The Effects of Temperature on Steelhead Trout, Coho Salmon, and Chinook Salmon Biology and Function by Life Stage

Implications for Klamath Basin TMDLs

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Introduction and Purpose

Temperature is one of the most important environmental influences on salmonid biology. Most aquatic organisms, including salmon and steelhead, are poikilotherms, meaning their temperature and metabolism is determined by the ambient temperature of water. Temperature therefore influences growth and feeding rates, metabolism, development of embryos and alevins, timing of life history events such as upstream migration, spawning, freshwater rearing, and seaward migration, and the availability of food. Temperature changes can also cause stress and lethality (Ligon et al. 1999). Temperatures at sub-lethal levels can effectively block migration, lead to reduced growth, stress fish, affect reproduction, inhibit smoltification, create disease problems, and alter competitive dominance (Elliott 1981, USEPA 1999). Further, the stressful impacts of water temperatures on salmonids are cumulative and positively correlated to the duration and severity of exposure. The longer the salmonid is exposed to thermal stress, the less chance it has for long-term survival (Ligon et al. 1999).

A literature review was performed to evaluate temperature needs for the various life stages of steelhead trout (*Oncorhynchus mykiss*), coho salmon (*Oncorhynchus kisutch*), and Chinook salmon (*Oncorhynchus tschawytscha)*. The purpose of this review was to identify temperature thresholds that are protective of salmonids by life stage, as a basis for evaluating Klamath River basin stream temperatures.

This review included USEPA temperature guidance, Oregons' and Washingtons' temperature standards reviews, reports that compiled and summarized existing scientific information, and laboratory and field studies. When possible, species-specific needs were summarized by the following life stages: migrating adults, spawning and incubation/emergence, and freshwater rearing and growth. Additionally, the effects of temperature on disease and lethality are also discussed. Some of the references reviewed covered salmonids as a general class of fish, while others were species specific. Information for fall run coho salmon, spring/summer, fall, and winter steelhead, and spring and fall run Chinook salmon are compiled by life stage in Table 1 through Table 12.

Temperature Metrics

In considering the effect of temperature on salmonids, it is useful to have a measure of chronic (i.e. sub-lethal) and acute (i.e. lethal) temperature exposures. A common measure of chronic exposure is the maximum weekly average temperature (MWAT). The MWAT is the maximum seasonal or yearly value of the mathematical mean of multiple, equally spaced, daily temperatures over a running seven-day consecutive period (Brungs and Jones 1977, p.10). In other words, it is the highest single value of the seven-day moving average temperature. A common measure of acute effects is the instantaneous maximum. A third metric, the maximum weekly maximum temperature (MWMT), can be used as a measure of both chronic and acute effects. The MWMT (also known as the seven-day average of the daily maximum temperatures (7-DADM)) is the maximum seasonal or yearly-value of the daily maximum temperatures over a running seven-day consecutive period. The MWMT is useful because it describes the maximum temperatures in a stream, but is not overly influenced by the maximum temperature of a single day.

Much of the information reported in the literature characterizes temperature needs with terms such as "preferred" or "optimum". Preferred stream temperatures are those that fish most frequently inhabit when allowed to freely select temperatures in a thermal gradient (USEPA 1999). An optimum range provides suitable temperatures for feeding activity, normal physiological response, and normal behavior (without symptoms of thermal stress) (USEPA 1999). Optimal temperatures have also been described as those temperatures at which growth rates, expressed as weight gain per unit of time, are maximal for the life stage (Armour 1991).

Salmonid stocks do not tend to vary much in their life history thermal needs, regardless of their geographic location. The USEPA (2001) in their *Summary of Technical Literature Examining the Physiological Effects of Temperature on Salmonids* makes the case that there is not enough significant genetic variation among stocks or among species of salmonids to warrant geographically specific water temperature standards.

> Climate conditions vary substantially among regions of the State and the entire Pacific Northwest. …Such [varying climatic] conditions could potentially have led to evolutionary adaptations, resulting in development of subspecies differences in thermal tolerance. …[However,] the literature on genetic variation in thermal effects indicates occasionally significant but very small differences among stocks and increasing differences among subspecies, species, and families of fishes. Many differences that had been attributed in the literature to stock differences are now considered to be statistical problems in analysis, fish behavioral responses under test conditions, or allowing insufficient time for fish to shift from field conditions to test conditions (Mathur & Silver 1980, Konecki et al. 1993, both as cited in USEPA 2001).

Additionally:

> There are many possible explanations why salmonids have not made a significant adaptation to high temperature in streams of the Pacific Northwest. Temperature tolerance is probably controlled by multiple genes, and consequently would be a core characteristic of the species not easily modified through evolutionary change without a radical shift in associated physiological systems. Also, the majority of the life cycle of salmon and steelhead is spent in the ocean rearing phase, where the smolt, subadults, and adults seek waters with temperatures less than 59°F (15°C) (Welch et al, 1995, as cited in USEPA 2001).

As a result, literature on the temperature needs of coho and Chinook salmon and steelhead trout stemming from data collected in streams outside Northern California are cited in this document and are considered relevant to characterizing the thermal needs of salmonids which use Northern California rivers and streams.

<u>Adult Migration and Holding</u>

All of the adult migration and holding temperature needs referenced in this section can be found in Table 1 through Table 3. Salmon and trout respond to temperatures during their upstream migration (Bjornn and Reiser 1991). Delays in migration have been observed in response to temperatures that were either too cold or too warm. Most salmonids have evolved with the temperature regime they historically used for migration and spawning, and deviations from the normal pattern can affect survival (Spence et al. 1996).

The USEPA document *EPA Region 10 Guidance for Pacific Northwest State and Tribal Water Quality Standards* (2003) recommends that the seven-day average of the daily maximum temperatures (7-DADM) should not exceed 18°C in waters where both adult salmonid migration and "non-core" juvenile rearing occur during the period of summer maximum temperatures. The document does not define what constitutes the "summer" period. Non-core juvenile rearing is defined as moderate to low density salmon and trout rearing usually occurring in the mid or lower part of the basin, as opposed to areas of high density rearing which are termed "core" rearing areas. This criterion is derived from analysis and synthesis of past laboratory and field research. The USEPA believes that this temperature recommendation will protect against lethal conditions, prevent migration blockage, provide optimal or near optimal juvenile growth conditions, and prevent high disease risk by minimizing the exposure time to temperatures which can lead to elevated disease rates.

A 7-DADM temperature of 20°C is recommended by the USEPA (2003) for waterbodies that are used almost exclusively for migration during the period of summer maximum temperatures.

> "EPA believes that a 20°C criterion would protect migrating juveniles and adults from lethal temperatures and would prevent migration blockage conditions. However, EPA is concerned that rivers with significant hydrologic alterations (e.g., rivers with dams and reservoirs, water withdrawals, and /or significant river channelization) may experience a

> loss of temperature diversity in the river, such that maximum temperatures occur for an extended period of time and there is little cold water refugia available for fish to escape maximum temperatures. In this case, even if the river meets a 20°C criterion for maximum temperatures, the duration of exposure to 20°C temperatures may cause adverse effects in the form of increased disease and decreased swimming performance in adults, and increased disease, impaired smoltification, reduced growth, and increased predation for late emigrating juveniles…."

Therefore, the USEPA recommends a narrative provision to protect and, if possible, restore the natural thermal regime accompany the 7-DADM 20°C criterion for rivers with significant hydrologic alterations.

