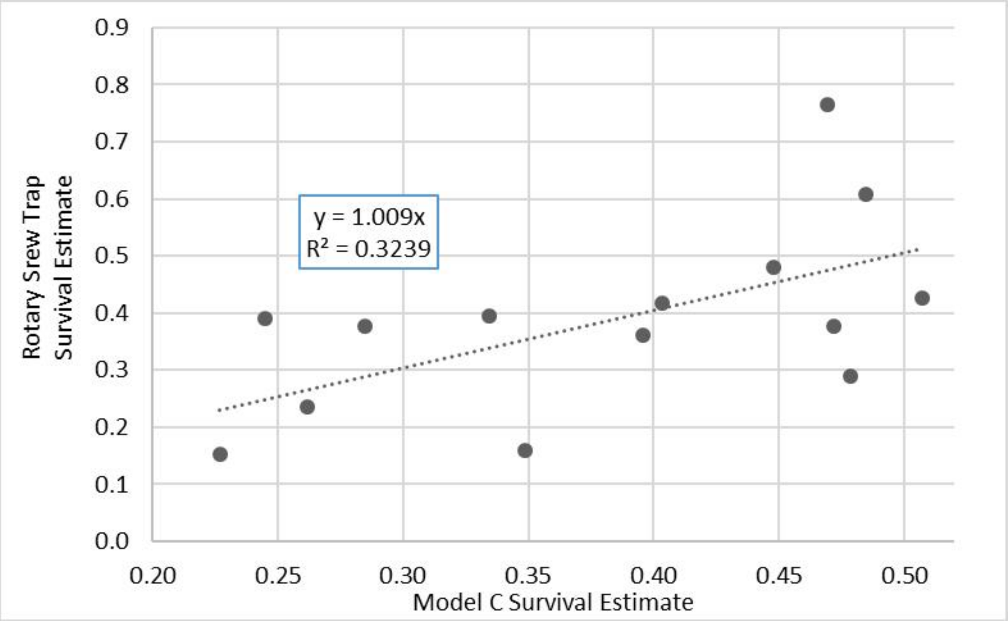

Figure 15. Simple linear regression of brood year survival as predicted by Model C and estimated by Rotary Screw Trap (broken line) and observed values (points). Regression assumes intercept is fixed at zero.

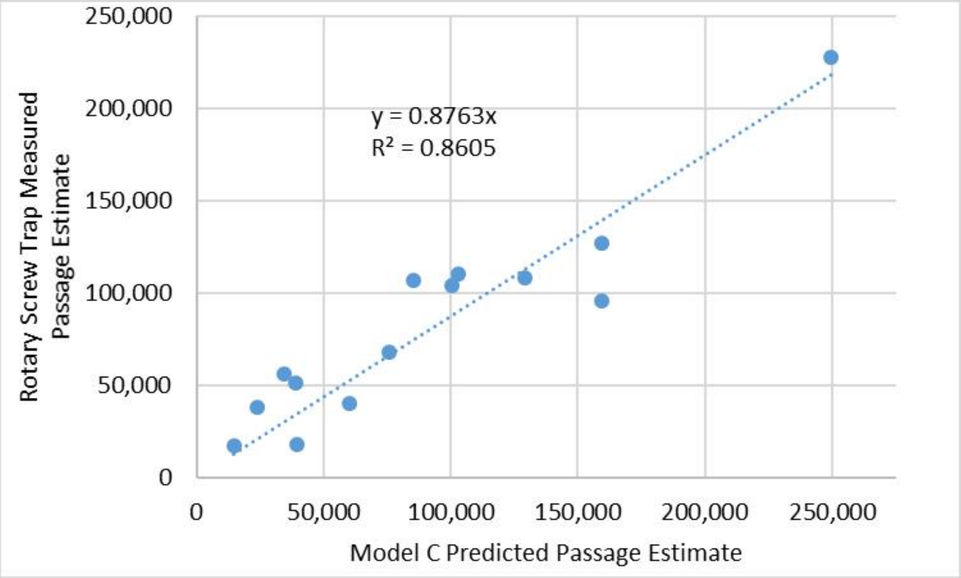

Figure 16. Simple regression of juvenile Spring Run Chinook Salmon Passage as predicted by Model C and estimated by Rotary Screw Trap (broken line) and observed values (points). Regression assumes intercept is fixed at zero.

Model D - Variable temperature and discharge dependent mortality model

This model explained nearly 74% of the variation in measured brood year survival (Table 4, Figure 18). The model term independent survival, U, was higher for this model than models A-C, suggesting the model could more often explain brood year survival better than an average value (Table 5). As with all three temperature models, the temperature based mortality threshold was lower than suggested by the literature. In contrast with model B, which modeled variable temperature dependent mortality alone, temperature sensitivity was found to be lower in the middle of development (i.e., a higher critical temperature at hatching). This finding was not supported by lab studies that suggest sensitivity is the greatest at the middle of incubation (Ciuhandu 2007). For the data used in this study, brood year survival is best explained by the temperatures found in the final quarter of development. The parameter estimates set likely reflect the nature of the data. The model and optimization routine was able to fit the temperature dependent survival and discharge accounted for some of the mortality. The critical high mean daily discharge was slightly lower for this model and with a slightly lower survival penalty than the discharge only model. This result may be more accurate than models A-C because multiple sources of mortality were incorporated.

