# CHINOOK SALMON EARLY LIFESTAGE SURVIVAL
# &
# FOLSOM DAM POWER BYPASS CONSIDERATIONS

*Prepared for:*

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# 1. BACKGROUND

Each year, the U.S. Bureau of Reclamation (USBR) conducts water temperature planning, including preparation of a draft Operations Forecast and Temperature Management Plan by May 1 for the lower American River, California. The American River Group (ARG), comprised of representatives from USBR, National Marine Fisheries Service (NMFS), United States Fish and Wildlife Service (USFWS), California Department of Fish and Wildlife (CDFW), NGOs, other stakeholders and the Sacramento Water Forum (Water Forum), makes recommendations regarding coldwater temperature management alternatives to improve water temperature conditions for fish. One management option recommended for consideration by USBR is to evaluate if a power bypass operation (i.e., using the lower release outlets at Folsom Dam to access coldwater located below the elevation of the power penstocks) would benefit fall-run Chinook salmon spawning.

# 2. PURPOSE OF THIS TECHNICAL MEMORANDUM

The purpose of this Technical Memorandum (TM) is to provide biological information to help inform considerations regarding Folsom Dam power bypass operations to provide water temperature benefits for fall-run Chinook salmon spawning in the lower American River. More specifically, the objectives of this TM are to identify the differences in water temperature-related embryonic survival rates associated with differences in initial release water temperatures, and to provide an automated tool to estimate those differences. This TM also describes and compares alternative water temperature and Chinook salmon early lifestage survival relationships, which have previously been developed based upon field and laboratory studies.

# 3. EARLY LIFESTAGE SURVIVAL AND WATER TEMPERATURE RELATIONSHIPS

## 3.1 OVERVIEW

Numerous studies report different early lifestage Chinook salmon water temperature-survival relationships and suitabilities. Also, as described in Bratovich et al. (2012), the literature on salmonid water temperature requirements generally reports water temperature thresholds using various descriptive terms including “optimal”, “preferred”, “suitable”, “suboptimal”, “tolerable”, “stressful – chronic and acute”, “sublethal”, “incipient lethal”, and “lethal”. Water temperature effects on salmonids are often discussed in terms of “lethal” and “sublethal” effects, and depend on the both the magnitude and the duration of exposure (Sullivan *et al.* 2000), as well as acclimation water temperature.

Based on a review of various water temperature studies on salmonid embryos summarized in McCullough et al. (2001), EPA (2003) indicated that “good survival” occurs at constant water temperatures of about 4-12°C (39.2-53.6°F). Other literature reviews utilize different terms, but report generally similar water temperature “thresholds” for Chinook salmon embryo incubation. For example, Stillwater Sciences (2006) identified “optimal”, “suboptimal”, and “chronic-to-acute stress” water temperature index values for Chinook salmon (spring-run) embryo incubation as

<54°F, 54-58°F, and >58°F, respectively. Bratovich et al. (2012) conducted a thorough literature review on Chinook salmon water temperature suitabilities, emphasizing Central Valley information as available. They identified Chinook salmon embryo incubation "upper optimal" and "upper tolerable" average daily water temperature index values of 56°F and 58°F, respectively. Based on a review of laboratory studies, Myrick and Cech (2004) reported that Chinook salmon embryo survival was optimal at approximately 6-12°C (~43-54°F), and that egg mortality increases rapidly at temperatures greater than about 59-60°F.

Chinook salmon-specific laboratory studies suggest that embryo survival decreases rapidly when water temperatures exceed approximately 56°F (Seymour 1956; USFWS 1999), and that 100% mortality occurs during the yolk-sac stage when embryos are incubated at 62.5°F (Seymour 1956). USFWS (1999) recommended that water temperatures in the upper Sacramento River not exceed 56°F during the winter-run Chinook salmon incubation period, and that incubation temperatures of 62ºF to 64°F appear to be the physiological upper limit for Chinook salmon embryo development.

As described by Myrick and Cech (2004), water temperature tolerance of eggs and alevins is most commonly measured in studies where the subjects are exposed to a fixed (constant) water temperature until a developmental endpoint is reached, or until a particular percentage of the individuals reach a certain endpoint. Data collected from these studies generally include time from fertilization to hatching, survival from fertilization to hatching or emergence, size at hatching, and survival during the sac-fry to emergence fry transition. This TM focuses on studies that address water temperature-dependent mortality for two specific early lifestages of Chinook salmon - from egg fertilization to hatching, and from hatching to emergence of fry (i.e., "pre-emergent fry").

## 3.2 STUDIES USED TO DERIVE WATER TEMPERATURE-EMBRYONIC MORTALITY RELATIONSHIPS

Development of a water temperature-dependent daily mortality rate for Chinook salmon embryos in this TM initiated with a review of the literature. Studies that used constant exposure water temperatures, controlled experimental conditions (e.g., light, water source, dissolved oxygen, etc.), similar experimental methods among studies, and those which reported exposure duration were identified for applicability for this TM, and are summarized below. For additional information, a very thorough review and evaluation of studies regarding Chinook salmon embryo incubation and the effects of water temperature is provided in Groves et al. (2007).

### 3.2.1 Seymour (1956)

Seymour (1956) generated data from incubation of Chinook salmon fertilized eggs at constant temperatures between 34°F and 67.5°F, by assessing mortality in weekly intervals through hatching and through yolk-sac absorption. Two experiments were run in consecutive years, each utilizing a single set of parents from the Green River, Washington. Embryos were divided into eight lots and incubated at specified temperatures. The first experiment averaged 547 eggs per lot, while the second averaged 518 eggs per lot. A fraction of fertilized eggs survived through 50% hatch at temperatures up to 64.6°F, while complete mortality occurred sometime prior to hatch at temperatures of 64.8°F and 67.5°F. Fertilized eggs incubated and surviving to hatch at temperatures of 60°F to 62.5°F did not survive additional exposure at those temperatures as pre-emergent fry. Fertilized eggs incubated and surviving to hatch at temperatures of 55°F to 57.5°F produced sac-fry mortalities in excess of 50% upon further exposure to the same temperatures. Seymour (1956) reported the duration to 50% hatch, but did not report any exposure durations associated with lots that did not survive to hatch, nor were any exposure durations reported for pre-emergent fry.

### 3.2.2 Murray and McPhail (1988)

Murray and McPhail (1988) collected adult Chinook salmon from the Babine River, British Columbia and conducted constant-temperature incubations of fertilized eggs and pre-emergent fry at five different temperatures, ranging from 35.6°F to 57.2°F. Each incubation lot consisted of approximately 240 eggs. Duration and mortality were reported at benchmarks of 50% hatch and 50% emergence. Cumulative mortality and daily mortality rates were higher for fertilized eggs relative to pre-emergent fry at the same water temperatures. At 57.2°F, the mortality of fertilized eggs was 52% and the mortality of pre-emergent fry was 3%.

### 3.2.3 Beacham and Murray (1989)

Beacham and Murray (1989) took Chinook salmon adults from three different salmon stocks in British Columbia and subjected eggs and pre-emergent fry to four constant-temperature treatments ranging from approximately 39°F to 59°F. Incubations of each stock were similar in egg count, which ranged from 750 to 1,900 eggs per temperature incubation. Duration to and mortality at 50% hatch and 50% emergence were reported. Cumulative mortality and daily mortality rates were similar for fertilized eggs and pre-emergent fry at the same temperatures, except for notably higher alevin (i.e., “pre-emergent fry”) mortality for one stock at 59°F.

### 3.2.4 Jensen and Groot (1991)

Jensen and Groot (1991) obtained eggs and milt from five female and five male Chinook salmon from the Big Qualicum hatchery and transported to the Pacific Biological Station, Nanaimo, British Columbia. Upon activation of pooled gametes, fertilized eggs were incubated in small groups (approximately 30 per group), with two groups per temperature treatment. Fertilized eggs were incubated at six water temperatures between 50.4°F and 68.4°F. For incubations in which a portion of eggs survived, egg mortalities were monitored until 50% hatch or until complete mortality was observed. Pre-emergent fry mortality was monitored for eggs which had survived incubation at the same treatment temperature. Mortality of pre-emergent fry was monitored until emergence, until the yolk-sac was no longer visible, or until complete mortality occurred. Higher cumulative mortality and daily mortality rates of fertilized eggs were observed relative to pre-emergent fry at water temperatures ranging from 50.4°F to 57.2°F.

### 3.2.5 USFWS (1999)

USFWS (1999) reported results from a study of thermally-induced, winter and fall-run Chinook salmon egg and pre-emergent fry mortality. Fall-run Chinook salmon eggs and pre-emergent fry from the Sacramento River were incubated at seven constant temperatures ranging from 50°F to 62°F, while winter-run eggs and pre-emergent fry were subject to five temperature treatments in the range of 56°F to 64°F. Five replicates of fall-run and three replicates of winter-run eggs and pre-emergent fry were utilized for each incubation temperature. Each replicate consisted of 80–100 eggs. Mortality was measured at the end of four development stages as determined by the number of ATUs: cleavage eggs (450 ATU), embryo (900 ATU), eleutheroembryo (1,350 ATU) and pre-emergent alevin (1,800 ATU). Incubations of both winter- and fall-run Chinook salmon showed that a fraction of eggs and pre-emergent fry survived through all developmental stages at temperatures of 50°F to 62°F, and complete mortality occurred sometime within the first 450 ATUs (14.1 days) exposure of winter-run pre-emergent fry to 64°F.

Additional water temperature treatments were performed by USFWS (1999) to evaluate the influence of water temperature during egg incubation on pre-emergent fry mortality. These treatments all consisted of a starting water temperature at the beginning of incubation of approximately 56°F, followed by an increase in water temperature to approximately 60 or 62°F at varying days into the incubation period. In comparison to mortality when both fertilized eggs and pre-emergent fry were incubated at the same elevated temperature (e.g., 60 or 62°F), pre-emergent fry mortality was less when the fertilized egg lifestage was incubated at 56°F. These results show that pre-emergent fry mortality is greater when, as eggs, they were exposed to elevated temperatures. The latent effect of elevated water temperature exposure to fertilized eggs on pre-emergent fry mortality is consistent with other thermal mortality studies, including Seymour (1956), Combs and Burrows (1957) and Johnson and Brice (1953). This phenomenon is relevant for the lower American River because water temperatures are warmer during the fertilized egg incubation period, which generally starts during mid-October, relative to the pre-emergent fry period potentially starting in mid-November.

## 3.3 OTHER LABORATORY STUDIES

### 3.3.1 Combs and Burrows (1957)

Based on water temperature treatments of 50°F, 55°F, 57.5°F and 60°F with Entiat River, WA Chinook salmon eggs, Combs and Burrows (1957) reported similar mortalities at treatments of 50, 55°F and 57.5°F, and substantially higher mortalities at 60°F. They concluded that an upper temperature threshold for Chinook salmon embryo incubation is somewhere between 57.5°F and 60°F. However, they did not report duration of exposure and, therefore, data from this study were not used in the development of water temperature-embryonic mortality in this TM.

### 3.3.2 Hinze (1959)

Chinook salmon egg mortality rates reported by Hinze (1959) at the Nimbus Hatchery were likely based on varying daily water temperatures, preventing use of those data for developing a daily mortality rate for specific water temperatures.

### 3.3.3 Healey (1979)

Based on several water temperature treatments on Sacramento River Chinook salmon embryos from Coleman National Fish Hatchery, Healey (1979) concluded that abnormally high losses of eggs and fry would be expected at incubation temperatures exceeding 57.5°F. However, constant temperatures were not maintained, exposure durations were not reported and, thus, data from this study were not used for the development of water temperature-embryonic mortality in this TM.

### 3.3.4 Heming (1982)

Eggs were taken from fall-run Chinook salmon adults captured in the Campbell River, B.C., and reared at 42.8°F, 46.4°F, 50°F and 53.6°F. Daily mean water temperatures varied less than 0.5°C

(0.9°F) from the design temperatures. Fertilized eggs were distributed to 16 incubation trays – 4 trays for each temperature treatment. Each tray was loaded with approximately 3,000 eggs, and was reduced to 2,500 eggs per tray when embryos developed eye pigment.

Cumulative survival and days to 50% hatch were reported for each treatment. Survival to hatching decreased slightly at the higher temperature treatments. Because no attempt was made to differentiate between non-fertile eggs and eggs that died prior to hatching, the reported survival values were underestimated, reliable fertilized egg daily mortality rates could not be estimated, and data from this study were not used in the development of this TM. Also, consistent pre-emergent fry survival and associated duration data were not reported and, therefore, pre-emergent fry daily mortality rates could not be estimated from this study.

### 3.3.5 Garling and Masterson (1985)

Eggs from 16 Chinook salmon were fertilized with milt from 8 males at the Little Manistee River weir (Lake Michigan), and transported to a laboratory to incubate at 49.8°F, 52.5°F, and 59.2°F. Mean weekly temperatures varied less than 0.6°C (about 1°F). Eggs were separated into 6 groups of about 300-500 eggs, such that 2 groups were incubated at each temperature. Cumulative survival and days to 50% hatch were reported for each treatment[1]. Cumulative fertilized egg and alevin survival were similar for the two cooler treatments, but were statistically significantly lower for the 59.2°F treatment relative to the other 2 treatments. The egg samples used in this study included unfertilized eggs and, therefore, resulted in underestimated survival values. By contrast to fertilized eggs, consistent pre-emergent fry survival and association duration data were not reported in this study and, therefore, pre-emergent fry daily mortality rates could not be estimated from this study.

### 3.3.6 Geist et al. (2006)

Geist et al. (2006) determined mortality of Chinook salmon embryos to hatching and emergence, but did not apply treatments of constant water temperatures. Instead, their treatment temperatures were only the starting temperature at the beginning of incubation – all treatments were subjected to a daily declining water temperature. Therefore, results from Geist et al. (2006) cannot be used to identify daily mortality rates corresponding to specific water temperatures, and data from Geist et al. (2006) were not used in this TM.

## 3.4 DATA APPLICATION FOR THIS TM

For the purposes of this TM, water temperature-dependent Chinook salmon embryonic mortality data were restricted to constant water temperature treatments conducted at water temperatures equal to or greater than 50°F. Examination of water temperatures that have occurred immediately prior to, and during, power bypass operations (see Section 5 of this TM) demonstrated that water temperatures less than approximately 50°F have not historically occurred during power bypass operations at Folsom Dam. Moreover, review of the literature indicates that water temperatures less than 50°F result in minimal, or no water temperature-dependent Chinook salmon embryonic mortality.

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[1] As stated by Jager (2011), the reported days to 50% hatch were switched for the 49.8 and 59.2°F treatments.

This TM focuses on development of thermal mortality relationships for the fertilized egg and pre-emergent fry lifestages of Chinook salmon in the lower American River, summarized below.

### 3.4.1 Fertilized Egg Mortality Rate

Fertilized egg mortality rates were derived using data from Seymour (1956), Murray and McPhail (1988), Beacham and Murray (1989), Jensen and Groot (1991), and USFWS (1999). Calculation of daily mortality rates requires cumulative mortality data and the exposure duration associated with mortality. From the studies described above, cumulative mortality and days to 50% hatch or days to 900 ATUs (USFWS 1999) were compiled where data were available. These conditions were met for eggs incubated for water temperatures up to 64.6°F. Duration for USFWS (1999) cumulative mortality was calculated as the number of degree days required to achieve 900 ATUs at the specified incubation temperature. These duration estimates were verified using the weekly ATU summaries for incubating eggs provided in Appendix 1 and Appendix 2 of USFWS (1999).