In an exhaustive study of both laboratory and field studies of temperature effects on salmonids and related species, USEPA (1999, 2001) concluded that temperatures of approximately 22-24°C limit salmonid distribution, i.e., they totally eliminate salmonids from a location. USEPA (1999) also notes that changes in competitive interactions between fish species can lead to a transition in dominance from salmonids to other species at temperatures 2-4°C lower than the range of total elimination.

Steelhead Trout Migration

In a review of numerous studies, WDOE (2002) concluded that daily average temperatures of 21-24°C are associated with avoidance behavior and migration blockage in steelhead trout. WDOE suggests that the MWMT should not exceed 17-18°C, and daily maximum temperatures should not exceed 21-22°C to be fully protective of adult steelhead migration.

Table 1: Effects of Temperature in Considering Adult Steelhead and Migration

<table>
<tr><th>C</th><th colspan="3">Migration</th></tr>
<tr><td>24</td><td rowspan="4">21-24 Average daily temperature associated with avoidance and migration blockage (2)</td><td colspan="2" rowspan="2">22-24 Temperature range which eliminates salmonids from an area (3,4)</td></tr>
<tr><td>23</td></tr>
<tr><td>22</td><td rowspan="2">21-22 Daily maximum temperature should not exceed this to be fully protective (2)</td><td rowspan="5">18-22 Temperature range at which transition in dominance from salmonids to other species occurs (4)</td></tr>
<tr><td>21</td></tr>
<tr><td>20</td><td colspan="2">20 MWMT should not exceed this in waterbodies used almost exclusively for migration. Should be used in conjunction with a narrative provision about protecting/restoring the natural thermal regime for rivers with significant hydrologic alterations (1)</td></tr>
<tr><td>19</td><td colspan="2"></td></tr>
<tr><td>18</td><td rowspan="2">17-18 MWMT should not exceed this to be fully protective (2)</td><td>18 MWMT should not exceed this where migration and non-core rearing occur (1)</td></tr>
<tr><td>17</td><td colspan="2"></td></tr>
</table>

References

1 USEPA 2003 (reviewed many literature sources to make assessments of temperature needs)
2 WDOE 2002 (reviewed many literature sources to make assessments of temperature needs)
3 USEPA 2001 (reviewed many literature sources to make assessments of temperature needs)
4 USEPA 1999 (reviewed many literature sources to make assessments of temperature needs)

Chinook Salmon Migration and Holding

USEPA (2001) cited various literature sources that identified thermal blockages to Chinook salmon migration at temperatures ranging from 19-23.9°C, with the majority of references citing migration barriers at temperatures around 21°C.

Table 2: Effects of Temperature in Considering Adult Chinook and Migration and Holding

°C	Migration			
24		22-24 Temperature range which eliminates salmonids from an area (3,5)	19-23.9 Range of temperatures causing thermal blockage to migration (3)	
23	23 Klamath Basin fall Chinook begin migration upstream at temperatures as high as 23C if temperatures are rapidly falling (6)			
22	22 Klamath Basin fall Chinook will not migrate upstream when mean daily temperatures are 22C or greater (6)			18-22 Temperature range at which transition in dominance from salmonids to other species occurs (5)
21	21-22 Daily maximum temperature should not exceed this range to be protective of migration (2)	21 Most references cite as thermal block to migration (3) 21 Klamath Basin fall Chinook will not migrate upstream if temperatures are 21C or above and rising (6)		
20	20 MWMT should not exceed this in waterbodies used almost exclusively for migration. Should be used in conjunction with a narrative provision about protecting/restoring the natural thermal regime for rivers with significant hydrologic alterations (1)			
19		10.6-19.6 Temperature range where adult fall Chinook migrate (4)		
18			18 MWMT should not exceed this where migration and non-core rearing occur (1)	
17	16-17 MWMT should be below this where Chinook are holding (2)			
16				
15				
14	7.2-14.5 Preferred temperatures for Chinook (4)		13-14 Average daily temperature should be below this where spring Chinook are holding (2)	
13				
12			3.3-13.3 Temperature range where adult spring Chinook migrate (4)	
11				
10				
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5				
4				
3				

References

1 USEPA 2003 (reviewed many literature sources to make assessments of temperature needs)
2 WDOE 2002 (reviewed many literature sources to make assessments of temperature needs)
3 USEPA 2001 (reviewed many literature sources to make assessments of temperature needs)
4 Bell 1986 (reviewed many literature sources to make assessments of temperature needs)
5 USEPA 1999 (reviewed many literature sources to make assessments of temperature needs)
6 Strange (personal communication 2005)

A radio tracking study on spring Chinook revealed that when maximum temperatures of 21.1°C were reached, a thermal barrier to migration was established (Bumgarner et al. 1997, as cited by USEPA 1999). Bell (1986) reviewed various studies and notes spring Chinook migrate at water temperatures ranging from 3.3-13.3°C, while fall Chinook migrate at temperatures of 10.6-19.6°C. Preferred temperatures for Chinook range from 7.2-14.5°C (Bell 1986). Based on a technical literature review, WDOE (2002) concluded that daily maximum temperatures should not exceed 21-22°C during Chinook migration.

Utilizing radio telemetry to track the movements and monitor the internal body temperatures of adult fall Chinook salmon during their upriver spawning migration in the Klamath basin, Strange (personal communication 2005) found that fall Chinook will not migrate upstream when mean daily temperatures are ≥22°C. Strange (personal communication 2005) also noted that adult fall Chinook in the Klamath basin will not migrate upstream if temperatures are 21°C or above and rising, but will migrate at temperatures as high as 23°C if temperatures are rapidly falling.

Spring Chinook begin entering freshwater streams during a relatively cool-water season but must hold throughout the warm summer period, awaiting cooler spawning temperatures (ODEQ 1995). The cumulative effects of management practices such as elevated water temperatures, reduced cover from large woody debris, and reduced resting pool area due to pool filling increase the susceptibility of holding adult fish to mortality from thermal effects (ODEQ 1995). WDOE (2002) states that where spring Chinook are holding over for the summer prior to spawning the average daily water temperature should be below 13-14°C and the MWMT should be below 16-17°C.

Coho Salmon Migration
Migration for coho is delayed when water temperatures reach 21.1°C (Bell 1986). Bell (1986) also notes that the preferred water temperatures for coho range from 11.7-14.5°C. In California coho salmon typically migrate upstream when water temperatures range from 4-14°C (Briggs, 1953 and Shapovalov and Taft, 1954, as cited by Hassler, 1987). WDOE (2002) reviewed various studies and concluded that to be protective of adult coho migration, MWMTs should not exceed 16.5°C.

Reutter and Herdendorf (1974) conducted laboratory experiments and found that the preferred temperature, that is the temperature where fish will ultimately congregate given an infinite gradient of temperatures to choose from (Fry 1947, as cited by Reutter and Herdendorf 1974), for coho salmon was 11.4°C.

