ERRATA

July 20, 2017

On May 11, 2017, the Districts circulated the water temperature index (WTI) literature review summary to the Plenary Group for review. At the May 18, 2017, Plenary Group meeting, attendees voted to adopt the WTI literature review and summary as presented to the Plenary Group. Following the meeting on May 18, the WTI literature review summary was modified as follows:

- Given that the FERC (1993) reference is a secondary or tertiary source of information, and not a primary source, references to FERC (1993) have been removed from the document (see pages 5 – 8, 10 – 11, 15, and 26).
- Several references to Marine and Cech (2004) were incomplete descriptions of the findings of the study; this has been corrected (see pages 20 – 24).
- Word processing errors were corrected (see pages 5 and 19 – 22).

UPPER TUOLUMNE RIVER REINTRODUCTION ASSESSMENT FRAMEWORK
WATER TEMPERATURE SUBCOMMITTEE

LIFESTAGE-SPECIFIC WATER TEMPERATURE BIOLOGICAL EFFECTS AND INDEX TEMPERATURE VALUES

Literature Review Summary

INTRODUCTION

The La Grange Hydroelectric Project (La Grange Project), owned and operated by the Turlock Irrigation District and Modesto Irrigation District (TID/MID, or the Districts), is currently undergoing the Federal Energy Regulatory Commission (FERC) Integrated Licensing Process (ILP). As part of this process, the Districts are implementing a FERC-approved Fish Passage Facilities Alternatives Assessment which consists of developing general design criteria and design considerations applicable to upstream and downstream fish passage facilities at the La Grange Project. Design criteria and considerations include items such as: site-specific physical and operational parameters; applicable regulatory requirements; National Marine Fisheries Service (NMFS), U.S. Fish and Wildlife Service (USFWS), and California Department of Fish and Wildlife (CDFW) biological and engineering design criteria; site-specific biological/habitat information relevant to the sizing and configuration of facilities; and any other information gaps that may affect siting, sizing, general design parameters, capital cost, and operating requirements of potential fish passage facilities.

To make certain that detailed, site-specific information is available to support and adequately inform decisions regarding fish reintroduction and fish passage, TID, MID, and licensing participants came to a consensus on the need for and utility of an Upper Tuolumne River Reintroduction Assessment Framework (Framework). The Framework is intended to provide a comprehensive, collaborative, and transparent approach for evaluating the full range of potential issues associated with the future reintroduction of anadromous salmonids to the upper Tuolumne River. In addition to considering aspects of the technical feasibility of building and operating fish passage facilities, the Framework considers the interrelated issues of ecological feasibility, biological constraints, economics, regulatory implications, and other considerations of reintroduction. Elements of the Framework are interconnected, with fish passage construction and operational requirements needing to properly reflect biological constraints, ecological considerations, and economic cost-benefit assessments.

Water temperature considerations are a primary component of assessing any potential anadromous salmonid reintroduction effort. In support of the Framework, the Districts and licensing participants established a Water Temperature Subcommittee to begin investigating water temperature considerations pertinent to anadromous salmonid reintroduction opportunities in the accessible reaches of the Tuolumne River upstream of Don Pedro Reservoir (upper Tuolumne River). On September 15, 2016, the Districts hosted the first conference call for the Water Temperature Subcommittee (draft meeting notes from this call were distributed on October 3 for a 30-day comment period). On the conference call, attendees discussed the need for a comprehensive literature review of regional and site-specific information to inform the selection of water temperature index (WTI) values to be used in an evaluation of the water temperature-related reintroduction potential in the reaches of the upper Tuolumne River. Meeting attendees agreed that the literature review performed for the Yuba Salmon Forum (Appendix A; Bratovich *et al.* 2012) to support the anadromous salmonid reintroduction assessment in this watershed coupled with site-specific temperature studies or data for the Tuolumne River, if available, would be a good basis for this effort. The following represents an updated literature review summary that is being provided to the Water Temperature Subcommittee to support selection of water temperature index values for the Framework.

The WTI values presented herein represent a gradation of potential biological effects from optimal to lethal water temperatures for each lifestage. 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. Acute, chronic, and optimal growth zones are displayed in Figure 1.

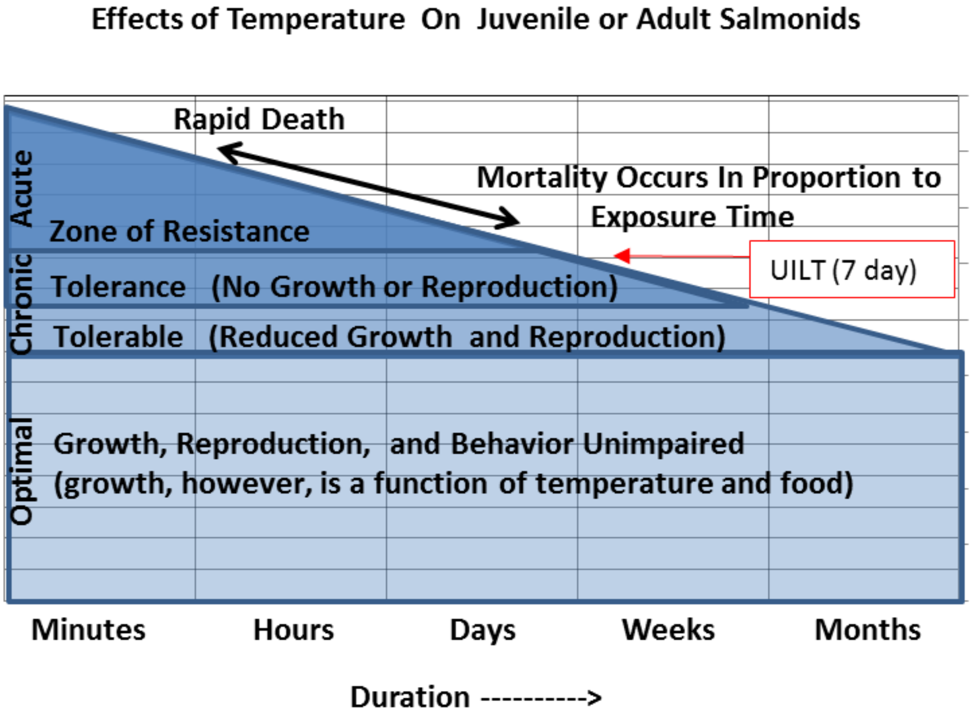

Figure 1. Illustration of acute, chronic, and optimal temperature zones (adapted from Sullivan et al. 2000).

STEELHEAD LIFESTAGE-SPECIFIC WATER TEMPERATURE INDEX VALUES

Adult Immigration and Holding

Water temperatures can control the timing of adult spawning migrations and can affect the viability of eggs in holding females. Yuba County Water Agency (YCWA) *et al.* (2007) suggests that few studies have been published examining the effects of water temperature on either steelhead immigration or steelhead holding, and none of the available studies were recent (Bruin and Waldsdorf 1975; McCullough *et al.* 2001). The available studies suggest that adverse effects occur to immigrating and holding steelhead at water temperatures exceeding the mid-50°F range, and that immigration will be delayed if water temperatures approach approximately 70°F (Table 1). WTI values of 52°F, 56°F, 61°F, 64°F, 65°F, 68°F and 70°F were identified because they provide a gradation of potential water temperature effects, and the available literature provided the strongest support for these values.

Because of the paucity of literature pertaining to steelhead adult immigration and holding, an evenly spaced range of WTI values could not be achieved. 52°F was identified as a WTI value because it has been referred to as a "recommended" (Reclamation 2003), "preferred" (McEwan and Jackson 1996; NMFS 2000; NMFS 2002), and "optimum" (Reclamation 1997a) water temperature for steelhead adult immigration. Increasing levels of thermal stress to this lifestage may reportedly occur above the 52°F WTI value. 56°F was identified as a WTI value because 56°F represents a water temperature above which adverse effects to migratory and holding steelhead begin to arise (Bruin and Waldsdorf 1975; Leitritz and Lewis 1980; McCullough *et al.* 2001; Smith *et al.* 1983). 50-59°F is referred to as the "preferred" range of water temperatures for California summer steelhead holding (Moyle *et al.* 1995). Water temperatures greater than 61°F may result in "chronic high stress" of holding Central Valley winter-run steelhead (USFWS 1995a). A water temperature of 64°F (7DADM) was identified as the value for steelhead adult lifestage for the San Joaquin River (CALFED 2009) and as the Upper Optimum Value for steelhead adult migration (maximum weekly average temperature; MWAT) for the Yuba Reintroduction Assessment (Bratovich *et al.* 2012). EPA Region 10 Guidance for Pacific Northwest State and Tribal Temperature Water Quality Standards identifies 64°F (7DADM) for "salmon and trout" migration (EPA 2003b). 65°F was identified as a WTI value because steelhead (and fall-run Chinook salmon) encounter potentially stressful temperatures between 64.4-73.4°F (Richter and Kolmes 2005). Additionally, over 93% of steelhead detections occurred in the 65.3-71.6°F range, although this may be above the temperature for optimal immigration (Salinger and Anderson 2006) and/or may modify migration timing due to holding in coldwater refugia (High *et al.* 2006). A water temperature of 68°F (MWAT) was identified as the Upper Tolerable Value for steelhead adult migration for the Yuba Reintroduction Assessment (Bratovich *et al.* 2012). A water temperature of 68°F was found to drop egg fertility in vivo to 5% after 4.5 days (McCullough *et al.* 2001). Additionally, empirical adult *O. mykiss* population data from the North Yuba, Middle Yuba, South Yuba, Middle Fork American, and Rubicon rivers were collected in 2007-2009 were plotted against temperature (Figure 4 of Bratovich *et al.* 2012). The data show a population density break at about 68°F. Although smaller population densities occurred at higher temperatures, the largest population densities occurred at temperatures near 68.0°F or less. 70°F was identified as the highest WTI value because the literature suggests that water temperatures near and above 70.0°F may result in a thermal barrier to adult steelhead migrating upstream (McCullough *et al.* 2001) and are water temperatures referred to as "stressful" to upstream migrating steelhead in the Columbia River (Lantz 1971 as cited in Beschta *et al.* 1987). Further, Coutant (1972) found that the upper incipient lethal temperature (UILT) for adult steelhead was 69.8°F and temperatures between 73-75°F are described as "lethal" to holding adult steelhead in Moyle (2002).

As part of the Framework, TID and MID, in collaboration with stakeholders developed a table of WTI values from select salmon and steelhead programs in the Central Valley (Temperature Criteria Matrix; presented at the September 15, 2016 Water Temperature Subcommittee conference call). The table was developed to support the Framework's Water Temperature Subcommittee whose purpose is to establish a technical basis to evaluate water temperature regimes for target anadromous salmonid reintroduction into the Tuolumne River upstream of Don Pedro Reservoir. For steelhead adult immigration, the Temperature Criteria Matrix identified 64°F for the San Joaquin (CALFED 2009) and 64°F (Upper Optimum Value) and 68°F (Upper Tolerable Value) for the Yuba Reintroduction Assessment (Bratovich *et al.* 2012).

For steelhead adult holding, the Temperature Criteria Matrix identified 61°F (Upper Optimum Value) and 65°F (Upper Tolerable Value), MWAT, for the Yuba Reintroduction Assessment (Bratovich *et al.* 2012).

Table 1. Steelhead Adult Immigration and Holding WTI Values and the Literature Supporting Each Value.

Index Value	Supporting Literature
52°F (11.1°C)	Preferred range for adult steelhead immigration of 46.0°F to 52.0°F (NMFS 2000; NMFS 2001a; SWRCB 2003). Optimum range for adult steelhead immigration of 46.0°F to 52.1°F[1] (Reclamation 1997a). Recommended adult steelhead immigration temperature range of 46.0°F to 52.0°F (Reclamation 2003).
56°F (13.3°C)	To produce rainbow trout eggs of good quality, brood fish must be held at water temperatures not exceeding 56.0°F (Leitritz and Lewis 1980). Rainbow trout brood fish must be held at water temperatures not exceeding 56°F for a period of 2 to 6 months before spawning to produce eggs of good quality (Bruin and Waldsdorf 1975). Holding migratory fish at constant water temperatures above 55.4°F to 60.1°F may impede spawning success (McCullough *et al.* 2001).
61°F (16.1°C)	Water temperatures greater than 61°F may result in "chronic high stress" of holding Central Valley winter- run steelhead (USFWS 1995a). Preferred range of water temperature for holding California summer steelhead occurs between 50-59°F (Moyle 1995). A water temperature of 61°F (MWAT) was identified as the Upper Optimum Value for steelhead adult holding for the Yuba Reintroduction Assessment (Bratovich *et al.* 2012).
64°F (17.8°C)	Steelhead (and fall-run Chinook salmon) encounter potentially stressful temperatures between 64.4-73.4°F (Richter and Kolmes 2005). Over 93% of steelhead detections occurred in the 65.3-71.6°F, although this may be above the temperature for optimal immigration (Salinger and Anderson 2006). A water temperature of 64°F was identified as the value for steelhead adult lifestage, 7DADM, for the San Joaquin River (CALFED 2009) and as the Upper Optimum Value for steelhead adult migration, MWAT, for the Yuba Reintroduction Assessment (Bratovich *et al.* 2012). EPA Region 10 Guidance for Pacific Northwest State and Tribal Temperature Water Quality Standards identifies 64°F (7DADM) for "salmon and trout" migration (EPA 2003b).
65°F (18.3°C)	A water temperature of 65°F (MWAT) was identified as the Upper Tolerable Value for steelhead adult holding for the Yuba Reintroduction Assessment (Bratovich *et al.* 2012).
68°F (20°C)	A water temperature of 68°F (MWAT) was identified as the Upper Tolerable Value for steelhead adult migration for the Yuba Reintroduction Assessment (Bratovich *et al.* 2012). A water temperature of 68°F was found to drop egg fertility in vivo to 5% after 4.5 days (McCullough *et al.* 2001).
70°F (21.1°C)	Migration barriers have frequently been reported for pacific salmonids when water temperatures reach 69.8°F to 71.6°F (McCullough *et al.* 2001). Snake River adult steelhead immigration was blocked when water temperatures reached 69.8 (McCullough *et al.* 2001). The UILT for adult steelhead was determined to be 69.8°F (Coutant 1972).

Spawning and Embryo Incubation

Relatively few studies have been published directly addressing the effects of water temperature on steelhead spawning and embryo incubation (Redding and Schreck 1979; Rombough 1988). Because anadromous steelhead and non-anadromous rainbow trout are

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[1] Similar to Bratovich *et al*. 2012, rounded whole integers were identified for index values to avoid unwarranted specificity.

genetically and physiologically similar, studies on non-anadromous rainbow trout also were considered in the development of WTI values for steelhead spawning and embryo incubation (Moyle 2002; McEwan 2001). From the available literature, water temperatures in the low 50°F range appear to support high embryo survival, with substantial mortality to steelhead eggs reportedly occurring at water temperatures in the high 50°F range and above (Table 2).

WTI values of 46°F, 52°F, 54°F, 55°F, 57°F, 59°F and 60°F were identified for two reasons. First, the available literature provided the strongest support for WTI values at or near these integers. Second, the index values reflect a gradation of potential water temperature effects ranging between optimal to lethal conditions for steelhead spawning and embryo incubation. Some literature suggests water temperatures ≤ 50°F are when steelhead spawn (Orcutt *et al.* 1968) and/or are optimal for steelhead spawning and embryo survival (Myrick and Cech 2001; Timoshina 1972) and temperatures between 39-52°F are "preferred" by spawning steelhead (IEP Steelhead Project Work Team (no date); McEwan and Jackson 1996). Orcutt *et al.* (1968) reported that steelhead spawning in late spring in the Clearwater and Salmon Rivers, Idaho, occurred at temperatures between 35.6 and 46.4°F. A larger body of literature suggests optimal conditions occur at water temperatures ≤ 52°F (Humpesch 1985; NMFS 2000; NMFS 2001a; NMFS 2002; Reclamation 1997b; SWRCB 2003; USFWS 1995b). Further, water temperatures between 48-52°F were referred to as "optimal" (McEwan and Jackson 1996; NMFS 2000) and "preferred" (Bell 1986) for steelhead embryo incubation. Therefore, 52°F was identified as the lowest WTI value. Increasing levels of thermal stress to the steelhead spawning and embryo incubation lifestage may reportedly occur above the 52°F WTI value.

A temperature of 54°F was identified as the next index value, because although most of the studies conducted at or near 54.0°F report high survival and normal development (Kamler and Kato 1983; Redding and Schreck 1979; Rombough 1988), some evidence suggests that symptoms of thermal stress arise at or near 54.0°F (Humpesch 1985; Timoshina 1972). Thus, water temperatures near 54°F may represent an inflection point between properly functioning water temperature conditions, and conditions that cause negative effects to steelhead spawning and embryo incubation. EPA Region 10 Guidance for Pacific Northwest State and Tribal Temperature Water Quality Standards identifies 55°F (7DADM) for "salmon and trout" spawning and egg incubation (EPA 2003b). For steelhead spawning and embryo incubation in the Yuba River, the Framework Temperature Criteria Matrix identified 54°F and 57°F for Upper Optimum and Upper Tolerable values, respectively (Bratovich *et al.* 2012). 57°F was identified as an index value because embryonic mortality increases sharply and development becomes retarded at incubation temperatures greater than or equal to 57°F. Velsen (1987) provided a compilation of data on rainbow trout and steelhead embryo mortality to 50% hatch under incubation temperatures ranging from 33.8°F to 60.8°F that demonstrated a two-fold increase in mortality for embryos incubated at 57.2°F, compared to embryos incubated at 53.6°F.

In a laboratory study using gametes from Big Qualicum River, Vancouver Island, steelhead mortality increased to 15% at a constant temperature of 59.0°F, compared to less than 4% mortality at constant temperatures of 42.8°F, 48.2°F, and 53.6°F (Rombough 1988). Also, alevins hatching at 59°F were considerably smaller and appeared less well developed than those incubated at the lower temperature treatments. From fertilization to 50% hatch, rainbow trout eggs from Ontario Provincial Normendale Hatchery had 56% survival when incubated at 59.0°F (Kwain 1975).

As part of the Don Pedro Hydroelectric Project FERC relicensing process, the Districts conducted an *O. mykiss* Population Study (TID/MID 2014) for the Lower Tuolumne River below La Grange Diversion Dam. The goal of the study is to provide a quantitative population model to investigate the relative influences of various factors on the lifestage-specific production of *O. mykiss* in the Tuolumne River including water temperature effects on population response for specific in-river lifestages. The study noted that although no literature information could be identified regarding upper temperature limits for spawning initiation, maximum temperature limits for spawning are assumed to be on the order of 15°C (59°F) inferred from egg mortality thresholds for resident *O. mykiss* (Velsen 1987) as well as steelhead (Rombough 1988). Similarly, for egg incubation, the model allowed for a broad range of flow and water temperature conditions using the completed model, an initial acute mortality threshold of 15°C (59°F) was included based upon a literature review by Myrick and Cech (2001).

From fertilization to 50% hatch, Big Qualicum River steelhead had 93% mortality at 60.8°F, 7.7% mortality at 57.2°F, and 1% mortality at 47.3°F and 39.2°F (Velsen 1987). Myrick and Cech (2001) similarly described water temperatures >59°F as "lethal" to incubating steelhead embryos.

Table 2. Steelhead Spawning and Embryo Incubation WTI Values and the Literature Supporting Each Value.