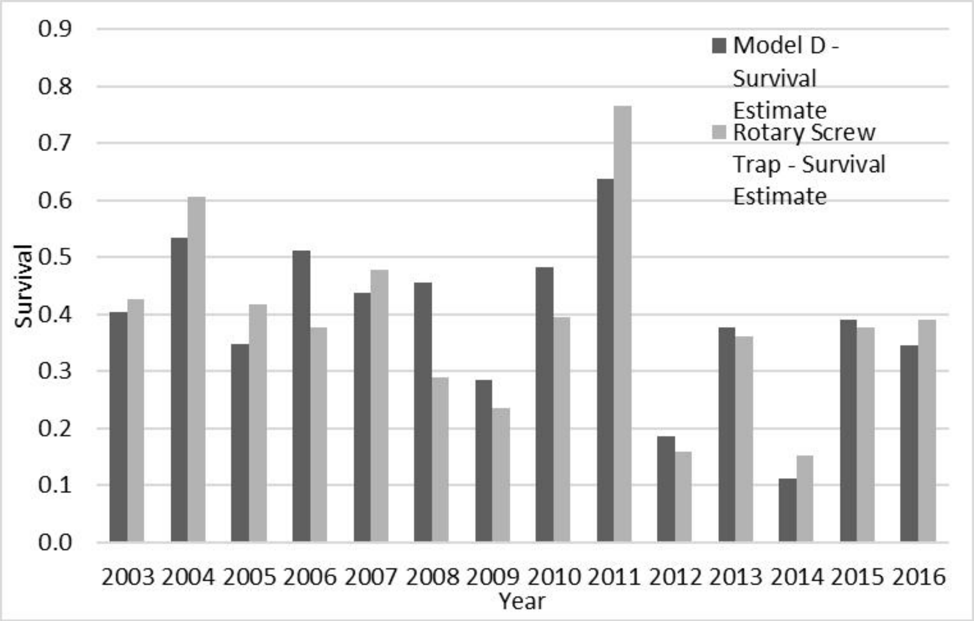

Figure 17. Brood year survival as predicted by Model D and Rotary Screw Trap

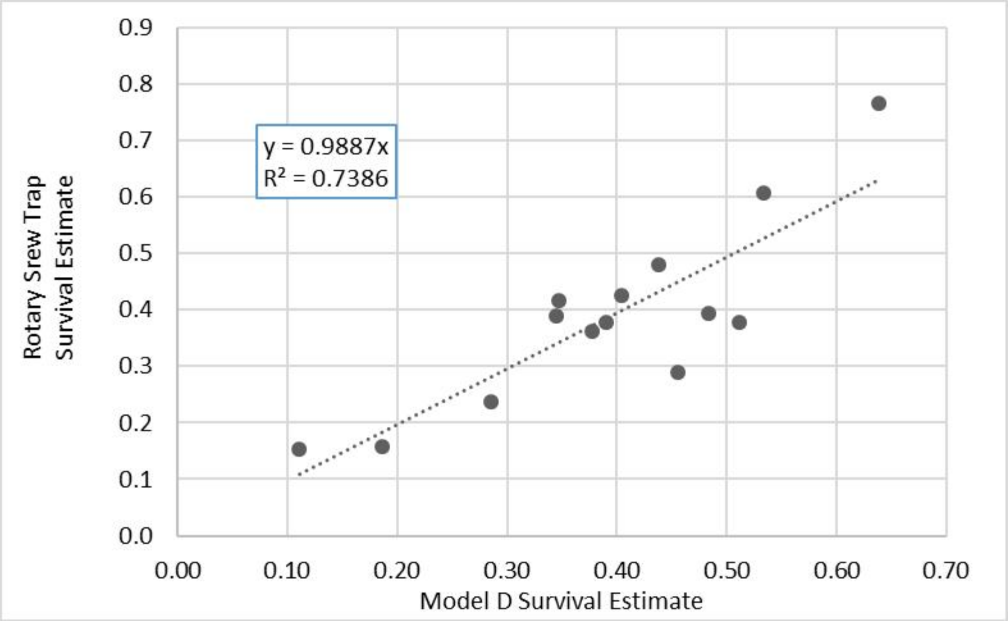

Figure 18. Simple linear regression of brood year survival as predicted by Model B and estimated by Rotary Screw Trap (broken line) and observed values (points). Regression assumes intercept is fixed at zero.

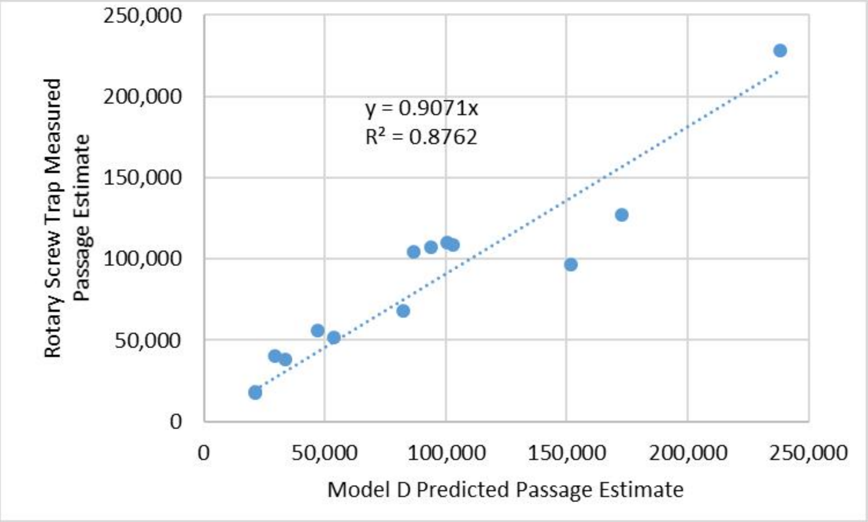

Figure 19. Simple regression of juvenile Spring Run Chinook Salmon Passage as predicted by Model D and estimated by Rotary Screw Trap (broken line) and observed values (points). Regression assumes intercept is fixed at zero.

Uncertainty evaluation

Model selection sensitivity to uncertainty

Error in outmigrant and redd estimates did not change the model that best described estimated survival (Figure 20). The range of coefficient of determination for models A, B and C overlap, it is possible that error in the outmigration estimate or redd count could alter the “best” model among these three. However, the range of coefficient of determination for Model D does not overlap with the other models. Thus, it is very unlikely that error in migration estimate or redd count would suggest any other model better describes juvenile survival to migration. The remainder of analysis will focus on Model D, the best fitting model.

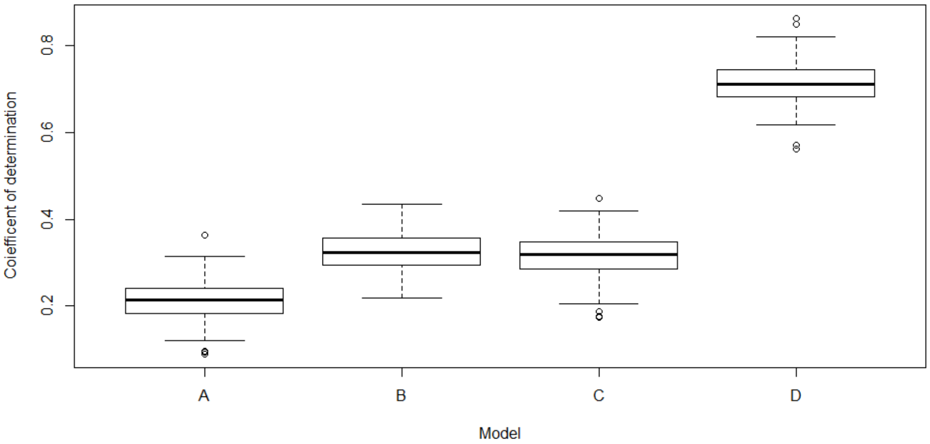

Figure 20. This boxplot displays the range of coefficients of determination for each model, generated by resampling brood year survival and redd count from statistical distributions representing expected error in the estimates.