Table 3: Effects of Temperature in Considering Adult Coho and Migration

<table>
<tr><th>°C</th><th colspan="3">Migration</th></tr>
<tr><td>24</td><td colspan="2" rowspan="3">22-24 Temperature range which eliminates salmonids from an area (3,6)</td><td></td></tr>
<tr><td>23</td><td></td></tr>
<tr><td>22</td><td rowspan="5">18-22 Temperature range at which transition in dominance from salmonids to other species occurs (6)</td></tr>
<tr><td>21</td><td colspan="2">21.1 Migration is delayed when temperatures reach this value (4)</td></tr>
<tr><td>20</td><td colspan="2">20 MWMT should not exceed this in waterbodies used almost exclusively for migration. Should be used in conjunction with a narrative provision about protecting/restoring the natural thermal regime for rivers with significant hydrologic alterations (1)</td></tr>
<tr><td>19</td><td colspan="2"></td></tr>
<tr><td>18</td><td colspan="2">18 MWMT should not exceed this where migration and non-core rearing occur (1)</td></tr>
<tr><td>17</td><td colspan="3"></td></tr>
<tr><td>16</td><td colspan="3">16.5 MWMT should not exceed this value to be fully protective (2)</td></tr>
<tr><td>15</td><td colspan="3"></td></tr>
<tr><td>14</td><td rowspan="4">11.7-14.5 Preferred temperature range (4)</td><td colspan="2" rowspan="5">4-14 Temperature range at which migration typically occurs (5)</td></tr>
<tr><td>13</td></tr>
<tr><td>12</td></tr>
<tr><td rowspan="2">11</td></tr>
<tr><td>11.4 Preferred temperature (7)</td></tr>
</table>

References
1 USEPA 2003 (reviewed many literature sources to make assessments of temperature needs)
2 WDOE 2002 (reviewed many literature sources to make assessments of temperature needs)
3 USEPA 2001 (reviewed many literature sources to make assessments of temperature needs)
4 Bell 1986 (reviewed many literature sources to make assessments of temperature needs)
5 Briggs 1953, and Shapovalov and Taft (1954, as cited by Hassler 1987)
6 USEPA 1999 (reviewed many literature sources to make assessments of temperature needs)
7 Reutter and Herdendorf 1974 (laboratory study)

<u>Spawning, Incubation, and Emergence</u>

All of the spawning, incubation, and emergence temperature needs referenced in this section can be found in Table 4 through Table 7. Many sources have stated that temperature affects the time of migration in adults and thus the time of spawning, which influences the incubation temperature regime, which in turn influences survival rates, development rates, and growth of embryos and alevins (Murray and McPhail 1988). USEPA Region 10 (2003) recommends that the 7-DADM temperatures should not exceed 13°C for salmonid spawning, egg incubation, and fry emergence. Optimum temperatures for salmonid egg survival ranges from 6-10°C (USEPA 2001).

Steelhead Spawning, Incubation, and Emergence

In a discussion paper and literature summary evaluating temperature criteria for fish species including salmonids and trout, WDOE (2002) cites studies showing that steelhead were observed spawning in temperatures ranging from 3.9-21.1°C, and that the preferred temperatures for steelhead spawning range from 4.4-12.8°C. In a review of various studies, Bell (1986) concludes that steelhead spawning occurs at water temperatures ranging from 3.9-9.4°C.

Steelhead and rainbow trout eggs had the highest survival rates between 5-10°C according to Myrick and Cech (2001) and while they can tolerate temperatures as low as 2°C or as high as 15°C, mortality is increased at these temperatures. WDOE (2002) reviewed literature on the survival of steelhead and rainbow trout embryos and alevins at various temperatures and concluded that the average water temperature should not exceed 7-10°C throughout development, and the maximum daily average temperature should be below 11-12°C at the time of hatching.

Table 4: Effects of Temperature in Considering Steelhead Incubation and Emergence

<table>
<tr><th>°C</th><th colspan="3">Incubation and Emergence</th></tr>
<tr><td>15</td><td colspan="3">15 Steelhead and rainbow trout eggs can survive at temperatures as high as this but mortality is high compared to lower temperatures (3)</td></tr>
<tr><td>14</td><td colspan="3"></td></tr>
<tr><td>13</td><td colspan="3">13 MWMT should not exceed this value to be protective of spawning, egg incubation, and fry emergence (1)</td></tr>
<tr><td>12</td><td colspan="3" rowspan="2">11-12 Maximum daily average temperature should be below this range at the time of hatching (2)</td></tr>
<tr><td>11</td></tr>
<tr><td>10</td><td rowspan="6">5-10 Steelhead and rainbow trout eggs had the highest survival within this range (3)</td><td rowspan="5">6-10 Optimum temperature for salmonid eggs survival to hatching (4)</td><td rowspan="4">7-10 Average daily temperature should not exceed this range throughout embryo development (2)</td></tr>
<tr><td>9</td></tr>
<tr><td>8</td></tr>
<tr><td>7</td></tr>
<tr><td>6</td><td></td></tr>
<tr><td>5</td><td colspan="2"></td></tr>
<tr><td>4</td><td colspan="3"></td></tr>
<tr><td>3</td><td colspan="3"></td></tr>
<tr><td>2</td><td colspan="3">2 Steelhead and rainbow trout eggs can survive at temperatures as low as this but mortality is high compared to higher temperatures (3)</td></tr>
</table>

References

1 USEPA 2003 (reviewed many literature sources to make assessments of temperature needs)
2 WDOE 2002 (reviewed many literature sources to make assessments of temperature needs)
3 Myrick and Cech 2001 (reviewed many literature sources to make assessments of temperature needs)
4 USEPA 2001 (reviewed many literature sources to make assessments of temperature needs)

Chinook Spawning, Incubation, and Emergence

The Oregon Department of Environmental Quality (ODEQ 1995) reviewed numerous studies and recommended a temperature range of 5.6-12.8°C for spawning Chinook. A discussion paper and literature summary by WDOE (2002) found that the literature reviewed noted a wide range of temperatures associated with Chinook spawning (5.6-17.7°C), although the majority of these temperature observations cite daily maximum temperatures below 14.5°C. Reiser and Bjornn (1979, as cited by Armour et al. 1991) cites recommended spawning temperature ranges for spring, summer and fall Chinook salmon populations in the Pacific Northwest of 5.6-13.9°C. When ripe adult spring Chinook females experience temperatures above 13-15.5°C, pre-spawning adult mortality becomes pronounced (ODEQ 1995). Additionally, there is decreased survival of eggs to the eyed stage and alevin development is inhibited due to the exposure of the ripe female to warm temperatures, even if the stream temperatures during the egg and alevin development are appropriate (ODEQ 1995).

WDOE (2002) reviewed numerous references on the effects of various temperatures on Chinook incubation and development and used these studies to derive the temperatures that are protective of Chinook salmon from fertilization through fry development. References reviewed by WDOE (2002) include laboratory studies assessing Chinook embryo survival at various constant temperatures, studies attempting to mimic naturally fluctuating temperatures experienced by incubating eggs, studies which have made stepwise reductions in the incubation temperatures as incubation progressed to evaluate survival of eggs, and studies on the effects of transferring eggs to optimal constant incubation temperatures after they had been exposed to higher temperatures for various periods. As a result of this review, WDOE (2002) recommends that average daily temperatures remain below 11-12.8°C at the initiation of incubation, and that the seasonal average should not exceed 8-9°C in order to provide full protection from fertilization through initial fry development. The highest single day maximum temperature should not exceed 17.5-20°C to protect eggs and embryos from acute lethal conditions.