Index Value	**Supporting Literature**
46°F (7.8°C)	Orcutt *et al.* (1968) reported that steelhead spawning in late spring in the Clearwater and Salmon Rivers, Idaho, occurred at temperatures between 35.6 and 46.4°F.
52°F (11.1°C)	Rainbow trout from Mattighofen (Austria) had highest egg survival at 52.0°F compared to 45.0°F, 59.4°F, and 66.0°F (Humpesch 1985). Water temperatures from 48.0°F to 52.0°F are suitable for steelhead incubation and emergence in the American River and Clear Creek (NMFS 2000; NMFS 2001a; NMFS 2002a). Optimum water temperature range of 46.0°F to 52.0°F for steelhead spawning in the Central Valley (USFWS 1995b). Optimum water temperature range of 46.0°F to 52.1°F for steelhead spawning and 48.0°F to 52.1°F for steelhead egg incubation (Reclamation 1997a). Upper limit of preferred water temperature of 52.0°F for steelhead spawning and egg incubation (SWRCB 2003).
54°F (12.2°C)	Big Qualicum River steelhead eggs had 96.6% survival to hatch at 53.6°F (Rombough 1988). Highest survival from fertilization to hatch for *Salmo gairdneri* incubated at 53.6°F (Kamler and Kato 1983). Emergent fry were larger when North Santiam River (Oregon) winter steelhead eggs were incubated at 53.6°F than at 60.8°F (Redding and Schreck 1979). The upper optimal water temperature regime based on constant or acclimation water temperatures necessary to achieve full protection of steelhead is 51.8°F to 53.6°F (EPA 2001). From fertilization to hatch, rainbow trout eggs and larvae had 47.3% mortality (Timoshina 1972). Survival of rainbow trout eggs declined at water temperatures between 52.0 and 59.4°F (Humpesch 1985). The optimal constant incubation water temperature for steelhead occurs below 53.6°F (McCullough *et al.* 2001). A water temperature of 54°F (MWAT) was identified as the Upper Optimum Value for steelhead spawning and embryo incubation for the Yuba Reintroduction Assessment (Bratovich *et al.* 2012).
55°F (12.8°C)	EPA Region 10 Guidance for Pacific Northwest State and Tribal Temperature Water Quality Standards identifies 55°F (7DADM) for "salmon and trout" spawning and egg incubation (EPA 2003b).

Index Value	Supporting Literature
57°F (13.9°C)	From fertilization to 50% hatch, Big Qualicum River steelhead had 93% mortality at 60.8°F, 7.7% mortality at 57.2°F, and 1% mortality at 47.3°F and 39.2°F (Velsen 1987). A sharp decrease in survival was observed for rainbow trout embryos incubated above 57.2°F (Kamler and Kato 1983). A water temperature of 57°F (MWAT) was identified as the Upper Tolerable Value for steelhead spawning and embryo incubation for the Yuba Reintroduction Assessment (Bratovich *et al.* 2012).
59°F (15°C)	Based on egg mortality thresholds for steelhead, maximum temperature limits for spawning are assumed to be 59°F (Rombaugh 1988 as cited in TID/MID 2014). A water temperature of 59°F was identified as the initial acute mortality threshold for steelhead egg incubation (Myrick and Cech 2001 as cited in TID/MID 2014). From fertilization to 50% hatch, rainbow trout eggs from Ontario Provincial Normendale Hatchery had 56% survival when incubated at 59.0°F (Kwain 1975).
60°F (15.6°C)	Water temperatures >59°F are described as "lethal" to incubating steelhead embryos (Myrick and Cech 2001), From fertilization to 50% hatch, Big Qualicum River steelhead had 93% mortality at 60.8°F, 7.7% mortality at 57.2°F, and 1% mortality at 47.3°F and 39.2°F (Velsen 1987).

Juvenile Rearing & Downstream Movement

Water temperature index values were developed to evaluate the combined steelhead rearing (fry and juvenile) and juvenile downstream movement lifestages. Some steelhead may rear in freshwater for up to three years before emigrating as yearling+ smolts, whereas other individuals move downstream shortly after emergence as post- emergent fry, or rear in the river for several months and move downstream as juveniles without exhibiting the ontogenetic characteristics of smolts. Presumably, these individuals continue to rear and grow in downstream areas and undergo the smoltification process prior to entry into saline environments. Thus, fry and juvenile rearing occur concurrently with post-emergent fry and juvenile downstream movement and are assessed in this Technical Memorandum using the fry and juvenile rearing WTI values.

The growth, survival, and successful smoltification of juvenile steelhead are controlled largely by water temperature. The duration of freshwater residence for juvenile steelhead is long relative to that of Chinook salmon, making the juvenile lifestage of steelhead more susceptible to the influences of water temperature, particularly during the over-summer rearing period. Central Valley juvenile steelhead have high growth rates at water temperatures in the mid-60°F range, but reportedly require lower water temperatures to successfully undergo the transformation to the smolt stage.

WTI values of 61°F, 63°F, 64°F, 65°F, 68°F, 72°F, 75°F, and 77°F were identified to represent a gradation of potential water temperature effects ranging between optimal to lethal conditions for steelhead juvenile rearing (Table 3). A water temperature of 61°F (7DADM) was identified as the value for steelhead juvenile rearing for the San Joaquin River (CALFED 2009). EPA Region 10 Guidance for Pacific Northwest State and Tribal Temperature Water Quality Standards (EPA 2003b) identifies 61°F (7DADM) for "salmon and trout" core juvenile rearing. The WTI value of 63°F was identified because Myrick and Cech (2001) describe 63°F as the "preferred" water temperature for wild juvenile steelhead, whereas "preferred" water temperatures for juvenile hatchery steelhead reportedly range between 64-66°F. EPA Region 10 Guidance for Pacific Northwest State and Tribal Temperature Water Quality Standards identifies

64°F (7DADM) for “salmon and trout” juvenile rearing (EPA 2003b). 65°F was also identified as a WTI value because NMFS (2000; 2002a) reported 65°F as the upper limit preferred for growth and development of Sacramento and American River juvenile steelhead. Also, 65°F was found to be within the optimum water temperature range for juvenile growth (i.e., 59-66°F) (Myrick and Cech 2001), and supported high growth of Nimbus strain juvenile steelhead (Cech and Myrick 1999). Increasing levels of thermal stress to this life stage may reportedly occur above the 65°F WTI value.

Kaya *et al.* (1977) reported that the upper avoidance water temperature for juvenile rainbow trout was measured at 68°F to 71.6°F. Cherry *et al.* (1977) observed an upper preference water temperature near 68.0°F for juvenile rainbow trout, duplicating the upper preferred limit for juvenile steelhead observed in Cech and Myrick (1999). Growth for 200 mm juvenile *O. mykiss* versus temperature for three food levels (percent of maximum consumption = 30%, 50%, and 70%) was evaluated. The average empirically derived percent of maximum consumption in the Middle Fork American Fork River was 50% (Hanson *et al.* 1997). Positive growth only occurs up to approximately 68°F. Because of the literature describing 68°F as both an upper preferred and an avoidance limit for juvenile *O. mykiss,* and because of the empirical fish population data and bioenergetics growth data, 68°F was identified as an upper tolerable WTI value.

A WTI value of 72°F was identified because symptoms of thermal stress in juvenile steelhead have been reported to arise at water temperatures approaching 72°F. For example, physiological stress to juvenile steelhead in Northern California streams was demonstrated by increased gill flare rates, decreased foraging activity, and increased agonistic activity as stream temperatures rose above 71.6°F (Nielsen *et al.* 1994). Also, 72°F was identified as a WTI value because 71.6°F has been reported as an upper avoidance water temperature (Kaya *et al.* 1977) and an upper thermal tolerance water temperature (Ebersole *et al.* 2001) for juvenile rainbow trout. The WTI value of 75°F was identified because NMFS and EPA report that direct mortality to rearing juvenile steelhead results when stream temperatures reach 75°F (EPA 2002; NMFS 2001b). Water temperatures >77°F have been referred to as “lethal” to juvenile steelhead (Myrick and Cech 2001). The UILT for juvenile rainbow trout, based on numerous studies, is between 75-79°F (Sullivan *et al.* 2000; McCullough 2001).

A swim tunnel study conducted on the Lower Tuolumne River (Verhille et al. 2016) generated high quality field data on the physiological performance of Tuolumne River *O. mykiss* acutely exposed to a temperature range of 13 to 25°C (55.4°F to 77°F). The data indicated that wild juvenile *O. mykiss* represents an exception to the expected based on the 7DADM criterion for juvenile rearing set out by EPA (2003b) for Pacific Northwest *O. mykiss*. The study recommended that a conservative upper aerobic performance limit of 71.6°F, instead of 64.4°F (EPA), be considered in re-determining a 7DADM for this population.

The Lower Tuolumne River *O. mykiss* Population Study (TID/MID 2014) identified the UILT for *O. mykiss* juveniles has been estimated at 22.8–25.9ºC (73–79°F) (Threader and Houston 1983). In the model, an initial mortality threshold of 25°C (77°F) daily average temperature was identified for *O. mykiss* juveniles. Note also that both fry rearing and resident adult rearing lifestages of *O. mykiss* also had UILT values of 77°F to support the model.

For steelhead juvenile rearing, the Temperature Criteria Matrix identified 65°F for the Lower American River (Water Forum 2007); 61°F for the San Joaquin (CALFED 2009); and 65°F (Upper Optimum Value) and 68°F (Upper Tolerable Value) for the Yuba River Basin (Bratovich *et al.* 2012).

Table 3. Steelhead Juvenile Rearing WTI Values and the Literature Supporting Each Value.

Index Value	**Supporting Literature**
61°F (16.1°C)	A water temperature of 61°F (7DADM) was identified as the value for steelhead juvenile rearing for the San Joaquin River (CALFED 2009).
63°F (17.2°C)	Preferred water temperature for wild juvenile steelhead is reportedly 63°F, whereas preferred water temperatures for juvenile hatchery steelhead reportedly range between 64-66°F. Myrick and Cech (2001)
64°F (17.8°C)	EPA Region 10 Guidance for Pacific Northwest State and Tribal Temperature Water Quality Standards identifies 64°F (7DADM) for "salmon and trout" juvenile rearing (EPA 2003b).
65°F (18.3°C)	Upper limit of 65°F preferred for growth and development of Sacramento River and American River juvenile steelhead (NMFS 2002a). Nimbus juvenile steelhead growth showed an increasing trend with water temperature to 66.2°F, irrespective of ration level or rearing temperature (Cech and Myrick 1999). The final preferred water temperature for rainbow fingerlings was between 66.2 and 68°F (Cherry *et al.* 1977). Nimbus juvenile steelhead preferred water temperatures between 62.6°F and 68.0°F (Cech and Myrick 1999). Rainbow trout fingerlings preferred or identified water temperatures in the 62.6°F to 68.0°F range (McCauley and Pond 1971). A water temperature of 65°F (daily average temperature) was identified as the value for steelhead juvenile rearing for the Lower American River (Water Forum 2007). A water temperature of 65°F (MWAT) was identified as the Upper Optimum Value for steelhead juvenile rearing for the Yuba Reintroduction Assessment (Bratovich *et al.* 2012).
68°F (20°C)	Nimbus juvenile steelhead preferred water temperatures between 62.6°F and 68.0°F (Cech and Myrick 1999). The final preferred water temperature for rainbow trout fingerlings was between 66.2°F and 68°F (Cherry *et al.* 1977). Rainbow trout fingerlings preferred or identified water temperatures in the 62.6°F to 68.0°F range (McCauley and Pond 1971). The upper avoidance water temperature for juvenile rainbow trout was measured at 68°F to 71.6°F (Kaya *et al.* 1977). Empirical fish population and water temperature data in the North Yuba, Middle Yuba, South Yuba, Middle Fork American, and Rubicon Rivers (Figure 4 of Bratovich *et al.* 2012) indicate a sharp reduction in O. *mykiss* population densities when temperatures exceed 68°F for greater than one week. Bioenergetics modeling of growth based on consumption (P value = 0.5) in the Middle Fork American River watershed (adjacent watershed) indicates that growth likely does not occur above 68°F (Figure 5 of Bratovich *et al.* 2012). A water temperature of 68°F (MWAT) was identified as the Upper Tolerable Value for steelhead juvenile rearing for the Yuba Reintroduction Assessment (Bratovich *et al.* 2012).
72°F (22.2°C)	Increased physiological stress, increased agonistic activity, and a decrease in forage activity in juvenile steelhead occur after ambient stream temperatures exceed 71.6°F (Nielsen *et al.* 1994). The upper avoidance water temperature for juvenile rainbow trout was measured at 68°F to 71.6°F (Kaya *et al.* 1977). Estimates of upper thermal tolerance or avoidance limits for juvenile rainbow trout (at maximum ration) ranged from 71.6°F to 79.9°F (Ebersole *et al.* 2001). A swim tunnel study conducted on the Lower Tuolumne recommended a conservative upper aerobic performance limit of 71.6°F for *O. mykiss* juvenile rearing (Verhille et al. 2016).
75°F (23.9°C)	The maximum weekly average water temperature for survival of juvenile and adult rainbow trout is 75.2°F (EPA 2002). Rearing steelhead juveniles have an upper lethal limit of 75.0°F (NMFS 2001a). Estimates of upper thermal tolerance or avoidance limits for juvenile rainbow trout (at maximum ration) ranged from 71.6 to 79.9°F (Ebersole *et al.* 2001). The UILT for juvenile rainbow trout, based on numerous studies, is between 75-79°F (Sullivan *et al.* 2000; McCullough 2001).

Index Value	Supporting Literature
77°F (25°C)	In the model associated with the Lower Tuolumne River *O. mykiss* Population Study (TID/MID 2014), an initial mortality threshold of 77°F daily average temperature was identified for *O. mykiss* juveniles.

Smolt Emigration

Laboratory data suggest that smoltification, and therefore successful emigration of steelhead smolts, is directly controlled by water temperature (Adams *et al.* 1975) (Table 4). WTI values of 52°F and 55°F were identified to evaluate the steelhead smolt emigration lifestage, because most literature on water temperature effects on steelhead smolting suggest that water temperatures less than 52°F (Adams *et al.*1975; Myrick and Cech 2001; Rich 1987a) or less than 55°F (EPA 2003a; McCullough *et al.* 2001; Wedemeyer *et al.* 1980; Zaugg and Wagner 1973) are required for successful smoltification to occur. Adams *et al.* (1973) tested the effect of water temperature (43.7°F, 50.0°F, 59.0°F or 68.0°F) on the increase of gill microsomal Na^+-, K^+-stimulated ATPase activity associated with parr-smolt transformation in steelhead and found a two-fold increase in Na^+-, K^+-ATPase at 43.7 and 50.0°F, but no increase at 59.0°F or 68.0°F. In a subsequent study, the highest water temperature where a parr-smolt transformation occurred was at 52.3°F (Adams *et al.* 1975). The results of Adams *et al.* (1975) were reviewed in Myrick and Cech (2001) and Rich (1987b), which both recommended that water temperatures below 52.3°F are required to successfully complete the parr-smolt transformation. Further, Myrick and Cech (2001) suggest that water temperatures between 43-50°F are the “physiologically optimal” temperatures required during the parr-smolt transformation and necessary to maximize saltwater survival. The 52°F WTI value identified for the steelhead smolt emigration lifestage is the index value generally reported in the literature as the upper limit of the water temperature range that provides successful smolt transformation thermal conditions. Increasing levels of thermal stress to this lifestage may reportedly occur above the 52°F WTI value.

Zaugg and Wagner (1973) examined the influence of water temperature on gill ATPase activity related to parr-smolt transformation and migration in steelhead. They found ATPase activity was decreased and migration reduced when juveniles were exposed to water temperatures of 55.4°F or greater. In a technical document prepared by the EPA to provide temperature water quality standards for the protection of Northwest native salmon and trout, water temperatures greater than 54.5°F were identified as an impairment to smoltification for juvenile steelhead (EPA 2003b). Water temperatures are considered “unsuitable” for steelhead smolts at >59°F (Myrick and Cech 2001).

For steelhead smolt emigration, the Temperature Criteria Matrix identified 57°F for the San Joaquin (CALFED 2009) and 52°F (Upper Optimum Value) and 55°F (Upper Tolerable Value) for the Yuba River Basin (Bratovich et al. 2012). EPA Region 10 Guidance for Pacific Northwest State and Tribal Temperature Water Quality Standards (EPA 2003b) identifies 57°F (7DADM) for steelhead smoltification.

The Lower Tuolumne River *O. mykiss* Population Study (TID/MID 2014) identified an initial UILT mortality threshold of 77°F daily average temperature for *O. mykiss* smolts on the basis of literature reviews by Myrick and Cech (2001).

Table 4. Steelhead Smolt Emigration WTI Values and the Literature Supporting Each Value.

Index Value	Supporting Literature
52°F (11.1°C)	Steelhead successfully smolt at water temperatures in the 43.7°F to 52.3°F range (Myrick and Cech 2001). Steelhead undergo the smolt transformation when reared in water temperatures below 52.3°F, but not at higher water temperatures (Adams *et al.* 1975). Optimum water temperature range for successful smoltification in young steelhead is 44.0°F to 52.3°F (Rich 1987a). A water temperature of 52°F (MWAT) was identified as the Upper Optimum Value for steelhead smolt emigration for the Yuba Reintroduction Assessment (Bratovich *et al.* 2012).
55°F (12.8°C)	ATPase activity was decreased and migration reduced for steelhead at water temperatures greater than or equal to 55.4°F (Zaugg and Wagner 1973). Water temperatures should be below 55.4°F at least 60 days prior to release of hatchery steelhead to prevent premature smolting and desmoltification (Wedemeyer *et al.* 1980). In winter steelhead, a temperature of 54.1°F is nearly the upper limit for smolting (McCullough *et al.* 2001; Zaugg and Wagner 1973). Water temperatures less than or equal to 54.5°F are suitable for emigrating juvenile steelhead (EPA 2003b). Water temperatures greater than 55°F prevent increases in ATPase activity in steelhead juveniles (Hoar 1988). Water temperatures greater than 56°F do not permit smoltification in summer steelhead (Zaugg *et al.* 1972). A water temperature of 55°F (MWAT) was identified as the Upper Tolerable Value for steelhead smolt emigration for the Yuba Reintroduction Assessment (Bratovich *et al.* 2012).
57°F (13.9°C)	A water temperature of 57°F (7DADM) was identified as the value for steelhead smolt emigration for the San Joaquin River (CALFED 2009). EPA Region 10 Guidance for Pacific Northwest State and Tribal Temperature Water Quality Standards identifies 57°F (7DADM) for steelhead smoltification (EPA 2003b).
59°F (15°C)	Yearling steelhead held at 43.7°F and transferred to 59°F had a substantial reduction in gill ATPase activity, indicating that physiological changes associated with smoltification were reversed (Wedemeyer *et al.* 1980).
77°F (25°C)	A water temperature of 77°F (daily average temperature) was identified as UILT mortality threshold for *O. mykiss* smolts (Myrick and Cech 2001 as cited in TID/MID 2014).

CHINOOK SALMON LIFESTAGE-SPECIFIC WATER TEMPERATURE INDEX VALUES

It has been suggested that separate water temperatures standards should be developed for each run-type of Chinook salmon. For example, McCullough (1999) states that spring-run Chinook salmon immigrate in spring and spawn in 3rd to 5th order streams and, therefore, face different migration and adult holding temperature regimes than do summer- or fall-run Chinook salmon, which spawn in streams of 5th order or greater . However:(1) there is a general paucity of literature specific to each lifestage of each run-type; (2) there is an insufficient amount of data available in the literature suggesting that Chinook salmon run-types respond to water temperatures differently; (3) the WTI values derived from all the literature pertaining to Chinook salmon for a particular lifestage will be sufficiently protective of that lifestage for each run-type; and (4) all run- types overlap in timing of adult immigration and holding and in some cases are not easily distinguished (Healey 1991). Information distinctly applicable to spring-run or fall-run Chinook salmon is identified where run-specific information is available.

Adult Immigration and Holding

The adult immigration and staging lifestages for fall-run Chinook salmon are evaluated together, because they are believed to not spend significant amounts of time after immigrating and prior to spawning. The adult immigration and holding lifestages are evaluated separately for spring-run Chinook salmon, because of the potential extended duration of holding after immigrating and prior to spawning.