Incorporating measurement error into parameter estimates

The incorporation of redd enumeration and brood year survival uncertainty increased range of likely parameter estimates within the structure of Model D (Table 6). The model estimates of temperature and discharge independent survival fluctuated from 66 to 100 percent; for some datasets the model was best minimized by suggesting each redd started with 66 percent survival, for other datasets the model was best fit by starting each redd with 100 percent survival. The range of the 95 percent confidence interval for temperature parameters was proportionally greater than for flow parameters. The critical high discharge and associated mortality penalty did not vary with randomly generated values of outmigrants and redds. It is critical that this result is not interpreted as 100 percent confidence that mortality begins above 29 CMS on Clear Creek, instead this result may say more about the distribution of available data. The 95 percent confidence interval for the "fit" of the model, as coefficient of determination, ranged between 80 and 74 percent. This high level of fit between model output and measured values might suggest a high potential management utility; but as with the discharge result this level of fit may be strongly shaped by the available data. For example, the Tcrit parameter varied nearly 4 Celsius to achieve this high level of fit. This model will improve with additional data input. Beyond error from unidentified sources of mortality and incorrect model structure, error in input data may play a role in the potential inaccuracy of the final result. A critical assumption of this approach to introduce uncertainty is the weighted distribution of redds in the creek, and the temperature to which they are exposed, does not change.

Table 6. Model D bootstrap confidence limits derived from brood year survival and redd count uncertainty

	Tcrit	bT	U	Tmid	Hflow_Crit	Hflow_b	Lflow_Crit	Lflow_b	Coeff. of Determ.
Mean	8.46	0.007	0.7816	11.45	1023.84	0.463	234.35	0.0005	0.738
95% CI -Low	6.385	0.005	0.6632	10.09	1023.84	0.463	231.505	0.0004	0.634
95% CI -High	10.37	0.009	1	12.105	1023.84	0.463	244.787	0.0006	0.8

Error introduced by estimating the number of eggs per redd.

Varying only the number of initial eggs in each redd led to significant changes in a few parameters. The coefficient of determination was highest at the test value (5,000 eggs) closest to the assumption value used by this model (4,895) (Figure 21). The two parameters describing critical temperature thresholds, Tmid and Tcrit, moved closer to each other as the number of eggs increased (Figure 22). The final two parameters that fluctuated largely with initial egg number were the critical low discharge temperature and temperature and discharge independent mortality. The critical low flow magnitude showed a positive correlation with initial egg count and temperature and discharge independent mortality showed a negative correlation with initial egg count (Figure 23). A single shared initial egg count for all redds is a known poor assumption. These results suggest that the value selected may be reasonable.

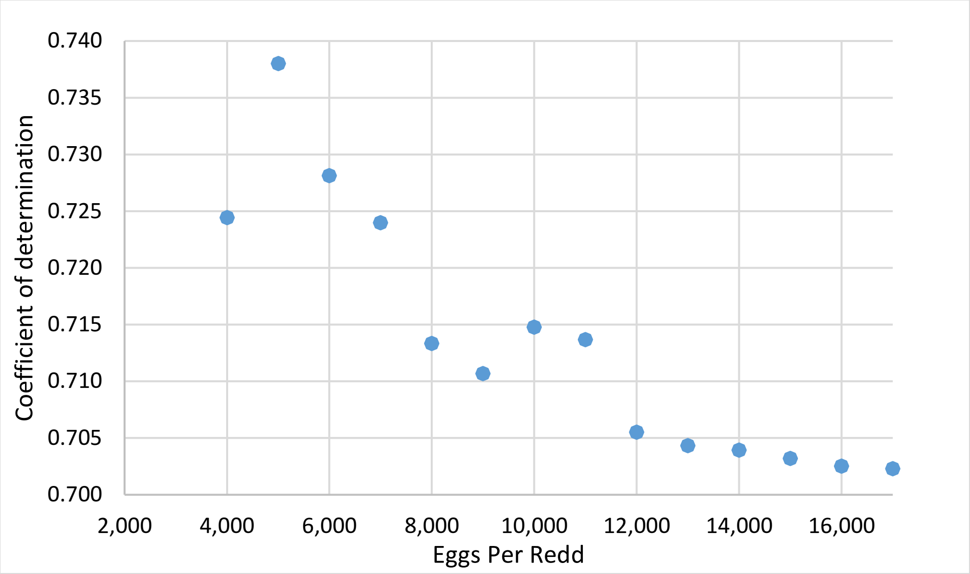

Figure 21. Mean coefficient of determination by number of initial eggs per redd, as calculated by optimizing model D, the best fitting model. The base model in this analysis uses a value of 4,985 eggs.

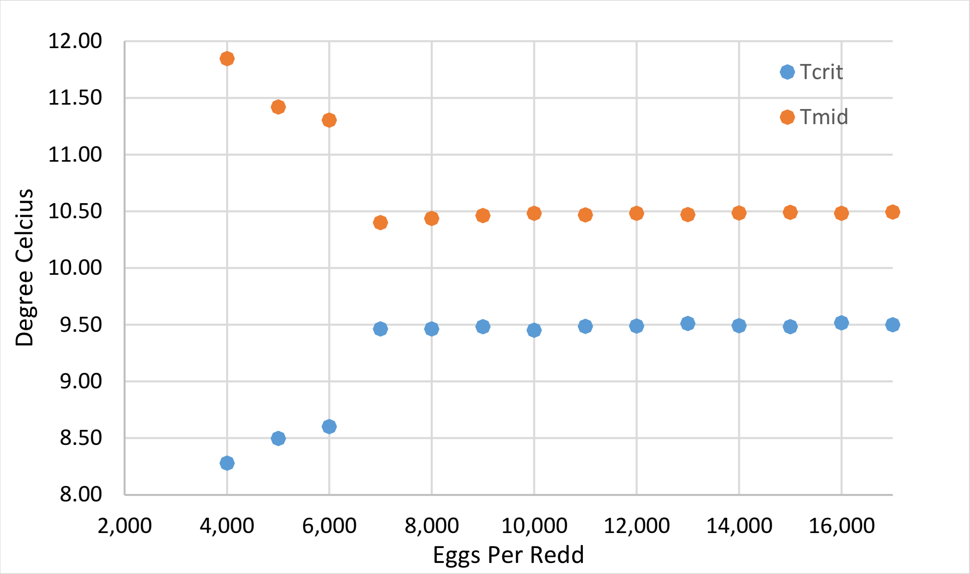

Figure 22. Tcrit and Tmid by number of initial eggs per redd, as calculated by optimizing model D. The base model in this analysis uses a value of 4,985 eggs.