Table 5: Effects of Temperature in Considering Chinook Incubation and Emergence

<table>
<tr><th>°C</th><th colspan="6">Incubation and Emergence</th></tr>
<tr><td>20</td><td colspan="6" rowspan="4">17.5-20 The highest single day maximum temperature should not exceed this range to protect eggs and embryos from acute lethal conditions (2)</td></tr>
<tr><td>19</td></tr>
<tr><td>18</td></tr>
<tr><td>17</td></tr>
<tr><td>16</td><td colspan="5"></td><td rowspan="16">1.7-16.7 Eggs can survive these temps. but mortality is greatly increased at the extremes (3)</td></tr>
<tr><td>15</td><td colspan="5"></td></tr>
<tr><td>14</td><td rowspan="10">5-14.4 Recom-mended temp. range for incubation (4)</td><td rowspan="2">13.5-14.5 Daily maximum temperatures should not exceed this from fertilization through initial fry development (5)</td><td colspan="2">14 Moderate embryo survival (6)</td><td rowspan="13">2-14 Range of temps. for normal embryo develop-ment (6)</td></tr>
<tr><td>13</td><td colspan="2">13 MWMT should not exceed this value to be protective of spawning, egg incubation, and fry emergence (1)</td></tr>
<tr><td>12</td><td></td><td rowspan="9">4-12 Lowest levels of egg mortality at these temps. (3)</td><td rowspan="2">11-12.8 Average daily temperatures should be below this range at beginning of incubation (2)</td></tr>
<tr><td>11</td><td>11 High embryo survival (6)</td></tr>
<tr><td>10</td><td>9-10 Optimal temp. should be below this range (5)</td><td rowspan="5">6-10 Optimum temperature for salmonid eggs survival to hatching (5)</td></tr>
<tr><td>9</td><td>8-9 Seasonal ave. temps. should not exceed this range from fertilization through initial fry development (2)</td></tr>
<tr><td>8</td><td>8 High embryo survival (6)</td></tr>
<tr><td>7</td><td></td></tr>
<tr><td>6</td><td></td></tr>
<tr><td>5</td><td>5 High embryo survival (6)</td><td></td></tr>
<tr><td>4</td><td></td><td></td><td></td></tr>
<tr><td>3</td><td colspan="4"></td></tr>
<tr><td>2</td><td colspan="4">2 Poor embryo survival (6)</td></tr>
<tr><td>1</td><td colspan="5"></td></tr>
</table>

References

1 USEPA 2003 (reviewed many literature sources to make assessments of temperature needs)
2 WDOE 2002 (reviewed many literature sources to make assessments of temperature needs)
3 Myrick and Cech 2001 (reviewed many literature sources to make assessments of temperature needs)
4 Reiser and Bjornn (1979, as cited by Armour et al. 1991)
5 USEPA 2001 (reviewed many literature sources to make assessments of temperature needs)
6 Murray and McPhail 1988 (laboratory study)

USEPA (2001) reviewed multiple literature sources and concluded that optimal protection from fertilization through initial fry development requires that temperatures be maintained below 9-10°C, and that daily maximum temperatures should not exceed 13.5-14.5°C. Reiser and Bjornn (1979, as cited by Armour et al. 1991) list recommended temperature ranges of 5.0-14.4°C for spring, summer and fall Chinook salmon incubation in the Pacific Northwest. Myrick and Cech (2001) reviewed studies on the Sacramento-San Joaquin R. and concluded that the lowest levels of Chinook egg mortality occurred at temperatures between 4-12°C, and while eggs can survive at temperatures from 1.7-16.7°C, mortality is greatly increased at the temperature extremes.

Embryo survival was studied in a laboratory experiment conducted by Murray and McPhail (1988). They incubated five species of Pacific salmon, including Chinook, at five incubation temperatures (2, 5, 8, 11, 14°C). Chinook embryo survival was high at 5, 8, and 11°C, but survival was moderate at 14°C and poor at 2°C. As a result of their study, Murray and McPhail (1988) concluded that the range of temperatures for normal embryo development is > 2°C and <14°C.

Coho Spawning, Incubation, and Emergence

WDOE (2002) found that several studies and literature reviews state that spawning activity in coho may typically occur in the range of 4.4-13.3ºC. According to a review by Bell (1986), preferred spawning temperatures range from 4.5-9.4ºC. Brungs and Jones (1977) used existing data on the optimum and range of temperatures for coho spawning and embryo survival to create criteria using protocols from the National Academy of Sciences and National Academy of Engineering. The resultant criteria were that the MWAT should not exceed 10ºC and the daily maximum temperature should not exceed 13ºC to be protective of coho (Brungs and Jones 1977, p.16).

Table 6: Effects of Temperature in Considering Coho Incubation and Emergence

<table>
<tr><th>°C</th><th colspan="6">Incubation and Emergence</th></tr>
<tr><td>14</td><td colspan="6">14 Upper limit for normal embryo development (5)</td></tr>
<tr><td>13</td><td colspan="3">13 MWMT should not exceed this value to be protective of spawning, egg incubation, and fry emergence (1)</td><td colspan="2">13 Daily maximum temperature should not exceed this value to be protective (6)</td><td rowspan="11">4.5-13.3 Preferred emergence temperature range (3)</td></tr>
<tr><td>12</td><td colspan="2"></td><td colspan="2" rowspan="4">9-12 MWMT should not exceed this range to be fully protective (4)</td><td></td></tr>
<tr><td>11</td><td colspan="2"></td><td></td></tr>
<tr><td>10</td><td rowspan="5">6-10 Optimum temperature for salmonid eggs survival to hatching (4)</td><td rowspan="3">8-10 Ave. daily temp. during incubation should be at or below this to be supportive (2)</td><td>10 MWAT should not exceed this to be protective (6)</td></tr>
<tr><td>9</td><td></td></tr>
<tr><td>8</td><td colspan="2"></td><td></td></tr>
<tr><td>7</td><td colspan="4"></td></tr>
<tr><td>6</td><td colspan="4"></td></tr>
<tr><td>5</td><td></td><td colspan="4"></td></tr>
<tr><td>4</td><td></td><td colspan="4"></td></tr>
</table>

References

1 USEPA 2003 (reviewed many literature sources to make assessments of temperature needs)
2 WDOE 2002 (reviewed many literature sources to make assessments of temperature needs)
3 Bell 1986 (reviewed many literature sources to make assessments of temperature needs)
4 USEPA 2001 (reviewed many literature sources to make assessments of temperature needs)
5 Murray and McPhail 1988 (laboratory study)
6 Brungs and Jones 1977 (used existing data on the optimum range of temperatures for spawning and embryo survival to create criteria using protocols from the National Academy of Engineering (1973)).

In a discussion paper and literature summary WDOE (2002) reviewed studies that assessed the survival of embryos and alevin at various temperatures. Based on the findings of these studies WDOE (2002) has determined that the average daily temperature during the incubation period should be at or below 8-10ºC to fully support this coho salmon life stage. According to a review of various literature sources by Bell (1986), the preferred emergence temperatures for coho range from 4.5-13.3ºC. USEPA (2001) concluded that to fully support pre-emergent stages of coho development MWMTs should not exceed 9-12°C.

Murray and McPhail (1988) incubated five species of Pacific salmon, including coho, at five temperatures (2, 5, 8, 11, 14°C) to determine embryo survival at various temperatures. Coho embryos suffered increased mortality above 11°C although survival was still high. They concluded that the upper limit for normal coho embryo development is 14°C (Murray and McPhail 1988).