The WTI values reflect a gradation of potential water temperature effects that range between those reported as "optimal" to those reported as "lethal" for adult Chinook salmon during upstream spawning migrations and holding. The WTI values identified for the Chinook salmon adult immigration and holding lifestage are 60°F, 61°F, 64°F, 65°F, 68°F and 70°F (Table 5). Although 56°F is referenced in the literature frequently as the upper "optimal" water temperature limit for upstream migration and holding, the references are not foundational studies and often are inappropriate citations. For example, Boles *et al.* (1988), Marine (1992), and NMFS (1997b) all cite Hinze (1959) in support of recommendations for a water temperature of 56°F for adult Chinook salmon immigration. However, Hinze (1959) is a study examining the effects of water temperature on incubating Chinook salmon eggs in the American River Basin. Further, water temperatures between 38-56°F are considered to represent the "observed range" for upstream migrating spring-run Chinook salmon (Bell 1986).

The lowest WTI value identified was 60°F because in a previous NMFS biological opinion for the proposed operation of the Central Valley Project (CVP) and State Water Project (SWP), 59°F to 60°F is reported as…"*The upper limit of the optimal temperature range for adults holding while eggs are maturing*" (NMFS 2000). Also, NMFS (1997b) states…"*Generally, the maximum temperature of adults holding, while eggs are maturing, is about 59°F to 60°F*". Oregon Department of Environmental Quality (ODEQ; 1995) reports that "*…many of the diseases that commonly affect Chinook become highly infectious and virulent above 60°F.*" Mature females subjected to prolonged exposure to water temperatures above 60°F have poor survival rates and produce less viable eggs than females exposed to lower water temperatures (USFWS 1995b).

Ward and Kier (1999) designated temperatures <60.8°F as an "optimum" water temperature threshold for holding Battle Creek spring-run Chinook salmon. EPA (2003a) chose a holding value of 61°F (7DADM) based on laboratory data various assumptions regarding diel temperature fluctuations. The 61°F WTI value identified for the Chinook salmon adult immigration and holding lifestage is the index value generally reported in the literature as the upper limit of the optimal range, and is within the reported acceptable range. Increasing levels of thermal stress to this lifestage may reportedly occur above the 61°F WTI value.

EPA Region 10 Guidance for Pacific Northwest State and Tribal Temperature Water Quality Standards (EPA 2003b) identifies 64°F (7DADM) for "salmon and trout" adult migration. A water temperature of 64°F (MWAT) was identified as the Upper Optimum Value for Chinook adult migration for the Yuba Reintroduction Assessment (Bratovich *et al*. 2012).

An index value of 65°F was identified because Berman (1990) suggests effects of thermal stress to pre-spawning adults are evident at water temperatures near 65°F. Berman (1990) conducted a laboratory study to determine if pre-spawning water temperatures experienced by adult Chinook salmon influenced reproductive success, and found evidence suggesting latent embryonic abnormalities associated with water temperature exposure to pre-spawning adults that ranged from 63.5°F to 66.2°F. During each of the years when Chinook salmon temperature mortality was not observed at Butte Creek (2001, 2004-2007), on average, daily temperature did not exceed 65.8°F for more than 7 days (Figure 6 of Bratovich *et al.* 2012). Tracy McReynolds (pers. comm. October 2011) suggested that an upper tolerable holding temperature of 65°F was reasonable. A water temperature of 65°F (MWAT) was identified as the Upper Tolerable Value for Chinook adult holding for the Yuba Reintroduction Assessment (Bratovich *et al.* 2012).

An index value of 68°F was identified because the Butte Creek data and the literature suggests that thermal stress at water temperatures greater than 68°F is pronounced, and severe adverse effects to immigrating and holding pre-spawning adults, including mortality, can be expected (Berman 1990; Marine 1997; NMFS 1997b; Ward *et al.* 2004).

Acceptable water temperatures for adults migrating upstream range from 57°F to 67°F (NMFS 1997b). For chronic exposures, an incipient upper lethal water temperature limit for pre-spawning adult salmon probably falls within the range of 62.6°F to 68°F (Marine 1992). Water temperatures of 68°F resulted in nearly 100% mortality of Chinook salmon during columnaris outbreaks (Ordal and Pacha 1963). Adult Chinook salmon migration rates through the lower Columbia River were slowed significantly when water temperatures exceeded 68°F (Goniea *et al.* 2006). A water temperature of 68°F (MWAT) was identified as the Upper Tolerable Value for Chinook adult migration for the Yuba Reintroduction Assessment (Bratovich *et al.* 2012).

Water temperatures between 70-77°F are reported as the range of maximum temperatures for holding pool conditions used by spring-run Chinook salmon in the Sacramento-San Joaquin system (Moyle *et al*. 1995). Migration blockage occurs for Chinook salmon at temperatures from 70-71+°F (McCollough 1999; McCullough *et al*. 2001; EPA 2003b). Strange (2010) found that the mean average body temperature during the first week of Chinook salmon migration on the Klamath River was 71.4°F. The UILT for Chinook salmon jacks is 69.8-71.6°F (McCullough 1999).

For spring-run Chinook salmon adult immigration, the Framework Temperature Criteria Matrix identified 64°F (Upper Optimum Value) and 68°F (Upper Tolerable Value), MWAT, for the Yuba River Basin (Bratovich *et al*. 2012). For spring-run Chinook salmon adult holding, the Framework Temperature Criteria Matrix identified 61°F (Upper Optimum Value) and 65°F (Upper Tolerable Value), MWAT, for the Yuba River Basin (Bratovich *et al.* 2012).

Table 5. Chinook Salmon Adult Immigration and Holding WTI Values and the Literature Supporting Each Value.

Index Value	Supporting Literature
60°F (15.6°C)	Maximum water temperature for adults holding, while eggs are maturing, is approximately 59°F to 60°F (NMFS 1997b). Upper limit of the optimal water temperature range for adults holding while eggs are maturing is 59°F to 60°F (NMFS 2000). Many of the diseases that commonly affect Chinook salmon become highly infectious and virulent above 60°F (ODEQ 1995). Mature females subjected to prolonged exposure to water temperatures above 60°F have poor survival rates and produce less viable eggs than females exposed to lower water temperatures (USFWS 1995b).

Index Value	Supporting Literature
61°F (16.1°C)	A water temperature of 61°F (MWAT) was identified as the Upper Optimum Value for Chinook adult holding for the Yuba Reintroduction Assessment (Bratovich *et al.* 2012). Ward and Kier (1999) designated temperatures <60.8°F as an "optimum" water temperature threshold for holding Battle Creek spring-run Chinook salmon.
64°F (17.8°C)	A water temperature of 64°F (MWAT) was identified as the Upper Optimum Value for Chinook adult migration for the Yuba Reintroduction Assessment (Bratovich *et al.* 2012). EPA Region 10 Guidance for Pacific Northwest State and Tribal Temperature Water Quality Standards identifies 64°F (7DADM) for "salmon and trout" adult migration (EPA 2003b).
65°F (18.3°C)	Acceptable range for adults migrating upstream is from 57°F to 67°F (NMFS 1997b). Disease risk becomes high at water temperatures above 64.4°F (EPA 2003b). Latent embryonic mortalities and abnormalities associated with water temperature exposure to pre-spawning adults occur at 63.5°F to 66.2°F (Berman 1990). During each of the years when Chinook salmon temperature mortality was not observed at Butte Creek (2001, 2004-2007), on average, daily temperature did not exceed 65.8°F for more than 7 days (Figure 6 of Bratovich *et al.* 2012). A water temperature of 65°F (MWAT) was identified as the Upper Tolerable Value for Chinook adult holding for the Yuba Reintroduction Assessment (Bratovich *et al.* 2012).
68°F (20°C)	Acceptable water temperatures for adults migrating upstream range from 57°F to 67°F (NMFS 1997b). For chronic exposures, an incipient upper lethal water temperature limit for pre-spawning adult salmon probably falls within the range of 62.6°F to 68.0°F (Marine 1992). Water temperatures of 68°F resulted in nearly 100% mortality of Chinook salmon during columnaris outbreaks (Ordal and Pacha 1963). Adult Chinook salmon migration rates through the lower Columbia River were slowed significantly when water temperatures exceeded 68°F (Goniea *et al.* 2006). A water temperature of 68°F (MWAT) was identified as the Upper Tolerable Value for Chinook adult migration for the Yuba Reintroduction Assessment (Bratovich *et al.* 2012).
70°F (21.1°C)	Migration blockage occurs for Chinook salmon at temperatures from 70-71+°F (McCollough 1999; McCullough *et al.* 2001; EPA 2003b). Strange (2010) found that the mean average body temperature during the first week of Chinook salmon migration on the Klamath River was 71.4°F. The UILT for Chinook salmon jacks is 69.8-71.6°F (McCullough 1999).

Spawning and Embryo Incubation

The adult spawning and embryo (i.e., eggs and alevins) incubation lifestages share one set of WTI values because spawning and embryonic survival and development typically are considered concurrently in the literature on the effects of water temperature. Spawning and incubation evaluations are conducted separately due to differences in their temporal distributions.

The WTI values identified for the Chinook salmon spawning and embryo incubation lifestages are 55°F, 56°F, 58°F, 60°F, and 62°F (Table 6). EPA Region 10 Guidance for Pacific Northwest State and Tribal Temperature Water Quality Standards identifies 55°F (7DADM) for "salmon and trout" spawning, egg incubation, and fry emergence (EPA 2003b). A water temperature of 55°F (7DADM) was identified as the value for Chinook incubation for the San Joaquin River fall-run Chinook salmon (CALFED 2009).

Much literature suggests that water temperatures must be less than or equal to 56°F for maximum survival of Chinook salmon embryos (i.e., eggs and alevins) during spawning and incubation. NMFS (1993b) reported that optimum water temperatures for egg development are between 43°F and 56°F. Similarly, Myrick and Cech (2001) reported the highest egg survival rates occur between water temperatures of 39-54°F. Reclamation (unpublished work) reports that water temperatures less than 56°F results in a natural rate of mortality for fertilized Chinook salmon eggs. Bell (1986) recommends water temperatures ranging between 42-57°F for spawning Chinook salmon, and water temperatures between 41-58°F for incubating embryos. USFWS (1995a) reported a water temperature range of 41°F to 56°F for maximum survival of eggs and yolk-sac larvae in the Central Valley of California. The preferred water temperature range for Chinook salmon egg incubation in the Sacramento River was suggested as 42°F to 56°F (NMFS 1997a). Alevin mortality is reportedly significantly higher when Chinook salmon embryos are incubated at water temperatures above 56°F (USFWS 1999). NMFS (2002a) reported 56°F as the upper limit of suitable water temperatures for spring-run Chinook salmon spawning in the Sacramento River. The 56°F WTI value identified for the Chinook salmon spawning and embryo incubation lifestage is the index value generally reported in the literature as the upper limit of the optimal range for egg development and the upper limit of the range reported to provide maximum survival of eggs and yolk-sac larvae in the Central Valley of California. Increasing levels of thermal stress to this lifestage may reportedly occur above the 56°F WTI value.

High survival of Chinook salmon embryos also has been suggested to occur at incubation temperatures at or near 58°F. For example, (Reclamation Unpublished Work) reported that the natural rate of mortality for alevins occurs at 58°F or less. Combs (1957) concluded constant incubation temperatures between 42.5°F and 57.5°F resulted in normal development of Chinook salmon eggs, and NMFS (2002a) suggests 53°F to 58°F is the preferred water temperature range for Chinook salmon eggs and fry. The model associated with the Chinook Salmon Population Model Study (TID/MID 2013), established an initial acute egg/alevin mortality threshold of 58°F. A water temperature of 58°F (MWAT) was identified as the Upper Tolerable Value for Chinook spawning and incubation for the Yuba Reintroduction Assessment (Bratovich *et al.* 2012).

Johnson (1953) found consistently higher Chinook salmon egg losses resulted at water temperatures above 60°F than at lower temperatures. In order to protect late incubating Chinook salmon embryos and newly emerged fry NMFS (1993a) determined that a water temperature criterion of less than or equal to 60°F be maintained in the Sacramento River from Keswick Dam to Bend Bridge from October 1 to October 31. Seymour (1956) provides evidence that 100% mortality occurs to late incubating Chinook salmon embryos when held at a constant water temperature greater than or equal to 60°F. For Chinook salmon eggs incubated at constant temperatures, mortality increases rapidly at temperatures greater than about 59-60°F (see data plots in Myrick and Cech 2001). Olsen and Foster (1957), however, found high survival of Chinook salmon eggs and fry (89.6%) when incubation temperatures started at 60.9°F and declined naturally for the Columbia River (about 7°F/month). The Chinook Salmon Population Model (TID/MID 2013) established an initial estimate of 60.4°F as the upper limit for initiation of spawning (Groves and Chandler 1999); also interpreted as the temperature at which spawning habitat will be considered usable by spawners.

The literature largely agrees that 100% mortality will result to Chinook salmon embryos incubated at water temperatures greater than or equal to about 62°F (Hinze 1959; Myrick and Cech 2003; Seymour 1956; USFWS 1999). Approximately 80% or greater mortality of eggs incubated at constant temperatures of 63°F or greater (see data plots in Myrick and Cech 2001). Geist *et al.* (2006) found low Chinook salmon incubation survival (1.7%) for naturally declining temperatures (0.36°F/day) when temperatures started at 62.6°F.

For Chinook salmon spawning and incubation, the Framework Temperature Criteria Matrix identified 60°F or less (as early in October as possible) and 56°F or less (as early in November as possible) as water temperature targets for lower American River fall-run Chinook salmon (Water Forum 2007); 64°F (spawning) and 55°F (incubation) for San Joaquin fall-run Chinook salmon (CALFED 2009); 56°F for Shasta River winter and spring-run Chinook salmon (SWRCB 2016); and 56°F (Upper Optimum Value) and 58°F (Upper Tolerable Value) in the Yuba River Basin (Bratovich *et al*. 2012).

Table 6. Chinook Salmon Spawning and Embryo Incubation WTI Values and the Literature Supporting Each Value.

Index Value	**Supporting Literature**
55°F (12.8°C)	EPA Region 10 Guidance for Pacific Northwest State and Tribal Temperature Water Quality Standards identifies 55°F (7DADM) for “salmon and trout” spawning, egg incubation, and fry emergence (EPA 2003b). A water temperature of 55°F (7DADM) was identified as the value for Chinook incubation for the San Joaquin River fall-run Chinook salmon (CALFED 2009).
56°F (13.3°C)	Less than 56°F results in a natural rate of mortality for fertilized Chinook salmon eggs (Reclamation Unpublished Work). Optimum water temperatures for egg development are between 43°F and 56°F (NMFS 1993b). Upper value of the water temperature range (i.e., 41°F to 56°F) suggested for maximum survival of eggs and yolk-sac larvae in the Central Valley of California (USFWS 1995b). Upper value of the range (i.e., 42°F to 56°F) given for the preferred water temperature for Chinook salmon egg incubation in the Sacramento River (NMFS 1997a). Incubation temperatures above 56°F result in significantly higher alevin mortality (USFWS 1999). 56°F is the upper limit of suitable water temperatures for spring-run Chinook salmon spawning in the Sacramento River (NMFS 2002a). Water temperatures averaged 56.5°F during the week of fall-run Chinook salmon spawning initiation on the Snake River (Groves and Chandler 1999). A water temperature of 56°F or less (daily average temperature), as early in November as possible, was identified as the value for fall-run Chinook salmon spawning and incubation for the lower American River (Water Forum 2007). A water temperature of 56°F (daily average temperature) was identified as the value for Chinook spawning and incubation for the Shasta River winter- and spring-run Chinook (SWRCB 2016). A water temperature of 56°F (MWAT) was identified as the Upper Optimum Value for Chinook spawning and incubation for the Yuba Reintroduction Assessment (Bratovich *et al.* 2012).
58°F (14.4°C)	Upper value of the range given for preferred water temperatures (i.e., 53°F to 58°F) for eggs and fry (NMFS 2002a). Constant egg incubation temperatures between 42.5°F and 57.5°F resulted in normal development (Combs and Burrows 1957). The natural rate of mortality for alevins occurs at 58°F or less (Reclamation Unpublished Work). The model associated with the Chinook Salmon Population Model Study, established an initial acute egg/alevin mortality threshold of 58°F (TID/MID 2013). A water temperature of 58°F (MWAT) was identified as the Upper Tolerable Value for Chinook spawning and incubation for the Yuba Reintroduction Assessment (Bratovich *et al.* 2012).

Index Value	Supporting Literature
60°F (15.6°C)	100% mortality can occur to late incubating Chinook salmon embryos (yolk-sac stage) if temperatures are 60°F or greater (Seymour 1956). An October 1 to October 31 water temperature criterion of less than or equal to 60°F in the Sacramento River from Keswick Dam to Bend Bridge has been determined for protection of late incubating larvae and newly emerged fry (NMFS 1993b). Mean weekly water temperature at first observed Chinook salmon spawning in the Columbia River was 59.5°F (Dauble and Watson 1997). Consistently higher egg losses resulted at water temperatures above 60°F than at lower temperatures (Johnson and Brice 1953). For Chinook Salmon eggs incubated at constant temperatures, mortality increases rapidly at temperatures greater than about 59-60°F (see data plots in Myrick and Cech 2001). Olsen and Foster (1957) found high survival of Chinook salmon eggs and fry (89.6%) when incubation temperatures started at 60.9°F and declined naturally for the Columbia River (about 7°F/month). A water temperature of 60°F or less (daily average temperature), as early in October as possible, was identified as a target value for Chinook spawning and incubation for the lower American River fall-run Chinook (Water Forum 2007). The model associated with the Chinook Salmon Population Model Study (TID/MID 2013), established an initial estimate of 60.4°F as the upper limit for initiation of spawning (Groves and Chandler 1999).
62°F (16.7°C)	100% mortality of fertilized Chinook salmon eggs after 12 days at 62°F (Reclamation Unpublished Work). Incubation temperatures of 62°F to 64°F appear to be the physiological limit for embryo development resulting in 80 to 100% mortality prior to emergence (USFWS 1999). 100% loss of eggs incubated at water temperatures above 62°F (Hinze 1959). 100% mortality occurs during yolk-sac stage when embryos are incubated at 62.5°F (Seymour 1956). Approximately 80% or greater mortality of eggs incubated at constant temperatures of 63°F or greater (see data plots in Myrick and Cech 2001). Geist *et al*. (2006) found low Chinook salmon incubation survival (1.7%) for naturally declining temperatures (0.36°F/day) when temperatures started at 62.6°F.

Juvenile Rearing and Downstream Movement

WTI values were developed to evaluate the Chinook salmon rearing (fry and juvenile) and juvenile downstream movement lifestages. Some Chinook salmon juveniles, both fall-run and spring-run, move downstream shortly after emergence as post- emergent fry, or rear in the river for several months and move downstream as YOY juveniles without exhibiting the ontogenetic characteristics of smolts. Presumably, these individuals undergo the smoltification process prior to entry into saline environments. Thus, fry and juvenile rearing occur concurrently with post-emergent fry and juvenile downstream movement and are presented in this Technical Memorandum using the fry and juvenile rearing WTI values.

The WTI values of 60°F, 61°F, 64°F, 65°F, 68°F, 70°F, 73°F, 75°F, and 77°F were identified for the Chinook salmon juvenile rearing and downstream movement lifestage. The lowest index value of 60°F was identified because regulatory documents as well as several source studies, including ones conducted on Central Valley Chinook salmon fry and juveniles, report 60°F as an optimal water temperature for growth (Banks *et al.* 1971; Brett *et al.* 1982; Marine 1997; NMFS 1997b; NMFS 2000; NMFS 2001a; NMFS 2002; Rich 1987b) (Table 7). Water temperatures below 60°F also have been reported as providing conditions optimal for fry and fingerling growth, but were not identified as index values, because the studies were conducted on fish from outside of the Central Valley (Brett 1952; Seymour 1956). Studies conducted using local fish may be particularly important because *Oncorhynchus* species show considerable variation in morphology, behavior, and physiology along latitudinal gradients (Myrick 1998; Taylor 1990b; Taylor 1990a). More specifically, it has been suggested that salmonid populations in the Central Valley prefer higher water temperatures than those from more northern latitudes (Myrick and Cech 2000).

The 60°F WTI value identified for the Chinook salmon juvenile rearing and downstream movement lifestage is the index value generally reported in the literature as the upper limit of the optimal range for fry and juvenile growth and the upper limit of the preferred range for growth and development of spring-run Chinook salmon fry and fingerlings. NMFS (2002a) identified 60°F as the “preferred” water temperature for juvenile spring-run Chinook salmon in the Central Valley. Increasing levels of thermal stress to this lifestage may reportedly occur above the 60°F WTI value.