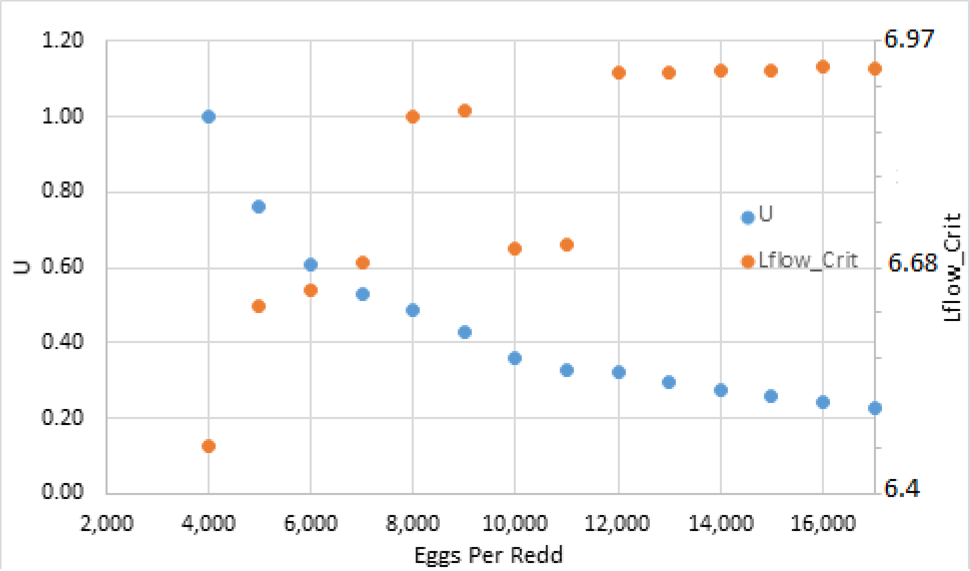

Figure 23. U and LFlow_Crit by number of initial eggs per redd, as calculated by optimizing model D. The base model in this analysis uses a value of 4,985 eggs.

Sensitivity analysis

Sensitivity to yearly measurement error

Many of the parameters in the solution-set for Model D were very sensitive to the fluctuation of individual input data points. The response of each individual parameter fell into one of three categories: some output parameters showed no fluctuation over the range of values tested for any input value, other parameters exhibited large fluctuations in response to perturbations in a few particular data points, and other parameters showed some sensitivity to many of the input points perturbed.

The critical high discharge value and associated mortality coefficient did not fluctuate over the range of test values. This was also the finding when all inputs were varied in the uncertainty analysis.

Tcrit and Tmid parameter estimates fluctuated greatly with variation in both the Juvenile passage index and redd counts made in 2004 and 2011 (Figure 25, Figure 28). Individually, each of these four input values could alter the overall Tcrit model estimate over 1 Degree C. This seems to be a high level of influence of a single estimate upon the modeling result.

All other parameters showed some response to fluctuation in individual input values (Figures 24, 26, 27, 29, 30). In general, response of all dynamic parameters appears to be greatest for 2004 and 2011 values, these were the two years when empirically measured survival was the highest.

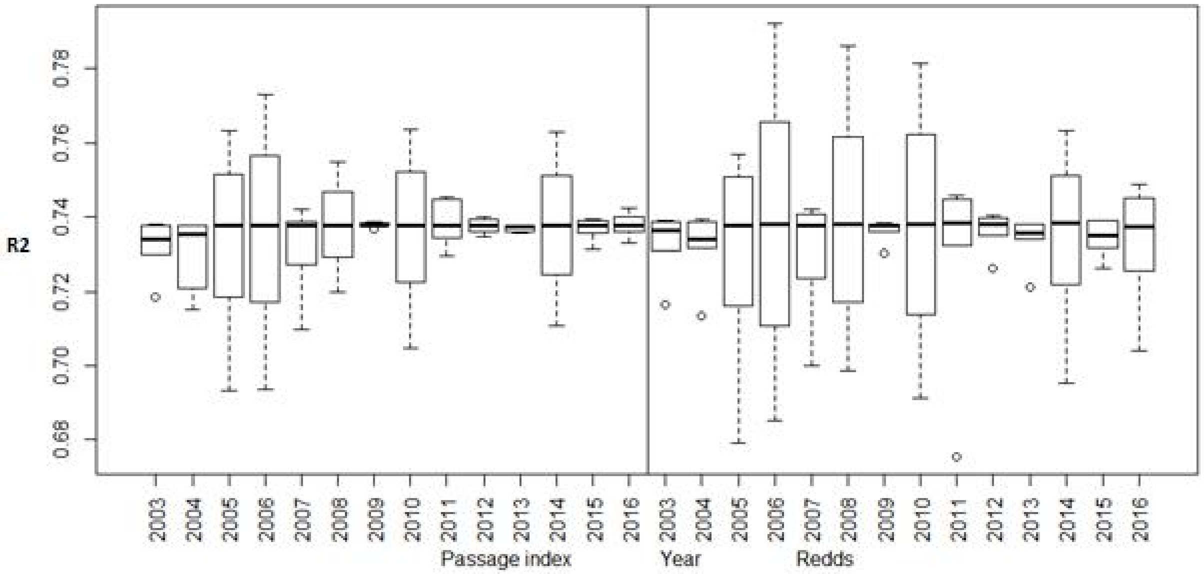

Figure 24. Range of Coefficient of Determination in response to alteration of individual input value. For each input, test values were generated 2 standard deviations (SD) above the mean, 1 SD above the mean, 1 unit above the mean, 1 unit below the mean, 1 SD below the mean and 2 SD below the mean (Figure 6, 7).

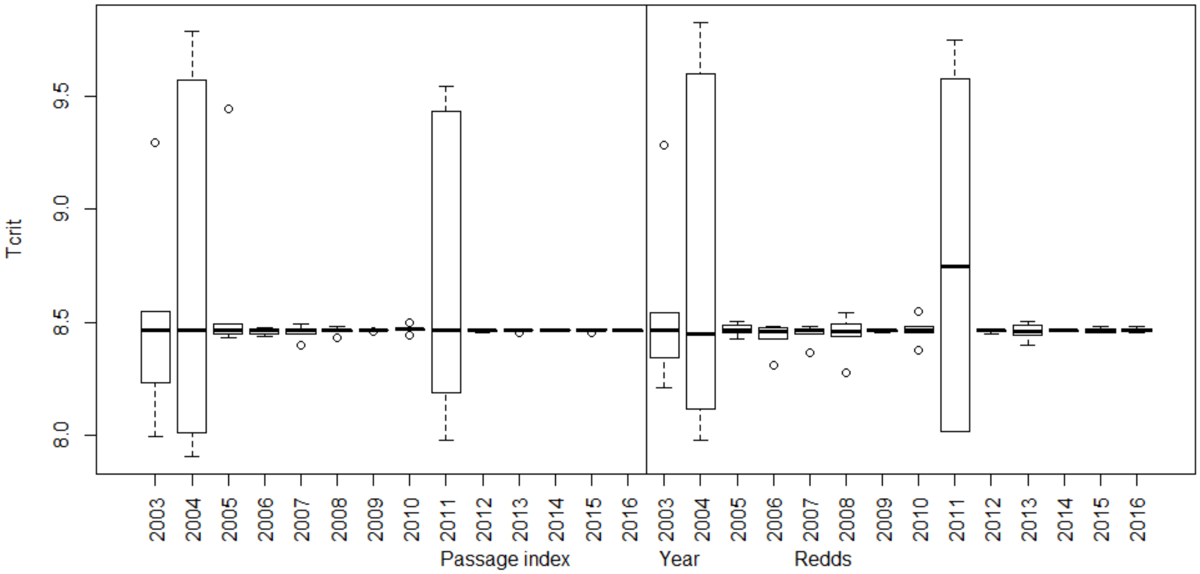

Figure 25. Range of Tcrit parameter solutions in response to alteration of individual input value. For each input, test values were generated 2 standard deviations (SD) above the mean, 1 SD above the mean, 1 unit above the mean, 1 unit below the mean, 1 SD below the mean and 2 SD below the mean (Figure 6, 7).