Table 7: Effects of Temperature in Considering Steelhead, Chinook, and Coho Spawning

<table>
<tr><th>°C</th><th colspan="3">Steelhead</th><th colspan="3">Chinook</th><th colspan="2">Coho</th><th>All Salmonids</th></tr>
<tr><td>21</td><td rowspan="19">3.9-21.2 Steelhead observed spawning in this temp. range (2)</td><td colspan="2"></td><td colspan="3"></td><td colspan="2"></td><td></td></tr>
<tr><td>20</td><td colspan="2"></td><td colspan="3"></td><td colspan="2"></td><td></td></tr>
<tr><td>19</td><td colspan="2"></td><td colspan="3"></td><td colspan="2"></td><td></td></tr>
<tr><td>18</td><td colspan="2"></td><td colspan="3"></td><td colspan="2"></td><td></td></tr>
<tr><td>17</td><td colspan="2"></td><td></td><td></td><td rowspan="13">5.6-17.7 Range of temps. associated with spawning from references reviewed (2)</td><td colspan="2"></td><td></td></tr>
<tr><td>16</td><td colspan="2"></td><td></td><td></td><td colspan="2"></td><td></td></tr>
<tr><td>15</td><td colspan="2"></td><td rowspan="3">13-15.5 Temp. range at which pre-spawning mortality becomes pronounced in ripe spring Chinook (4)</td><td></td><td colspan="2"></td><td></td></tr>
<tr><td>14</td><td colspan="2"></td><td>14.5 Majority of refs. cite daily max temps. associated with spawning below this level (2)</td><td colspan="2"></td><td></td></tr>
<tr><td>13</td><td></td><td></td><td rowspan="9">5.6-13.9 Recommended temperature range for spawning (5)</td><td>13 Daily maximum temp. not to exceed this value to be protective (6)</td><td rowspan="10">4.4-13.3 Typical temps. during which spawning occurs (2)</td><td>13 MWMT not exceed this value during spawning, egg incubation, and fry emergence (1)</td></tr>
<tr><td>12</td><td></td><td rowspan="9">4.4-12.8 Preferred temp. range for spawning (2)</td><td rowspan="8">5.6-12.8 Recom-mended temperature range for spawning (4)</td><td></td><td></td></tr>
<tr><td>11</td><td></td><td></td><td></td></tr>
<tr><td>10</td><td></td><td>10 MWAT not exceed this value to be protective (6)</td><td></td></tr>
<tr><td>9</td><td rowspan="7">3.9-9.4 Temp. range where spawning occurs (3)</td><td rowspan="6">4.5-9.4 Preferred spawning temperature range (3)</td><td></td></tr>
<tr><td>8</td><td></td></tr>
<tr><td>7</td><td></td></tr>
<tr><td>6</td><td></td></tr>
<tr><td>5</td><td></td></tr>
<tr><td>4</td><td colspan="3"></td><td></td></tr>
<tr><td>3</td><td></td><td colspan="3"></td><td colspan="2"></td><td></td></tr>
</table>

References

1 USEPA 2003 (reviewed many literature sources to make assessments of temperature needs)
2 WDOE 2002 (reviewed many literature sources to make assessments of temperature needs)
3 Bell 1986 (reviewed many literature sources to make assessments of temperature needs)
4 ODEQ 1995 (reviewed many literature sources to make assessments of temperature needs)
5 Reiser and Bjornn (1979, as cited by Armour et al. 1991)
6 Brungs and Jones 1977 (used existing data on the optimum range of temperatures for spawning and embryo survival to create criteria using protocols from the National Academy of Engineering (1973))

Freshwater Rearing and Growth

All of the freshwater rearing and growth temperature needs referenced in this section can be found in Table 8 through Table 10. Temperature affects metabolism, behavior, and survival of both juvenile fish as well as other aquatic organisms that may be food sources. In streams of the Northern California Coast, including the Klamath River, young Chinook, coho and steelhead may rear in freshwater from one to four years before migrating to the ocean.

In an exhaustive study of both laboratory and field studies of temperature effects on salmonids and related species, USEPA (1999) concluded that temperatures of approximately 22-24°C limit salmonid distribution, i.e., they totally eliminate salmonids from a location. USEPA (1999) also notes that changes in competitive interactions between fish species can lead to a transition in dominance from salmonids to other species at temperatures 2-4°C lower than the range of total elimination.

To protect salmon and trout during summer juvenile rearing the USEPA (2003) for Region 10 provided a single guidance metric designating 16°C as the 7-DADM temperature that should not be exceeded in areas designated as "core" rearing locations. Core rearing areas are defined as areas with moderate to high densities of summertime salmonid juvenile rearing generally found in the mid- to upper portions of river basins. This criterion will protect juvenile salmonids from lethal temperatures, provide optimal to upper optimal conditions for juvenile growth depending on the time of year, avoid temperatures where salmonids are at a competitive disadvantage with other fish species, protect against increased disease rates caused by elevated temperatures, and provide temperatures which salmonids prefer according to scientific studies.

Steelhead Freshwater Rearing and Growth

Nielsen et al. (1994) studied thermally stratified pools and their use by juvenile steelhead in three California North Coast rivers including the Middle Fork Eel River, Redwood Creek at Redwood National Park, and Rancheria Creek, located in the Navarro River watershed. In detailed observations of juvenile steelhead behavior in and near thermally stratified pools in Rancheria Creek, Nielsen et al. (1994) noted behavioral changes including decreased foraging and increased aggressive behavior as pool temperature reached approximately 22°C. As pool temperature increased above 22°C, juveniles left the observation pools and moved into stratified pools where temperatures were lower.

Wurtsbaugh and Davis (1977, as cited by USEPA 2001) found that steelhead trout growth could be enhanced by temperature increases up to 16.5°C. Using a risk assessment approach which took into account "realistic food estimates", Sullivan et al. (2000) report temperatures of 13-17.0°C (MWAT), 14.5-21°C (MWMT), and 15.5-21°C (annual maximum) will ensure no more than a 10% reduction from maximum growth for steelhead. Reduction from maximum growth will be ≤20% for temperatures ranging from 10-19.0°C (MWAT), 10-24°C (MWMT), and 10.5-26°C (annual maximum).

Table 8: Effects of Temperature in Considering Juvenile Steelhead Rearing and Growth

°C	Rearing and Growth					
26						21-26 Annual maximum temp. which will ensure no more than 20% reduction from max. growth (4)
25						
24	22-24 Temperature range which totally eliminates salmonids from area, limiting their distribution (6)				21-24 MWMT which will ensure no more than 20% reduction from max growth (4)	
23		>22 Juveniles left observation pools and moved to pools with lower temperatures (2)				
22		22 Decreased foraging, increased aggressive behavior (2)		18-22 Temperature range at which transition in dominance from salmonids to other species occurs (6)		
21					14.5-21 MWMT which will ensure no more than 10% reduction from maximum growth (4)	15.5-21 Annual maximum temperature which will ensure no more than 10% reduction from maximum growth (4)
20						
19		17-19 MWAT will ensure no more than 20% reduction from max. growth (4)	17.2-19 Growth may be maximized at temperatures as high as this under satiated feeding conditions, lab studies at constant temperature (5)			
18				15.5-18 Average daily temperatures at which maximum growth occurs under satiated feeding, lab studies at varying temps (5)		
17		13-17 MWAT range which will ensure no more than 10% reduction from maximum growth (4)				
16	16.5 Growth enhanced by temp. increases up to this temp. (3) 16.2 Mean temp. at which max. growth occurred during the summer, lab studies using natural feeding conditions and varying temps. (5)		16 MWMT should not exceed this value to be protective of core rearing locations (1)			
15	15.2 Mean temp. at which max. growth occurred during the fall, lab studies using natural feeding conditions and varying temps. (5)					10.5-15.5 Annual maximum temperature which will ensure no more than 20% reduction from maximum growth (4)
14					10-14.5 MWMT which will ensure no more than 20% reduction from maximum growth (4)	
13	13.3 Mean temp. at which max. growth occurred during the spring, lab studies using natural feeding conditions and varying temps. (5)	10-13 MWAT will ensure no more than 20% reduction from maximum growth (4)				
12						
11						
10						