A water temperature of 61°F (7DADM) was identified as the value for Chinook juvenile rearing for the San Joaquin River (CALFED 2009). A water temperature of 61°F (MWAT) was identified as the Upper Optimum Value for Chinook juvenile rearing for the Yuba Reintroduction Assessment for both fall- and spring-run Chinook (Bratovich *et al.* 2012). EPA Region 10 Guidance for Pacific Northwest State and Tribal Temperature Water Quality Standards identifies 61°F (7DADM; early year) for salmon juvenile rearing (EPA 2003b).

EPA Region 10 Guidance for Pacific Northwest State and Tribal Temperature Water Quality Standards identifies 64°F (7DADM; late year) for salmon juvenile rearing (EPA 2003b). Recommended summer maximum water temperature of 64.4°F for migration and non-core rearing (EPA 2003b). Water temperatures greater than 64°F are considered not ″properly functioning” by NMFS in Amendment 14 to the Pacific Coast Salmon Plan (NMFS 1995). Fatal infection rates caused by *C. columnaris* are high at temperatures greater than or equal to 64°F (EPA 2001). Optimal range for Chinook salmon survival and growth from 53°F to 64°F (USFWS 1995b). Survival of Central Valley juvenile Chinook salmon declines at temperatures greater than 64.4°F (Myrick and Cech 2001).

The index value of 66°F was identified because it represents the upper end of the range of 64°F to 66.2°F, at which both adverse and beneficial effects to juvenile salmonids have been reported to occur. For example, at temperatures approaching and beyond 65°F, sub-lethal effects associated with increased incidence of disease reportedly become severe for juvenile Chinook salmon (EPA 2003a; Johnson and Brice 1953; Ordal and Pacha 1963; Rich 1987a). Conversely, numerous studies report that temperatures between 64.0°F and 66.2°F provide conditions ranging from suitable to optimal for juvenile Chinook salmon growth (Brett *et al.* 1982; Cech and Myrick 1999; Clarke and Shelbourn 1985; EPA 2003a; Myrick and Cech 2001; NMFS 2002; USFWS 1995b). Maximum growth of juvenile fall-run Chinook salmon has been reported to occur in the American River at water temperatures between 56-59°F (Rich 1987b) and in Nimbus Hatchery spring-run Chinook salmon at 66°F (Cech and Myrick 1999). Bioenergetics modeling of growth based on consumption for 100 mm juvenile Chinook salmon in the Middle Fork American River watershed indicates that growth likely does not occur above about 65°F (Figure 5 of Bratovich *et al*. 2012). A water temperature of 65°F (MWAT) was identified as the Upper Tolerable Value for Chinook juvenile rearing for the Yuba Reintroduction Assessment for both fall- and spring-run Chinook salmon (Bratovich *et al.* 2012).

A WTI value of 68°F was identified because, at water temperatures above 68°F, sub-lethal effects become severe such as reductions in appetite and growth of juveniles (Marine 1997; Rich 1987a; Zedonis and Newcomb 1997). Significant reductions in growth rates may occur when chronic elevated temperatures exceed 68°F (Marine 1997; Marine and Cech 2004). Juvenile spring-run Chinook salmon were not found in areas having mean weekly water temperatures between 67.1°F and 71.6°F (Burck *et al.* 1980; Zedonis and Newcomb 1997). Results from a study on wild spring-run Chinook salmon in the John Day River system indicate that juvenile fish were not found in areas having mean weekly water temperatures between 67.1°F and 72.9°F (McCullough 1999; Zedonis and Newcomb 1997).

Chronic stress associated with water temperature can be expected when conditions reach the index value of 70°F. For example, growth becomes drastically reduced at temperatures close to 70.0°F and has been reported to be completely prohibited at 70.5°F (Brett *et al.* 1982; Marine 1997). No growth at all would occur for Nechako River juvenile Chinook salmon at 70.5°F (Brett *et al.* 1982; Zedonis and Newcomb 1997). Juvenile spring-run Chinook salmon were not found in areas having mean weekly water temperatures between 67.1°F and 71.6°F (Burck *et al.* 1980; Zedonis and Newcomb 1997). Results from a study on wild spring-run Chinook salmon in the John Day River system indicate that juvenile fish were not found in areas having mean weekly water temperatures between 67.1°F and 72.9°F (McCullough 1999; Zedonis and Newcomb 1997). Increased incidence of disease, hyperactivity, reduced appetite, and reduced growth rates occur at 69.8 ± 1.8°F (Rich 1987b). In a laboratory study, juvenile fall-run Chinook salmon from the Sacramento River reared in water temperatures between 70°F and 75°F experienced significantly decreased growth rates and increased predation vulnerability compared with juveniles reared at temperatures below 68°F (Marine 1997; Marine and Cech 2004).

A WTI value of 73.4°F was identified because, in a laboratory study of juvenile fall-run Chinook salmon from the Mokelumne River Hatchery, in testing across a range of environmentally relevant acute temperature changes (from 53.6°F to 78.8°F), routine metabolic rate (RMR) and maximal metabolic rate (MMR) increased with acute warming, but aerobic capacity was unaffected by test temperatures up to 73.4°F in both acclimation groups of 59°F and 62.2°F (Poletto et al. 2017).

75°F was identified as a WTI value because high levels of direct mortality to juvenile Chinook salmon reportedly result at this water temperature (Cech and Myrick 1999; Hanson 1991; Myrick and Cech 2001; Rich 1987b). Other studies have suggested higher upper lethal water temperature levels (Brett 1952; Orsi 1971), but 75°F was identified because it was derived from experiments using Central Valley Chinook salmon and it is a more rigorous index value representing a more protective upper lethal water temperature level. Furthermore, the lethal level determined in Rich (1987b) was derived using slow rates of water temperature change and, thus, is ecologically relevant. The juvenile Chinook Salmon UILT based on numerous studies is 75-77°F (Sullivan *et al.* 2000; McCullough *et al.* 2001; Myrick and Cech 2001). Based upon information reviewed for Chinook salmon juvenile mortality (Brett 1952; Orsi 1971), the Chinook Salmon Population Model (TID/MID 2013) identified an initial UILT mortality threshold of 77°F for Chinook salmon juveniles as a daily average water temperature. Note that the model also identified this same value for fry mortality.

Table 7. Chinook Salmon Juvenile Rearing and Downstream Movement WTI Values and the Literature Supporting Each Value.

Index Value	Supporting Literature
60°F (15.6°C)	Optimum water temperature for Chinook salmon fry growth is between 55°F and 60°F (Seymour 1956). Water temperature range that produced optimum growth in juvenile Chinook salmon was between 54°F and 60°F (Rich 1987b). Water temperature criterion of less than or equal to 60°F for the protection of Sacramento River winter-run Chinook salmon from Keswick Dam to Bend Bridge (NMFS 1993b). Upper optimal water temperature limit of 61°F for Sacramento River fall-run Chinook salmon juvenile rearing (Marine 1997; Marine and Cech 2004). Upper water temperature limit of 60°F preferred for growth and development of spring-run Chinook salmon fry and fingerlings (NMFS 2000; NMFS 2002a). To protect salmon fry and juvenile Chinook salmon in the upper Sacramento River, daily average water temperatures should not exceed 60°F after September 30 (NMFS 1997b). A water temperature of 60°F appeared closest to the optimum for growth of fingerlings (Banks et al. 1971). Optimum growth of Nechako River Chinook salmon juveniles would occur at 59°F at a feeding level that is 60% of that required to satiate them (Brett et al. 1982). In a laboratory study, juvenile fall-run Chinook salmon from the Sacramento River reared in water temperatures between 70°F and 75°F experienced significantly decreased growth rates, and increased predation vulnerability compared with juveniles reared between 55°F and 61°F (Marine 1997; Marine and Cech 2004).
61°F (16.1°C)	A water temperature of 61°F (7DADM) was identified as the value for Chinook juvenile rearing for the San Joaquin River (CALFED 2009). A water temperature of 61°F (MWAT) was identified as the Upper Optimum Value for Chinook juvenile rearing for the Yuba Reintroduction Assessment for both fall- and spring-run Chinook (Bratovich et al. 2012). EPA Region 10 Guidance for Pacific Northwest State and Tribal Temperature Water Quality Standards identifies 61°F (7DADM; early year) for salmon juvenile rearing (EPA 2003b).
64°F (17.8°C)	EPA Region 10 Guidance for Pacific Northwest State and Tribal Temperature Water Quality Standards identifies 64°F (7DADM; late year) for salmon juvenile rearing (EPA 2003b). Recommended summer maximum water temperature of 64.4°F for migration and non-core rearing (EPA 2003b). Water temperatures greater than 64°F are considered not ″properly functioning" by NMFS in Amendment 14 to the Pacific Coast Salmon Plan (NMFS 1995). Fatal infection rates caused by C. columnaris are high at temperatures greater than or equal to 64°F (EPA 2001). Optimal range for Chinook salmon survival and growth from 53°F to 64°F (USFWS 1995b). Survival of Central Valley juvenile Chinook salmon declines at temperatures greater than 64.4°F (Myrick and Cech 2001).
66°F (18.9°C)	Water temperatures between 45°F to 65°F are preferred for growth and development of fry and juvenile spring-run Chinook salmon in the Feather River (NMFS 2002a). Disease mortalities diminish at water temperatures below 65°F (Ordal and Pacha 1963). Fingerling Chinook salmon reared in water greater than 65°F contracted C. columnaris and exhibited high mortality (Johnson and Brice 1953). Water temperatures greater than 64.9°F identified as being stressful in the Columbia River Ecosystem (Independent Scientific Group 1996). Juvenile Chinook salmon have an optimum temperature for growth that appears to occur at about 66.2°F (Brett et al. 1982). Juvenile Chinook salmon reached a growth maximum at 66.2°F (Cech and Myrick 1999). Increased incidence of disease, reduced appetite, and reduced growth rates occur at 66.2 ± 1.4 °F (Rich 1987a). Bioenergetics modeling of growth based on consumption for 100 mm juvenile Chinook salmon in the Middle Fork American River watershed indicates that growth likely does not occur above about 65°F (Figure 5 of Bratovich et al. 2012). A water temperature of 65°F (MWAT) was identified as the Upper Tolerable Value for Chinook juvenile rearing for the Yuba Reintroduction Assessment for both fall- and spring-run Chinook salmon (Bratovich et al. 2012).
68°F (20°C)	Sacramento River juvenile Chinook salmon reared at water temperatures greater than

Index Value	Supporting Literature
	68°F suffer reductions in appetite and growth (Marine 1997; Marine and Cech 2004). Significant reductions in growth rates may occur when chronic elevated temperatures exceed 68°F (Marine 1997; Marine and Cech 2004). Juvenile spring-run Chinook salmon were not found in areas having mean weekly water temperatures between 67.1°F and 71.6°F (Burck et al. 1980; Zedonis and Newcomb 1997). Results from a study on wild spring-run Chinook salmon in the John Day River system indicate that juvenile fish were not found in areas having mean weekly water temperatures between 67.1°F and 72.9°F (McCullough 1999; Zedonis and Newcomb 1997).
70°F (21.1°C)	No growth at all would occur for Nechako River juvenile Chinook salmon at 70.5°F (Brett et al. 1982; Zedonis and Newcomb 1997). Juvenile spring-run Chinook salmon were not found in areas having mean weekly water temperatures between 67.1°F and 71.6°F (Burck et al. 1980; Zedonis and Newcomb 1997). Results from a study on wild spring-run Chinook salmon in the John Day River system indicate that juvenile fish were not found in areas having mean weekly water temperatures between 67.1°F and 72.9°F (McCullough 1999; Zedonis and Newcomb 1997). Increased incidence of disease, hyperactivity, reduced appetite, and reduced growth rates occur at 69.8 ± 1.8 °F (Rich 1987b).
73°F (23°C)	In a laboratory study of juvenile fall-run Chinook salmon from the Mokelumne River Hatchery, RMR and MMR increased with acute warming, but aerobic capacity was unaffected by test temperatures up to 23°C in both acclimation groups of 59°F and 62.2°F (Poletto et al. 2017).
75°F (23.9°C)	For juvenile Chinook salmon in the lower American River fed maximum rations under laboratory conditions, 75.2°F was determined to be 100% lethal due to hyperactivity and disease (Rich 1987b; Zedonis and Newcomb 1997). Lethal temperature threshold for fall-run juvenile Chinook salmon between 74.3°F and 76.1°F (McCullough 1999). In a laboratory study, juvenile fall-run Chinook salmon from the Sacramento River reared in water temperatures between 70°F and 75°F experienced significantly decreased growth rates, and increased predation vulnerability compared with juveniles reared between 55°F and 61°F (Marine 1997; Marine and Cech 2004). The juvenile Chinook Salmon UILT based on numerous studies is 75-77°F (Sullivan et al. 2000; McCullough et al. 2001; Myrick and Cech 2001).
77°F (25°C)	The model associated with the Chinook Salmon Population Model Study, established an initial UILT mortality threshold of 77°F (daily average temperatures) for Chinook salmon fry and juveniles (Brett 1952 and Orsi 1971, as cited in TID/MID 2013).

Smolt Emigration

Juvenile Chinook salmon that exhibit extended rearing in a riverine environment are assumed to undergo the smoltification process and volitionally emigrate from the river as smolts. WTI values of 57°F, 59°F, 63°F, 68°F 72°F, and 77°F were identified for the Chinook salmon smolt emigration lifestage (Table 8).

A water temperature of 57°F (7DADM) was identified as the value for Chinook smolt migration for the San Joaquin River (CALFED 2009). EPA Region 10 Guidance for Pacific Northwest State and Tribal Temperature Water Quality Standards identifies 59°F (7DADM; late year) for salmon smolts (EPA 2003b).

A WTI value of 63°F was identified because water temperatures at or below this value allow for successful transformation to the smolt stage, and water temperatures above this value may result in impaired smoltification indices, inhibition of smolt development, and decreased survival and successful smoltification of juvenile Chinook salmon. Laboratory experiments suggest that water temperatures at or below 62.6°F provide conditions that allow for successful transformation to the smolt stage (Clarke and Shelbourn 1985; Marine 1997; Zedonis and Newcomb 1997). 62.6°F was rounded and used to support an index value of 63°F. A water temperature of 63°F (MWAT) was identified as the Upper Optimum Value for Chinook smolt migration for the Yuba Reintroduction Assessment for both fall- and spring-run Chinook (Bratovich *et al.* 2012).

Indirect evidence from tagging studies suggests that the survival of fall-run Chinook salmon smolts decreases with increasing water temperatures between 59°F and 75°F in the Sacramento-San Joaquin Delta (Kjelson and Brandes 1989). A WTI value of 68°F was identified because water temperatures above 68°F prohibit successful smoltification (Marine 1997; Rich 1987a; Zedonis and Newcomb 1997). Significant inhibition of gill sodium ATPase activity and associated reductions of hyposmoregulatory capacity, and significant reductions in growth rates, may occur when chronic elevated temperatures exceed 68°F (Marine 1997; Marine and Cech 2004). Water temperatures supporting smoltification of fall-run Chinook salmon range between 50°F to 68°F, the colder temperatures represent more optimal conditions (50°F to 62.6°F), and the warmer conditions (62.6°F to 68°F) represent marginal conditions (Zedonis and Newcomb 1997). A water temperature of 68°F (MWAT) was identified as the Upper Tolerable Value for Chinook smolt migration for the Yuba Reintroduction Assessment for spring-run Chinook salmon (Bratovich *et al*. 2012).

Support for an index value of 72°F is provided from a study conducted by (Baker *et al.* 1995) in which a statistical model is presented that treats survival of Chinook salmon smolts fitted with coded wire tags in the Sacramento River as a logistic function of water temperature. Using data obtained from mark-recapture surveys, the statistical model suggests a 95% confidence interval for the upper incipient lethal water temperature for Chinook salmon smolts as 71.5°F to 75.4°F. In a laboratory study, juvenile fall-run Chinook salmon from the Sacramento River reared in water temperatures between 70°F and 75°F experienced significantly decreased growth rates, impaired smoltification indices, and increased predation vulnerability compared with juveniles reared between 55°F and 61°F. Furthermore, fish reared between 63°F and 68°F did not have different growth rates compared to those reared at 55°F and 61°F (Marine 1997; Marine and Cech 2004). Indirect evidence from tagging studies suggests that the survival of fall-run Chinook salmon smolts decreases with increasing water temperatures between 59°F and 75°F in the Sacramento-San Joaquin Delta (Kjelson and Brandes 1989).

Based upon information reviewed for Chinook salmon juvenile mortality (Brett 1952), the Chinook Salmon Population Model (TID/MID 2013) identified an initial mortality threshold of 77°F for Chinook salmon smolts as a daily average water temperature.

Table 8. Chinook Salmon Smolt Emigration WTI Values and the Literature Supporting Each Value.

Index Value	Supporting Literature
57°F (13.9°C)	A water temperature of 57°F (7DADM) was identified as the value for Chinook smolt migration for the San Joaquin River (CALFED 2009).
59°F (15°C)	EPA Region 10 Guidance for Pacific Northwest State and Tribal Temperature Water Quality Standards identifies 59°F (7DADM; late year) for salmon smolts (EPA 2003b).

Index Value	Supporting Literature
63°F (17.2°C)	Acceleration and inhibition of Sacramento River Chinook salmon smolt development reportedly may occur at water temperatures above 63°F (Marine 1997; Marine and Cech 2004). Laboratory evidence suggest that survival and smoltification become compromised at water temperatures above 62.6°F (Zedonis and Newcomb 1997). Juvenile Chinook salmon growth was highest at 62.6°F (Clarke and Shelbourn 1985). A water temperature of 63°F (MWAT) was identified as the Upper Optimum Value for Chinook smolt migration for the Yuba Reintroduction Assessment for both fall- and spring-run Chinook (Bratovich *et al.* 2012).
68°F (20°C)	Significant inhibition of gill sodium ATPase activity and associated reductions of hyposmoregulatory capacity, and significant reductions in growth rates, may occur when chronic elevated temperatures exceed 68°F (Marine 1997; Marine and Cech 2004). Water temperatures supporting smoltification of fall-run Chinook salmon range between 50°F to 68°F, the colder temperatures represent more optimal conditions (50°F to 62.6°F), and the warmer conditions (62.6°F to 68°F) represent marginal conditions (Zedonis and Newcomb 1997). A water temperature of 68°F (MWAT) was identified as the Upper Tolerable Value for Chinook smolt migration for the Yuba Reintroduction Assessment for both fall- and spring-run Chinook (Bratovich *et al.* 2012).
72°F (22.2°C)	In a laboratory study, juvenile fall-run Chinook salmon from the Sacramento River reared in water temperatures between 70°F and 75°F experienced significantly decreased growth rates, impaired smoltification indices, and increased predation vulnerability compared with juveniles reared between 55°F and 61°F or between 63°F and 68°F (Marine 1997; Marine and Cech 2004). Indirect evidence from tagging studies suggests that the survival of fall-run Chinook salmon smolts decreases with increasing water temperatures between 59°F and 75°F in the Sacramento-San Joaquin Delta (Kjelson and Brandes 1989).
77°F (25°C)	The model associated with the Chinook Salmon Population Model Study, established an initial mortality threshold of 77°F (daily average temperatures) for Chinook salmon smolts (Brett 1952 as cited in TID/MID 2013).