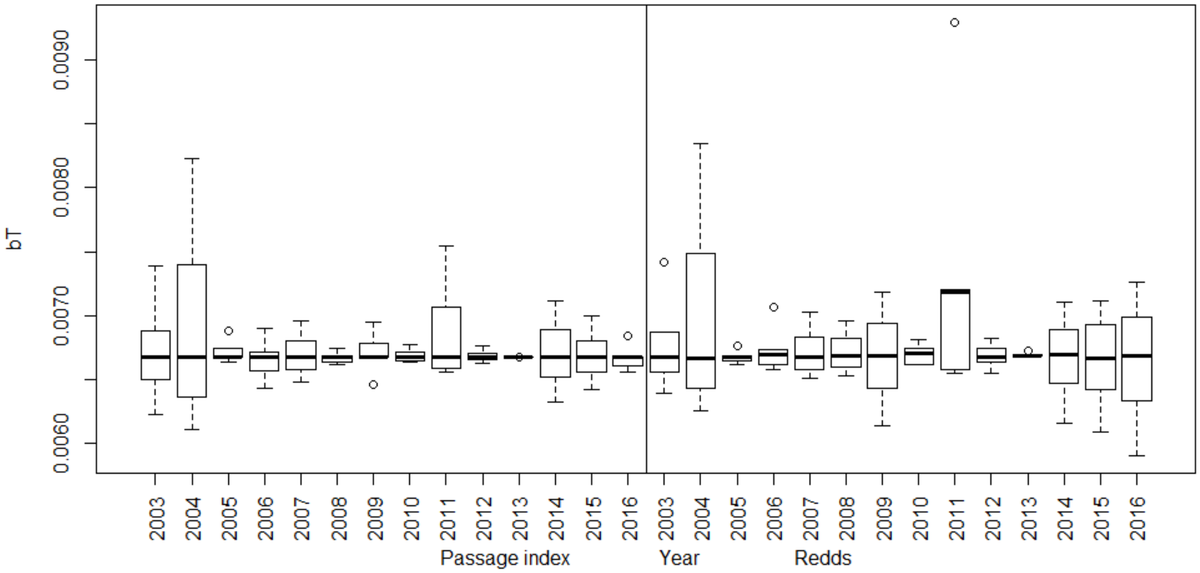

Figure 26. Range of bT parameter solutions in response to alteration of individual input value. For each input, test values were generated 2 standard deviations (SD) above the mean, 1 SD above the mean, 1 unit above the mean, 1 unit below the mean, 1 SD below the mean and 2 SD below the mean (Figure 6, 7).

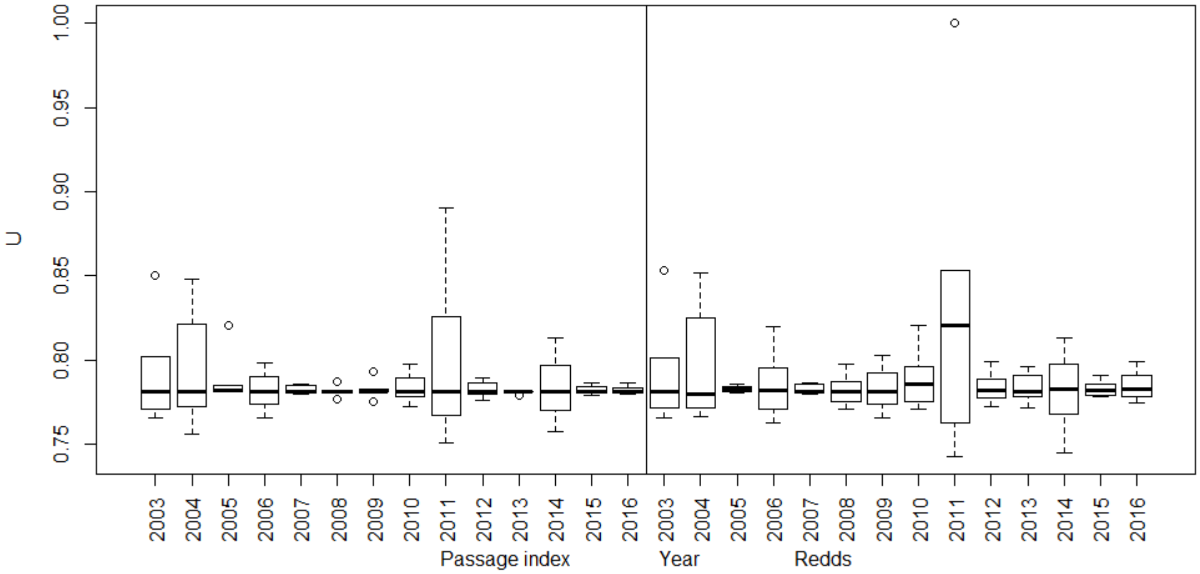

Figure 27. Range of U parameter solutions in response to alteration of individual input value. For each input, test values were generated 2 standard deviations (SD) above the mean, 1 SD above the mean, 1 unit above the mean, 1 unit below the mean, 1 SD below the mean and 2 SD below the mean (Figure 6, 7).