References

1 USEPA 2003 (reviewed many literature sources to make assessments of temperature needs)
2 Nielsen et al. 1994. (field study)
3 Wurtsbaugh and Davis (1977, as cited by USEPA 2001)
4 Sullivan et al. 2000 (developed method for estimating effects of temperature and food consumption on gain/ loss of weight, using previously collected data)
5 WDOE 2002 (reviewed many literature sources to make assessments of temperature needs)
6 USEPA (1999)

A literature review was conducted by WDOE (2002) in which studies to determine the water temperature that would allow for maximum growth of steelhead trout were analyzed. These included laboratory studies conducted at constant and fluctuating temperatures. One of the studies was conducted using feeding rates comparable to those observed in natural creeks, although most of the laboratory studies were conducted under satiated feeding conditions. As a result of this review of laboratory studies conducted at constant temperatures, WDOE (2002) concludes that under satiated rations growth may be maximized at temperatures as high as 17.2-19°C. Results from laboratory studies using variable temperatures show maximum growth occurs at average daily temperatures between 15.5-18°C, and that under feeding rates similar to natural conditions at various times of the year maximum growth rates occurred at mean temperatures of 13.3°C (spring season), 15.2°C (fall season) and 16.2°C (summer season).

Chinook Freshwater Rearing and Growth

In a laboratory study, Brett (1952) demonstrated that juvenile Chinook salmon, acclimated to a temperature of 20°C, selectively aggregated in areas where the temperature was in the region of 12-13°C.

ODEQ (1995), reviewed numerous studies and concluded for juvenile spring Chinook salmon rearing, positive growth takes place at temperatures between 4.5-19°C, and that optimum rearing production is between 10.0-15.6°C. However, as the extremes of this temperature range are reached growth reaches zero. Above and below these thresholds growth becomes negative as feeding ceases and respiration rates increase and/or decrease rapidly.

After synthesizing data from several sources USEPA (2001), came up with the same recommended optimum temperature zone for all Chinook salmon as ODEQ (1995) of 10.0-15.6°C. While there is research suggesting that some Chinook stocks exhibit adequate rearing capabilities above 15.6°C, USEPA (2001) conclude that anything over this threshold significantly increases the risk of mortality from warm-water diseases.

In a laboratory study Marine and Cech (2004) studied the incremental effects of chronic exposure to three temperature regimes (13-16 °C, 17-20 °C, and 21-24 °C) on Chinook juveniles during rearing and smoltification. Their findings reflected that Chinook juveniles reared at the 17-20 ºC and 21-24 ºC temperature ranges experienced significantly decreased growth rates, impaired smoltification indices, and increased predation vulnerability compared with juveniles reared at 13-16 ºC.

In a field study Chinook grew faster in a stream where temperatures peaked at 16°C compared to a stream where temperatures peaked at 20°C (ODFW 1992, as cited by WDOE 2002). WDOE (2002) reviewed literature on Chinook growth including laboratory studies conducted at a constant temperature, laboratory studies conducted at fluctuating temperatures, and field studies to evaluate the water temperature that would be protective of Chinook and allow for maximum growth. Most of the laboratory studies were conducted under satiated feeding conditions, although one of the studies was conducted using feeding rates more comparable to those observed in natural creeks. As a result of this review of laboratory studies conducted at constant temperatures, WDOE (2002) concludes that maximum growth is expected to occur with exposure to constant temperatures from 15.6-19°C. However, increased growth at temperatures above 15.6°C was inconsistently greater, and under natural rations the temperatures at which maximum growth occurs may decline by as much as 4.2°C. Recommendations based on the review of two laboratory studies conducted at fluctuating temperatures are that "…average temperatures below 19°C are necessary to support maximum growth rates in Chinook salmon, and that the average temperature that produces maximum growth rates likely lies between 15-18°C (median 16.5°C)".

Table 9: Effects of Temperature in Considering Juvenile Chinook Rearing and Growth

<table>
<tr><th>°C</th><th colspan="5">Rearing and Growth</th></tr>
<tr><td>24</td><td colspan="2" rowspan="3">22-24 Temperature range which totally eliminates salmonids from area, limiting their distribution (7)</td><td></td><td colspan="2" rowspan="4">21-24 Decreased growth, impaired smoltification, increased predation compared to juveniles reared at 13-16 (6)</td></tr>
<tr><td>23</td><td></td></tr>
<tr><td>22</td><td></td></tr>
<tr><td>21</td><td colspan="2"></td><td rowspan="4">18-22 Temperature range at which transition in dominance from salmonids to other species occurs (7)</td></tr>
<tr><td>20</td><td colspan="2"></td><td rowspan="4">17-20 Decreased growth, impaired smoltification, increased predation compared to juveniles reared at 13-16 (6)</td><td></td></tr>
<tr><td>19</td><td>19 Temperatures above this do not support maximum growth, lab studies at varying temperatures (3)</td><td rowspan="5">15.6-19 Maximum growth expected according to lab studies conducted at constant temperature and satiated rations. Under natural feeding conditions maximum growth may occur at temperatures as much as 4.2C lower (3)</td><td rowspan="16">4.5-19 Temperature range at which positive growth takes place (5)</td></tr>
<tr><td>18</td><td rowspan="4">15-18 Average temperature where maximum growth occurs, lab studies conducted at varying temperatures (3)</td></tr>
<tr><td>17</td><td></td></tr>
<tr><td>16</td><td>16 Chinook grew faster in a stream where temperatures peaked at 16 than when they peaked at 19C (3)
16 MWMT should not exceed this value to be protective of core rearing locations (2)</td><td rowspan="4">13-16 Increased growth, unimpaired smoltification, lower predation compared to juveniles reared at 21-24, or 17-20 (6)</td></tr>
<tr><td>15</td><td rowspan="6">10-15.6 Optimal temperature range for rearing (5)</td></tr>
<tr><td>14</td><td rowspan="5">10-15.6 Temperature range for optimal growth. Anything over this threshold increases the risk of mortality from warm water disease (1)</td><td></td></tr>
<tr><td>13</td><td></td></tr>
<tr><td>12</td><td></td><td>12-13 Juvenile Chinook acclimated to 20 selectively aggregate to these water temperatures (4)</td></tr>
<tr><td>11</td><td></td><td></td></tr>
<tr><td>10</td><td></td><td></td></tr>
<tr><td>9</td><td colspan="4"></td></tr>
<tr><td>8</td><td colspan="4"></td></tr>
<tr><td>7</td><td colspan="4"></td></tr>
<tr><td>6</td><td colspan="4"></td></tr>
<tr><td>5</td><td colspan="4"></td></tr>
<tr><td>4</td><td colspan="4"></td></tr>
</table>

References

1 USEPA 2001 (reviewed many literature sources to make assessments of temperature needs)
2 USEPA 2003 (reviewed many literature sources to make assessments of temperature needs)
3 WDOE 2002 (reviewed many literature sources to make assessments of temperature needs)
4 Brett 1952 (laboratory study)
5 ODEQ 1995 (reviewed many literature sources to make assessments of temperature needs)
6 Marine and Cech 2004 (laboratory study)
7 USEPA (1999)

Coho Freshwater Rearing and Growth

In a study of juvenile coho presence and absence in the Mattole watershed, Welsh et al. (2001) used logistic regression to determine that an MWAT greater than 16.8°C or a MWMT greater than 18.1°C may preclude the presence of juvenile coho salmon in the stream. The criterion correctly determined the presence or absence of juvenile coho in 18 of 21 streams. Welsh et al. (2001) also reported that juvenile coho were found in all streams with an MWAT less than 14.5°C, or a MWMT less than 16.3°C.