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UPPER TUOLUMNE RIVER REINTRODUCTION ASSESSMENT FRAMEWORK WATER TEMPERATURE SUBCOMMITTEE

LIFESTAGE-SPECIFIC WATER TEMPERATURE BIOLOGICAL EFFECTS AND INDEX TEMPERATURE VALUES

Literature Review Summary

INTRODUCTION

The La Grange Hydroelectric Project (La Grange Project), owned and operated by the Turlock Irrigation District and Modesto Irrigation District (TID/MID, or the Districts), is currently undergoing the Federal Energy Regulatory Commission (FERC) Integrated Licensing Process (ILP). As part of this process, the Districts are implementing a FERC-approved Fish Passage Facilities Alternatives Assessment which consists of developing general design criteria and design considerations applicable to upstream and downstream fish passage facilities at the La Grange Project. Design criteria and considerations include items such as: site-specific physical and operational parameters; applicable regulatory requirements; National Marine Fisheries Service (NMFS), U.S. Fish and Wildlife Service (USFWS), and California Department of Fish and Wildlife (CDFW) biological and engineering design criteria; site-specific biological/habitat information relevant to the sizing and configuration of facilities; and any other information gaps that may affect siting, sizing, general design parameters, capital cost, and operating requirements of potential fish passage facilities.

To make certain that detailed, site-specific information is available to support and adequately inform decisions regarding fish reintroduction and fish passage, TID, MID, and licensing participants came to a consensus on the need for and utility of an Upper Tuolumne River Reintroduction Assessment Framework (Framework). The Framework is intended to provide a comprehensive, collaborative, and transparent approach for evaluating the full range of potential issues associated with the future reintroduction of anadromous salmonids to the upper Tuolumne River. In addition to considering aspects of the technical feasibility of building and operating fish passage facilities, the Framework considers the interrelated issues of ecological feasibility, biological constraints, economics, regulatory implications, and other considerations of reintroduction. Elements of the Framework are interconnected, with fish passage construction and operational requirements needing to properly reflect biological constraints, ecological considerations, and economic cost-benefit assessments.

Water temperature considerations are a primary component of assessing any potential anadromous salmonid reintroduction effort. In support of the Framework, the Districts and licensing participants established a Water Temperature Subcommittee to begin investigating water temperature considerations pertinent to anadromous salmonid reintroduction opportunities in the accessible reaches of the Tuolumne River upstream of Don Pedro Reservoir (upper Tuolumne River). On September 15, 2016, the Districts hosted the first conference call for the Water Temperature Subcommittee (draft meeting notes from this call were distributed on October 3 for a 30-day comment period). On the conference call, attendees discussed the need for a comprehensive literature review of regional and site-specific information to inform the selection of water temperature index (WTI) values to be used in an evaluation of the water temperature-related reintroduction potential in the reaches of the upper Tuolumne River. Meeting attendees agreed that the literature review performed for the Yuba Salmon Forum (Appendix A; Bratovich *et al.* 2012) to support the anadromous salmonid reintroduction assessment in this watershed coupled with site-specific temperature studies or data for the Tuolumne River, if available, would be a good basis for this effort. The following represents an updated literature review summary that is being provided to the Water Temperature Subcommittee to support selection of water temperature index values for the Framework.

The WTI values presented herein represent a gradation of potential biological effects from optimal to lethal water temperatures for each lifestage. 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. Acute, chronic, and optimal growth zones are displayed in Figure 1.

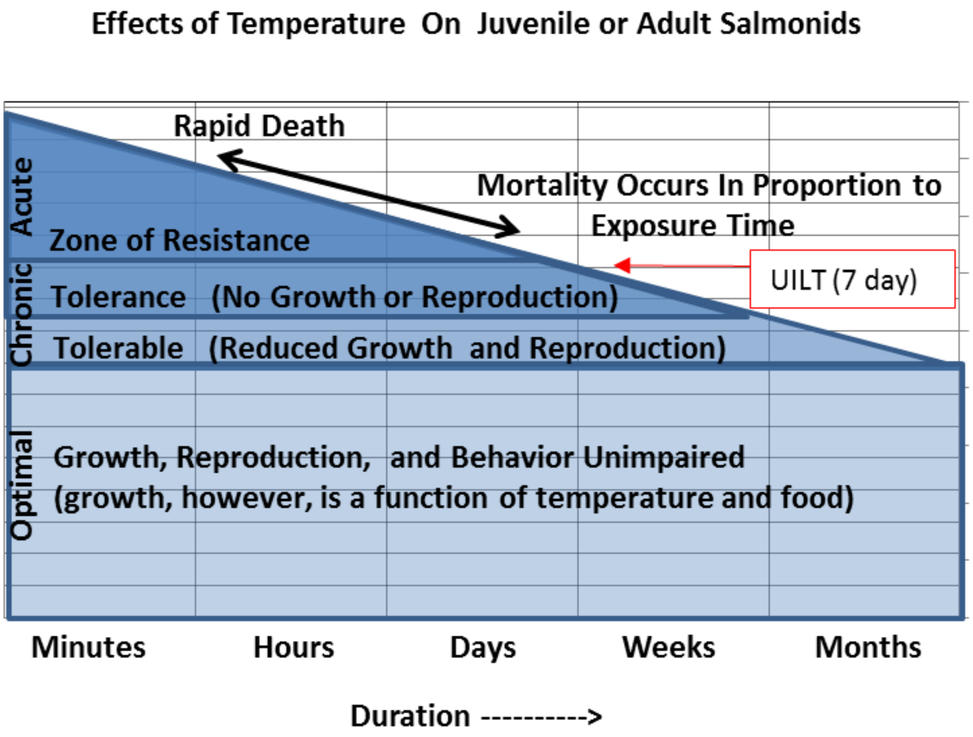

Figure 1. Illustration of acute, chronic, and optimal temperature zones (adapted from Sullivan et al. 2000).

STEELHEAD LIFESTAGE-SPECIFIC WATER TEMPERATURE INDEX VALUES

Adult Immigration and Holding

Water temperatures can control the timing of adult spawning migrations and can affect the viability of eggs in holding females. Yuba County Water Agency (YCWA) *et al.* (2007) suggests that few studies have been published examining the effects of water temperature on either steelhead immigration or steelhead holding, and none of the available studies were recent (Bruin and Waldsdorf 1975; McCullough *et al.* 2001). The available studies suggest that adverse effects occur to immigrating and holding steelhead at water temperatures exceeding the mid-50°F range, and that immigration will be delayed if water temperatures approach approximately 70°F (Table 1). WTI values of 52°F, 56°F, 61°F, 64°F, 65°F, 68°F and 70°F were identified because they provide a gradation of potential water temperature effects, and the available literature provided the strongest support for these values.

Because of the paucity of literature pertaining to steelhead adult immigration and holding, an evenly spaced range of WTI values could not be achieved. 52°F was identified as a WTI value because it has been referred to as a "recommended" (Reclamation 2003), "preferred" (McEwan and Jackson 1996; NMFS 2000; NMFS 2002), and "optimum" (Reclamation 1997a) water temperature for steelhead adult immigration. Increasing levels of thermal stress to this lifestage may reportedly occur above the 52°F WTI value. 56°F was identified as a WTI value because 56°F represents a water temperature above which adverse effects to migratory and holding steelhead begin to arise (Bruin and Waldsdorf 1975; Leitritz and Lewis 1980; McCullough *et al.* 2001; Smith *et al.* 1983). 50-59°F is referred to as the "preferred" range of water temperatures for California summer steelhead holding (Moyle *et al.* 1995). Water temperatures greater than 61°F may result in "chronic high stress" of holding Central Valley winter-run steelhead (USFWS 1995a). A water temperature of 64°F (7DADM) was identified as the value for steelhead adult lifestage for the San Joaquin River (CALFED 2009) and as the Upper Optimum Value for steelhead adult migration (maximum weekly average temperature; MWAT) for the Yuba Reintroduction Assessment (Bratovich *et al.* 2012). EPA Region 10 Guidance for Pacific Northwest State and Tribal Temperature Water Quality Standards identifies 64°F (7DADM) for "salmon and trout" migration (EPA 2003b). 65°F was identified as a WTI value because steelhead (and fall-run Chinook salmon) encounter potentially stressful temperatures between 64.4-73.4°F (Richter and Kolmes 2005). Additionally, over 93% of steelhead detections occurred in the 65.3-71.6°F range, although this may be above the temperature for optimal immigration (Salinger and Anderson 2006) and/or may modify migration timing due to holding in coldwater refugia (High *et al.* 2006). A water temperature of 68°F (MWAT) was identified as the Upper Tolerable Value for steelhead adult migration for the Yuba Reintroduction Assessment (Bratovich *et al.* 2012). A water temperature of 68°F was found to drop egg fertility in vivo to 5% after 4.5 days (McCullough *et al.* 2001). Additionally, empirical adult *O. mykiss* population data from the North Yuba, Middle Yuba, South Yuba, Middle Fork American, and Rubicon rivers were collected in 2007-2009 were plotted against temperature (Figure 4 of Bratovich *et al.* 2012). The data show a population density break at about 68°F. Although smaller population densities occurred at higher temperatures, the largest population densities occurred at temperatures near 68.0°F or less. 70°F was identified as the highest WTI value because the literature suggests that water temperatures near and above 70.0°F may result in a thermal barrier to adult steelhead migrating upstream (McCullough *et al.* 2001) and are water temperatures referred to as "stressful" to upstream migrating steelhead in the Columbia River (Lantz 1971 as cited in Beschta *et al.* 1987). Further, Coutant (1972) found that the upper incipient lethal temperature (UILT) for adult steelhead was 69.8°F and temperatures between 73-75°F are described as "lethal" to holding adult steelhead in Moyle (2002).

As part of the Framework, TID and MID, in collaboration with stakeholders developed a table of WTI values from select salmon and steelhead programs in the Central Valley (Temperature Criteria Matrix; presented at the September 15, 2016 Water Temperature Subcommittee conference call). The table was developed to support the Framework's Water Temperature Subcommittee whose purpose is to establish a technical basis to evaluate water temperature regimes for target anadromous salmonid reintroduction into the Tuolumne River upstream of Don Pedro Reservoir. For steelhead adult immigration, the Temperature Criteria Matrix identified 64°F for the San Joaquin (CALFED 2009) and 64°F (Upper Optimum Value) and

68°F (Upper Tolerable Value) for the Yuba Reintroduction Assessment (Bratovich *et al.* 2012). For steelhead adult holding, the Temperature Criteria Matrix identified 61°F (Upper Optimum Value) and 65°F (Upper Tolerable Value), MWAT, for the Yuba Reintroduction Assessment (Bratovich *et al.* 2012).

Table 1. Steelhead Adult Immigration and Holding WTI Values and the Literature Supporting Each Value.

Index Value	**Supporting Literature**
52°F (11.1°C)	Preferred range for adult steelhead immigration of 46.0°F to 52.0°F (NMFS 2000; NMFS 2001a; SWRCB 2003). Optimum range for adult steelhead immigration of 46.0°F to 52.1°F[1] (Reclamation 1997a). Recommended adult steelhead immigration temperature range of 46.0°F to 52.0°F (Reclamation 2003).
56°F (13.3°C)	To produce rainbow trout eggs of good quality, brood fish must be held at water temperatures not exceeding 56.0°F (Leitritz and Lewis 1980). Rainbow trout brood fish must be held at water temperatures not exceeding 56°F for a period of 2 to 6 months before spawning to produce eggs of good quality (Bruin and Waldsdorf 1975). Holding migratory fish at constant water temperatures above 55.4°F to 60.1°F may impede spawning success (McCullough *et al.* 2001).
61°F (16.1°C)	Water temperatures greater than 61°F may result in “chronic high stress” of holding Central Valley winter- run steelhead (USFWS 1995a). Preferred range of water temperature for holding California summer steelhead occurs between 50-59°F (Moyle 1995). A water temperature of 61°F (MWAT) was identified as the Upper Optimum Value for steelhead adult holding for the Yuba Reintroduction Assessment (Bratovich *et al.* 2012).
64°F (17.8°C)	Steelhead (and fall-run Chinook salmon) encounter potentially stressful temperatures between 64.4-73.4°F (Richter and Kolmes 2005). Over 93% of steelhead detections occurred in the 65.3-71.6°F, although this may be above the temperature for optimal immigration (Salinger and Anderson 2006). A water temperature of 64°F was identified as the value for steelhead adult lifestage, 7DADM, for the San Joaquin River (CALFED 2009) and as the Upper Optimum Value for steelhead adult migration, MWAT, for the Yuba Reintroduction Assessment (Bratovich *et al.* 2012). EPA Region 10 Guidance for Pacific Northwest State and Tribal Temperature Water Quality Standards identifies 64°F (7DADM) for “salmon and trout” migration (EPA 2003b).
65°F (18.3°C)	A water temperature of 65°F (MWAT) was identified as the Upper Tolerable Value for steelhead adult holding for the Yuba Reintroduction Assessment (Bratovich *et al.* 2012).
68°F (20°C)	A water temperature of 68°F (MWAT) was identified as the Upper Tolerable Value for steelhead adult migration for the Yuba Reintroduction Assessment (Bratovich *et al.* 2012). A water temperature of 68°F was found to drop egg fertility in vivo to 5% after 4.5 days (McCullough *et al.* 2001).
70°F (21.1°C)	Migration barriers have frequently been reported for pacific salmonids when water temperatures reach 69.8°F to 71.6°F (McCullough *et al.* 2001). Snake River adult steelhead immigration was blocked when water temperatures reached 69.8 (McCullough *et al.* 2001). The UILT for adult steelhead was determined to be 69.8°F (Coutant 1972).

Spawning and Embryo Incubation

Relatively few studies have been published directly addressing the effects of water temperature on steelhead spawning and embryo incubation (Redding and Schreck 1979;

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[1] Similar to Bratovich *et al*. 2012, rounded whole integers were identified for index values to avoid unwarranted specificity.

Rombough 1988). Because anadromous steelhead and non-anadromous rainbow trout are genetically and physiologically similar, studies on non-anadromous rainbow trout also were considered in the development of WTI values for steelhead spawning and embryo incubation (Moyle 2002; McEwan 2001). From the available literature, water temperatures in the low 50°F range appear to support high embryo survival, with substantial mortality to steelhead eggs reportedly occurring at water temperatures in the high 50°F range and above (Table 2). ~~Water temperatures in the 45-50°F range have been referred to as the "optimum" for spawning steelhead (FERC 1993).~~

WTI values of 46°F, 52°F, 54°F, 55°F, 57°F, 59°F and 60°F were identified for two reasons. First, the available literature provided the strongest support for WTI values at or near these integers. Second, the index values reflect a gradation of potential water temperature effects ranging between optimal to lethal conditions for steelhead spawning and embryo incubation. Some literature suggests water temperatures ≤ 50°F are when steelhead spawn (Orcutt *et al.* 1968) and/or are optimal for steelhead spawning and embryo survival (~~FERC 1993;~~ Myrick and Cech 2001; Timoshina 1972) and temperatures between 39-52°F are "preferred" by spawning steelhead (IEP Steelhead Project Work Team (no date); McEwan and Jackson 1996). Orcutt *et al.* (1968) reported that steelhead spawning in late spring in the Clearwater and Salmon Rivers, Idaho, occurred at temperatures between 35.6 and 46.4°F. A larger body of literature suggests optimal conditions occur at water temperatures ≤ 52°F (Humpesch 1985; NMFS 2000; NMFS 2001a; NMFS 2002; Reclamation 1997b; SWRCB 2003; USFWS 1995b). Further, water temperatures between 48-52°F were referred to as "optimal" (~~FERC 1993;~~ McEwan and Jackson 1996; NMFS 2000) and "preferred" (Bell 1986) for steelhead embryo incubation. Therefore, 52°F was identified as the lowest WTI value. Increasing levels of thermal stress to the steelhead spawning and embryo incubation lifestage may reportedly occur above the 52°F WTI value.

A temperature of 54°F was identified as the next index value, because although most of the studies conducted at or near 54.0°F report high survival and normal development (Kamler and Kato 1983; Redding and Schreck 1979; Rombough 1988), some evidence suggests that symptoms of thermal stress arise at or near 54.0°F (Humpesch 1985; Timoshina 1972). Thus, water temperatures near 54°F may represent an inflection point between properly functioning water temperature conditions, and conditions that cause negative effects to steelhead spawning and embryo incubation. ~~Further, water temperatures greater than 55°F were referred to as "stressful" for incubating steelhead embryos (FERC 1993).~~ EPA Region 10 Guidance for Pacific Northwest State and Tribal Temperature Water Quality Standards identifies 55°F (7DADM) for "salmon and trout" spawning and egg incubation (EPA 2003b). For steelhead spawning and embryo incubation in the Yuba River, the Framework Temperature Criteria Matrix identified 54°F and 57°F for Upper Optimum and Upper Tolerable values, respectively (Bratovich *et al.* 2012). 57°F was identified as an index value because embryonic mortality increases sharply and development becomes retarded at incubation temperatures greater than or equal to 57°F. Velsen (1987) provided a compilation of data on rainbow trout and steelhead embryo mortality to 50% hatch under incubation temperatures ranging from 33.8°F to 60.8°F that demonstrated a two-fold increase in mortality for embryos incubated at 57.2°F, compared to embryos incubated at 53.6°F.

In a laboratory study using gametes from Big Qualicum River, Vancouver Island, steelhead mortality increased to 15% at a constant temperature of 59.0°F, compared to less than 4% mortality at constant temperatures of 42.8°F, 48.2°F, and 53.6°F (Rombough 1988). Also, alevins hatching at 59°F were considerably smaller and appeared less well developed than those incubated at the lower temperature treatments. From fertilization to 50% hatch, rainbow trout eggs from Ontario Provincial Normendale Hatchery had 56% survival when incubated at 59.0°F (Kwain 1975).

As part of the Don Pedro Hydroelectric Project FERC relicensing process, the Districts conducted an *O. mykiss* Population Study (TID/MID 2014) for the Lower Tuolumne River below La Grange Diversion Dam. The goal of the study is to provide a quantitative population model to investigate the relative influences of various factors on the lifestage-specific production of *O. mykiss* in the Tuolumne River including water temperature effects on population response for specific in-river lifestages. The study noted that although no literature information could be identified regarding upper temperature limits for spawning initiation, maximum temperature limits for spawning are assumed to be on the order of 15°C (59°F) inferred from egg mortality thresholds for resident *O. mykiss* (Velsen 1987) as well as steelhead (Rombough 1988). Similarly, for egg incubation, the model allowed for a broad range of flow and water temperature conditions using the completed model, an initial acute mortality threshold of 15°C (59°F) was included based upon a literature review by Myrick and Cech (2001).

From fertilization to 50% hatch, Big Qualicum River steelhead had 93% mortality at 60.8°F, 7.7% mortality at 57.2°F, and 1% mortality at 47.3°F and 39.2°F (Velsen 1987). Myrick and Cech (2001) similarly described water temperatures >59°F as "lethal" to incubating steelhead embryos~~, although FERC (1993) suggested that water temperatures exceeding 68°F were "stressful" to spawning steelhead and "lethal" when greater than 72°F~~.

Table 2. Steelhead Spawning and Embryo Incubation WTI Values and the Literature Supporting Each Value.

Index Value	**Supporting Literature**
46°F (7.8°C)	Orcutt *et al.* (1968) reported that steelhead spawning in late spring in the Clearwater and Salmon Rivers, Idaho, occurred at temperatures between 35.6 and 46.4°F.
52°F (11.1°C)	Rainbow trout from Mattighofen (Austria) had highest egg survival at 52.0°F compared to 45.0°F, 59.4°F, and 66.0°F (Humpesch 1985). Water temperatures from 48.0°F to 52.0°F are suitable for steelhead incubation and emergence in the American River and Clear Creek (NMFS 2000; NMFS 2001a; NMFS 2002a). Optimum water temperature range of 46.0°F to 52.0°F for steelhead spawning in the Central Valley (USFWS 1995b). Optimum water temperature range of 46.0°F to 52.1°F for steelhead spawning and 48.0°F to 52.1°F for steelhead egg incubation (Reclamation 1997a). Upper limit of preferred water temperature of 52.0°F for steelhead spawning and egg incubation (SWRCB 2003).