Data for the temperature treatments of 64.8°F and 67.5°F in Seymour (1956), and for the temperature treatments of 64.4°F and 68.4°F in Jenson and Groot (1991), were not used because 100% mortality occurred prior to 50% hatch and, therefore, the duration that resulted in complete mortality was unknown, prohibiting calculation of daily mortality rates for these treatments.

Cumulative mortality and exposure duration were used to calculate daily mortality rate for fertilized eggs. Literature-derived cumulative mortality, exposure duration, and daily mortality rates for fertilized eggs used to develop water temperature-mortality relationships for fertilized eggs in this TM are provided in **Table 1**.

Regression analysis minimzing mean square error (MSE) was used to fit an exponential function to the fertilized egg daily mortality and temperature exposure data. This function shown below relates average daily temperature in degrees Fahrenheit ($T_F$) to the daily mortality of Chinook salmon fertilized eggs as a fraction. The equation is applicable at water temperatures less than or equal to 67.8°F. At water temperatures greater than 67.8°F, the function produces daily mortality rates in excess of 100% and, therefore, it is assumed that the daily mortality rate is 100% at temperatures greater than this threshold. However, it should be noted that the range of water temperature data used to develop the function only extends up to 64.6°F. Therefore, there is greater certainty in the mortality-water temperature relationship at water temperatures less than 64.6°F.

$$\text{Fertilized Egg} \qquad M = 1.517\text{x}10^{-20}\, e^{(0.6729 \text{ x } T_F)}$$

The fertilized egg mortality rate is plotted (as a percentage) along with the literature-derived, fertilized egg-mortality data in **Figure 1**. Examination of the insert in Figure 1, emphasizing the lowermost portion of the daily mortality rate function, demonstrates that the function initially deviates from no mortality to notable mortality (e.g., $\geq$ 0.1%) at approximately 57.5°F.

The regression analysis also included exploring the inclusion of a vertical adjustment factor (typically called a transformation, or a vertical shift) for the fertilized egg mortality function in order to provide a better fit to the data at relatively low water temperature values (less than about 58°F). For example, examination of the function relative to the data points in Figure 1 suggests that the function potentially underestimates mortality at these lower temperatures based upon its relative relationship to the data points themselves. Potential inclusion of a vertical adjustment factor consisted of solving for an additional constant parameter in the exponential equation to

**Table 1. Literature-derived Chinook salmon fertilized egg mortality data used to develop the daily mortality relationship in this TM.**

| Water Temperature (°F) | Cumulative Mortality (%) | Exposure Duration (Days) | Daily Mortality Rate (%) | Reference |
|---|---|---|---|---|
| 50 | 6.1 | 50.0 | 0.13 | USFWS 1999 |
| 50 | 13.9 | 50.0 | 0.30 | USFWS 1999 |
| 50 | 2.8 | 50.0 | 0.06 | USFWS 1999 |
| 50 | 6.3 | 50.0 | 0.13 | USFWS 1999 |
| 50 | 2.5 | 50.0 | 0.05 | USFWS 1999 |
| 50.2 | 2.0 | 50.9 | 0.04 | Seymour 1956 |
| 50.4 | 25.0 | 51.2 | 0.56 | Jensen & Groot 1991 |
| 50.4 | 17.6 | 51.2 | 0.38 | Jensen & Groot 1991 |
| 50.6 | 13.0 | 50.2 | 0.28 | Seymour 1956 |
| 51.8 | 10.0 | 46.9 | 0.22 | Murray & McPhail 1988 |
| 52 | 7.6 | 45.0 | 0.18 | USFWS 1999 |
| 52 | 22.5 | 45.0 | 0.56 | USFWS 1999 |
| 52 | 1.2 | 45.0 | 0.03 | USFWS 1999 |
| 52 | 8.8 | 45.0 | 0.20 | USFWS 1999 |
| 52 | 0.0 | 45.0 | 0.00 | USFWS 1999 |
| 53.1 | 24.1 | 43.6 | 0.63 | Jensen & Groot 1991 |
| 53.1 | 33.3 | 42.7 | 0.94 | Jensen & Groot 1991 |
| 53.6 | 0.8 | 44.1 | 0.02 | Beacham & Murray 1989 |
| 53.6 | 2.2 | 44.1 | 0.05 | Beacham & Murray 1989 |
| 53.8 | 0.6 | 42.2 | 0.01 | Beacham & Murray 1989 |
| 54 | 4.3 | 40.9 | 0.11 | USFWS 1999 |
| 54 | 30.3 | 40.9 | 0.88 | USFWS 1999 |
| 54 | 9.8 | 40.9 | 0.25 | USFWS 1999 |
| 54 | 11.4 | 40.9 | 0.30 | USFWS 1999 |
| 54 | 0.0 | 40.9 | 0.00 | USFWS 1999 |
| 54.6 | 2.0 | 38.8 | 0.05 | Seymour 1956 |
| 55.1 | 5.0 | 40.0 | 0.13 | Seymour 1956 |
| 56 | 10.8 | 37.5 | 0.30 | USFWS 1999 |
| 56 | 18.5 | 37.5 | 0.54 | USFWS 1999 |
| 56 | 2.6 | 37.5 | 0.07 | USFWS 1999 |
| 56 | 19.5 | 37.5 | 0.58 | USFWS 1999 |
| 56 | 0.0 | 37.5 | 0.00 | USFWS 1999 |
| 56 | 2.2 | 37.5 | 0.06 | USFWS 1999 |
| 56 | 25.6 | 37.5 | 0.78 | USFWS 1999 |
| 56 | 14.6 | 37.5 | 0.42 | USFWS 1999 |
| 57.2 | 21.9 | 35.8 | 0.69 | Jensen & Groot 1991 |

| | | | | |
|---|---|---|---|---|
| 57.2 | 20.7 | 35.6 | 0.65 | Jensen & Groot 1991 |
| 57.2 | 52.0 | 38.4 | 1.89 | Murray & McPhail 1988 |
| 57.8 | 2.0 | 34.0 | 0.06 | Seymour 1956 |
| 58 | 17.0 | 34.6 | 0.54 | USFWS 1999 |
| 58 | 29.7 | 34.6 | 1.01 | USFWS 1999 |
| 58 | 9.2 | 34.6 | 0.28 | USFWS 1999 |
| 58 | 4.2 | 34.6 | 0.12 | USFWS 1999 |
| 58 | 6.6 | 34.6 | 0.20 | USFWS 1999 |
| 58 | 5.6 | 34.6 | 0.17 | USFWS 1999 |
| 58 | 32.5 | 34.6 | 1.13 | USFWS 1999 |
| 58 | 16.9 | 34.6 | 0.53 | USFWS 1999 |
| 59 | 6.9 | 36.1 | 0.20 | Beacham & Murray 1989 |
| 59 | 4.3 | 34.1 | 0.13 | Beacham & Murray 1989 |
| 59.4 | 8.7 | 34.3 | 0.27 | Beacham & Murray 1989 |
| 59.8 | 35.0 | 32.1 | 1.33 | Seymour 1956 |
| 60 | 11.1 | 32.1 | 0.37 | USFWS 1999 |
| 60 | 29.1 | 32.1 | 1.06 | USFWS 1999 |
| 60 | 9.6 | 32.1 | 0.31 | USFWS 1999 |
| 60 | 20.3 | 32.1 | 0.70 | USFWS 1999 |
| 60 | 5.2 | 32.1 | 0.17 | USFWS 1999 |
| 60 | 4.6 | 32.1 | 0.15 | USFWS 1999 |
| 60 | 15.7 | 32.1 | 0.53 | USFWS 1999 |
| 60 | 21.8 | 32.1 | 0.76 | USFWS 1999 |
| 60.2 | 22.0 | 34.0 | 0.73 | Seymour 1956 |
| 61.5 | 57.6 | 31.5 | 2.69 | Jensen & Groot 1991 |
| 61.5 | 71.0 | 32.8 | 3.70 | Jensen & Groot 1991 |
| 62 | 85.0 | 30.7 | 5.99 | Seymour 1956 |
| 62 | 12.3 | 30.0 | 0.44 | USFWS 1999 |
| 62 | 59.2 | 30.0 | 2.94 | USFWS 1999 |
| 62 | 32.9 | 30.0 | 1.32 | USFWS 1999 |
| 62 | 61.4 | 30.0 | 3.13 | USFWS 1999 |
| 62 | 20.0 | 30.0 | 0.74 | USFWS 1999 |
| 62 | 10.2 | 30.0 | 0.36 | USFWS 1999 |
| 62 | 26.7 | 30.0 | 1.03 | USFWS 1999 |
| 62 | 34.1 | 30.0 | 1.38 | USFWS 1999 |
| 62.4 | 78.0 | 31.4 | 4.71 | Seymour 1956 |
| 64 | 55.4 | 28.1 | 2.83 | USFWS 1999 |
| 64 | 76.7 | 28.1 | 5.04 | USFWS 1999 |
| 64 | 90.7 | 28.1 | 8.10 | USFWS 1999 |
| 64.6 | 99.0 | 28.0 | 15.17 | Seymour 1956 |

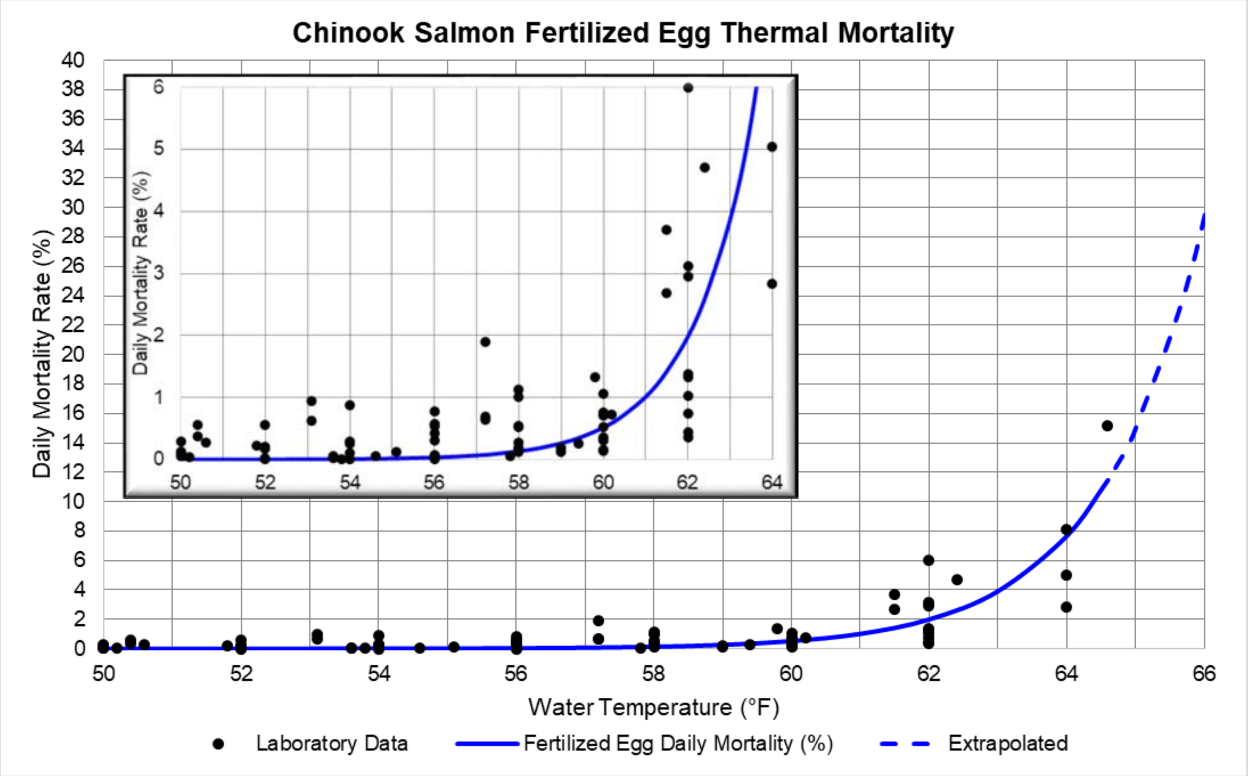

**Figure 1. Water temperature-dependent daily mortality rate of Chinook salmon fertilized eggs.**

minimize MSE. Thus, the vertical adjustment factor was applied over the extent of the function. However, application of this modified function with inclusion of the constant parameter resulted in a laterally static mortality rate at the lower water temperature values (from about 50°F - 60°F) because the constant parameter becomes the driving factor in the function in this temperature range. Therefore, the daily mortality rate would never approach 0, indicating an artificially elevated (and constant) daily mortality rate at the lower temperatures. This could be interpreted as incorporating a background or baseline temperature-dependent mortality in the function which:

- implies that there is always some temperature-dependent mortality, which is counterintuitive and not supported in the laboratory studies
- does not fit the laboratory data as well as the original function from 59°F to 60°F
- dampens the difference in mortality rates between temperatures over the range from about 57°F to 60°F (which is an important range considering bypass operations)
- is not included in the other mortality functions in SacPAS, which also confounds comparison with those other relationships, which is one of the purposes of this TM (see Section 3.5.3, below)

In addition, a similar exploration was conducted for the pre-emergent fry function, but the inclusion of a constant parameter did not improve the fit of the function to the data. Because no vertical adjustment factor is included in the pre-emergent fry relationship, including such a factor in the fertilized egg function confounds comparison between the two relationships. Therefore, for the above reasons, the original egg mortality function (without the inclusion of a constant parameter) was carried forward for the purposes of this TM.

### 3.4.2 Pre-Emergent Fry Mortality Rate

Pre-emergent fry mortality rates were derived using data from Murray and McPhail (1988), Beacham and Murray (1989), Jensen and Groot (1991), and USFWS (1999). From these studies, the cumulative mortality and exposure duration data was compiled for pre-emergent fry that had survived the same incubating temperature as eggs. Overall, pre-emergent fry mortality and duration data were available for water temperatures from about 50°F up to 64°F.

The duration of exposure used to calculate daily mortality rates was slightly different among studies. Duration of exposure was equivalent to: (1) the duration required to accrue 1,800 ATUs in USFWS (1999); (2) the duration associated with emergence and/or yolk-sac absorption in Jensen and Groot (1991); and (3) the duration between 50% hatch and 50% emergence in Murray and McPhail (1988) and Beacham and Murray (1989). Data derived from USFWS (1999) was for cumulative mortality through what the study called the "pre-emergent alevin" lifestage, which ended 900 ATUs after the fertilized egg lifestage (i.e., the cleavage embryo and embryo stages). USFWS (1999) reported cumulative egg mortality at the end of each lifestage, which required calculation of the mortality that occurred specifically during the pre-emergent fry lifestage[2].

Data for the pre-emergent fry lifestage from Seymour (1956) were not applicable to this TM because he did not report any exposure durations for pre-emergent fry. Data for treatments of 64.4°F and 68.4°F in Jenson and Groot (1991) for pre-emergent fry were not used because 100% mortality occurred prior to reaching this lifestage. Additionally, 100% mortality of pre-emergent fry occurred prior to the end of the study for the 61.5°F treatment, and insufficient information was presented to verify that the time to the end of the study corresponded to the date that 100% pre-emergent fry mortality occurred, prohibiting calculation of the daily mortality rate.