Sullivan et al. (2000) reviewed sub-lethal and acute temperature thresholds from a wide range of studies, incorporating information from laboratory-based research, field observations, and risk assessment approaches. Using a risk assessment approach based on "realistic food estimates" Sullivan et al (2000) suggest that MWATs ranging from 12.5-14.5°C for coho will result in no more than a 10% reduction from maximum growth, and that a range for the MWAT of 9-18.5°C will reduce growth no more than 20% from maximum. Sullivan et al. (2000) also calculated temperature ranges for MWMT (13-16.5°C) and the annual maximum temperature (13-17.5°C) that will result in no more than a 10% reduction in maximum growth. They further calculated ranges for MWMT (9-22.5°C) and the annual maximum temperature (9.5-23°C) that will result in no more than a 20% growth loss.

In an attempt to determine the water temperature that will allow for maximum growth of coho salmon, WDOE (2002) reviewed literature on laboratory studies conducted at a constant temperature and fluctuating temperatures, and field studies. The two laboratory studies reviewed were conducted under satiated feeding conditions. Shelbourn (1980, as cited by WDOE 2002) found that maximum growth occurred at a constant temperature of 17°C, while Everson (1973, as cited by WDOE 2002) tested fish at different temperatures and determined that coho had the greatest growth at the temperature test regime from 12.1-20.8°C (median 16.5°C). While the various field studies reviewed did not provide an estimate of the temperature best for maximum growth they did allow for WDOE (2002) to conclude that weekly average temperatures of 14-15°C were more beneficial to growth than lower temperature regimes, and daily maximum temperatures of 21-26°C were detrimental to growth.

Brett (1952) acclimated five different species of salmon to various temperatures ranging from 5-24°C and found that coho salmon showed the greatest preference for temperatures between 12-14°C. It was also determined that coho showed a general avoidance of temperatures above 15°C even in fish who were acclimated to temperatures as high as 24°C.

Konecki et al. (1995a) raised two groups of juvenile coho salmon under identical regimes to test the hypothesis that the group from a stream with lower and less variable temperature would have a lower and less variable preferred temperature than the group from a stream with warmer and more variable temperatures. Results reflected that the two groups tended to differ in their preferred temperature range as predicted above, but the differences were slight. Konecki et al. (1995a) concluded that the temperature preference of juvenile coho salmon in their study was 10-12°C.

Table 10: Effects of Temperature in Considering Juvenile Coho Rearing and Growth

<table>
<tr><th>°C</th><th colspan="5">Rearing and Growth</th></tr>
<tr><td>26</td><td colspan="2" rowspan="6">21-26 Daily maximum temperatures in this range are detrimental to growth, according to field studies (3)</td><td colspan="3"></td></tr>
<tr><td>25</td><td colspan="3"></td></tr>
<tr><td>24</td><td colspan="2" rowspan="3">22-24 Temperature range which totally eliminates salmonids from an area, limiting their distribution (9)</td><td></td></tr>
<tr><td>23</td><td rowspan="6">17.5-23 Annual maximum temperature will ensure no more than 20% reduction from maximum growth (2)</td></tr>
<tr><td>22</td></tr>
<tr><td>21</td><td rowspan="6">16.5-22.5 MWMT will ensure no more than 20% reduction from maximum growth (2)</td><td rowspan="4">18-22 Temperature range at which transition in dominance from salmonids to other species occurs (9)</td></tr>
<tr><td>20</td><td></td><td rowspan="9">12.1-20.8 Greatest growth occurs in this temperature range under satiated conditions, lab study (7)</td></tr>
<tr><td>19</td><td></td></tr>
<tr><td>18</td><td>18.1 MWMT above this may preclude the presence of juvenile coho in steams (5)</td></tr>
<tr><td>17</td><td rowspan="3">14.5-18.5 MWAT will ensure no more than 20% reduction from maximum growth (2)</td><td>17 Maximum growth at this constant temperature, at satiated rations in a lab study (6)</td><td rowspan="5">13.5 17.5 Annual maximum temperature will ensure no more than 10% reduction from maximum growth (2)</td></tr>
<tr><td>16</td><td>16.8 MWAT above this may preclude the presence of juvenile coho in streams (5)
16.3 Juveniles found in all streams with MWMT less than this value (5)
16 MWMT not exceed this value to be protective of core rearing locations (1)</td></tr>
<tr><td>15</td><td rowspan="3">13-16.5 MWMT will ensure no more than 10% reduction from maximum growth (2)</td><td>>15 Juveniles show avoidance, even those acclimated to 24C (4)</td></tr>
<tr><td>14</td><td>14.5 Juvenile coho found in all streams with MWAT less than this value (5)</td><td>14-15 Weekly average temperatures in this range are more beneficial than lower temperatures (3)</td></tr>
<tr><td>13</td><td rowspan="2">12.5-14.5 MWAT will ensure no more than 10% reduction from maximum growth (2)</td><td rowspan="2">12-14 Preferred temperature range (4)</td></tr>
<tr><td>12</td><td rowspan="4">9-13 MWMT will ensure no more than 20% reduction from maximum growth (2)</td><td rowspan="4">9.5-13.5 Annual maximum temperature will ensure no more than 20% reduction from max. growth (2)</td></tr>
<tr><td>11</td><td rowspan="3">9-12.5 MWAT will ensure no more than 20% reduction from maximum growth (2)</td><td></td><td rowspan="2">10-12 Preferred temperature range (8)</td></tr>
<tr><td>10</td><td></td></tr>
<tr><td>9</td><td></td><td></td></tr>
</table>

References

1 USEPA 2003 (reviewed many literature sources to make assessments of temperature needs)
2 Sullivan et al. 2000 (developed method for estimating effects of temperature and food consumption on gain/ loss of weight, using previously collected data)
3 WDOE 2002 (reviewed many literature sources to make assessments of temperature needs)
4 Brett 1952 (laboratory study)
5 Welsh et al. 2001 (study on coho presence and absence in the Mattole watershed, using logistic regression to determine temperature needs)
6 Shelbourn (1980, as cited by WDOE 2002) (laboratory study)
7 Everson (1973, as cited by WDOE 2002) (laboratory study)
8 Konecki et al. 1995a (laboratory study)
9 USEPA (1999)

Lethality

All of the lethal temperatures referenced in this section can be found in Table 11. WDOE (2002) reviewed literature on three types of studies (constant exposure temperature studies, fluctuating temperature lethality studies, and field studies) and used this information to calculate the MWMT that, if exceeded, may result in adult and juvenile salmonid mortality. The resultant MWMTs for these various types of studies are as follows: constant exposure studies 22.64°C, fluctuating lethality studies 23.05°C , and field studies 22.18°C.