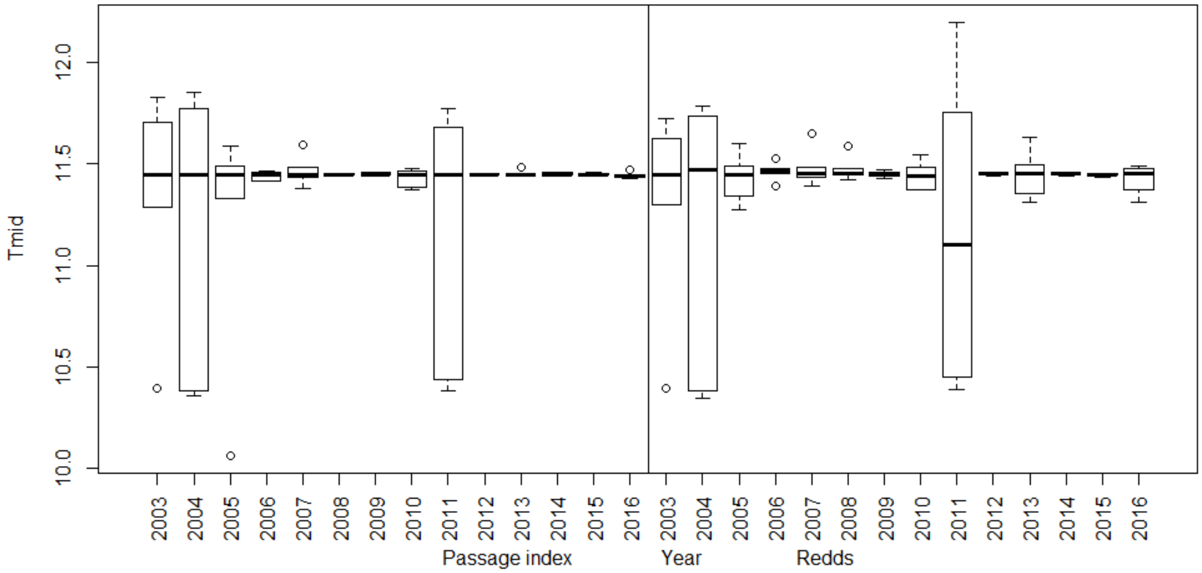

Figure 28. Range of Tmid parameter solutions in response to alteration of individual input value. For each input, test values were generated 2 standard deviations (SD) above the mean, 1 SD above the mean, 1 unit above the mean, 1 unit below the mean, 1 SD below the mean and 2 SD below the mean (Figure 6, 7).

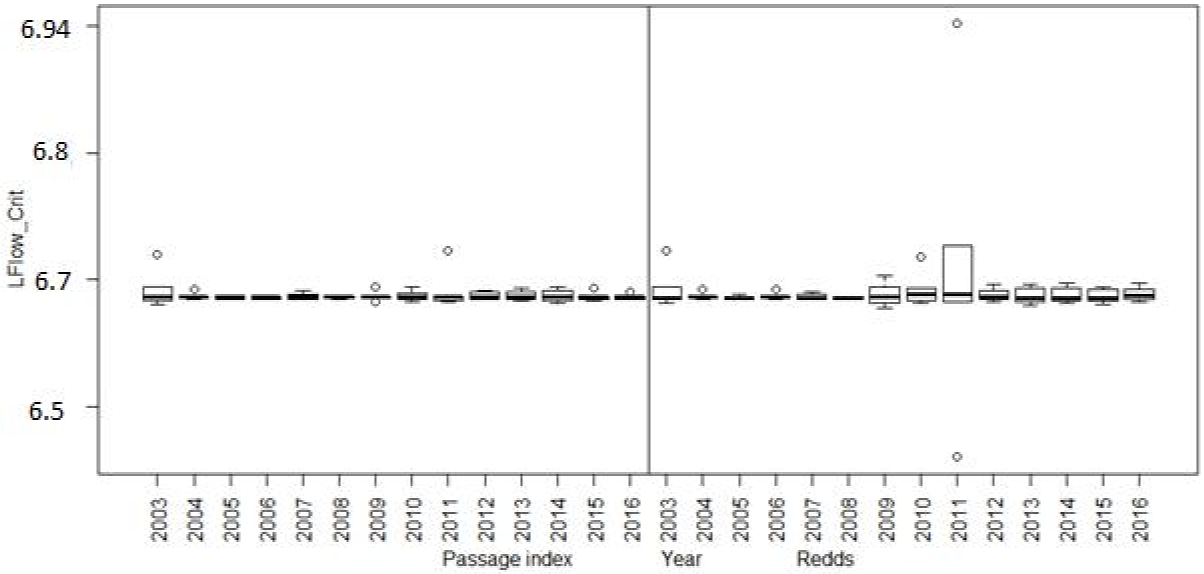

Figure 29. Range of LFlow_Crit parameter solutions in response to alteration of individual input value. For each input, test values were generated 2 standard deviations (SD) above the mean, 1 SD above the mean, 1 unit above the mean, 1 unit below the mean, 1 SD below the mean and 2 SD below the mean (Figure 6, 7).

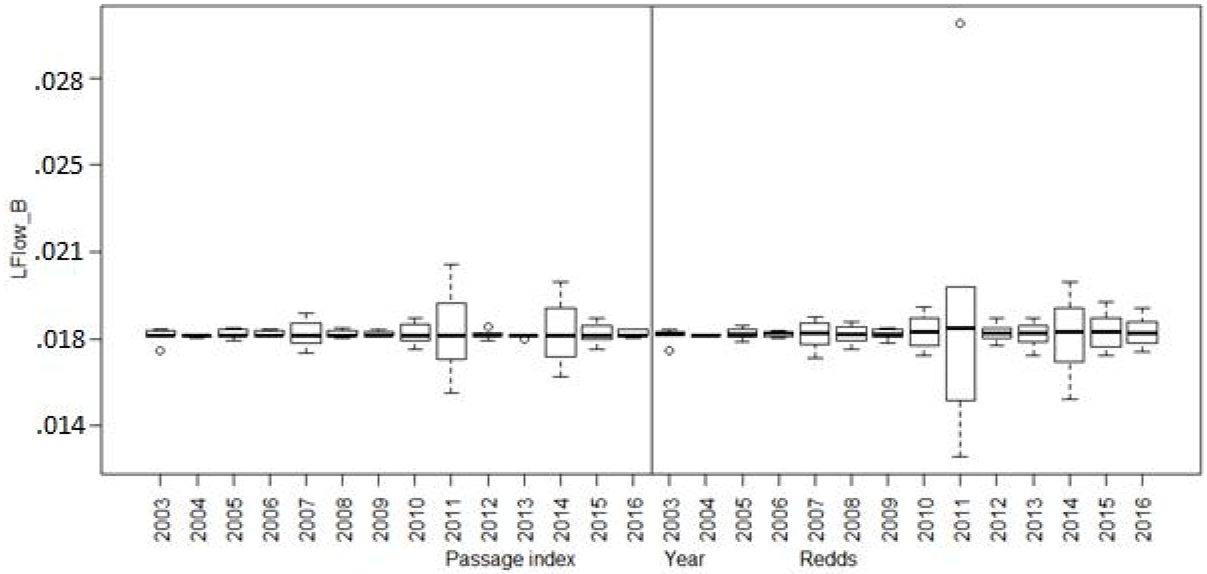

Figure 30. Range of LFlow_B parameter solutions in response to alteration of individual input value. For each input, test values were generated 2 standard deviations (SD) above the mean, 1 SD above the mean, 1 unit above the mean, 1 unit below the mean, 1 SD below the mean and 2 SD below the mean (Figure 6, 7).

Sensitivity to Systematic Error

Simulation of systematic error lead to large variations in some parameter estimates and had little influence on other parameter estimates (Table 7). The range of parameter estimates due to systematic error is similar to the range of parameter estimates due to error in the single value to which a parameter was most sensitive. Notably, the coefficient of determination was quite consistently high despite the introduction of systematic error.

Table 7. Response of Model D parameter estimates to fixed levels of error shared by all similar measurements. e.g. in the Juvenile Passage +2 SD treatment, all passage estimates were increased by 2 standard deviations prior to parameter estimation.