Cumulative mortality and exposure duration were used to calculate daily mortality rate using the same methods described above for fertilized eggs. Literature-derived cumulative mortality, exposure duration, and the associated daily mortality rates for pre-emergent fry are given in **Table 2**. The function shown below relates average daily temperature in degrees Fahrenheit ($T_F$) to the daily mortality of Chinook salmon pre-emergent fry as a fraction. The equation is applicable at water temperatures less than or equal to 65.3°F. At water temperatures greater than 65.3°F, the function produces daily mortality rates in excess of 100% and, therefore, it is assumed that the daily mortality rate is 100% at temperatures greater than this threshold. The range of water temperature data used to develop the function extends up to 64.0°F. Therefore, there is greater certainty in the water temperature-pre-emergent fry relationship at water temperatures $\leq$ 64.0°F.

Pre-emergent Fry $$M = 2.671\text{x}10^{-20}\, e^{(0.6894 \text{ x } T_F)}$$

The pre-emergent fry mortality function is plotted (as a percentage) along with the literature-derived pre-emergent fry mortality data in **Figure 2**. Examination of the insert in Figure 2, emphasizing the lowermost portion of the daily mortality rate function, demonstrates that the function initially deviates from no mortality to notable mortality (e.g., $\geq$ 0.1%) at approximately 55.4°F.

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[2] For the 64°F treatment in USFWS (1999) for pre-emergent fry, 100% mortality was reported for the eluetheroembryo lifestage. To calculate daily mortality rate, the ATUs through completion of that lifestage (450 ATUs) were used and a cumulative mortality of 99.9% (rather than 100%) was used for computational feasibility.

**Table 2. Literature-derived Chinook salmon pre-emergent fry mortality data used to develop the daily mortality relationship in this TM.**

| Water Temperature (°F) | Cumulative Mortality (%) | Exposure Duration (Days) | Daily Mortality Rate (%) | Reference |
|---|---|---|---|---|
| 50.4 | 0.0 | 35.5 | 0.00 | Jensen & Groot 1991 |
| 50.4 | 0.0 | 35.5 | 0.00 | Jensen & Groot 1991 |
| 51.8 | 4.0 | 37.1 | 0.11 | Murray & McPhail 1988 |
| 52 | 5.5 | 45.0 | 0.13 | USFWS 1999 |
| 52 | 2.9 | 45.0 | 0.07 | USFWS 1999 |
| 52 | 10.0 | 45.0 | 0.23 | USFWS 1999 |
| 52 | 9.6 | 45.0 | 0.22 | USFWS 1999 |
| 52 | 0.0 | 45.0 | 0.00 | USFWS 1999 |
| 53.1 | 0.0 | 26.9 | 0.00 | Jensen & Groot 1991 |
| 53.1 | 0.0 | 27.8 | 0.00 | Jensen & Groot 1991 |
| 53.4 | 2.3 | 32.7 | 0.07 | Beacham & Murray 1989 |
| 53.6 | 0.7 | 34.1 | 0.02 | Beacham & Murray 1989 |
| 53.6 | 0.3 | 33.9 | 0.01 | Beacham & Murray 1989 |
| 54 | 4.5 | 40.9 | 0.11 | USFWS 1999 |
| 54 | 0.0 | 40.9 | 0.00 | USFWS 1999 |
| 54 | 1.4 | 40.9 | 0.03 | USFWS 1999 |
| 54 | 16.1 | 40.9 | 0.43 | USFWS 1999 |
| 54 | 3.8 | 40.9 | 0.10 | USFWS 1999 |
| 56 | 3.0 | 37.5 | 0.08 | USFWS 1999 |
| 56 | 7.6 | 37.5 | 0.21 | USFWS 1999 |
| 56 | 5.3 | 37.5 | 0.14 | USFWS 1999 |
| 56 | 9.1 | 37.5 | 0.25 | USFWS 1999 |
| 56 | 3.9 | 37.5 | 0.11 | USFWS 1999 |
| 56 | 2.2 | 37.5 | 0.06 | USFWS 1999 |
| 56 | 7.5 | 37.5 | 0.21 | USFWS 1999 |
| 56 | 0.0 | 37.5 | 0.00 | USFWS 1999 |
| 57.2 | 4.0 | 27.0 | 0.15 | Jensen & Groot 1991 |
| 57.2 | 3.6 | 27.2 | 0.13 | Jensen & Groot 1991 |
| 57.2 | 3.0 | 24.6 | 0.12 | Murray & McPhail 1988 |
| 58 | 8.0 | 34.6 | 0.24 | USFWS 1999 |
| 58 | 18.8 | 34.6 | 0.60 | USFWS 1999 |
| 58 | 44.9 | 34.6 | 1.71 | USFWS 1999 |
| 58 | 11.6 | 34.6 | 0.36 | USFWS 1999 |
| 58 | 8.5 | 34.6 | 0.25 | USFWS 1999 |
| 58 | 0.0 | 34.6 | 0.00 | USFWS 1999 |

| | | | | |
|---|---|---|---|---|
| 58 | 3.6 | 34.6 | 0.11 | USFWS 1999 |
| 58 | 40.5 | 34.6 | 1.49 | USFWS 1999 |
| 59 | 39.4 | 26.7 | 1.86 | Beacham & Murray 1989 |
| 59 | 6.3 | 27.6 | 0.24 | Beacham & Murray 1989 |
| 59.4 | 4.8 | 27.6 | 0.18 | Beacham & Murray 1989 |
| 60 | 31.3 | 32.1 | 1.16 | USFWS 1999 |
| 60 | 8.9 | 32.1 | 0.29 | USFWS 1999 |
| 60 | 25.3 | 32.1 | 0.90 | USFWS 1999 |
| 60 | 16.9 | 32.1 | 0.58 | USFWS 1999 |
| 60 | 16.4 | 32.1 | 0.56 | USFWS 1999 |
| 60 | 81.9 | 32.1 | 5.18 | USFWS 1999 |
| 60 | 50.7 | 32.1 | 2.17 | USFWS 1999 |
| 60 | 91.2 | 32.1 | 7.27 | USFWS 1999 |
| 62 | 99.9 | 30.0 | 20.57 | USFWS 1999 |
| 62 | 90.3 | 30.0 | 7.49 | USFWS 1999 |
| 62 | 92.2 | 30.0 | 8.14 | USFWS 1999 |
| 62 | 51.9 | 30.0 | 2.41 | USFWS 1999 |
| 62 | 75.0 | 30.0 | 4.52 | USFWS 1999 |
| 62 | 96.2 | 30.0 | 10.33 | USFWS 1999 |
| 62 | 84.1 | 30.0 | 5.95 | USFWS 1999 |
| 62 | 99.9 | 30.0 | 20.57 | USFWS 1999 |
| 64 | 99.9 | 14.1 | 38.81 | USFWS 1999 |
| 64 | 99.9 | 14.1 | 38.81 | USFWS 1999 |
| 64 | 99.9 | 14.1 | 38.81 | USFWS 1999 |

### 3.4.3 Comparison of Fertilized Egg and Pre-Emergent Fry Mortality Rates

Although exhibiting similar trends, pre-emergent fry mortality rates are somewhat higher than the fertilized egg mortality rates at a given water temperature (**Figure 3**). This may result from the physiological sensitivity of pre-emergent fry which have had a history of high incubation temperatures as eggs (USFWS 1999), or it may truly reflect a greater susceptibility of pre-emergent fry to elevated water temperatures, as shown by short-duration (1-8 hour) experiments at very high water temperatures (>71.5°F) (Neitzel and Becker 1985). Also, the relationships developed in this TM are for constant water temperature-dependent mortality only, and do not take into account myriad other factors (e.g., dissolved oxygen concentration and differential $O_2$ uptake between developmental stages, interstitial permeability and water velocity, waste metabolite removal, density-dependent influences, etc.) that could differentially affect water temperature-dependent survival between the fertilized egg and pre-emergent fry developmental stages.

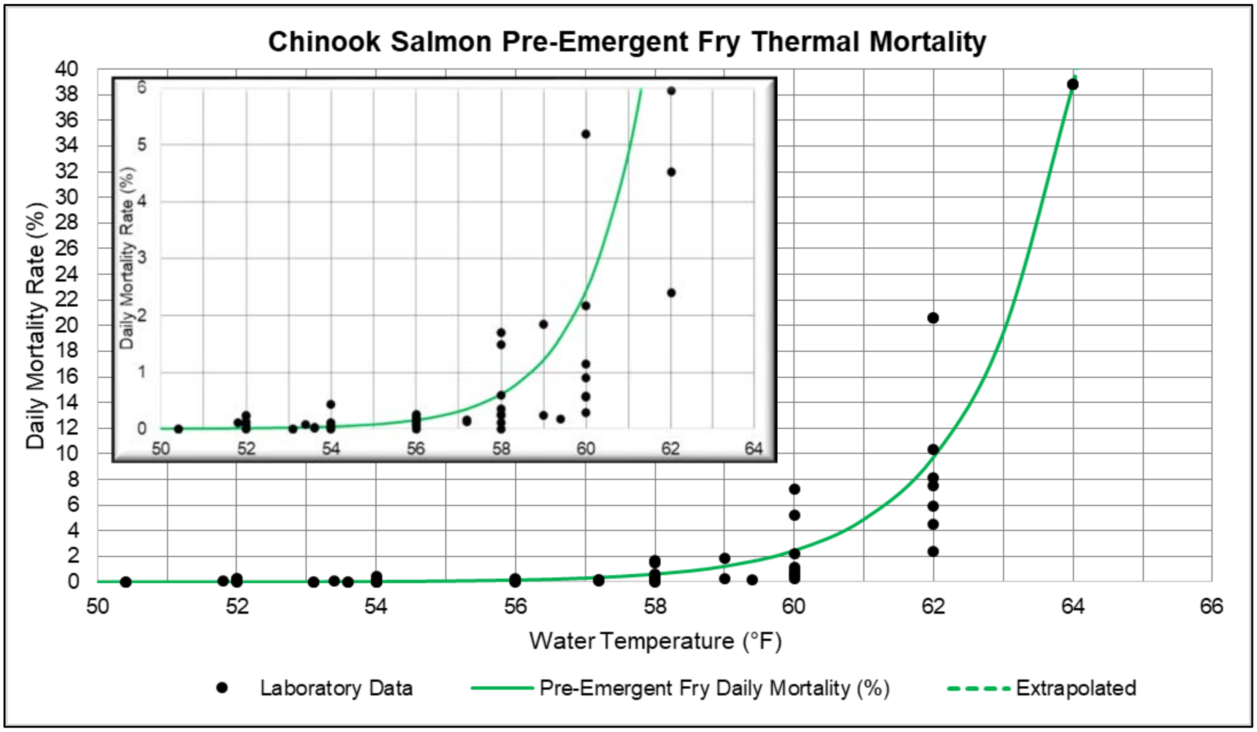


**Figure 2. Water temperature-dependent daily mortality of Chinook salmon pre-emergent fry.**

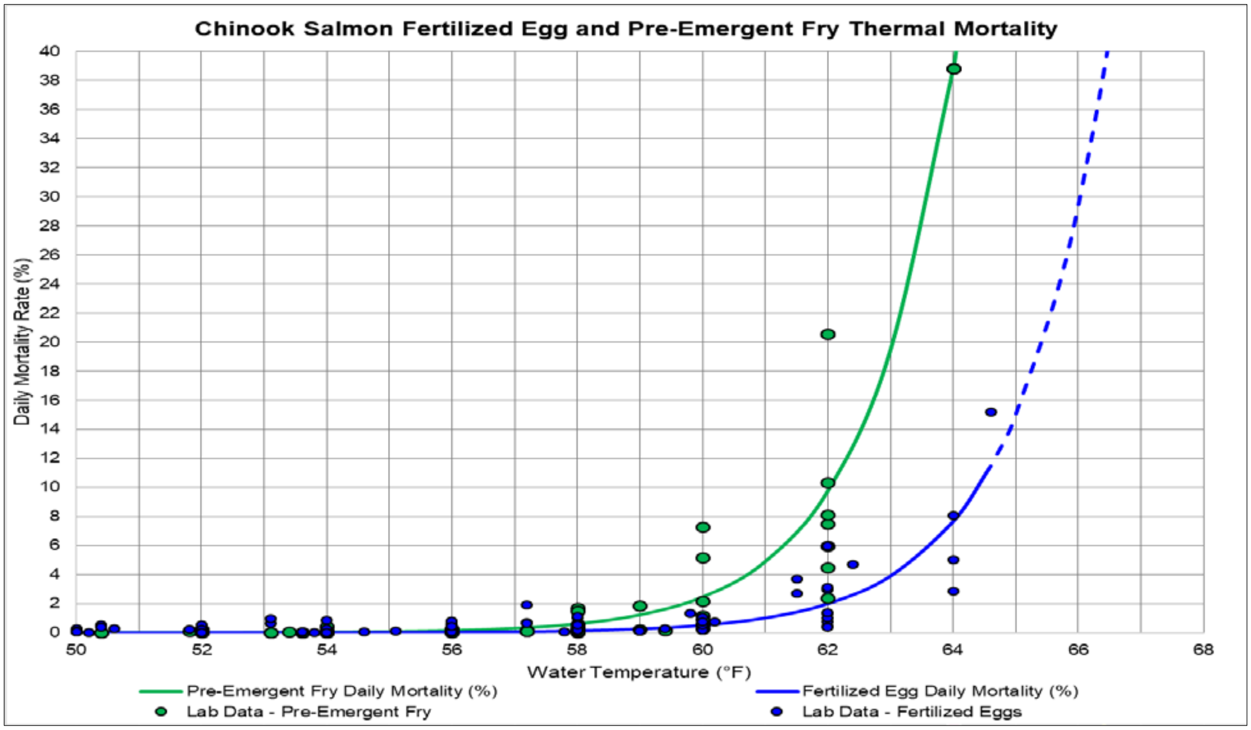


**Figure 3. Water temperature-dependent daily mortality rate of Chinook salmon fertilized eggs compared with the daily mortality rate for pre-emergent fry.**

Studies used to develop water temperature-embryonic mortality rates in this TM are inconsistent regarding the relative sensitivity to elevated water temperatures of fertilized eggs compared to pre-emergent fry. Results from USFWS (1999) indicate that daily mortality rates of fertilized eggs were similar to those of pre-emergent fry at the same water temperatures ranging from 52-56°F, but lower daily mortality rates were observed for fertilized eggs relative to pre-emergent fry for water temperatures ranging from 58-62°F. Data from Beacham and Murray (1989) demonstrated that daily mortality rates were similar for fertilized eggs and pre-emergent fry at the same temperatures, except for a notably higher pre-emergent fry mortality rate for one stock at 59°F. Conversely, Murray and McPhail (1988) and Jensen and Groot (1991) reported higher mortality rates for fertilized eggs relative to pre-emergent fry at the same water temperatures.

Regarding the water temperature-dependent relative survival of fertilized eggs versus pre-emergent fry, the following discussion was taken directly from Jennings and Hendrix (2020).

> The embryonic stage is the most sensitive to elevated temperatures in the Chinook life cycle (McCullough 1999), with thermal tolerance of winter-run embryos likely set by oxygen availability (Martin et al. 2017). As salmonid embryos develop, their metabolic rate ($\mu gO_2 \cdot h^{-1}$) increases 7-fold from fertilization to hatching (Alderdice et al. 1958), with a further 5-fold increase from hatching through most of larval (alevin) development, and then a slight decrease before emergence (Rombough 1986; Rombough 1994). Because water temperature has a determinant effect on dissolved oxygen levels, <u>the timing of temperature sensitivity should be highest in the later stages of egg development and the first half of larval development (Anderson 2018)</u>. [Underline emphasis added].