Index Value	Supporting Literature
54°F (12.2°C)	Big Qualicum River steelhead eggs had 96.6% survival to hatch at 53.6°F (Rombough 1988). Highest survival from fertilization to hatch for *Salmo gairdneri* incubated at 53.6°F (Kamler and Kato 1983). Emergent fry were larger when North Santiam River (Oregon) winter steelhead eggs were incubated at 53.6°F than at 60.8°F (Redding and Schreck 1979). The upper optimal water temperature regime based on constant or acclimation water temperatures necessary to achieve full protection of steelhead is 51.8°F to 53.6°F (EPA 2001). From fertilization to hatch, rainbow trout eggs and larvae had 47.3% mortality (Timoshina 1972). Survival of rainbow trout eggs declined at water temperatures between 52.0 and 59.4°F (Humpesch 1985). The optimal constant incubation water temperature for steelhead occurs below 53.6°F (McCullough *et al.* 2001). A water temperature of 54°F (MWAT) was identified as the Upper Optimum Value for steelhead spawning and embryo incubation for the Yuba Reintroduction Assessment (Bratovich *et al.* 2012).
55°F (12.8°C)	EPA Region 10 Guidance for Pacific Northwest State and Tribal Temperature Water Quality Standards identifies 55°F (7DADM) for "salmon and trout" spawning and egg incubation (EPA 2003b). ~~Water temperatures greater than 55°F were referred to as "stressful" for incubating steelhead embryos (FERC 1993).~~
57°F (13.9°C)	From fertilization to 50% hatch, Big Qualicum River steelhead had 93% mortality at 60.8°F, 7.7% mortality at 57.2°F, and 1% mortality at 47.3°F and 39.2°F (Velsen 1987). A sharp decrease in survival was observed for rainbow trout embryos incubated above 57.2°F (Kamler and Kato 1983). A water temperature of 57°F (MWAT) was identified as the Upper Tolerable Value for steelhead spawning and embryo incubation for the Yuba Reintroduction Assessment (Bratovich *et al.* 2012).
59°F (15°C)	Based on egg mortality thresholds for steelhead, maximum temperature limits for spawning are assumed to be 59°F (Rombaugh 1988 as cited in TID/MID 2014). A water temperature of 59°F was identified as the initial acute mortality threshold for steelhead egg incubation (Myrick and Cech 2001 as cited in TID/MID 2014). From fertilization to 50% hatch, rainbow trout eggs from Ontario Provincial Normendale Hatchery had 56% survival when incubated at 59.0°F (Kwain 1975).
60°F (15.6°C)	Water temperatures >59°F are described as "lethal" to incubating steelhead embryos (Myrick and Cech 2001), From fertilization to 50% hatch, Big Qualicum River steelhead had 93% mortality at 60.8°F, 7.7% mortality at 57.2°F, and 1% mortality at 47.3°F and 39.2°F (Velsen 1987).

Juvenile Rearing & Downstream Movement

Water temperature index values were developed to evaluate the combined steelhead rearing (fry and juvenile) and juvenile downstream movement lifestages. Some steelhead may rear in freshwater for up to three years before emigrating as yearling+ smolts, whereas other individuals move downstream shortly after emergence as post- emergent fry, or rear in the river for several months and move downstream as juveniles without exhibiting the ontogenetic characteristics of smolts. Presumably, these individuals continue to rear and grow in downstream areas and undergo the smoltification process prior to entry into saline environments. Thus, fry and juvenile rearing occur concurrently with post-emergent fry and juvenile downstream movement and are assessed in this Technical Memorandum using the fry and juvenile rearing WTI values.

The growth, survival, and successful smoltification of juvenile steelhead are controlled largely by water temperature. The duration of freshwater residence for juvenile steelhead is long relative to that of Chinook salmon, making the juvenile lifestage of steelhead more susceptible to the influences of water temperature, particularly during the over-summer rearing period.

Central Valley juvenile steelhead have high growth rates at water temperatures in the mid-60°F range, but reportedly require lower water temperatures to successfully undergo the transformation to the smolt stage.

WTI values of 61°F, 63°F, 64°F, 65°F, 68°F, 72°F, 75°F, and 77°F were identified to represent a gradation of potential water temperature effects ranging between optimal to lethal conditions for steelhead juvenile rearing (Table 3). A water temperature of 61°F (7DADM) was identified as the value for steelhead juvenile rearing for the San Joaquin River (CALFED 2009). EPA Region 10 Guidance for Pacific Northwest State and Tribal Temperature Water Quality Standards (EPA 2003b) identifies 61°F (7DADM) for "salmon and trout" core juvenile rearing. The WTI value of 63°F was identified because Myrick and Cech (2001) describe 63°F as the "preferred" water temperature for wild juvenile steelhead, whereas "preferred" water temperatures for juvenile hatchery steelhead reportedly range between 64-66°F. EPA Region 10 Guidance for Pacific Northwest State and Tribal Temperature Water Quality Standards identifies 64°F (7DADM) for "salmon and trout" juvenile rearing (EPA 2003b). 65°F was also identified as a WTI value because NMFS (2000; 2002a) reported 65°F as the upper limit preferred for growth and development of Sacramento and American River juvenile steelhead. Also, 65°F was found to be within the optimum water temperature range for juvenile growth (i.e., 59-66°F) (Myrick and Cech 2001), and supported high growth of Nimbus strain juvenile steelhead (Cech and Myrick 1999). Increasing levels of thermal stress to this life stage may reportedly occur above the 65°F WTI value.

Kaya *et al.* (1977) reported that the upper avoidance water temperature for juvenile rainbow trout was measured at 68°F to 71.6°F. Cherry *et al.* (1977) observed an upper preference water temperature near 68.0°F for juvenile rainbow trout, duplicating the upper preferred limit for juvenile steelhead observed in Cech and Myrick (1999)~~ and FERC (1993)~~. Growth for 200 mm juvenile *O. mykiss* versus temperature for three food levels (percent of maximum consumption = 30%, 50%, and 70%) was evaluated. The average empirically derived percent of maximum consumption in the Middle Fork American Fork River was 50% (Hanson *et al.* 1997). Positive growth only occurs up to approximately 68°F. Because of the literature describing 68°F as both an upper preferred and an avoidance limit for juvenile *O. mykiss*, and because of the empirical fish population data and bioenergetics growth data, 68°F was identified as an upper tolerable WTI value.

A WTI value of 72°F was identified because symptoms of thermal stress in juvenile steelhead have been reported to arise at water temperatures approaching 72°F. For example, physiological stress to juvenile steelhead in Northern California streams was demonstrated by increased gill flare rates, decreased foraging activity, and increased agonistic activity as stream temperatures rose above 71.6°F (Nielsen *et al.* 1994). Also, 72°F was identified as a WTI value because 71.6°F has been reported as an upper avoidance water temperature (Kaya *et al.* 1977) and an upper thermal tolerance water temperature (Ebersole *et al.* 2001) for juvenile rainbow trout. The WTI value of 75°F was identified because NMFS and EPA report that direct mortality to rearing juvenile steelhead results when stream temperatures reach 75°F (EPA 2002; NMFS 2001b). Water temperatures >77°F have been referred to as "lethal" to juvenile steelhead (~~FERC 1993; ~~Myrick and Cech 2001). The UILT for juvenile rainbow trout, based on numerous studies, is between 75-79°F (Sullivan *et al.* 2000; McCullough 2001).

A swim tunnel study conducted on the Lower Tuolumne River (Verhille et al. 2016) generated high quality field data on the physiological performance of Tuolumne River *O. mykiss* acutely exposed to a temperature range of 13 to 25°C (55.4°F to 77°F). The data indicated that wild juvenile *O. mykiss* represents an exception to the expected based on the 7DADM criterion for juvenile rearing set out by EPA (2003b) for Pacific Northwest *O. mykiss*. The study recommended that a conservative upper aerobic performance limit of 71.6°F, instead of 64.4°F (EPA), be considered in re-determining a 7DADM for this population.

The Lower Tuolumne River *O. mykiss* Population Study (TID/MID 2014) identified the UILT for *O. mykiss* juveniles has been estimated at 22.8–25.9ºC (73–79°F) (Threader and Houston 1983). In the model, an initial mortality threshold of 25°C (77°F) daily average temperature was identified for *O. mykiss* juveniles. Note also that both fry rearing and resident adult rearing lifestages of *O. mykiss* also had UILT values of 77°F to support the model.

For steelhead juvenile rearing, the Temperature Criteria Matrix identified 65°F for the Lower American River (Water Forum 2007); 61°F for the San Joaquin (CALFED 2009); and 65°F (Upper Optimum Value) and 68°F (Upper Tolerable Value) for the Yuba River Basin (Bratovich *et al.* 2012).

Table 3. Steelhead Juvenile Rearing WTI Values and the Literature Supporting Each Value.

Index Value	**Supporting Literature**
61°F (16.1°C)	A water temperature of 61°F (7DADM) was identified as the value for steelhead juvenile rearing for the San Joaquin River (CALFED 2009).
63°F (17.2°C)	Preferred water temperature for wild juvenile steelhead is reportedly 63°F, whereas preferred water temperatures for juvenile hatchery steelhead reportedly range between 64-66°F. Myrick and Cech (2001)
64°F (17.8°C)	EPA Region 10 Guidance for Pacific Northwest State and Tribal Temperature Water Quality Standards identifies 64°F (7DADM) for “salmon and trout” juvenile rearing (EPA 2003b).
65°F (18.3°C)	Upper limit of 65°F preferred for growth and development of Sacramento River and American River juvenile steelhead (NMFS 2002a). Nimbus juvenile steelhead growth showed an increasing trend with water temperature to 66.2°F, irrespective of ration level or rearing temperature (Cech and Myrick 1999). The final preferred water temperature for rainbow fingerlings was between 66.2 and 68°F (Cherry *et al.* 1977). Nimbus juvenile steelhead preferred water temperatures between 62.6°F and 68.0°F (Cech and Myrick 1999). Rainbow trout fingerlings preferred or identified water temperatures in the 62.6°F to 68.0°F range (McCauley and Pond 1971). A water temperature of 65°F (daily average temperature) was identified as the value for steelhead juvenile rearing for the Lower American River (Water Forum 2007). A water temperature of 65°F (MWAT) was identified as the Upper Optimum Value for steelhead juvenile rearing for the Yuba Reintroduction Assessment (Bratovich *et al.* 2012).

Index Value	Supporting Literature
68°F (20°C)	Nimbus juvenile steelhead preferred water temperatures between 62.6°F and 68.0°F (Cech and Myrick 1999). The final preferred water temperature for rainbow trout fingerlings was between 66.2°F and 68°F (Cherry *et al.* 1977). Rainbow trout fingerlings preferred or identified water temperatures in the 62.6°F to 68.0°F range (McCauley and Pond 1971). The upper avoidance water temperature for juvenile rainbow trout was measured at 68°F to 71.6°F (Kaya *et al.* 1977). ~~FERC (1993) referred to 68°F as "stressful" to juvenile steelhead.~~ Empirical fish population and water temperature data in the North Yuba, Middle Yuba, South Yuba, Middle Fork American, and Rubicon Rivers (Figure 4 of Bratovich *et al.* 2012) indicate a sharp reduction in O. *mykiss* population densities when temperatures exceed 68°F for greater than one week. Bioenergetics modeling of growth based on consumption (P value = 0.5) in the Middle Fork American River watershed (adjacent watershed) indicates that growth likely does not occur above 68°F (Figure 5 of Bratovich *et al.* 2012). A water temperature of 68°F (MWAT) was identified as the Upper Tolerable Value for steelhead juvenile rearing for the Yuba Reintroduction Assessment (Bratovich *et al.* 2012).
72°F (22.2°C)	Increased physiological stress, increased agonistic activity, and a decrease in forage activity in juvenile steelhead occur after ambient stream temperatures exceed 71.6°F (Nielsen *et al.* 1994). The upper avoidance water temperature for juvenile rainbow trout was measured at 68°F to 71.6°F (Kaya *et al.* 1977). Estimates of upper thermal tolerance or avoidance limits for juvenile rainbow trout (at maximum ration) ranged from 71.6°F to 79.9°F (Ebersole *et al.* 2001). A swim tunnel study conducted on the Lower Tuolumne recommended a conservative upper aerobic performance limit of 71.6°F for *O. mykiss* juvenile rearing (Verhille et al. 2016).
75°F (23.9°C)	The maximum weekly average water temperature for survival of juvenile and adult rainbow trout is 75.2°F (EPA 2002). Rearing steelhead juveniles have an upper lethal limit of 75.0°F (NMFS 2001a). Estimates of upper thermal tolerance or avoidance limits for juvenile rainbow trout (at maximum ration) ranged from 71.6 to 79.9°F (Ebersole *et al.* 2001). The UILT for juvenile rainbow trout, based on numerous studies, is between 75-79°F (Sullivan *et al.* 2000; McCullough 2001).
77°F (25°C)	In the model associated with the Lower Tuolumne River *O. mykiss* Population Study (TID/MID 2014), an initial mortality threshold of 77°F daily average temperature was identified for *O. mykiss* juveniles.

Smolt Emigration

Laboratory data suggest that smoltification, and therefore successful emigration of steelhead smolts, is directly controlled by water temperature (Adams *et al.* 1975) (Table 4). WTI values of 52°F and 55°F were identified to evaluate the steelhead smolt emigration lifestage, because most literature on water temperature effects on steelhead smolting suggest that water temperatures less than 52°F (Adams *et al.*1975; Myrick and Cech 2001; Rich 1987a) or less than 55°F (EPA 2003a; McCullough *et al.* 2001; Wedemeyer *et al.* 1980; Zaugg and Wagner 1973) are required for successful smoltification to occur. Adams *et al.* (1973) tested the effect of water temperature (43.7°F, 50.0°F, 59.0°F or 68.0°F) on the increase of gill microsomal Na^+-, K^+-stimulated ATPase activity associated with parr-smolt transformation in steelhead and found a two-fold increase in Na^+-, K^+-ATPase at 43.7 and 50.0°F, but no increase at 59.0°F or 68.0°F. In a subsequent study, the highest water temperature where a parr-smolt transformation occurred was at 52.3°F (Adams *et al.* 1975). The results of Adams *et al.* (1975) were reviewed in Myrick and Cech (2001) and Rich (1987b), which both recommended that water temperatures below 52.3°F are required to successfully complete the parr-smolt transformation. Further, Myrick and Cech (2001) suggest that water temperatures between 43-50°F are the "physiologically optimal" temperatures required during the parr-smolt transformation and necessary to maximize saltwater survival. The 52°F WTI value identified for the steelhead smolt emigration lifestage is the index value generally reported in the literature as the upper limit of the water temperature range that provides successful smolt transformation thermal conditions. Increasing levels of thermal stress to this lifestage may reportedly occur above the 52°F WTI value.

Zaugg and Wagner (1973) examined the influence of water temperature on gill ATPase activity related to parr-smolt transformation and migration in steelhead. They found ATPase activity was decreased and migration reduced when juveniles were exposed to water temperatures of 55.4°F or greater. In a technical document prepared by the EPA to provide temperature water quality standards for the protection of Northwest native salmon and trout, water temperatures greater than 54.5°F were identified as an impairment to smoltification for juvenile steelhead (EPA 2003b). Water temperatures are considered "unsuitable" for steelhead smolts at >59°F (Myrick and Cech 2001)~~ and "lethal" at 77°F (FERC 1993)~~.

For steelhead smolt emigration, the Temperature Criteria Matrix identified 57°F for the San Joaquin (CALFED 2009) and 52°F (Upper Optimum Value) and 55°F (Upper Tolerable Value) for the Yuba River Basin (Bratovich et al. 2012). EPA Region 10 Guidance for Pacific Northwest State and Tribal Temperature Water Quality Standards (EPA 2003b) identifies 57°F (7DADM) for steelhead smoltification.

The Lower Tuolumne River *O. mykiss* Population Study (TID/MID 2014) identified an initial UILT mortality threshold of 77°F daily average temperature for *O. mykiss* smolts on the basis of literature reviews by Myrick and Cech (2001).

Table 4. Steelhead Smolt Emigration WTI Values and the Literature Supporting Each Value.

Index Value	**Supporting Literature**
52°F (11.1°C)	Steelhead successfully smolt at water temperatures in the 43.7°F to 52.3°F range (Myrick and Cech 2001). Steelhead undergo the smolt transformation when reared in water temperatures below 52.3°F, but not at higher water temperatures (Adams *et al.* 1975). Optimum water temperature range for successful smoltification in young steelhead is 44.0°F to 52.3°F (Rich 1987a). A water temperature of 52°F (MWAT) was identified as the Upper Optimum Value for steelhead smolt emigration for the Yuba Reintroduction Assessment (Bratovich *et al.* 2012).
55°F (12.8°C)	ATPase activity was decreased and migration reduced for steelhead at water temperatures greater than or equal to 55.4°F (Zaugg and Wagner 1973). Water temperatures should be below 55.4°F at least 60 days prior to release of hatchery steelhead to prevent premature smolting and desmoltification (Wedemeyer *et al.* 1980). In winter steelhead, a temperature of 54.1°F is nearly the upper limit for smolting (McCullough *et al.* 2001; Zaugg and Wagner 1973). Water temperatures less than or equal to 54.5°F are suitable for emigrating juvenile steelhead (EPA 2003b). Water temperatures greater than 55°F prevent increases in ATPase activity in steelhead juveniles (Hoar 1988). Water temperatures greater than 56°F do not permit smoltification in summer steelhead (Zaugg *et al.* 1972). A water temperature of 55°F (MWAT) was identified as the Upper Tolerable Value for steelhead smolt emigration for the Yuba Reintroduction Assessment (Bratovich *et al.* 2012).
57°F (13.9°C)	A water temperature of 57°F (7DADM) was identified as the value for steelhead smolt emigration for the San Joaquin River (CALFED 2009). EPA Region 10 Guidance for Pacific Northwest State and Tribal Temperature Water Quality Standards identifies 57°F (7DADM) for steelhead smoltification (EPA 2003b).

Index Value	Supporting Literature
59°F (15°C)	Yearling steelhead held at 43.7°F and transferred to 59°F had a substantial reduction in gill ATPase activity, indicating that physiological changes associated with smoltification were reversed (Wedemeyer *et al.* 1980).
77°F (25°C)	A water temperature of 77°F (daily average temperature) was identified as UILT mortality threshold for *O. mykiss* smolts (Myrick and Cech 2001 as cited in TID/MID 2014).

CHINOOK SALMON LIFESTAGE-SPECIFIC WATER TEMPERATURE INDEX VALUES

It has been suggested that separate water temperatures standards should be developed for each run-type of Chinook salmon. For example, McCullough (1999) states that spring-run Chinook salmon immigrate in spring and spawn in 3rd to 5th order streams and, therefore, face different migration and adult holding temperature regimes than do summer- or fall-run Chinook salmon, which spawn in streams of 5th order or greater . However:(1) there is a general paucity of literature specific to each lifestage of each run-type; (2) there is an insufficient amount of data available in the literature suggesting that Chinook salmon run-types respond to water temperatures differently; (3) the WTI values derived from all the literature pertaining to Chinook salmon for a particular lifestage will be sufficiently protective of that lifestage for each run-type; and (4) all run- types overlap in timing of adult immigration and holding and in some cases are not easily distinguished (Healey 1991). Information distinctly applicable to spring-run or fall-run Chinook salmon is identified where run-specific information is available.

Adult Immigration and Holding

The adult immigration and staging lifestages for fall-run Chinook salmon are evaluated together, because they are believed to not spend significant amounts of time after immigrating and prior to spawning. The adult immigration and holding lifestages are evaluated separately for spring-run Chinook salmon, because of the potential extended duration of holding after immigrating and prior to spawning.

The WTI values reflect a gradation of potential water temperature effects that range between those reported as “optimal” to those reported as “lethal” for adult Chinook salmon during upstream spawning migrations and holding. The WTI values identified for the Chinook salmon adult immigration and holding lifestage are 60°F, 61°F, 64°F, 65°F, 68°F and 70°F (Table 5). Although 56°F is referenced in the literature frequently as the upper “optimal” water temperature limit for upstream migration and holding, the references are not foundational studies and often are inappropriate citations. For example, Boles *et al.* (1988), Marine (1992), and NMFS (1997b) all cite Hinze (1959) in support of recommendations for a water temperature of 56°F for adult Chinook salmon immigration. However, Hinze (1959) is a study examining the effects of water temperature on incubating Chinook salmon eggs in the American River Basin. Further, water temperatures between 38-56°F are considered to represent the “observed range” for upstream migrating spring-run Chinook salmon (Bell 1986).