Treatment	**Tcrit**	**bT**	**U**	**Tmid**	**Hflow_crit**	**Hflow_b**	**Lflow**	**Lflow_b**	**R2**
Juvenile Passage +2SD	9.549	0.008	0.976	10.373	28.992	16.421	6.633	0.035	0.719
Juvenile Passage +1SD	8.624	0.007	0.862	11.288	28.992	16.421	6.635	0.035	0.726
Juvenile Passage -1SD	8.17	0.006	0.714	11.687	28.992	16.421	6.635	0.035	0.746
Juvenile Passage -2SD	7.962	0.006	0.651	11.775	28.992	16.421	6.633	0.035	0.747
Redd Count +2 SD	8.605	0.006	0.623	11.296	28.992	16.421	6.651	0	0.722
Redd Count +1 SD	8.605	0.006	0.678	11.297	28.992	16.421	6.652	0	0.731
Redd Count - 1 SD	8.507	0.007	0.889	11.386	28.992	16.421	6.63	0.035	0.748
Redd Count - 2 SD	8.213	0.008	1	12.32	28.992	16.421	6.403	0.035	0.72

Elasticity

The relative sensitivity of model parameters to data input error, or elasticity, provides some insight into the driving forces of this model (Table 8). All output parameters and data inputs weighted equally, this model is slightly more sensitive to redd count error (.130) than Juvenile passage estimation error (.124). As was suggested by the sensitivity analysis, redd count and juvenile passage from 2004 and 2011, had some of the highest influence on parameter estimates. The elasticity associated with redd count error in 2011 (.613) and 2004 (.273) was closely mirrored by the juvenile passage error in 2011 (.619) and 2004 (.252). Overall The Lflow_b parameter was the most sensitive to input variation (.288), closely followed by bT (.286). Interestingly, these patterns were not as strong in the sensitivity of coefficient of variation to input variation. As expected, the model fit was kept more constant by capitalizing on the mortality explained by variation in model parameters. One limitation to the approach here is that elasticity was only calculated at 4 uncertainty scaled test values for each relationship. Elasticity could vary at finer scale than this. These elasticity results are good indication of how a good level of fit is achieved by this approach.

Table 8. Elasticity of Model D parameters to fluctuation in input data. Greater parameter (columns) sensitivity to error in specific inputs (rows) is indicated by a higher elasticity value at the intersection of a row and column. The color scale reflects this relationship; warmer colors indicate lower sensitivity of a parameter.

	R2	Tcrit	bT	U	Tmid	Hflow_Crit	Hflow_Bt	Lflow_Crit	LFlow_bT	Params (Mean)
Juvenile Count (Mean)	0.143	0.169	0.266	0.156	0.134	0.000	0.000	0.009	0.260	0.124
Juvenile Passage 2003	0.063	0.252	0.321	0.209	0.221	0.000	0.000	0.015	0.079	0.137
Juvenile Passage 2004	0.072	0.643	0.685	0.263	0.409	0.000	0.000	0.003	0.014	0.252
Juvenile Passage 2005	0.235	0.166	0.071	0.079	0.206	0.000	0.000	0.002	0.075	0.075
Juvenile Passage 2006	0.371	0.019	0.199	0.143	0.021	0.000	0.000	0.003	0.071	0.057
Juvenile Passage 2007	0.104	0.021	0.178	0.024	0.036	0.000	0.000	0.004	0.232	0.062
Juvenile Passage 2008	0.292	0.024	0.099	0.053	0.006	0.000	0.000	0.004	0.143	0.041
Juvenile Passage 2009	0.012	0.003	0.280	0.066	0.012	0.000	0.000	0.010	0.088	0.057
Juvenile Passage 2010	0.298	0.018	0.079	0.112	0.044	0.000	0.000	0.009	0.269	0.066
Juvenile Passage 2011	0.122	1.180	0.732	0.809	0.847	0.000	0.000	0.025	1.357	0.619
Juvenile Passage 2012	0.037	0.010	0.083	0.077	0.008	0.000	0.000	0.010	0.096	0.035
Juvenile Passage 2013	0.020	0.007	0.002	0.011	0.017	0.000	0.000	0.014	0.032	0.010
Juvenile Passage 2014	0.212	0.003	0.345	0.207	0.006	0.000	0.000	0.009	0.651	0.153
Juvenile Passage 2015	0.044	0.006	0.332	0.044	0.005	0.000	0.000	0.007	0.280	0.084
Juvenile Passage 2016	0.123	0.020	0.323	0.081	0.033	0.000	0.000	0.011	0.255	0.090
Redds Count (Mean)	0.153	0.131	0.307	0.168	0.103	0.000	0.000	0.015	0.316	0.130
Redd Count 2003	0.068	0.226	0.322	0.244	0.226	0.000	0.000	0.017	0.094	0.141
Redd Count 2004	0.071	0.677	0.762	0.293	0.432	0.000	0.000	0.003	0.008	0.272
Redd Count 2005	0.254	0.023	0.044	0.024	0.070	0.000	0.000	0.002	0.091	0.032
Redd Count 2006	0.362	0.041	0.134	0.166	0.030	0.000	0.000	0.003	0.049	0.053
Redd Count 2007	0.131	0.025	0.188	0.028	0.039	0.000	0.000	0.004	0.237	0.065
Redd Count 2008	0.290	0.054	0.160	0.077	0.025	0.000	0.000	0.002	0.149	0.058
Redd Count 2009	0.021	0.004	0.384	0.116	0.009	0.000	0.000	0.013	0.083	0.076
Redd Count 2010	0.285	0.029	0.065	0.131	0.036	0.000	0.000	0.013	0.263	0.067
Redd Count 2011	0.164	0.701	0.916	0.797	0.455	0.000	0.000	0.111	1.922	0.613
Redd Count 2012	0.040	0.006	0.094	0.079	0.006	0.000	0.000	0.007	0.135	0.041
Redd Count 2013	0.046	0.028	0.021	0.080	0.066	0.000	0.000	0.010	0.196	0.050
Redd Count 2014	0.220	0.002	0.343	0.207	0.005	0.000	0.000	0.010	0.657	0.153
Redd Count 2015	0.047	0.007	0.359	0.033	0.005	0.000	0.000	0.008	0.293	0.088
Redd Count 2016	0.143	0.006	0.503	0.081	0.042	0.000	0.000	0.009	0.247	0.111
Juv & Redds (Mean)	0.148	0.150	0.286	0.162	0.118	0.000	0.000	0.012	0.288	

Sensitivity to temperature data source

Most parameter estimates from a fixed temperature source were similar to parameter estimates from temperature interpolated at the redd sites. Tcrit and Tmid, however, changed between the two sources of temperature data (Table 9). The single temperature site parameter estimates better reflect the literature, in that temperature sensitivity is greatest at hatching. However, the critical temperatures estimated by the model are far lower than literature values.

Table 9.