## 3.5 OTHER EMBRYONIC MORTALITY MODELS

Several relationships or models have been developed to estimate mortality of embryonic lifestages of Chinook salmon associated with water temperature based on multiple laboratory experiments, as well as based on modeling of thermal mortality associated with estimated egg-to-fry survival in the wild.

### 3.5.1 Myrick and Cech (2001)

Myrick and Cech (2001) combined mortality data of Chinook salmon eggs from fertilization to hatching from laboratory experiments for multiple water temperature treatments, ranging from 35°F to 68.4°F (~2 to 20°C) (**Figure 4**). The function applied to the mortality data appears to be a quadratic function, where mortality decreases at an increasing rate as water temperature warms from about 35°F to 50°F, and higher mortality at an increasing rate as water temperature warms from about 50°F to 65°F. Because these data represent total mortality of incubating eggs over the course of the respective incubation periods for each treatment and study, this relationship was not used to estimate daily mortality rates in this TM. However, it does illustrate the notable increases in mortality that occur with increases in water temperature above about 15°C (59°F).

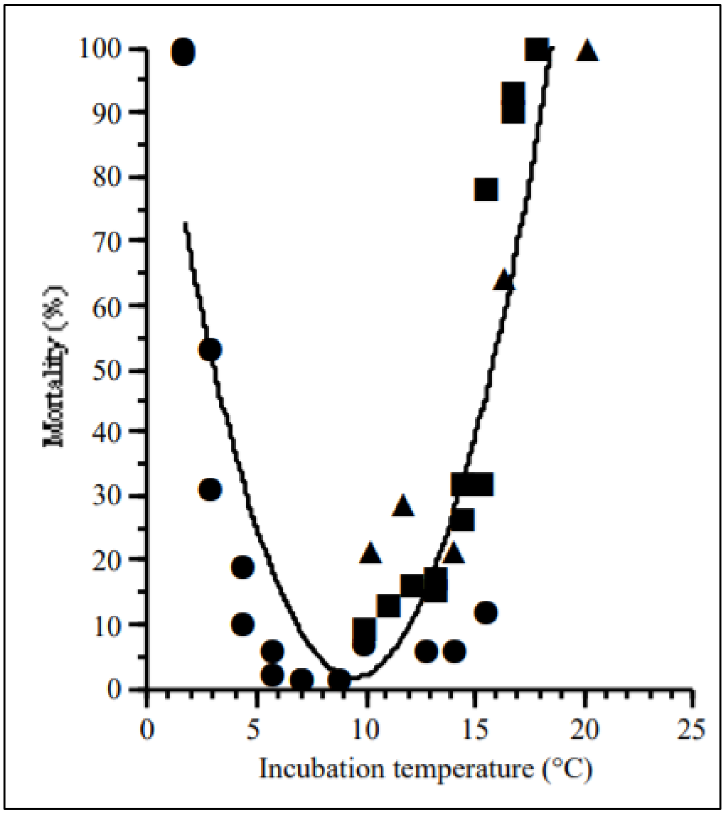


**Figure 4. Relationship between incubation water temperature and mortality of Chinook salmon eggs. Data from Combs and Burrows 1957 (solid circles], USFWS 1999 (solid squares), and Jensen and Groot 1991 (solid triangles).** ***Note: 0, 5, 10, 15, and 20°C correspond to 32, 41, 50, 59, and 68°F.*** **Source: Myrick and Cech 2001.**

### 3.5.2 Anderson (2018)

Anderson (2018) expanded on the Chinook salmon embryo incubation thermal mortality modeling conducted by Martin et al. (2017) by considering stage of incubation in water temperature-dependent mortality of winter-run Chinook salmon embryos. Studies suggest that embryo mortality occurs in a limited range of days around a critical age or over several distinct developmental stages (egg hatch and maximum total dry mass). Therefore, Anderson (2018) developed a model which only allows mortality of embryos at a specified critical age of development, which contrasts with the model developed by Martin et al. (2017) which allows mortality during any day of the simulated embryo incubation period. Models developed by Anderson (2018) produced similar fits to the annual patterns of the estimated Sacramento River egg-to-fry survival as the model developed by Martin et al. (2017). Therefore, the modeling carried out by Anderson (2018) suggests that water temperature may be able to exceed $T_{crit}$ (~12°C) in the upper Sacramento River outside of the period encompassing egg hatching dates of the first and last redds of the season without increasing water temperature-dependent embryo mortality. Therefore, providing suitable water temperatures for embryo incubation may be most critical during the period starting when hatching begins, which is expected to begin in mid-November in the lower American River.

### 3.5.3 The Sacramento Prediction and Assessment of Salmon (SacPAS)

The Sacramento Prediction and Assessment of Salmon (SacPAS) data and analysis tools were developed by the Columbia Basin Research department of the University of Washington for the USBR. The SacPAS model is intended to assist managers and interested parties in understanding and forecasting salmon emergence, migration and survival. It is a suite of integrated tools for data selection and manipulation, coupled to a spawning-to-emergence model, as well as a juvenile migration model.

The "Egg Growth Model-Spawning to Emergence" component of the SacPAS platform includes the sub-component "Mortality Models (Temperature)". This sub-component provides "families" of daily mortality rates for Chinook salmon embryos from which the user can select one (or more) options, and is located at: http://www.cbr.washington.edu/sacramento/grow/index.html. The "families" of daily mortality rate functions, and the options contained therein, include:

- Linear
    - Martin et al. (2017)
- Exponential
    - Water Forum (2020)
    - Zeug (2012)
    - SALMOD (2006), USBR (2008), HCI (1996)
- Threshold
    - USGS (2018)
- Weibull-type
    - Jager (2011)

A brief description of the relationships/models for water temperature-dependent daily mortality rates included in the SacPAS model are provided below.

**Martin et al. (2017)**

Martin et al. (2017) developed a water temperature-dependent model of Chinook salmon embryo incubation survival from fertilization to emergence using laboratory data from Jensen and Groot (1991) and USWFS (1999) which, combined, encompassed survival to emergence at water temperatures ranging from about 50°F to 68°F. The model uses a water temperature-dependent instantaneous (i.e., daily) mortality rate, assuming a critical temperature threshold ($T_{crit}$) (15.4°C = 59.7°) below which no mortality associated with temperature occurs, and a directional relationship with slope $b_T$ between mortality and temperature above $T_{crit}$. The model explained much of the variation in embryonic survival observed during the laboratory studies using estimates for the thermal tolerance parameters of $T_{crit} = 15.4$ °C and $b_T = 0.034$ °C$^{-1}$d$^{-1}$.

Martin et al. (2017) then tested whether the lab-derived water temperature-dependent survival rates could accurately predict estimated egg-to-fry survival rates from the Red Bluff Diversion Dam (RBDD) rotary screw-trap (RST) program in the upper Sacramento River, based on redd survey data and a water temperature model from 1996-2015. However, the field-parameterized model predicted negligible temperature-dependent mortality (<1%) during any year from 1996-2015.

Therefore, the model explained no more variation in the observed estimates of egg-to-fry survival than a null model, with or without incorporation of a density-dependent mortality term.

In an effort to determine whether thermal tolerance of Chinook salmon embryos in the field differs from their thermal tolerance in the lab, Martin et al. (2017) re-parameterized the model using field data, treating $T_{crit}$ and $b_T$ as free parameters rather than assuming the lab-based estimates. Based on Figure 2 in Martin et al. (2017), 95% of daily water temperatures experienced by Chinook salmon redds over the 1996-2015 period were below 13°C (55.4°F) during all years except for 2014-2015, when 95% of daily temperatures were below 14°C (57.2°F). The field parameterized model included thermal tolerance parameters of $T_{crit}$ = 12.0 °C and $b_T$ = 0.024 $°C^{-1}d^{-1}$. The parameter $T_{crit}$, below which no mortality associated with temperature occurs, was identified as 12.0°C (53.6°F). The field-parameterized model was based on a range of redd exposure water temperatures extending up to about 57°F in the upper Sacramento River.

Both the lab-based and field-based models of water temperature and Chinook salmon embryo incubation survival from fertilization to emergence developed by Martin et al. (2017) were linear, maintaining a consistent slope over a range of water temperatures (**Figure 5**).

## Water Forum (2020)

Water Forum (2020) refers to the Chinook salmon fertilized egg and pre-emergent fry water temperature-mortality relationships developed in this TM.

## Zeug et al. (2012)

As part of a Sacramento River winter-run Chinook salmon life cycle model, Zeug et al. (2012) developed an exponential relationship between daily mortality and water temperature from fertilization to emergence based on the winter-run Chinook salmon water temperature-mortality results from USFWS (1999). They converted model-predicted mortality over the entire incubation period to a daily mortality rate to apply temperature. The resultant water temperature-embryonic daily mortality relationship was expressed as daily mortality = $1.38\text{x}10^{-15}e^{(.503*\text{Temp})}$.

## SALMOD (2006), USBR (2008), HCI (1996)

SALMOD is a component of the Instream Flow Incremental Methodology, or IFIM (Stalnaker et al. 1995). SALMOD simulates population dynamics for freshwater salmonids. The premise of SALMOD is that egg and fish mortality are directly related to spatially and temporally variable habitat limitations which, in turn, are related to flow and other meteorological variables, such as water temperature. One subcomponent of SALMOD includes egg thermal mortality rates.

The SALMOD model (SALMOD 2006) and Lower American River Salmon Mortality Model (as referenced in USBR 2008) utilized mortality rates for Chinook salmon fertilized eggs and pre-emergent fry for defined water temperature-specific exposure durations that were originally developed by USFWS (1990), and were used to develop the USBR Salmon Mortality Model (USBR 1991). As described in SALMOD (2006), USFWS (1990) calculated what is referred to as "crude" mortality rates. For the majority of the rates presented, the percent mortality was divided by the number of days in the reference period in order to calculate the average daily mortality (SALMOD 2006).

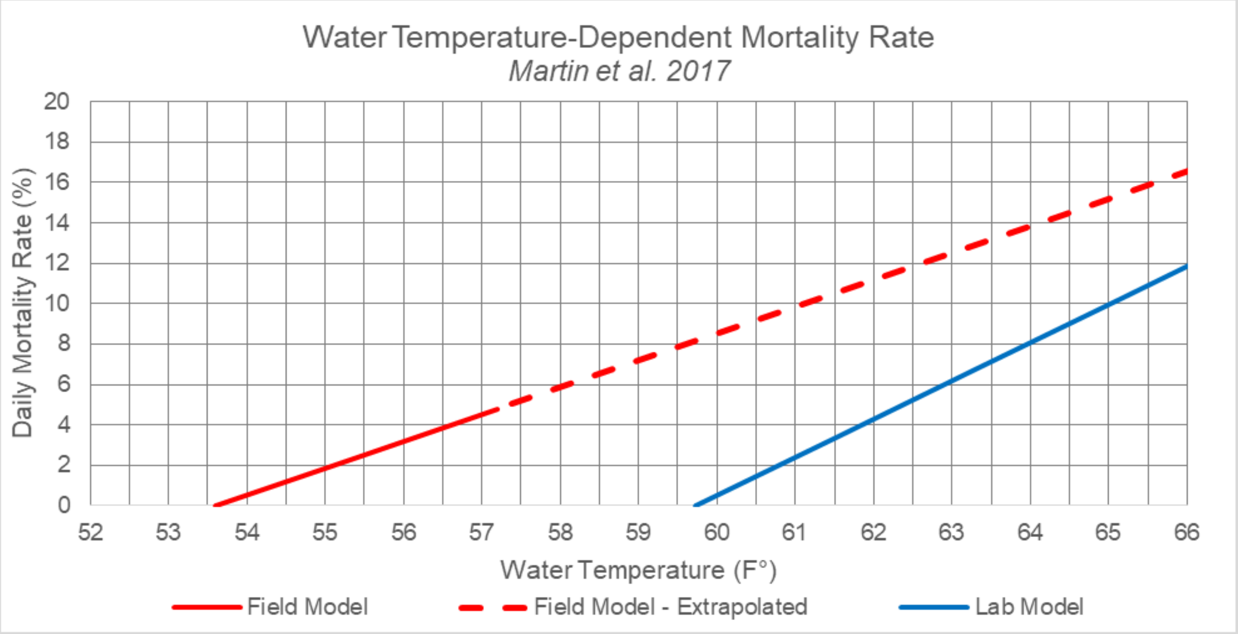


**Figure 5. Modeled relationship between daily mortality rate of Chinook salmon embryos from fertilization to emergence and water temperature. Two relationships are provided: (1) based on laboratory studies; and (2) based on field-based parameterization in the upper Sacramento River. Dashed line represents extrapolation to water temperatures greater than approximately 57°F. (relationships provided by Martin et al. 2017).**

USBR's model was updated in 1996 (HCI 1996) to include daily mortality rates for a given reference period using the following equation:

$$M_i = (1\text{-}M_n)^{(1/n)}$$

Where: Mi = daily mortality rate, $M_n$ = mortality rate after exposure time, and n = exposure time in days

Information was limited at the time the fertilized egg mortality rates were reported. USFWS (1990) developed the mortality rates based upon data from studies including Combs and Burrows (1957), Seymour (1956) and Healey (1979). Although USFWS (1990) presented fertilized egg mortality rates at 57°F, 58°F, and 59°F, the rationale for the assumed fertilized egg mortality rates at these temperatures is unknown.

At the time the original mortality rates were developed, there was virtually no data available on thermally-induced pre-emergent fry mortality (USFWS 1990). None of the studies referenced by USBR (1991) contain a rigorous study of pre-emergent fry mortality from which mortality rates could be developed. Limitations in the early lifestage mortality rates were generally recognized, as indicated by HCI (1996) for both fertilized eggs and pre-emergent fry. As stated by HCI (1996) in reference to the mortality rates for pre-emergent fry from USBR (1991), there is "*virtually a total lack of data to base this relationship on…..*" In an application of SALMOD to the Klamath River, Bartholow and Henriksen (2006) indicate that the exact origin of the mortality rate values from USFWS (1990) are somewhat unclear.

Overall, there is a lack of coherent documentation for most of the data serving as the basis for the water temperature-mortality rates for both fertilized eggs and pre-emergent fry in the USBR

Salmon Mortality model. Moreover, these relationships were developed prior to the availability of more comprehensive Chinook salmon early lifestage mortality studies, particularly USFWS (1999).

## USGS (2018) – Perry et al. (2018) – (S3)

The reference to USGS (2018) in SacPAS is directed to the model developed by Perry et al. (2018) which is also referred to as the Stream Salmonid Simulator (S3) model. They developed a model that tracks daily growth, movement, and survival of juvenile salmon. When accounting for egg survival from fertilization to emergence, the model references Geist et al. (2006) to assume that daily egg survival probability was 100% for temperatures less than or equal to 17 °C (62.6°F), and survival was 0.25 for temperatures greater than 17 °C, resulting in nearly total mortality after 4 days above this threshold temperature (Perry et al. 2018). However, as previously described, Geist et al. (2006) did not apply constant water temperatures, but instead applied daily declining water temperatures. In addition, Geist et al. (2006) found high (>90%) Chinook salmon incubation survival through emergence for starting incubation temperatures as high as 16.5°C (61.7°F), but reported very low survival at 17°C (62.6°F). The rationale for application of a 1.0 survival rate at water temperatures less than or equal to 17°C, and a 0.25 survival rate at temperatures greater than 17°C, could not be identified.