The lowest WTI value identified was 60°F because in a previous NMFS biological opinion for the proposed operation of the Central Valley Project (CVP) and State Water Project

(SWP), 59°F to 60°F is reported as…"*The upper limit of the optimal temperature range for adults holding while eggs are maturing*" (NMFS 2000). Also, NMFS (1997b) states…"*Generally, the maximum temperature of adults holding, while eggs are maturing, is about 59°F to 60°F*". Oregon Department of Environmental Quality (ODEQ; 1995) reports that "*…many of the diseases that commonly affect Chinook become highly infectious and virulent above 60°F.*" Mature females subjected to prolonged exposure to water temperatures above 60°F have poor survival rates and produce less viable eggs than females exposed to lower water temperatures (USFWS 1995b).

Ward and Kier (1999) designated temperatures <60.8°F as an "optimum" water temperature threshold for holding Battle Creek spring-run Chinook salmon. EPA (2003a) chose a holding value of 61°F (7DADM) based on laboratory data various assumptions regarding diel temperature fluctuations. The 61°F WTI value identified for the Chinook salmon adult immigration and holding lifestage is the index value generally reported in the literature as the upper limit of the optimal range, and is within the reported acceptable range. Increasing levels of thermal stress to this lifestage may reportedly occur above the 61°F WTI value.

EPA Region 10 Guidance for Pacific Northwest State and Tribal Temperature Water Quality Standards (EPA 2003b) identifies 64°F (7DADM) for "salmon and trout" adult migration. A water temperature of 64°F (MWAT) was identified as the Upper Optimum Value for Chinook adult migration for the Yuba Reintroduction Assessment (Bratovich *et al*. 2012).

An index value of 65°F was identified because Berman (1990) suggests effects of thermal stress to pre-spawning adults are evident at water temperatures near 65°F. Berman (1990) conducted a laboratory study to determine if pre-spawning water temperatures experienced by adult Chinook salmon influenced reproductive success, and found evidence suggesting latent embryonic abnormalities associated with water temperature exposure to pre-spawning adults that ranged from 63.5°F to 66.2°F. During each of the years when Chinook salmon temperature mortality was not observed at Butte Creek (2001, 2004-2007), on average, daily temperature did not exceed 65.8°F for more than 7 days (Figure 6 of Bratovich *et al.* 2012). Tracy McReynolds (pers. comm. October 2011) suggested that an upper tolerable holding temperature of 65°F was reasonable. A water temperature of 65°F (MWAT) was identified as the Upper Tolerable Value for Chinook adult holding for the Yuba Reintroduction Assessment (Bratovich *et al.* 2012).

An index value of 68°F was identified because the Butte Creek data and the literature suggests that thermal stress at water temperatures greater than 68°F is pronounced, and severe adverse effects to immigrating and holding pre-spawning adults, including mortality, can be expected (Berman 1990; Marine 1997; NMFS 1997b; Ward *et al.* 2004).

Acceptable water temperatures for adults migrating upstream range from 57°F to 67°F (NMFS 1997b). For chronic exposures, an incipient upper lethal water temperature limit for pre-spawning adult salmon probably falls within the range of 62.6°F to 68°F (Marine 1992). Water temperatures of 68°F resulted in nearly 100% mortality of Chinook salmon during columnaris outbreaks (Ordal and Pacha 1963). Adult Chinook salmon migration rates through the lower Columbia River were slowed significantly when water temperatures exceeded 68°F (Goniea *et al.* 2006). A water temperature of 68°F (MWAT) was identified as the Upper Tolerable Value for Chinook adult migration for the Yuba Reintroduction Assessment (Bratovich *et al.* 2012).

Water temperatures between 70-77°F are reported as the range of maximum temperatures for holding pool conditions used by spring-run Chinook salmon in the Sacramento-San Joaquin system (Moyle *et al*. 1995). Migration blockage occurs for Chinook salmon at temperatures from 70-71+°F (McCollough 1999; McCullough *et al*. 2001; EPA 2003b). Strange (2010) found that the mean average body temperature during the first week of Chinook salmon migration on the Klamath River was 71.4°F. The UILT for Chinook salmon jacks is 69.8-71.6°F (McCullough 1999).

For spring-run Chinook salmon adult immigration, the Framework Temperature Criteria Matrix identified 64°F (Upper Optimum Value) and 68°F (Upper Tolerable Value), MWAT, for the Yuba River Basin (Bratovich *et al*. 2012). For spring-run Chinook salmon adult holding, the Framework Temperature Criteria Matrix identified 61°F (Upper Optimum Value) and 65°F (Upper Tolerable Value), MWAT, for the Yuba River Basin (Bratovich *et al.* 2012).

Table 5. Chinook Salmon Adult Immigration and Holding WTI Values and the Literature Supporting Each Value.

Index Value	Supporting Literature
60°F (15.6°C)	Maximum water temperature for adults holding, while eggs are maturing, is approximately 59°F to 60°F (NMFS 1997b). Upper limit of the optimal water temperature range for adults holding while eggs are maturing is 59°F to 60°F (NMFS 2000). Many of the diseases that commonly affect Chinook salmon become highly infectious and virulent above 60°F (ODEQ 1995). Mature females subjected to prolonged exposure to water temperatures above 60°F have poor survival rates and produce less viable eggs than females exposed to lower water temperatures (USFWS 1995b).
61°F (16.1°C)	A water temperature of 61°F (MWAT) was identified as the Upper Optimum Value for Chinook adult holding for the Yuba Reintroduction Assessment (Bratovich *et al.* 2012). Ward and Kier (1999) designated temperatures <60.8°F as an "optimum" water temperature threshold for holding Battle Creek spring-run Chinook salmon.
64°F (17.8°C)	A water temperature of 64°F (MWAT) was identified as the Upper Optimum Value for Chinook adult migration for the Yuba Reintroduction Assessment (Bratovich *et al.* 2012). EPA Region 10 Guidance for Pacific Northwest State and Tribal Temperature Water Quality Standards identifies 64°F (7DADM) for "salmon and trout" adult migration (EPA 2003b).
65°F (18.3°C)	Acceptable range for adults migrating upstream is from 57°F to 67°F (NMFS 1997b). Disease risk becomes high at water temperatures above 64.4°F (EPA 2003b). Latent embryonic mortalities and abnormalities associated with water temperature exposure to pre-spawning adults occur at 63.5°F to 66.2°F (Berman 1990). During each of the years when Chinook salmon temperature mortality was not observed at Butte Creek (2001, 2004-2007), on average, daily temperature did not exceed 65.8°F for more than 7 days (Figure 6 of Bratovich *et al.* 2012). A water temperature of 65°F (MWAT) was identified as the Upper Tolerable Value for Chinook adult holding for the Yuba Reintroduction Assessment (Bratovich *et al.* 2012).

Index Value	**Supporting Literature**
68°F (20°C)	Acceptable water temperatures for adults migrating upstream range from 57°F to 67°F (NMFS 1997b). For chronic exposures, an incipient upper lethal water temperature limit for pre-spawning adult salmon probably falls within the range of 62.6°F to 68.0°F (Marine 1992). Water temperatures of 68°F resulted in nearly 100% mortality of Chinook salmon during columnaris outbreaks (Ordal and Pacha 1963). Adult Chinook salmon migration rates through the lower Columbia River were slowed significantly when water temperatures exceeded 68°F (Goniea *et al.* 2006). A water temperature of 68°F (MWAT) was identified as the Upper Tolerable Value for Chinook adult migration for the Yuba Reintroduction Assessment (Bratovich *et al.* 2012).
70°F (21.1°C)	Migration blockage occurs for Chinook salmon at temperatures from 70-71+°F (McCollough 1999; McCullough *et al.* 2001; EPA 2003b). Strange (2010) found that the mean average body temperature during the first week of Chinook salmon migration on the Klamath River was 71.4°F. The UILT for Chinook salmon jacks is 69.8-71.6°F (McCullough 1999).

Spawning and Embryo Incubation

The adult spawning and embryo (i.e., eggs and alevins) incubation lifestages share one set of WTI values because spawning and embryonic survival and development typically are considered concurrently in the literature on the effects of water temperature. Spawning and incubation evaluations are conducted separately due to differences in their temporal distributions.

The WTI values identified for the Chinook salmon spawning and embryo incubation lifestages are 55°F, 56°F, 58°F, 60°F, and 62°F (Table 6). ~~Anomalously, FERC (1993) refers to 50°F as the "optimum" water temperature for spawning and incubating Chinook salmon.~~ EPA Region 10 Guidance for Pacific Northwest State and Tribal Temperature Water Quality Standards identifies 55°F (7DADM) for "salmon and trout" spawning, egg incubation, and fry emergence (EPA 2003b). A water temperature of 55°F (7DADM) was identified as the value for Chinook incubation for the San Joaquin River fall-run Chinook salmon (CALFED 2009).

~~Additionally, for the adult spawning lifestage, FERC (1993) reports "stressful" and "lethal" water temperatures occurring at >60°F and >70°F, respectively, whereas for incubating Chinook salmon embryos, water temperatures are considered to be "stressful" at <56°F or "lethal" at >60°F.~~ Much literature suggests that water temperatures must be less than or equal to 56°F for maximum survival of Chinook salmon embryos (i.e., eggs and alevins) during spawning and incubation. NMFS (1993b) reported that optimum water temperatures for egg development are between 43°F and 56°F. Similarly, Myrick and Cech (2001) reported the highest egg survival rates occur between water temperatures of 39-54°F. Reclamation (unpublished work) reports that water temperatures less than 56°F results in a natural rate of mortality for fertilized Chinook salmon eggs. Bell (1986) recommends water temperatures ranging between 42-57°F for spawning Chinook salmon, and water temperatures between 41-58°F for incubating embryos. USFWS (1995a) reported a water temperature range of 41°F to 56°F for maximum survival of eggs and yolk-sac larvae in the Central Valley of California. The preferred water temperature range for Chinook salmon egg incubation in the Sacramento River was suggested as 42°F to 56°F (NMFS 1997a). Alevin mortality is reportedly significantly higher when Chinook salmon embryos are incubated at water temperatures above 56°F (USFWS 1999). NMFS (2002a) reported 56°F as the upper limit of suitable water temperatures for spring-run Chinook salmon spawning in the Sacramento River. The 56°F WTI value identified for the Chinook salmon spawning and embryo incubation lifestage is the index value generally reported in the literature as the upper limit of the optimal range for egg development and the upper limit of the range reported to provide maximum survival of eggs and yolk-sac larvae in the Central Valley of California. Increasing levels of thermal stress to this lifestage may reportedly occur above the 56°F WTI value.

High survival of Chinook salmon embryos also has been suggested to occur at incubation temperatures at or near 58°F. For example, (Reclamation Unpublished Work) reported that the natural rate of mortality for alevins occurs at 58°F or less. Combs (1957) concluded constant incubation temperatures between 42.5°F and 57.5°F resulted in normal development of Chinook salmon eggs, and NMFS (2002a) suggests 53°F to 58°F is the preferred water temperature range for Chinook salmon eggs and fry. The model associated with the Chinook Salmon Population Model Study (TID/MID 2013), established an initial acute egg/alevin mortality threshold of 58°F. A water temperature of 58°F (MWAT) was identified as the Upper Tolerable Value for Chinook spawning and incubation for the Yuba Reintroduction Assessment (Bratovich *et al.* 2012).

Johnson (1953) found consistently higher Chinook salmon egg losses resulted at water temperatures above 60°F than at lower temperatures. In order to protect late incubating Chinook salmon embryos and newly emerged fry NMFS (1993a) determined that a water temperature criterion of less than or equal to 60°F be maintained in the Sacramento River from Keswick Dam to Bend Bridge from October 1 to October 31. Seymour (1956) provides evidence that 100% mortality occurs to late incubating Chinook salmon embryos when held at a constant water temperature greater than or equal to 60°F. For Chinook salmon eggs incubated at constant temperatures, mortality increases rapidly at temperatures greater than about 59-60°F (see data plots in Myrick and Cech 2001). Olsen and Foster (1957), however, found high survival of Chinook salmon eggs and fry (89.6%) when incubation temperatures started at 60.9°F and declined naturally for the Columbia River (about 7°F/month). The Chinook Salmon Population Model (TID/MID 2013) established an initial estimate of 60.4°F as the upper limit for initiation of spawning (Groves and Chandler 1999); also interpreted as the temperature at which spawning habitat will be considered usable by spawners.

The literature largely agrees that 100% mortality will result to Chinook salmon embryos incubated at water temperatures greater than or equal to about 62°F (Hinze 1959; Myrick and Cech 2003; Seymour 1956; USFWS 1999). Approximately 80% or greater mortality of eggs incubated at constant temperatures of 63°F or greater (see data plots in Myrick and Cech 2001). Geist *et al.* (2006) found low Chinook salmon incubation survival (1.7%) for naturally declining temperatures (0.36°F/day) when temperatures started at 62.6°F.

For Chinook salmon spawning and incubation, the Framework Temperature Criteria Matrix identified 60°F or less (as early in October as possible) and 56°F or less (as early in November as possible) as water temperature targets for lower American River fall-run Chinook salmon (Water Forum 2007); 64°F (spawning) and 55°F (incubation) for San Joaquin fall-run Chinook salmon (CALFED 2009); 56°F for Shasta River winter and spring-run Chinook salmon (SWRCB 2016); and 56°F (Upper Optimum Value) and 58°F (Upper Tolerable Value) in the Yuba River Basin (Bratovich *et al.* 2012).

Table 6. Chinook Salmon Spawning and Embryo Incubation WTI Values and the Literature Supporting Each Value.

Index Value	**Supporting Literature**
55°F (12.8°C)	EPA Region 10 Guidance for Pacific Northwest State and Tribal Temperature Water Quality Standards identifies 55°F (7DADM) for "salmon and trout" spawning, egg incubation, and fry emergence (EPA 2003b). A water temperature of 55°F (7DADM) was identified as the value for Chinook incubation for the San Joaquin River fall-run Chinook salmon (CALFED 2009).
56°F (13.3°C)	Less than 56°F results in a natural rate of mortality for fertilized Chinook salmon eggs (Reclamation Unpublished Work). Optimum water temperatures for egg development are between 43°F and 56°F (NMFS 1993b). Upper value of the water temperature range (i.e., 41°F to 56°F) suggested for maximum survival of eggs and yolk-sac larvae in the Central Valley of California (USFWS 1995b). Upper value of the range (i.e., 42°F to 56°F) given for the preferred water temperature for Chinook salmon egg incubation in the Sacramento River (NMFS 1997a). Incubation temperatures above 56°F result in significantly higher alevin mortality (USFWS 1999). 56°F is the upper limit of suitable water temperatures for spring-run Chinook salmon spawning in the Sacramento River (NMFS 2002a). Water temperatures averaged 56.5°F during the week of fall-run Chinook salmon spawning initiation on the Snake River (Groves and Chandler 1999). A water temperature of 56°F or less (daily average temperature), as early in November as possible, was identified as the value for fall-run Chinook salmon spawning and incubation for the lower American River (Water Forum 2007). A water temperature of 56°F (daily average temperature) was identified as the value for Chinook spawning and incubation for the Shasta River winter- and spring-run Chinook (SWRCB 2016). A water temperature of 56°F (MWAT) was identified as the Upper Optimum Value for Chinook spawning and incubation for the Yuba Reintroduction Assessment (Bratovich *et al.* 2012).
58°F (14.4°C)	Upper value of the range given for preferred water temperatures (i.e., 53°F to 58°F) for eggs and fry (NMFS 2002a). Constant egg incubation temperatures between 42.5°F and 57.5°F resulted in normal development (Combs and Burrows 1957). The natural rate of mortality for alevins occurs at 58°F or less (Reclamation Unpublished Work). The model associated with the Chinook Salmon Population Model Study, established an initial acute egg/alevin mortality threshold of 58°F (TID/MID 2013). A water temperature of 58°F (MWAT) was identified as the Upper Tolerable Value for Chinook spawning and incubation for the Yuba Reintroduction Assessment (Bratovich *et al.* 2012).
60°F (15.6°C)	100% mortality can occur to late incubating Chinook salmon embryos (yolk-sac stage) if temperatures are 60°F or greater (Seymour 1956). An October 1 to October 31 water temperature criterion of less than or equal to 60°F in the Sacramento River from Keswick Dam to Bend Bridge has been determined for protection of late incubating larvae and newly emerged fry (NMFS 1993b). Mean weekly water temperature at first observed Chinook salmon spawning in the Columbia River was 59.5°F (Dauble and Watson 1997). Consistently higher egg losses resulted at water temperatures above 60°F than at lower temperatures (Johnson and Brice 1953). For Chinook Salmon eggs incubated at constant temperatures, mortality increases rapidly at temperatures greater than about 59-60°F (see data plots in Myrick and Cech 2001). Olsen and Foster (1957) found high survival of Chinook salmon eggs and fry (89.6%) when incubation temperatures started at 60.9°F and declined naturally for the Columbia River (about 7°F/month). A water temperature of 60°F or less (daily average temperature), as early in October as possible, was identified as a target value for Chinook spawning and incubation for the lower American River fall-run Chinook (Water Forum 2007). The model associated with the Chinook Salmon Population Model Study (TID/MID 2013), established an initial estimate of 60.4°F as the upper limit for initiation of spawning (Groves and Chandler 1999).

Index Value	Supporting Literature
62°F (16.7°C)	100% mortality of fertilized Chinook salmon eggs after 12 days at 62°F (Reclamation Unpublished Work). Incubation temperatures of 62ºF to 64°F appear to be the physiological limit for embryo development resulting in 80 to 100% mortality prior to emergence (USFWS 1999). 100% loss of eggs incubated at water temperatures above 62°F (Hinze 1959). 100% mortality occurs during yolk-sac stage when embryos are incubated at 62.5°F (Seymour 1956). Approximately 80% or greater mortality of eggs incubated at constant temperatures of 63°F or greater (see data plots in Myrick and Cech 2001). Geist *et al*. (2006) found low Chinook salmon incubation survival (1.7%) for naturally declining temperatures (0.36°F/day) when temperatures started at 62.6°F.

Juvenile Rearing and Downstream Movement

WTI values were developed to evaluate the Chinook salmon rearing (fry and juvenile) and juvenile downstream movement lifestages. Some Chinook salmon juveniles, both fall-run and spring-run, move downstream shortly after emergence as post- emergent fry, or rear in the river for several months and move downstream as YOY juveniles without exhibiting the ontogenetic characteristics of smolts. Presumably, these individuals undergo the smoltification process prior to entry into saline environments. Thus, fry and juvenile rearing occur concurrently with post-emergent fry and juvenile downstream movement and are presented in this Technical Memorandum using the fry and juvenile rearing WTI values.

The WTI values of 60°F, 61°F, 64°F, 65°F, 68°F, 70°F, 73°F, 75°F, and 77°F were identified for the Chinook salmon juvenile rearing and downstream movement lifestage. The lowest index value of 60°F was identified because regulatory documents as well as several source studies, including ones conducted on Central Valley Chinook salmon fry and juveniles, report 60°F as an optimal water temperature for growth (Banks *et al.* 1971; Brett *et al.* 1982; Marine 1997; NMFS 1997b; NMFS 2000; NMFS 2001a; NMFS 2002; Rich 1987b) (Table 7). Water temperatures below 60°F also have been reported as providing conditions optimal for fry and fingerling growth, but were not identified as index values, because the studies were conducted on fish from outside of the Central Valley (Brett 1952; Seymour 1956). Studies conducted using local fish may be particularly important because *Oncorhynchus* species show considerable variation in morphology, behavior, and physiology along latitudinal gradients (Myrick 1998; Taylor 1990b; Taylor 1990a). More specifically, it has been suggested that salmonid populations in the Central Valley prefer higher water temperatures than those from more northern latitudes (Myrick and Cech 2000).

The 60°F WTI value identified for the Chinook salmon juvenile rearing and downstream movement lifestage is the index value generally reported in the literature as the upper limit of the optimal range for fry and juvenile growth and the upper limit of the preferred range for growth and development of spring-run Chinook salmon fry and fingerlings. NMFS (2002a) identified 60°F as the “preferred” water temperature for juvenile spring-run Chinook salmon in the Central Valley. Increasing levels of thermal stress to this lifestage may reportedly occur above the 60°F WTI value.