Model	Tcrit	bT	U	Tmid	Hflow_Crit	Hflow_b	Lflow_Crit	Lflow_b	R2
Base D – Interpolated Temperatures	8.46	0.0067	0.782	11.45	28.992	16.354	6.636	0.018	0.74
Modified D – Single Temperature Site	10.16	0.0067	0.785	9.91	28.992	16.432	6.623	0.018	0.69

Management Implications

Since 2009, temperature in Clear Creek is managed to meet the critera established in a National Marine Fisheries Service biological opinion. This criteria (RPA I.1.5), has the stated objective to reduce thermal stress to spring run Chinook Salmon during holding, spawning, and embryo incubation. This RPA directs the Bureau of Reclamation to manage water releases from Whiskeytown Dam to meet certain daily mean temperatures at the Igo temperature gauge (rkm 17.9). These temperature criteria are to maintain mean daily water temperature at Igo of ≤ 15.5 C° from June 1 through September 15 and ≤ 13.3C° from September 15 to October 31. Most years, the June-September criteria are met. In warmer years, when cool water was limited in Whiskeytown Reservoir, the September to October criteria was met less frequently (Figure 31). The proportion of dates that criteria was met, in the September to October period, describes less than 10% of the variation in brood year egg-to-fry survival. There are many causes of poor fit between meeting the criteria and brood year survival, the most direct is that meeting or missing criteria does not fully reflect the reduction of survival caused by a very warm day or the potential survival buffering effect of temperatures below the criteria. Additionally, temperatures measured at the gage at krm 17.9 will be different than the temperature at the dam 12.9 kilometers upstream (Figure 32). The temperature measured at rkm 17.9 may be a reasonable management analog for temperature at the redd because it is generally warmer at this location than upstream during spring run Chinook Salmon incubation. In general however, temperature measured at a fixed location alone has poor predictive power on egg-to-migration survival, partially due to misrepresenting the temperature at the redd location, and partially due to being an incomplete description of the allostatic load experienced by eggs, alevins, and fry. The fixed temperature source analysis above attempted to describe egg-to-migration mortality with the IGO temperature gage alone, in the same way that the RPA criteria is described and measured. While this model describes spring run Chinook Salmon survival to migration (R^2: 0.69) significantly better than the average temperature at the IGO gage (R^2: 0.095), it does not offer any concrete insight to modify temperature criteria.

Relative to lab findings, this model suggests that lower temperatures benefit egg-to-migration survival. Unidentified, or poorly parametrized factors may strongly influence our metric of egg-to-migration survival (rotary screw trap captures), and these factors may correlate with cooler temperatures leading to low temperature parameter estimates. As these factors are discovered and/or as the input dataset become larger and representative of more conditions, the results of this approach will have more application to temperature management for spring run Chinook Salmon on Clear Creek.

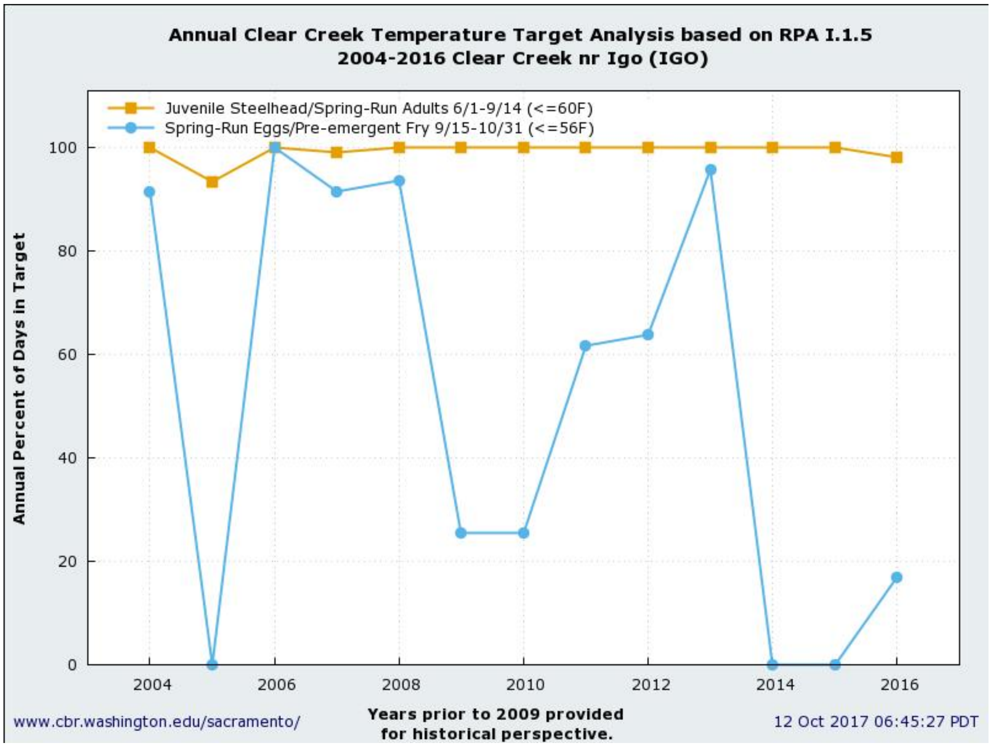

Figure 31. Annual Clear Creek Temperature Target Analysis based on RPA I.1.5 2004-2016

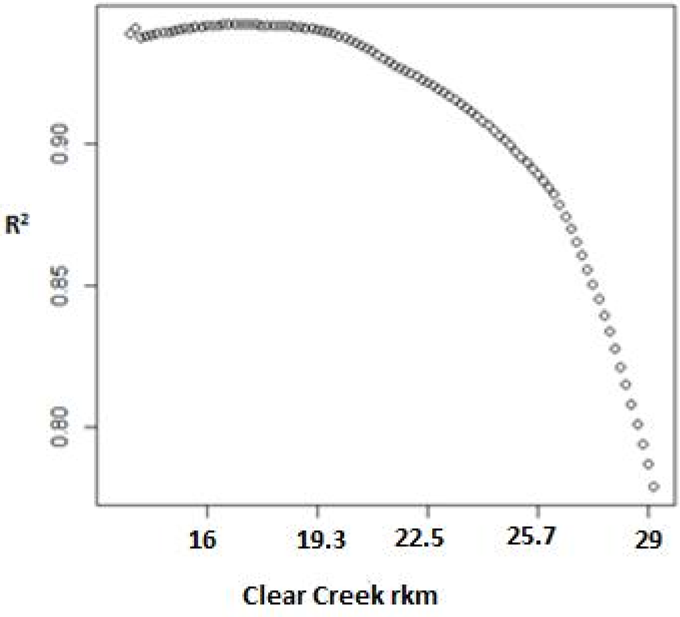

Figure 32. Coefficient of determination between Temperature measured at IGO temperature gage rkm 17.9 and temperature interpolated between loggers at upstream locations.

Conclusion

Egg to migration survival of spring run Chinook Salmon is influenced by many factors including local water temperature and stream discharge. This modeling effort found some strong relationships between these factors and survival, but a more complete suite of data describing additional (potentially unidentified) egg-to-migration survival factors may be needed to more quantitatively describe the influence of temperature and stream discharge.

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