## Jager (2011)

Jager (2011) reviewed and compiled mortality and exposure duration data from constant temperature laboratory studies for Chinook salmon eggs (fertilization to hatching) and alevins (hatching to emergence). For each study, Jager (2011) standardized the survival data by dividing by the maximum survival over all temperature treatments for each study. If the study did not report the duration of the two lifestages, a temperature relationship was fitted to the lifestage to estimate duration.

Studies incorporated for the fertilized egg relationship included Murray and McPhail (1988), Combs and Burrows (1957), Garling and Masterson (1985), Beacham and Murray (1989), Jensen and Groot (1991), and Heming (1982). Due to lack of duration data, exposure durations were estimated for fertilized eggs for the Combs and Burrows (1957) data. Studies used in the alevin relationship included Murray and McPhail (1988), Garling and Masterson (1985), Beacham and Murray (1989), and Jensen and Groot (1991). Due to a reported lack of lifestage duration data, durations were estimated for alevins for the Garling and Masterson (1985) and Jensen and Groot (1991) data. For studies where replicate treatments were conducted, survival rates from the replicates were averaged (using a weighted average based on starting number of eggs or alevin) together for each water temperature treatment.

Based on these data, Jager (2011) developed a model relating daily survival of Chinook salmon fertilized eggs and alevins to water temperature using a double Weibull model (**Figure 6**). The right-hand side of the function for eggs (i.e., at 0% daily survival) is driven by two data points from Jensen and Groot (1991). These two data points were excluded from the Water Forum fertilized egg function development (this TM) because mortality reached 100% prior to 50% hatch, and duration to mortality was not reported. In addition, although mortality reached 100% prior to 50% hatch, it is unlikely that the daily survival rate was actually 0%, particularly for the 64.4°F treatment. Although the equation to calculate daily survival based on cumulative survival and duration will result in a 0% daily survival rate, results from other laboratory studies (Seymour

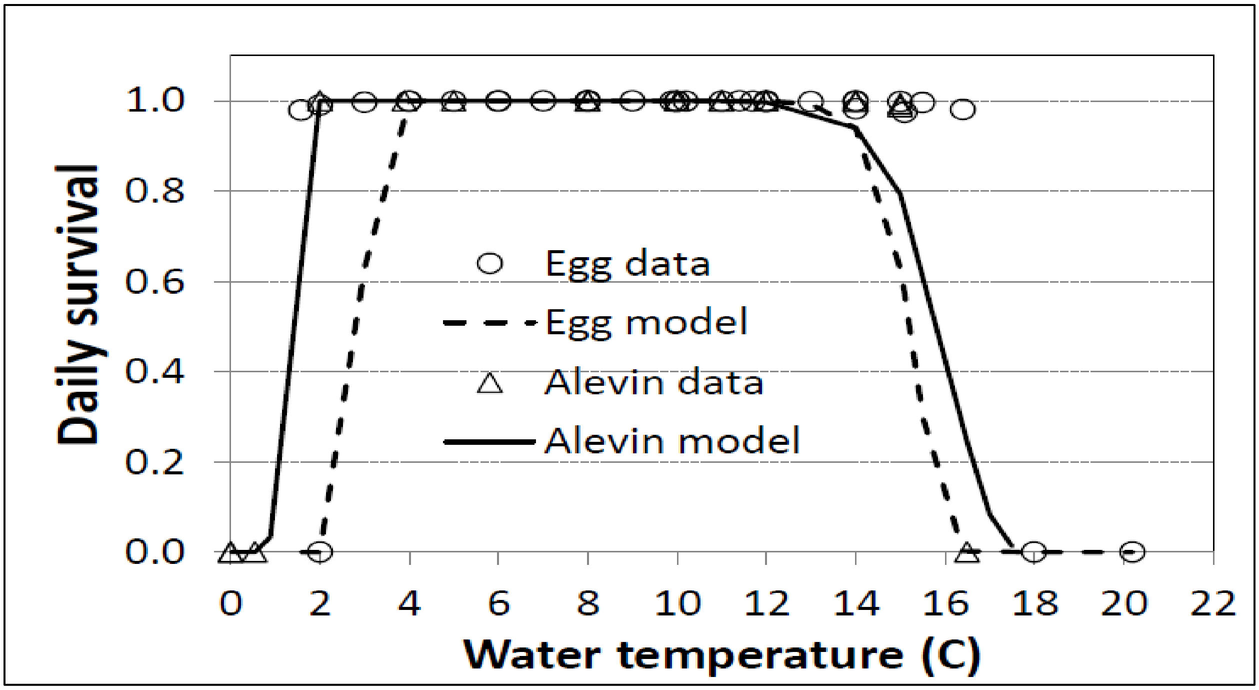


**Figure 6. Chinook salmon egg and alevin thermal daily mortality functions developed by Jager (2011).**

1956 and USFWS 1999) that exposed fertilized eggs to water temperatures of 64-64.6°F indicate that daily mortality rates ranged from 2.8% to 15%. In addition, short-term thermal exposure ("heat shock") experiments found that mortality rates of Chinook salmon cleavage egg and embryo lifestages exposed to 22°C (71.6°F) for 8 hours were 10% and 3%, respectively (Neitzel and Becker 1985).

Similar to the fertilized egg function, the right-hand side of the pre-emergent fry ("alevin") function is driven by only one data point, also from Jensen and Groot (1991), for the 61.5°F treatment. This data point also was excluded from the Water Forum alevin function (this TM) due to concern over the inconsistency in the duration from 50% hatch to emergence for this temperature treatment relative to other treatments. Although Jager (2011) calculated the exposure duration based on water temperature, it is unlikely that, despite the cumulative survival of 0%, that the daily survival rate was 0% (i.e., all alevins perished in one day) at 61.5°F, in consideration of the other water temperature studies. For example, daily alevin mortality rates of Sacramento River fall-run and winter-run Chinook salmon associated with exposure to 62°F across 8 replicates ranged from 2.4% to 20.6% (USFWS 1999).

## Compendium of Water Temperature-Embryonic Morality Relationships in SacPAS

Various relationships developed based on varying datasets, different manipulations to the laboratory data (e.g., scaled cumulative survival estimation), various assumptions (e.g., calculation of exposure duration based on ATUs), and mathematical functions explaining early lifestage mortality due to water temperature (e.g., linear, exponential, double Weibull) provide different functions representing the relationships between water temperature and Chinook salmon embryonic mortality. A compendium of these relationships presented in SacPAS, including the relationships developed in this TM, is presented in **Figure 7**.

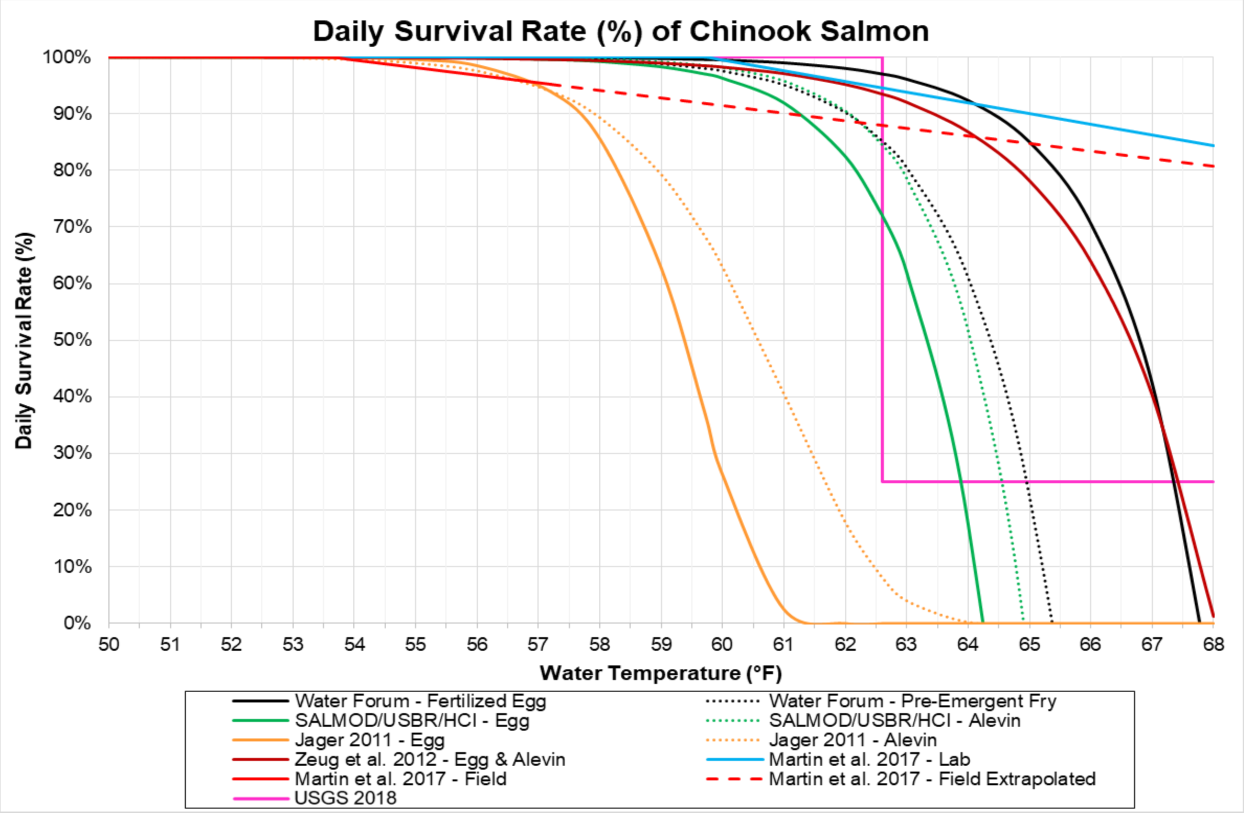


**Figure 7. Chinook salmon fertilized egg and pre-emergent fry water temperature-daily survival functions presented in SacPAS, including relationships developed in this TM (Water Forum 2020).**

# 4. CHANGES IN SURVIVAL WITH CHANGES IN WATER TEMPERATURE

Based on the duration of the power bypass, and the expected water temperature with and without the power bypass, changes in total Chinook salmon embryonic survival can then be estimated for the water temperature-mortality relationships developed in this TM for variable durations of the power bypass. Total survival over a specified number of days is calculated as the daily survival rate raised to the number of days. For example, with a daily survival rate of 99% (.99), and a duration of 10 days, the total survival over the 10 days would equal .99^10 = .9, or 90% total survival.

For visually displaying the total survival of early lifestages over a range of water temperatures for specified durations, **Figures 8** and **9** display the total survival over the specified numbers of days (1, 5, 10, 15, 20, 25, 30 days), assuming a constant mortality rate and water temperature for each consecutive day, for the fertilized egg function, and for the pre-emergent fry function. These figures allow one to identify total mortality over the specified durations for any water temperature. Alternatively, **Figures 10** and **11** can be used to determine total survival for specified water temperatures (56°F, 57°F, 58°F, 59°F, 60°F, 61°F and 62°F), for any number of days up to 30 days.

For identification of changes in total survival with and without a power bypass over specified durations, a tool was developed to allow the user to input the starting temperature (water

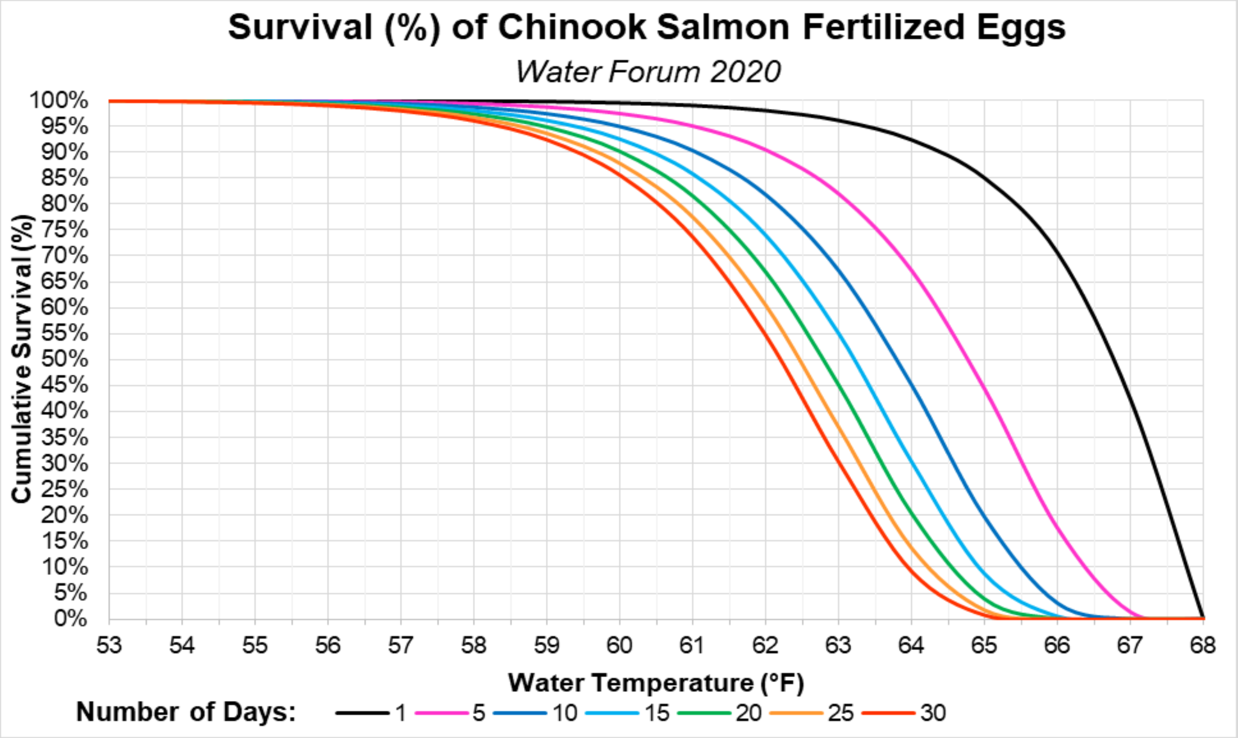


**Figure 8. Cumulative survival of fertilized eggs for specified numbers of days (1, 5, 10, 15, 20, 25, 30) over a range of water temperatures (53-68°F).**