A water temperature of 61°F (7DADM) was identified as the value for Chinook juvenile rearing for the San Joaquin River (CALFED 2009). A water temperature of 61°F (MWAT) was identified as the Upper Optimum Value for Chinook juvenile rearing for the Yuba Reintroduction Assessment for both fall- and spring-run Chinook (Bratovich *et al.* 2012). EPA Region 10 Guidance for Pacific Northwest State and Tribal Temperature Water Quality Standards identifies 61°F (7DADM; early year) for salmon juvenile rearing (EPA 2003b).

EPA Region 10 Guidance for Pacific Northwest State and Tribal Temperature Water Quality Standards identifies 64°F (7DADM; late year) for salmon juvenile rearing (EPA 2003b). Recommended summer maximum water temperature of 64.4°F for migration and non-core rearing (EPA 2003b). Water temperatures greater than 64°F are considered not ″properly functioning” by NMFS in Amendment 14 to the Pacific Coast Salmon Plan (NMFS 1995). Fatal infection rates caused by *C. columnaris* are high at temperatures greater than or equal to 64°F (EPA 2001). Optimal range for Chinook salmon survival and growth from 53°F to 64°F (USFWS 1995b). Survival of Central Valley juvenile Chinook salmon declines at temperatures greater than 64.4°F (Myrick and Cech 2001).

The index value of ~~65~~66°F was identified because it represents ~~an intermediate value between~~the upper end of the range of 64°F ~~and~~ to 66.2°F, at which both adverse and beneficial effects to juvenile salmonids have been reported to occur. For example, at temperatures approaching and beyond 65°F, sub-lethal effects associated with increased incidence of disease reportedly become severe for juvenile Chinook salmon (EPA 2003a; Johnson and Brice 1953; Ordal and Pacha 1963; Rich 1987a). Conversely, numerous studies report that temperatures between 64.0°F and 66.2°F provide conditions ranging from suitable to optimal for juvenile Chinook salmon growth (Brett *et al.* 1982; Cech and Myrick 1999; Clarke and Shelbourn 1985; EPA 2003a; Myrick and Cech 2001; NMFS 2002; USFWS 1995b). Maximum growth of juvenile fall-run Chinook salmon has been reported to occur in the American River at water temperatures between 56-59°F (Rich 1987b) and in Nimbus Hatchery spring-run Chinook salmon at 66°F (Cech and Myrick 1999). Bioenergetics modeling of growth based on consumption for 100 mm juvenile Chinook salmon in the Middle Fork American River watershed indicates that growth likely does not occur above about 65°F (Figure 5 of Bratovich *et al.* 2012). A water temperature of 65°F (MWAT) was identified as the Upper Tolerable Value for Chinook juvenile rearing for the Yuba Reintroduction Assessment for both fall- and spring-run Chinook salmon (Bratovich *et al.* 2012).

A WTI value of 68°F was identified because, at water temperatures above 68°F, sub-lethal effects become severe such as reductions in appetite and growth of juveniles (Marine 1997; Rich 1987a; Zedonis and Newcomb 1997). Significant reductions in growth rates may occur when chronic elevated temperatures exceed 68°F (Marine 1997; Marine and Cech 2004). Juvenile spring-run Chinook salmon were not found in areas having mean weekly water temperatures between 67.1°F and 71.6°F (Burck *et al.* 1980; Zedonis and Newcomb 1997). Results from a study on wild spring-run Chinook salmon in the John Day River system indicate that juvenile fish were not found in areas having mean weekly water temperatures between 67.1°F and 72.9°F (McCullough 1999; Zedonis and Newcomb 1997).

Chronic stress associated with water temperature can be expected when conditions reach the index value of 70°F. For example, growth becomes drastically reduced at temperatures close to 70.0°F and has been reported to be completely prohibited at 70.5°F (Brett *et al.* 1982; Marine 1997). No growth at all would occur for Nechako River juvenile Chinook salmon at 70.5°F

(Brett *et al.* 1982; Zedonis and Newcomb 1997). Juvenile spring-run Chinook salmon were not found in areas having mean weekly water temperatures between 67.1°F and 71.6°F (Burck *et al.* 1980; Zedonis and Newcomb 1997). Results from a study on wild spring-run Chinook salmon in the John Day River system indicate that juvenile fish were not found in areas having mean weekly water temperatures between 67.1°F and 72.9°F (McCullough 1999; Zedonis and Newcomb 1997). Increased incidence of disease, hyperactivity, reduced appetite, and reduced growth rates occur at 69.8 ± 1.8°F (Rich 1987b). In a laboratory study, juvenile fall-run Chinook salmon from the Sacramento River reared in water temperatures between 70°F and 75°F experienced significantly decreased growth rates and increased predation vulnerability compared with juveniles reared at temperatures below 68~~between 55°F and 61~~°F (Marine 1997; Marine and Cech 2004).

A WTI value of 73.4°F was identified because, in a laboratory study of juvenile fall-run Chinook salmon from the Mokelumne River Hatchery, in testing across a range of environmentally relevant acute temperature changes (from 53.6°F to 78.8°F), routine metabolic rate (RMR) and maximal metabolic rate (MMR) increased with acute warming, but aerobic capacity was unaffected by test temperatures up to 73.4°F in both acclimation groups of 59°F and 62.2°F (Poletto et al. 2017).

75°F was identified as a WTI value because high levels of direct mortality to juvenile Chinook salmon reportedly result at this water temperature (Cech and Myrick 1999; Hanson 1991; Myrick and Cech 2001; Rich 1987b). Other studies have suggested higher upper lethal water temperature levels (Brett 1952; Orsi 1971), but 75°F was identified because it was derived from experiments using Central Valley Chinook salmon and it is a more rigorous index value representing a more protective upper lethal water temperature level. Furthermore, the lethal level determined in Rich (1987b) was derived using slow rates of water temperature change and, thus, is ecologically relevant. The juvenile Chinook Salmon UILT based on numerous studies is 75-77°F (Sullivan *et al.* 2000; McCullough *et al.* 2001; Myrick and Cech 2001). Based upon information reviewed for Chinook salmon juvenile mortality (Brett 1952; Orsi 1971), the Chinook Salmon Population Model (TID/MID 2013) identified an initial UILT mortality threshold of 77°F for Chinook salmon juveniles as a daily average water temperature. Note that the model also identified this same value for fry mortality.

Table 7. Chinook Salmon Juvenile Rearing and Downstream Movement WTI Values and the Literature Supporting Each Value.

Index Value	**Supporting Literature**
60°F (15.6°C)	Optimum water temperature for Chinook salmon fry growth is between 55°F and 60°F (Seymour 1956). Water temperature range that produced optimum growth in juvenile Chinook salmon was between 54°F and 60°F (Rich 1987b). Water temperature criterion of less than or equal to 60°F for the protection of Sacramento River winter-run Chinook salmon from Keswick Dam to Bend Bridge (NMFS 1993b). Upper optimal water temperature limit of 61°F for Sacramento River fall-run Chinook salmon juvenile rearing (Marine 1997; Marine and Cech 2004). Upper water temperature limit of 60°F preferred for growth and development of spring-run Chinook salmon fry and fingerlings (NMFS 2000; NMFS 2002a). To protect salmon fry and juvenile Chinook salmon in the upper Sacramento River, daily average water temperatures should not exceed 60°F after September 30 (NMFS 1997b). A water temperature of 60°F appeared closest to the optimum for growth of fingerlings (Banks et al. 1971). Optimum growth of Nechako

Index Value	Supporting Literature
	River Chinook salmon juveniles would occur at 59°F at a feeding level that is 60% of that required to satiate them (Brett et al. 1982). In a laboratory study, juvenile fall-run Chinook salmon from the Sacramento River reared in water temperatures between 70°F and 75°F experienced significantly decreased growth rates, and increased predation vulnerability compared with juveniles reared between 55°F and 61°F (Marine 1997; Marine and Cech 2004).
61°F (16.1°C)	A water temperature of 61°F (7DADM) was identified as the value for Chinook juvenile rearing for the San Joaquin River (CALFED 2009). A water temperature of 61°F (MWAT) was identified as the Upper Optimum Value for Chinook juvenile rearing for the Yuba Reintroduction Assessment for both fall- and spring-run Chinook (Bratovich et al. 2012). EPA Region 10 Guidance for Pacific Northwest State and Tribal Temperature Water Quality Standards identifies 61°F (7DADM; early year) for salmon juvenile rearing (EPA 2003b).
64°F (17.8°C)	EPA Region 10 Guidance for Pacific Northwest State and Tribal Temperature Water Quality Standards identifies 64°F (7DADM; late year) for salmon juvenile rearing (EPA 2003b). Recommended summer maximum water temperature of 64.4°F for migration and non-core rearing (EPA 2003b). Water temperatures greater than 64°F are considered not ″properly functioning” by NMFS in Amendment 14 to the Pacific Coast Salmon Plan (NMFS 1995). Fatal infection rates caused by C. columnaris are high at temperatures greater than or equal to 64°F (EPA 2001). Optimal range for Chinook salmon survival and growth from 53°F to 64°F (USFWS 1995b). Survival of Central Valley juvenile Chinook salmon declines at temperatures greater than 64.4°F (Myrick and Cech 2001).
~~65~~66°F (18.~~3~~9°C)	Water temperatures between 45°F to 65°F are preferred for growth and development of fry and juvenile spring-run Chinook salmon in the Feather River (NMFS 2002a). Disease mortalities diminish at water temperatures below 65°F (Ordal and Pacha 1963). Fingerling Chinook salmon reared in water greater than 65°F contracted C. columnaris and exhibited high mortality (Johnson and Brice 1953). Water temperatures greater than 64.9°F identified as being stressful in the Columbia River Ecosystem (Independent Scientific Group 1996). Juvenile Chinook salmon have an optimum temperature for growth that appears to occur at about 66.2°F (Brett et al. 1982). Juvenile Chinook salmon reached a growth maximum at 66.2°F (Cech and Myrick 1999). Increased incidence of disease, reduced appetite, and reduced growth rates occur at 66.2 ± 1.4 °F (Rich ~~1987b~~1987a). Bioenergetics modeling of growth based on consumption for 100 mm juvenile Chinook salmon in the Middle Fork American River watershed indicates that growth likely does not occur above about 65°F (Figure 5 of Bratovich et al. 2012). A water temperature of 65°F (MWAT) was identified as the Upper Tolerable Value for Chinook juvenile rearing for the Yuba Reintroduction Assessment for both fall- and spring-run Chinook salmon (Bratovich et al. 2012).
68°F (20°C)	Sacramento River juvenile Chinook salmon reared at water temperatures greater than ~~or equal to~~ 68°F suffer reductions in appetite and growth (Marine 1997; Marine and Cech 2004). Significant reductions in growth rates may occur when chronic elevated temperatures exceed 68°F (Marine 1997; Marine and Cech 2004). Juvenile spring-run Chinook salmon were not found in areas having mean weekly water temperatures between 67.1°F and 71.6°F (Burck et al. 1980; Zedonis and Newcomb 1997). Results from a study on wild spring-run Chinook salmon in the John Day River system indicate that juvenile fish were not found in areas having mean weekly water temperatures between 67.1°F and 72.9°F (McCullough 1999; Zedonis and Newcomb 1997).
70°F (21.1°C)	No growth at all would occur for Nechako River juvenile Chinook salmon at 70.5°F (Brett et al. 1982; Zedonis and Newcomb 1997). Juvenile spring-run Chinook salmon were not found in areas having mean weekly water temperatures between 67.1°F and 71.6°F (Burck et al. 1980; Zedonis and Newcomb 1997). Results from a study on wild spring-run Chinook salmon in the John Day River system indicate that juvenile fish were not found in areas having mean weekly water temperatures between 67.1°F and 72.9°F (McCullough 1999; Zedonis and Newcomb 1997). Increased incidence of

Index Value	Supporting Literature
	disease, hyperactivity, reduced appetite, and reduced growth rates occur at 69.8 ± 1.8 °F (Rich 1987b). ~~In a laboratory study, juvenile fall-run Chinook salmon from the Sacramento River reared in water temperatures between 70°F and 75°F experienced significantly decreased growth rates and increased predation vulnerability compared with juveniles reared between 55°F and 61°F (Marine 1997; Marine and Cech 2004).~~
73°F (23°C)	In a laboratory study of juvenile fall-run Chinook salmon from the Mokelumne River Hatchery, RMR and MMR increased with acute warming, but aerobic capacity was unaffected by test temperatures up to 23°C in both acclimation groups of 59°F and 62.2°F (Poletto et al. 2017).
75°F (23.9°C)	For juvenile Chinook salmon in the lower American River fed maximum rations under laboratory conditions, 75.2°F was determined to be 100% lethal due to hyperactivity and disease (Rich 1987b; Zedonis and Newcomb 1997). Lethal temperature threshold for fall-run juvenile Chinook salmon between 74.3°F and 76.1°F (McCullough 1999). In a laboratory study, juvenile fall-run Chinook salmon from the Sacramento River reared in water temperatures between 70°F and 75°F experienced significantly decreased growth rates, and increased predation vulnerability compared with juveniles reared between 55°F and 61°F (Marine 1997; Marine and Cech 2004). The juvenile Chinook Salmon UILT based on numerous studies is 75-77°F (Sullivan et al. 2000; McCullough et al. 2001; Myrick and Cech 2001).
77°F (25°C)	The model associated with the Chinook Salmon Population Model Study, established an initial UILT mortality threshold of 77°F (daily average temperatures) for Chinook salmon fry and juveniles (Brett 1952 and Orsi 1971, as cited in TID/MID 2013).

Smolt Emigration

Juvenile Chinook salmon that exhibit extended rearing in a riverine environment are assumed to undergo the smoltification process and volitionally emigrate from the river as smolts. WTI values of 57°F, 59°F, 63°F, 68°F 72°F, and 77°F were identified for the Chinook salmon smolt emigration lifestage (Table 8).

A water temperature of 57°F (7DADM) was identified as the value for Chinook smolt migration for the San Joaquin River (CALFED 2009). EPA Region 10 Guidance for Pacific Northwest State and Tribal Temperature Water Quality Standards identifies 59°F (7DADM; late year) for salmon smolts (EPA 2003b).

A WTI value of 63°F was identified because water temperatures at or below this value allow for successful transformation to the smolt stage, and water temperatures above this value may result in impaired smoltification indices, inhibition of smolt development, and decreased survival and successful smoltification of juvenile Chinook salmon. Laboratory experiments suggest that water temperatures at or below 62.6°F provide conditions that allow for successful transformation to the smolt stage (Clarke and Shelbourn 1985; Marine 1997; Zedonis and Newcomb 1997). 62.6°F was rounded and used to support an index value of 63°F. A water temperature of 63°F (MWAT) was identified as the Upper Optimum Value for Chinook smolt migration for the Yuba Reintroduction Assessment for both fall- and spring-run Chinook (Bratovich *et al.* 2012).

Indirect evidence from tagging studies suggests that the survival of fall-run Chinook salmon smolts decreases with increasing water temperatures between 59°F and 75°F in the Sacramento-San Joaquin Delta (Kjelson and Brandes 1989). A WTI value of 68°F was identified because water temperatures above 68°F prohibit successful smoltification (Marine 1997; Rich 1987a; Zedonis and Newcomb 1997). Significant inhibition of gill sodium ATPase activity and associated reductions of hyposmoregulatory capacity, and significant reductions in growth rates, may occur when chronic elevated temperatures exceed 68°F (Marine 1997; Marine and Cech 2004). Water temperatures supporting smoltification of fall-run Chinook salmon range between 50°F to 68°F, the colder temperatures represent more optimal conditions (50°F to 62.6°F), and the warmer conditions (62.6°F to 68°F) represent marginal conditions (Zedonis and Newcomb 1997). A water temperature of 68°F (MWAT) was identified as the Upper Tolerable Value for Chinook smolt migration for the Yuba Reintroduction Assessment for spring-run Chinook salmon (Bratovich *et al*. 2012).

Support for an index value of 72°F is provided from a study conducted by (Baker *et al.* 1995) in which a statistical model is presented that treats survival of Chinook salmon smolts fitted with coded wire tags in the Sacramento River as a logistic function of water temperature. Using data obtained from mark-recapture surveys, the statistical model suggests a 95% confidence interval for the upper incipient lethal water temperature for Chinook salmon smolts as 71.5°F to 75.4°F. In a laboratory study, juvenile fall-run Chinook salmon from the Sacramento River reared in water temperatures between 70°F and 75°F experienced significantly decreased growth rates, impaired smoltification indices, and increased predation vulnerability compared with juveniles reared between 55°F and 61°F. Furthermore, fish reared between 63°F and 68°F did not have ~~significantly~~ different growth rates compared to those reared at 55°F and 61°F (Marine 1997; Marine and Cech 2004). Indirect evidence from tagging studies suggests that the survival of fall-run Chinook salmon smolts decreases with increasing water temperatures between 59°F and 75°F in the Sacramento-San Joaquin Delta (Kjelson and Brandes 1989).

Based upon information reviewed for Chinook salmon juvenile mortality (Brett 1952), the Chinook Salmon Population Model (TID/MID 2013) identified an initial mortality threshold of 77°F for Chinook salmon smolts as a daily average water temperature.

Table 8. Chinook Salmon Smolt Emigration WTI Values and the Literature Supporting Each Value.

Index Value	Supporting Literature
57°F (13.9°C)	A water temperature of 57°F (7DADM) was identified as the value for Chinook smolt migration for the San Joaquin River (CALFED 2009).
59°F (15°C)	EPA Region 10 Guidance for Pacific Northwest State and Tribal Temperature Water Quality Standards identifies 59°F (7DADM; late year) for salmon smolts (EPA 2003b).
63°F (17.2°C)	Acceleration and inhibition of Sacramento River Chinook salmon smolt development reportedly may occur at water temperatures above 63°F (Marine 1997; Marine and Cech 2004). Laboratory evidence suggest that survival and smoltification become compromised at water temperatures above 62.6°F (Zedonis and Newcomb 1997). Juvenile Chinook salmon growth was highest at 62.6°F (Clarke and Shelbourn 1985). A water temperature of 63°F (MWAT) was identified as the Upper Optimum Value for Chinook smolt migration for the Yuba Reintroduction Assessment for both fall- and spring-run Chinook (Bratovich *et al.* 2012).

Index Value	Supporting Literature
68°F (20°C)	Significant inhibition of gill sodium ATPase activity and associated reductions of hyposmoregulatory capacity, and significant reductions in growth rates, may occur when chronic elevated temperatures exceed 68°F (Marine 1997; Marine and Cech 2004). Water temperatures supporting smoltification of fall-run Chinook salmon range between 50°F to 68°F, the colder temperatures represent more optimal conditions (50°F to 62.6°F), and the warmer conditions (62.6°F to 68°F) represent marginal conditions (Zedonis and Newcomb 1997). A water temperature of 68°F (MWAT) was identified as the Upper Tolerable Value for Chinook smolt migration for the Yuba Reintroduction Assessment for both fall- and spring-run Chinook (Bratovich *et al.* 2012).
72°F (22.2°C)	In a laboratory study, juvenile fall-run Chinook salmon from the Sacramento River reared in water temperatures between 70°F and 75°F experienced significantly decreased growth rates, impaired smoltification indices, and increased predation vulnerability compared with juveniles reared between 55°F and 61°F or~~. Furthermore, fish reared~~ between 63°F and 68°F ~~did not have significantly different growth rates compared to those reared at 55°F and 61°F~~ (Marine 1997; Marine and Cech 2004). Indirect evidence from tagging studies suggests that the survival of fall-run Chinook salmon smolts decreases with increasing water temperatures between 59°F and 75°F in the Sacramento-San Joaquin Delta (Kjelson and Brandes 1989).
77°F (25°C)	The model associated with the Chinook Salmon Population Model Study, established an initial mortality threshold of 77°F (daily average temperatures) for Chinook salmon smolts (Brett 1952 as cited in TID/MID 2013).

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