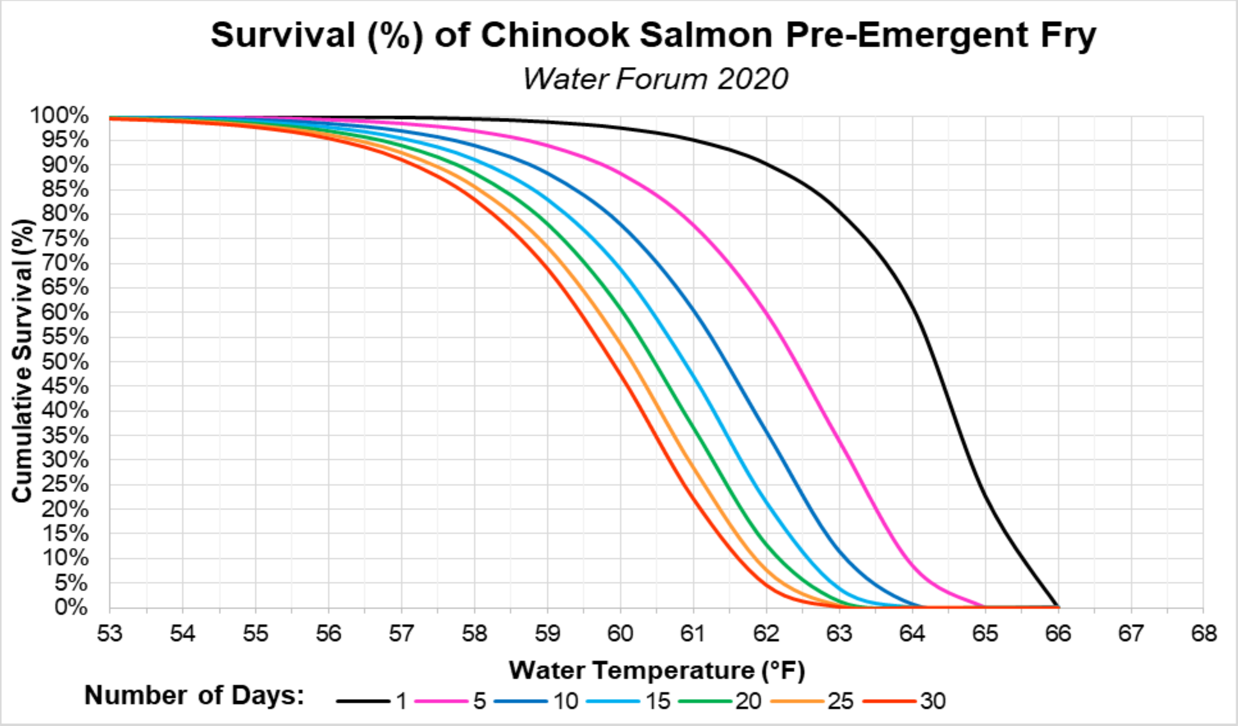


**Figure 9. Cumulative survival of pre-emergent fry for specified numbers of days (1, 5, 10, 15, 20, 25, 30) over a range of water temperatures (53-68°F).**

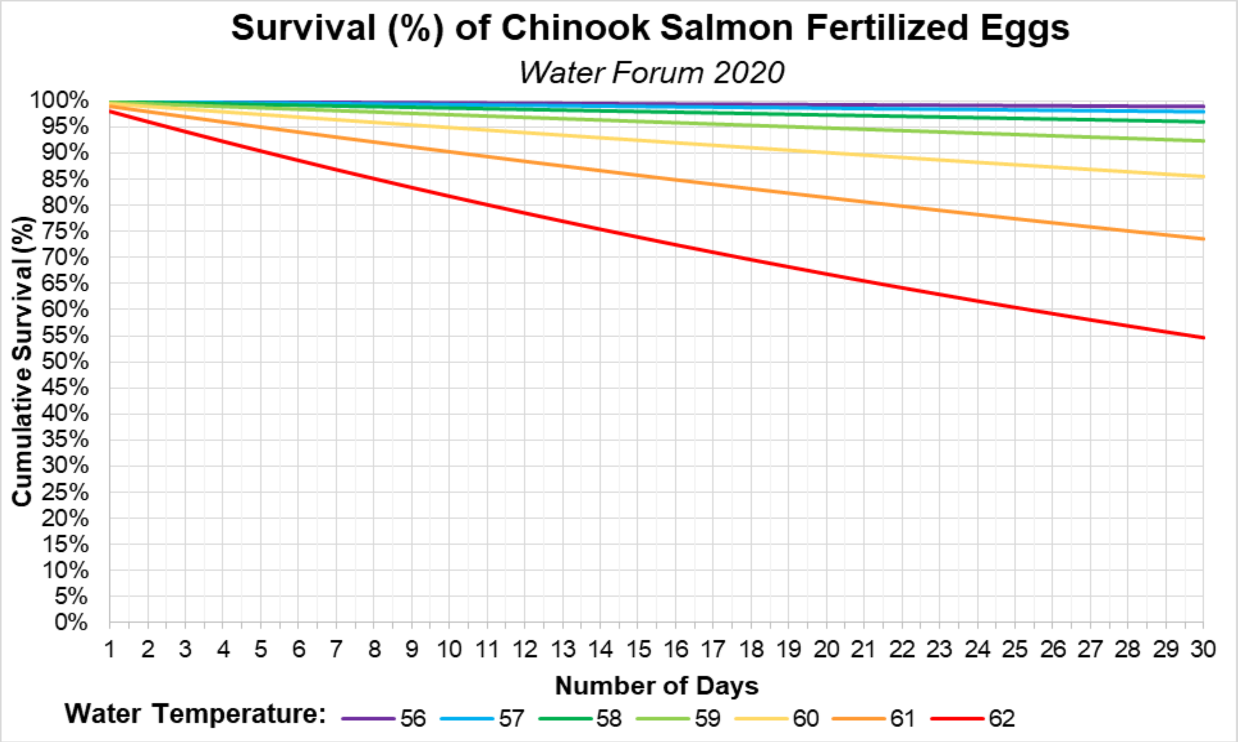


**Figure 10. Cumulative survival of fertilized eggs for specified water temperatures (56, 57, 58, 59, 60, 61, 62°F) for a range of days (1-30 days).**

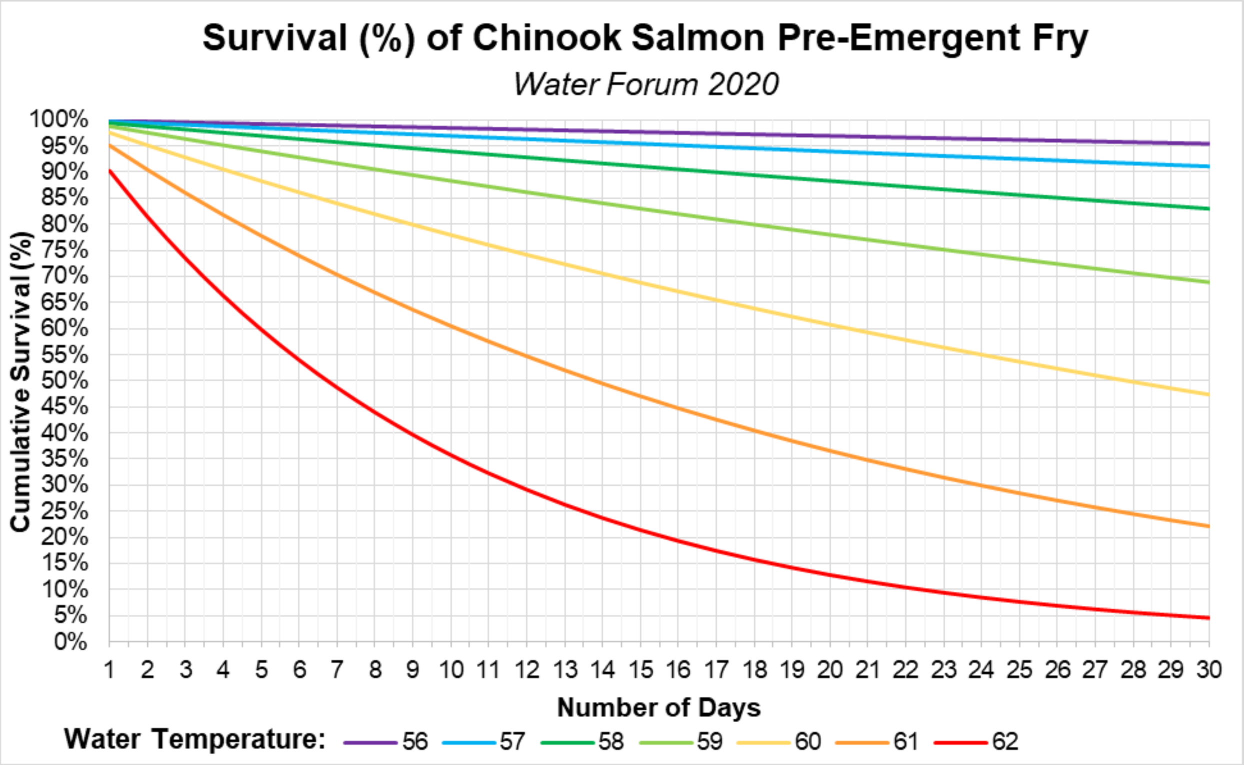


**Figure 11. Cumulative survival of pre-emergent fry for specified water temperatures (56, 57, 58, 59, 60, 61, 62°F) for a range of days (1-30 days).**

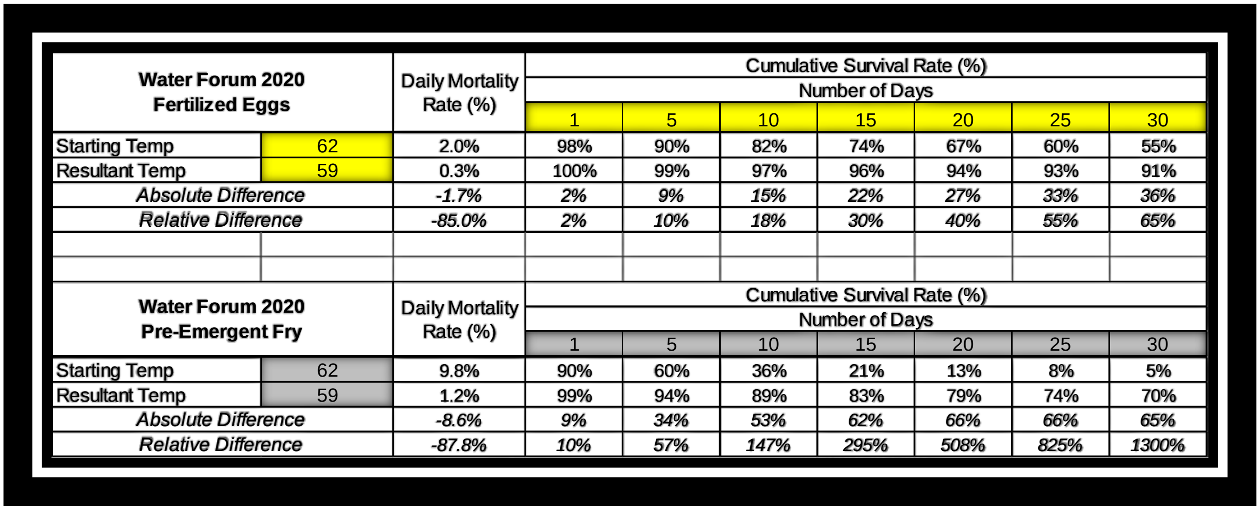
temperature without the power bypass), the water temperature with implementation of the power bypass, and it provides results over a range of durations of the power bypass. **Figure 12** provides an example screenshot of the tool, displaying survival results for a starting temperature of 62°F prior to a bypass, and a resultant temperature of 59°F with the power bypass, over various durations for both the fertilized egg and pre-emergent fry water temperature-mortality relationships.

The tool assumes constant water temperatures over the duration of the bypass, and provides estimated differences in cumulative survival of fertilized eggs and pre-emergent fry (alevins) at the specified resultant temperature relative to the starting temperature, over variable durations of the bypass. The total survival rates shown by the tool are only indicators of survival. The tool is only intended to serve as one piece of information to assist in real-time decision-making, regarding the potential effects of the use of the power bypass on the initial changes in Chinook salmon early lifestage survival. It is recognized that water temperatures do not remain constant over the duration of a typical bypass operation, but it is common to observe decreasing water temperature during the fall when bypass operations are conducted (see Section 5 of this TM). Also, the tool does not account for the proportion of fertilized eggs or pre-emergent fry present at any one time in the river, and is not intended to be a complete early lifestage survival model.

The tool can be accessed at the Water Forum website:

https://www.waterforum.org/water-forum-water-temp-embryo-survival-worksheet/

The tool can be downloaded for user application specifying any water temperatures characterizing pre- and post-bypass operations.



| Water Forum 2020<br>Fertilized Eggs | | Daily Mortality Rate (%) | Cumulative Survival Rate (%) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Number of Days | | | | | | |
| | | | 1 | 5 | 10 | 15 | 20 | 25 | 30 |
| Starting Temp | 62 | 2.0% | 98% | 90% | 82% | 74% | 67% | 60% | 55% |
| Resultant Temp | 59 | 0.3% | 100% | 99% | 97% | 96% | 94% | 93% | 91% |
| *Absolute Difference* | | *-1.7%* | *2%* | *9%* | *15%* | *22%* | *27%* | *33%* | *36%* |
| *Relative Difference* | | *-85.0%* | *2%* | *10%* | *18%* | *30%* | *40%* | *55%* | *65%* |

| Water Forum 2020<br>Pre-Emergent Fry | | Daily Mortality Rate (%) | Cumulative Survival Rate (%) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Number of Days | | | | | | |
| | | | 1 | 5 | 10 | 15 | 20 | 25 | 30 |
| Starting Temp | 62 | 9.8% | 90% | 60% | 36% | 21% | 13% | 8% | 5% |
| Resultant Temp | 59 | 1.2% | 99% | 94% | 89% | 83% | 79% | 74% | 70% |
| *Absolute Difference* | | *-8.6%* | *9%* | *34%* | *53%* | *62%* | *66%* | *66%* | *65%* |
| *Relative Difference* | | *-87.8%* | *10%* | *57%* | *147%* | *295%* | *508%* | *825%* | *1300%* |

**Figure 12. Example screenshot of daily Chinook salmon early lifestage survival tool to evaluate changes in survival associated with changes in water temperature.**

# 5. HISTORICAL POWER BYPASS OPERATIONS

Since 2000, power bypass operations have occurred during 2001, 2002, 2007 through 2009, 2012 through 2016, and 2018. Power bypass operations typically occurred between about late-October and late-November during most years (**Table 3**).

Because cooler water is released to the lower American River during power bypass operations, water temperatures are reduced to more suitable levels for Chinook salmon embryonic incubation during the fall. Water temperatures generally decrease during October through November, due to changing ambient conditions such as decreasing air temperatures during this time period. Examination of water temperatures in the lower American River prior to, during, and subsequent to power bypass operations generally show a more steep reduction in water temperature as the cooler bypass flows influence downstream (e.g., Hazel Ave.) water temperatures (typically starting approximately 2 days after bypass flow releases ramp up to about 300-500 cfs).

**Table 3. Year, starting and ending dates, and total days of power bypass operations at Folsom Dam.**

| Year | Start | End | Total Days of Bypass | Year | Start | End | Total Days of Bypass |
|---|---|---|---|---|---|---|---|
| 2000 | n/a | | | 2010 | n/a | | |
| 2001 | 11/10/2001 | 11/26/2001 | 17 | 2011 | n/a | | |
| 2002 | 10/25/2002 | 11/19/2002 | 26 | 2012 | 10/22/2012 | 11/24/2012 | 34 |
| 2003 | n/a | | | 2013 | 10/28/2013 | 11/27/2013 | 31 |
| 2004 | n/a | | | 2014 | 10/20/2014 | 11/25/2014 | 37 |
| 2005 | n/a | | | 2015 | 10/29/2015 | 12/04/2015 | 37 |
| 2006 | n/a | | | 2016 | 10/28/2016 | 11/24/2016 | 28 |
| 2007 | 11/09/2007 | 11/29/2007 | 21 | 2017 | n/a | | |
| 2008 | 11/10/2008 | 11/28/2008 | 19 | 2018 | 11/04/2018 | 11/19/2018 | 16 |
| 2009 | 11/10/2009 | 11/25/2009 | 16 | 2019 | n/a | | |

Due to the naturally-declining water temperatures during the periods in which power bypass flows have been released historically, it is difficult to ascertain the magnitude of the reduced downstream water temperatures due to only the bypass flows without detailed water temperature modeling.

## 5.1 WATER TEMPERATURE REDUCTIONS

**Figures 13** and **14** display the daily monitored flows at the Fair Oaks Gage, bypass flows, and water temperatures at Hazel Avenue in the lower American River during each of the bypass operation years, as well as average daily air temperatures prior to, during, and after power bypass operations during those years at the Fair Oaks station of the California Irrigation Management Information System (CIMIS), a program under the California Department of Water Resources. In addition to the observable increased rate of water temperature reduction in the lower American River as the bypass flows ramp-up during each bypass year, the water temperature reduction benefits of the bypass operation also are observable at the end of the bypass operation during some years (e.g., 2007, 2015) when instream water temperatures increase as the bypass operation ceases. It should be noted that naturally-declining water temperatures due to ambient conditions such as

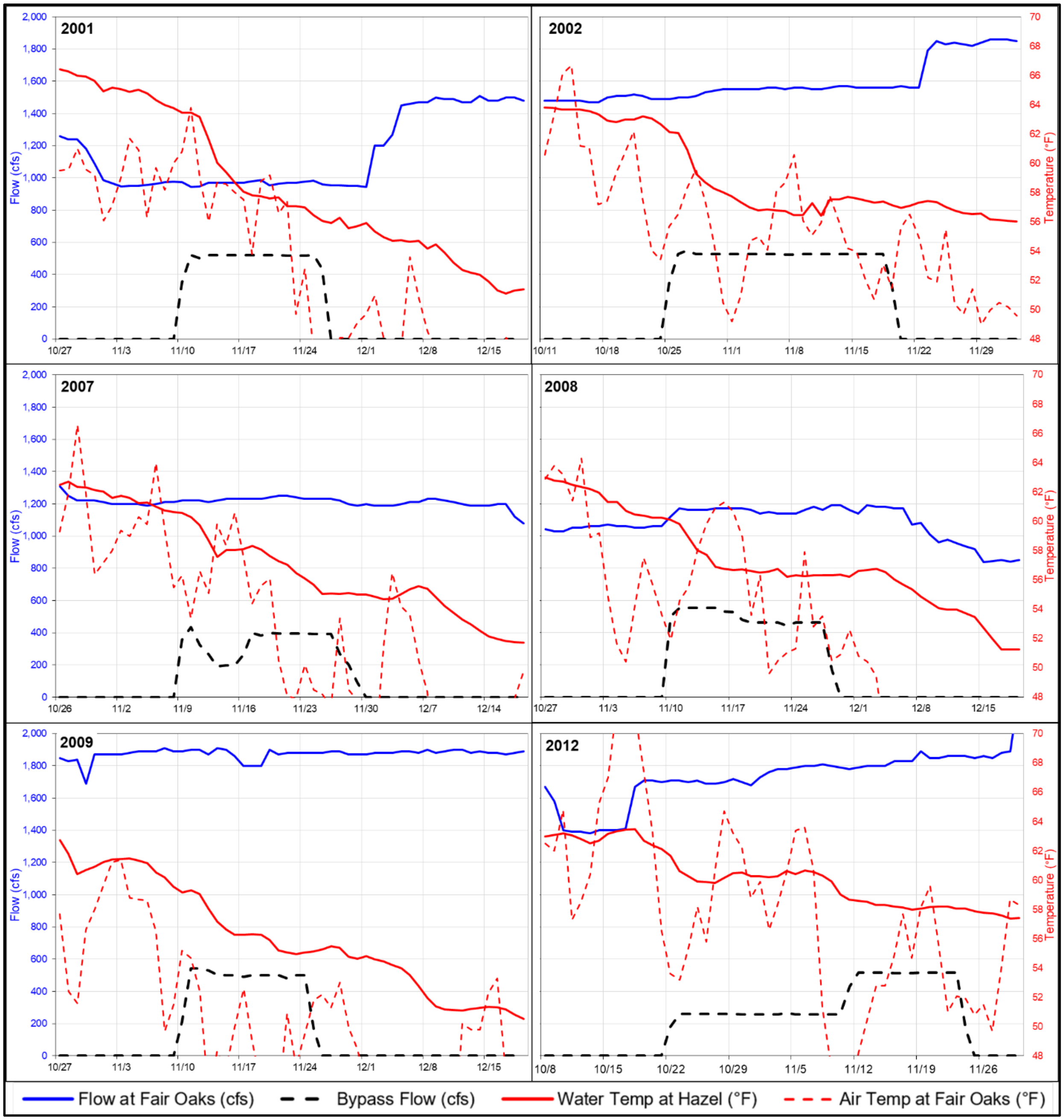


**Figure 13. Monitored flows, bypass flows, and water temperatures in the lower American River for 2001, 2002, 2007, 2008, 2009 and 2012 (years when power bypasses occurred) and average daily air temperatures at Fair Oaks prior to, during, and after power bypass operations.**

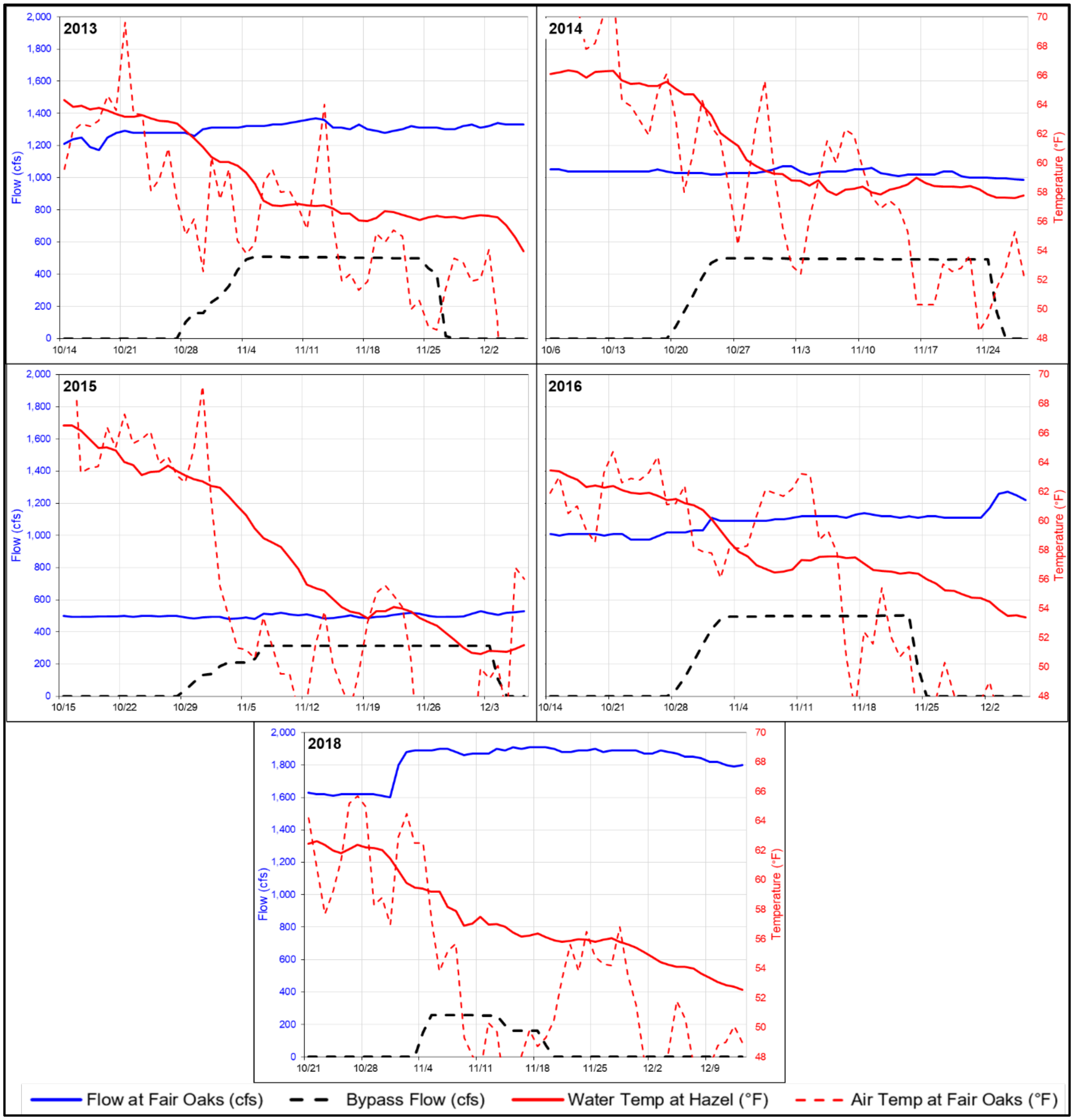


**Figure 14. Monitored flows, bypass flows, and water temperatures in the lower American River during 2013 – 2016, and 2018 (years when power bypasses occurred), and average daily air temperatures at Fair Oaks prior to, during, and after power bypass operations.**

reduced air temperatures also are influencing the reduced water temperatures subsequent to the bypass flow operation (e.g., ranging from about 0.1°F – 0.5°F per day).

**Table 4** summarizes the bypass flow rates, initiation and ramp up dates, and monitored water temperatures at Hazel Ave prior to bypass initiation and 2 days after bypass ramp-up for each bypass year from 2001 through 2018. Water temperatures are identified 2 days after bypass ramp-up because bypass flows released at Folsom Dam require approximately 2 days to notably influence water temperatures at Hazel Avenue due to the nearly 7 mile distance between Folsom Dam and Hazel Avenue, and the retention influence of Lake Natoma. Water temperatures typically decrease after bypass flows ramp-up by about 1-6°F over the course of about 1 to 7 days, depending on the bypass flow timing, bypass flow rates, ramp-up duration, and prevailing flows and water temperatures in the lower American River during each bypass year. As indicators of potential increases in Chinook salmon early lifestage survival associated with the bypass flows, **Tables 5** through **15** display the results of the water temperature-survival tool for both the fertilized egg and pre-emergent fry water temperature-mortality relationships, for each of the bypass years.

**Table 4. Summary of Folsom Dam bypass flow operations and pre- and post-bypass water temperatures at Hazel Ave in the lower American River.**

| Year | Bypass Initiation Date | Bypass Flow (cfs) | Date Full Bypass Flow Achieved | Total Volume of Bypass (AF) | Pre-Bypass Water Temperature (°F) | Post-Bypass Water Temperature (°F) | Water Temperature Difference (°F) |
|---|---|---|---|---|---|---|---|
| 2001 | 11/10/2001 | 522 | 11/11/2001 | 17,006 | 63.8 | 61.7 | -2.1 |
| 2002 | 10/25/2002 | 528 | 10/26/2002 | 26,491 | 62.7 | 59.3 | -3.4 |
| 2007 | 11/9/2007 | 436 | 11/10/2007 | 13,363 | 60.6 | 58.7 | -1.9 |
| 2008 | 11/10/2008 | 554 | 11/11/2008 | 18,085 | 60.2 | 58.0 | -2.2 |
| 2009 | 11/10/2009 | 544 | 11/11/2009 | 14,833 | 59.5 | 58.0 | -1.5 |
| 2012 | 10/22/2012 | 517 | 11/12/2012 | 23,602 | 62.1 | 59.9 | -2.2 |
| 2013 | 10/28/2013 | 508 | 11/5/2013 | 25,942 | 62.7 | 57.1 | -5.6 |
| 2014 | 10/20/2014 | 498 | 10/25/2014 | 33,394 | 65.6 | 61.2 | -4.4 |
| 2015 | 10/29/2015 | 314 | 11/7/2015 | 19,830 | 63.4 | 58.2 | -5.2 |
| 2016 | 10/28/2016 | 495 | 11/3/2016 | 24,244 | 61.4 | 57.6 | -3.8 |
| 2018 | 11/4/2018 | 258 | 11/5/2018 | 6,689 | 59.5 | 58.2 | -1.3 |

**Table 5. Modeled survival rates of Chinook salmon early lifestages based on starting water temperature (pre-bypass) and resultant water temperature (post-bypass) during 2001 power bypass initiation.**

| **Water Forum 2020 Fertilized Eggs** | | Daily Mortality Rate (%) | Cumulative Survival Rate (%) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Number of Days | | | | | | |
| | | | 1 | 5 | 10 | 15 | 20 | 25 | 30 |
| Starting Temp | 63.8 | 6.7% | 93% | 71% | 50% | 35% | 25% | 18% | 12% |
| Resultant Temp | 61.7 | 1.6% | 98% | 92% | 85% | 79% | 72% | 67% | 62% |
| *Absolute Difference* | | *-5.1%* | *5%* | *21%* | *35%* | *44%* | *47%* | *49%* | *50%* |
| *Relative Difference* | | *-76.1%* | *5%* | *30%* | *70%* | *126%* | *188%* | *272%* | *417%* |
| | | | | | | | | | |
| | | | | | | | | | |
| **Water Forum 2020 Pre-Emergent Fry** | | Daily Mortality Rate (%) | Cumulative Survival Rate (%) | | | | | | |
| | | | Number of Days | | | | | | |
| | | | 1 | 5 | 10 | 15 | 20 | 25 | 30 |
| Starting Temp | 63.8 | 33.8% | 66% | 13% | 2% | 0% | 0% | 0% | 0% |
| Resultant Temp | 61.7 | 7.9% | 92% | 66% | 44% | 29% | 19% | 13% | 8% |
| *Absolute Difference* | | *-25.9%* | *26%* | *53%* | *42%* | *29%* | *19%* | *13%* | *8%* |
| *Relative Difference* | | *-76.6%* | *39%* | *408%* | *2100%* | *n/a* | *n/a* | *n/a* | *n/a* |

**Table 6. Modeled survival rates of Chinook salmon early lifestages based on starting water temperature (pre-bypass) and resultant water temperature (post-bypass) during 2002 power bypass initiation.**

| **Water Forum 2020 Fertilized Eggs** | | Daily Mortality Rate (%) | Cumulative Survival Rate (%) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Number of Days | | | | | | |
| | | | 1 | 5 | 10 | 15 | 20 | 25 | 30 |
| Starting Temp | 62.7 | 3.2% | 97% | 85% | 72% | 61% | 52% | 44% | 38% |
| Resultant Temp | 59.3 | 0.3% | 100% | 99% | 97% | 96% | 94% | 93% | 91% |
| *Absolute Difference* | | *-2.9%* | *3%* | *14%* | *25%* | *35%* | *42%* | *49%* | *53%* |
| *Relative Difference* | | *-90.6%* | *3%* | *16%* | *35%* | *57%* | *81%* | *111%* | *139%* |
| | | | | | | | | | |
| | | | | | | | | | |
| **Water Forum 2020 Pre-Emergent Fry** | | Daily Mortality Rate (%) | Cumulative Survival Rate (%) | | | | | | |
| | | | Number of Days | | | | | | |
| | | | 1 | 5 | 10 | 15 | 20 | 25 | 30 |
| Starting Temp | 62.7 | 15.8% | 84% | 42% | 18% | 8% | 3% | 1% | 1% |
| Resultant Temp | 59.3 | 1.5% | 99% | 93% | 86% | 80% | 74% | 69% | 64% |
| *Absolute Difference* | | *-14.3%* | *15%* | *51%* | *68%* | *72%* | *71%* | *68%* | *63%* |
| *Relative Difference* | | *-90.5%* | *18%* | *121%* | *378%* | *900%* | *2367%* | *6800%* | *6300%* |

**Table 7. Modeled survival rates of Chinook salmon early lifestages based on starting water temperature (pre-bypass) and resultant water temperature (post-bypass) during 2007 power bypass initiation.**

| **Water Forum 2020 Fertilized Eggs** | | Daily Mortality Rate (%) | Cumulative Survival Rate (%) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Number of Days | | | | | | |
| | | | 1 | 5 | 10 | 15 | 20 | 25 | 30 |
| Starting Temp | 60.6 | 0.8% | 99% | 96% | 92% | 89% | 85% | 82% | 79% |
| Resultant Temp | 58.7 | 0.2% | 100% | 99% | 98% | 97% | 96% | 95% | 94% |
| *Absolute Difference* | | *-0.6%* | *1%* | *3%* | *6%* | *8%* | *11%* | *13%* | *15%* |
| *Relative Difference* | | *-75.0%* | *1%* | *3%* | *7%* | *9%* | *13%* | *16%* | *19%* |
| | | | | | | | | | |
| | | | | | | | | | |
| **Water Forum 2020 Pre-Emergent Fry** | | Daily Mortality Rate (%) | Cumulative Survival Rate (%) | | | | | | |
| | | | Number of Days | | | | | | |
| | | | 1 | 5 | 10 | 15 | 20 | 25 | 30 |
| Starting Temp | 60.6 | 3.7% | 96% | 83% | 69% | 57% | 47% | 39% | 32% |
| Resultant Temp | 58.7 | 1.0% | 99% | 95% | 90% | 86% | 82% | 78% | 74% |
| *Absolute Difference* | | *-2.7%* | *3%* | *12%* | *21%* | *29%* | *35%* | *39%* | *42%* |
| *Relative Difference* | | *-73.0%* | *3%* | *14%* | *30%* | *51%* | *74%* | *100%* | *131%* |

**Table 8. Modeled survival rates of Chinook salmon early lifestages based on starting water temperature (pre-bypass) and resultant water temperature (post-bypass) during 2008 power bypass initiation.**

| **Water Forum 2020 Fertilized Eggs** | | Daily Mortality Rate (%) | Cumulative Survival Rate (%) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Number of Days | | | | | | |
| | | | 1 | 5 | 10 | 15 | 20 | 25 | 30 |
| Starting Temp | 60.2 | 0.6% | 99% | 97% | 94% | 91% | 89% | 86% | 83% |
| Resultant Temp | 58 | 0.1% | 100% | 100% | 99% | 99% | 98% | 98% | 97% |
| *Absolute Difference* | | *-0.5%* | *1%* | *3%* | *5%* | *8%* | *9%* | *12%* | *14%* |
| *Relative Difference* | | *-83.3%* | *1%* | *3%* | *5%* | *9%* | *10%* | *14%* | *17%* |

| **Water Forum 2020 Pre-Emergent Fry** | | Daily Mortality Rate (%) | Cumulative Survival Rate (%) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Number of Days | | | | | | |
| | | | 1 | 5 | 10 | 15 | 20 | 25 | 30 |
| Starting Temp | 60.2 | 2.8% | 97% | 87% | 75% | 65% | 57% | 49% | 43% |
| Resultant Temp | 58 | 0.6% | 99% | 97% | 94% | 91% | 89% | 86% | 83% |
| *Absolute Difference* | | *-2.2%* | *2%* | *10%* | *19%* | *26%* | *32%* | *37%* | *40%* |
| *Relative Difference* | | *-78.6%* | *2%* | *11%* | *25%* | *40%* | *56%* | *76%* | *93%* |

**Table 9. Modeled survival rates of Chinook salmon early lifestages based on starting water temperature (pre-bypass) and resultant water temperature (post-bypass) during 2009 power bypass initiation.**

| **Water Forum 2020 Fertilized Eggs** | | Daily Mortality Rate (%) | Cumulative Survival Rate (%) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Number of Days | | | | | | |
| | | | 1 | 5 | 10 | 15 | 20 | 25 | 30 |
| Starting Temp | 59.5 | 0.4% | 100% | 98% | 96% | 94% | 92% | 90% | 89% |
| Resultant Temp | 58 | 0.1% | 100% | 100% | 99% | 99% | 98% | 98% | 97% |
| *Absolute Difference* | | *-0.3%* | *0%* | *2%* | *3%* | *5%* | *6%* | *8%* | *8%* |
| *Relative Difference* | | *-75.0%* | *0%* | *2%* | *3%* | *5%* | *7%* | *9%* | *9%* |

| **Water Forum 2020 Pre-Emergent Fry** | | Daily Mortality Rate (%) | Cumulative Survival Rate (%) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Number of Days | | | | | | |
| | | | 1 | 5 | 10 | 15 | 20 | 25 | 30 |
| Starting Temp | 59.5 | 1.7% | 98% | 92% | 84% | 77% | 71% | 65% | 60% |
| Resultant Temp | 58 | 0.6% | 99% | 97% | 94% | 91% | 89% | 86% | 83% |
| *Absolute Difference* | | *-1.1%* | *1%* | *5%* | *10%* | *14%* | *18%* | *21%* | *23%* |
| *Relative Difference* | | *-64.7%* | *1%* | *5%* | *12%* | *18%* | *25%* | *32%* | *38%* |

**Table 10. Modeled survival rates of Chinook salmon early lifestages based on starting water temperature (pre-bypass) and resultant water temperature (post-bypass) during 2012 power bypass initiation.**

| **Water Forum 2020 Fertilized Eggs** | | Daily Mortality Rate (%) | Cumulative Survival Rate (%) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Number of Days | | | | | | |
| | | | 1 | 5 | 10 | 15 | 20 | 25 | 30 |
| Starting Temp | 62.1 | 2.1% | 98% | 90% | 81% | 73% | 65% | 59% | 53% |
| Resultant Temp | 59.9 | 0.5% | 100% | 98% | 95% | 93% | 90% | 88% | 86% |
| *Absolute Difference* | | *-1.6%* | *2%* | *8%* | *14%* | *20%* | *25%* | *29%* | *33%* |
| *Relative Difference* | | *-76.2%* | *2%* | *9%* | *17%* | *27%* | *38%* | *49%* | *62%* |

| **Water Forum 2020 Pre-Emergent Fry** | | Daily Mortality Rate (%) | Cumulative Survival Rate (%) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Number of Days | | | | | | |
| | | | 1 | 5 | 10 | 15 | 20 | 25 | 30 |
| Starting Temp | 62.1 | 10.5% | 90% | 57% | 33% | 19% | 11% | 6% | 4% |
| Resultant Temp | 59.9 | 2.3% | 98% | 89% | 79% | 71% | 63% | 56% | 50% |
| *Absolute Difference* | | *-8.2%* | *8%* | *32%* | *46%* | *52%* | *52%* | *50%* | *46%* |
| *Relative Difference* | | *-78.1%* | *9%* | *56%* | *139%* | *274%* | *473%* | *833%* | *1150%* |

**Table 11. Modeled survival rates of Chinook salmon early lifestages based on starting water temperature (pre-bypass) and resultant water temperature (post-bypass) during 2013 power bypass initiation.**

| **Water Forum 2020 Fertilized Eggs** | | Daily Mortality Rate (%) | Cumulative Survival Rate (%) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Number of Days | | | | | | |
| | | | 1 | 5 | 10 | 15 | 20 | 25 | 30 |
| Starting Temp | 62.7 | 3.2% | 97% | 85% | 72% | 61% | 52% | 44% | 38% |
| Resultant Temp | 57.1 | 0.1% | 100% | 100% | 99% | 99% | 98% | 98% | 97% |
| *Absolute Difference* | | *-3.1%* | *3%* | *15%* | *27%* | *38%* | *46%* | *54%* | *59%* |
| *Relative Difference* | | *-96.9%* | *3%* | *18%* | *38%* | *62%* | *88%* | *123%* | *155%* |

| **Water Forum 2020 Pre-Emergent Fry** | | Daily Mortality Rate (%) | Cumulative Survival Rate (%) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Number of Days | | | | | | |
| | | | 1 | 5 | 10 | 15 | 20 | 25 | 30 |
| Starting Temp | 62.7 | 15.8% | 84% | 42% | 18% | 8% | 3% | 1% | 1% |
| Resultant Temp | 57.1 | 0.3% | 100% | 99% | 97% | 96% | 94% | 93% | 91% |
| *Absolute Difference* | | *-15.5%* | *16%* | *57%* | *79%* | *88%* | *91%* | *92%* | *90%* |
| *Relative Difference* | | *-98.1%* | *19%* | *136%* | *439%* | *1100%* | *3033%* | *9200%* | *9000%* |

**Table 12. Modeled survival rates of Chinook salmon early lifestages based on starting water temperature (pre-bypass) and resultant water temperature (post-bypass) during 2014 power bypass initiation.**

| **Water Forum 2020 Fertilized Eggs** | | Daily Mortality Rate (%) | Cumulative Survival Rate (%) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Number of Days | | | | | | |
| | | | 1 | 5 | 10 | 15 | 20 | 25 | 30 |
| Starting Temp | 65.6 | 22.5% | 78% | 28% | 8% | 2% | 1% | 0% | 0% |
| Resultant Temp | 61.2 | 1.2% | 99% | 94% | 89% | 83% | 79% | 74% | 70% |
| *Absolute Difference* | | *-21.3%* | *21%* | *66%* | *81%* | *81%* | *78%* | *74%* | *70%* |
| *Relative Difference* | | *-94.7%* | *27%* | *236%* | *1013%* | *4050%* | *7800%* | *n/a* | *n/a* |

| **Water Forum 2020 Pre-Emergent Fry** | | Daily Mortality Rate (%) | Cumulative Survival Rate (%) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Number of Days | | | | | | |
| | | | 1 | 5 | 10 | 15 | 20 | 25 | 30 |
| Starting Temp | 65.6 | 100.0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| Resultant Temp | 61.2 | 5.6% | 94% | 75% | 56% | 42% | 32% | 24% | 18% |
| *Absolute Difference* | | *-94.4%* | *94%* | *75%* | *56%* | *42%* | *32%* | *24%* | *18%* |
| *Relative Difference* | | *-94.4%* | *n/a* | *n/a* | *n/a* | *n/a* | *n/a* | *n/a* | *n/a* |

**Table 13. Modeled survival rates of Chinook salmon early lifestages based on starting water temperature (pre-bypass) and resultant water temperature (post-bypass) during 2015 power bypass initiation.**

| **Water Forum 2020 Fertilized Eggs** | | Daily Mortality Rate (%) | Cumulative Survival Rate (%) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Number of Days | | | | | | |
| | | | 1 | 5 | 10 | 15 | 20 | 25 | 30 |
| Starting Temp | 63.4 | 5.1% | 95% | 77% | 59% | 46% | 35% | 27% | 21% |
| Resultant Temp | 58.2 | 0.2% | 100% | 99% | 98% | 97% | 96% | 95% | 94% |
| *Absolute Difference* | | *-4.9%* | *5%* | *22%* | *39%* | *51%* | *61%* | *68%* | *73%* |
| *Relative Difference* | | *-96.1%* | *5%* | *29%* | *66%* | *111%* | *174%* | *252%* | *348%* |

| **Water Forum 2020 Pre-Emergent Fry** | | Daily Mortality Rate (%) | Cumulative Survival Rate (%) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Number of Days | | | | | | |
| | | | 1 | 5 | 10 | 15 | 20 | 25 | 30 |
| Starting Temp | 63.4 | 25.6% | 74% | 23% | 5% | 1% | 0% | 0% | 0% |
| Resultant Temp | 58.2 | 0.7% | 99% | 97% | 93% | 90% | 87% | 84% | 81% |
| *Absolute Difference* | | *-24.9%* | *25%* | *74%* | *88%* | *89%* | *87%* | *84%* | *81%* |
| *Relative Difference* | | *-97.3%* | *34%* | *322%* | *1760%* | *8900%* | *n/a* | *n/a* | *n/a* |

**Table 14. Modeled survival rates of Chinook salmon early lifestages based on starting water temperature (pre-bypass) and resultant water temperature (post-bypass) during 2016 power bypass initiation.**

| **Water Forum 2020 Fertilized Eggs** | | Daily Mortality Rate (%) | Cumulative Survival Rate (%) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Number of Days | | | | | | |
| | | | 1 | 5 | 10 | 15 | 20 | 25 | 30 |
| Starting Temp | 61.4 | 1.3% | 99% | 94% | 88% | 82% | 77% | 72% | 68% |
| Resultant Temp | 57.6 | 0.1% | 100% | 100% | 99% | 99% | 98% | 98% | 97% |
| *Absolute Difference* | | *-1.2%* | *1%* | *6%* | *11%* | *17%* | *21%* | *26%* | *29%* |
| *Relative Difference* | | *-92.3%* | *1%* | *6%* | *13%* | *21%* | *27%* | *36%* | *43%* |
| | | | | | | | | | |
| | | | | | | | | | |
| **Water Forum 2020 Pre-Emergent Fry** | | Daily Mortality Rate (%) | Cumulative Survival Rate (%) | | | | | | |
| | | | Number of Days | | | | | | |
| | | | 1 | 5 | 10 | 15 | 20 | 25 | 30 |
| Starting Temp | 61.4 | 6.5% | 94% | 71% | 51% | 36% | 26% | 19% | 13% |
| Resultant Temp | 57.6 | 0.5% | 100% | 98% | 95% | 93% | 90% | 88% | 86% |
| *Absolute Difference* | | *-6.0%* | *6%* | *27%* | *44%* | *57%* | *64%* | *69%* | *73%* |
| *Relative Difference* | | *-92.3%* | *6%* | *38%* | *86%* | *158%* | *246%* | *363%* | *562%* |

**Table 15. Modeled survival rates of Chinook salmon early lifestages based on starting water temperature (pre-bypass) and resultant water temperature (post-bypass) during 2018 power bypass initiation.**

| **Water Forum 2020 Fertilized Eggs** | | Daily Mortality Rate (%) | Cumulative Survival Rate (%) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Number of Days | | | | | | |
| | | | 1 | 5 | 10 | 15 | 20 | 25 | 30 |
| Starting Temp | 59.5 | 0.4% | 100% | 98% | 96% | 94% | 92% | 90% | 89% |
| Resultant Temp | 58.2 | 0.2% | 100% | 99% | 98% | 97% | 96% | 95% | 94% |
| *Absolute Difference* | | *-0.2%* | *0%* | *1%* | *2%* | *3%* | *4%* | *5%* | *5%* |
| *Relative Difference* | | *-50.0%* | *0%* | *1%* | *2%* | *3%* | *4%* | *6%* | *6%* |
| | | | | | | | | | |
| | | | | | | | | | |
| **Water Forum 2020 Pre-Emergent Fry** | | Daily Mortality Rate (%) | Cumulative Survival Rate (%) | | | | | | |
| | | | Number of Days | | | | | | |
| | | | 1 | 5 | 10 | 15 | 20 | 25 | 30 |
| Starting Temp | 59.5 | 1.7% | 98% | 92% | 84% | 77% | 71% | 65% | 60% |
| Resultant Temp | 58.2 | 0.7% | 99% | 97% | 93% | 90% | 87% | 84% | 81% |
| *Absolute Difference* | | *-1.0%* | *1%* | *5%* | *9%* | *13%* | *16%* | *19%* | *21%* |
| *Relative Difference* | | *-58.8%* | *1%* | *5%* | *11%* | *17%* | *23%* | *29%* | *35%* |

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