Table 11: Effects of Temperature in Considering Lethality and Salmonids

°C	Steelhead	Chinook	Coho	All Salmonids
28			28 LT50[1] for age 0-fish acclimated to a 10-13C cycle (6)	
27				
26			26 LT50[1] for presmolts (age 2-fish) acclimated to a 10-13C cycle (6)	
25		25.1 Upper lethal temp. at which 50% of the population would die after infinite exposure, juvenile Chinook acclimated to temperatures from 5-24C (4)	25.6 Upper lethal threshold (3)	
		25 Upper lethal threshold (3)	25 Upper lethal temp. at which 50% of the population would die after infinite exposure, juvenile coho acclimated to temps. from 5-24C (4)	
		25 Chronic (exposure >7 days) upper lethal limit for juvenile Chinook (5).		
24		24-24.5 Survival becomes less than 100% for juvenile Chinook acclimated to temperatures from 5-24C (4)		
23	23.9 Upper lethal threshold for steelhead (3)			23.05 do not exceed this value to prevent adult and juvenile mortality, data from fluctuating temp. studies (1)
22				22.64 do not exceed this value to prevent adult and juvenile mortality, data from constant exposure studies (1)
				22.18 do not exceed this value to prevent adult and juvenile mortality, data from field studies (1)
21	21.1 Temperature lethal to adults (7)			
	21 Lethal threshold for steelhead acclimated to 19C (2)			

[1] Maximum temperature in the cycle at which 50% mortality occurred

References

1 WDOE 2002 (reviewed many literature sources to make assessments of temperature needs)
2 Coutant (1970, as cited by USEPA 1999)
3 Bell 1986 (reviewed many literature sources to make assessments of temperature needs)
4 Brett 1952 (laboratory study)
5 Myrick and Cech 2001 (reviewed many literature sources to make assessments of temperature needs)
6 Thomas et al. 1986 (laboratory study)
7 CDFG 2001 (reviewed literature sources to make assessments)

Steelhead Lethality

Coutant (1970, as cited by USEPA 1999) found that Columbia River steelhead, which were acclimated to a river temperature of 19°C, had a lethal threshold of 21°C. Bell (1986) reviewed various studies and states that the lethal threshold for steelhead is 23.9°C. According to the California Department of Fish and Game (2001, p.419), temperatures of 21.1°C have been reported as being lethal to adults.

Chinook Lethality

In a laboratory study Brett (1952) acclimated five different species of juvenile salmon to various temperatures ranging from 5-24°C. At temperatures of 24°C and below there was 100% survival of fish during the one-week duration of the experiment. Brett (1952) concluded that the lethal temperature (temperature where survival becomes less than 100%) was between 24.0 and 24.5°C, and the ultimate upper lethal temperature was 25.1°C (temperature at which 50% of the population is dead after infinite exposure). A review of numerous studies led Bell (1986) to conclude that the upper lethal temperature for Chinook is 25°C. Myrick and Cech (2001) reviewed literature on studies from the Central Valley and found data to suggest that the chronic (exposure >7 days) upper lethal limit for juvenile Chinook is approximately 25°C.

Coho Lethality

In a review of various literature sources, Bell (1986) found that the upper lethal temperature for coho is 25.6°C. Brett (1952) concluded that the ultimate upper lethal temperature of juvenile coho salmon was 25.0°C (temperature at which 50% of the population is dead after infinite exposure). Thomas et al. (1986) conducted a study to determine the mortality of coho subjected to fluctuating temperatures. It was determined that the LT50 (the temperature at which 50% of the population will die) for fish acclimated to a 10-13°C cycle was 26°C for presmolts (age-2 fish), and 28°C for age-0 fish.

<u>Disease</u>

All of the effects of temperatures on disease risk in salmonids referenced in this section can be found in Table 12. WDOE (2002) reviewed studies of disease outbreak in salmonids and estimates that an MWMT of 14.38°C will virtually prevent warm water disease effects. To avoid serious rates of infection and mortality the MWMT should not exceed 17.38°C, and that severe infections and catastrophic outbreaks become a serious concern when the MWMTs exceed 20.88°C.

In a summary of temperature considerations, USEPA (2003) states that disease risks for juvenile rearing and adult migration are minimized at temperatures from 12-13°C, elevated from 14-17°C, and high at temperatures from 18-20°C.

Acknowledging that there are many diseases that affect salmonids, the following discussion will focus on three which are common in the Klamath Basin: Ichthyophthiriasis (Ich), Ceratomyxosis, and Columnaris. *Ichthyophthirius multifiliis* is a protozoan parasite that causes the disease known as Ichthyophthiriasis (Ich). The disease ceratomyxosis is caused by a parasite, *Ceratomyxa shasta* (*C. shasta*). Columnaris disease is a bacterial infection caused by *Flavobacterium columnare* (synomyms*: Bacillus columnaris, Chondrococcus columnaris, Cytophaga columnaris, Flexibacter columnaris*).

Ichthyophthiriasis (Ich)

Nigrelli et al. (1976, as cited by Dickerson et al. 1995) proposed that there are physiological races of Ich, which are related to the temperature tolerance of the host fishes. Thus, there are races of Ich that infect cold-water (7.2-10.6°C) fishes such as salmon, and others that infect warm-water (12.8-16.1°C) tropical fishes. Bell (1986) discusses Ich and states that at water temperatures above 15.6°C, this disease often breaks out in salmon fingerlings, especially Chinook. CDWR (1988) states that serious outbreaks of Ich occur at temperatures from 18.3-21.2°C.

Numerous studies and reviews have been conducted on the optimal temperature for Ich. Piper et al. (1982, p.316.) wrote that optimal temperatures range from 21-23.9°C. CDWR (1988) stated the optimum temperature for Ich is in the range of 25 to 26.7°C, while Bell (1986) states optimum temperatures are noted from 21.2-26.7°C.

Temperature is an important factor in the persistence of Ich infections in salmonids. The growth period varies from 1 week at 20 °C to 20 days at 7 °C (Nigrelli et al. 1976, as cited by Dickerson et al. 1995). Piper et al. (1982, p.316) state that at optimal temperatures of 21-23.9°C, the life cycle may take as few as 3-4 days. The cycle requires 2 weeks at 15.5°C, and more than 5 weeks at 10°C (Piper et al. 1982, p.316). Durborow et al. (1998) note that to complete its lifecycle, Ich requires from less than 4 days at temperatures higher than 24°C, to more than 5 weeks at temperatures lower than 7°C. Although studies report varying lengths of time for Ich to complete its lifecycle at similar temperatures, it is clear that the speed at which Ich develops increases as temperatures increase.

Ceratomyxosis

In reviewing the literature on Ceratomyxosis it is clear that the intensity of the disease increases, and the incubation period decreases, as water temperatures increase (CDWR 1988, Letritz and Lewis, Udey et al. 1975). At water temperatures greater than 10°C steelhead will show evidence of Ceratomyxosis in approximately 38 days (Leitritz and Lewis 1976, p.154). In a study of juvenile coho salmon by Udey et al. (1975), time from exposure to death was more than 90% temperature dependent, and increased from 12.5 days at 23.3°C to 146 days at 9.4°C indicating the accelerating effect of higher temperatures on the progress of the disease. The time from exposure to death of juvenile rainbow trout was nearly 97% temperature dependent, increasing from 14 days at 23.3°C to 155 days at 6.7°C (Udey et al. 1975).

C. shasta appears to become infective at temperatures around 10-11°C (CDWR 1988). According to Leitritz and Lewis (1976, p.154), steelhead from the Klamath River are quite susceptible to *C. shasta* infections and suffer severe losses when exposed.

Udey et al. (1975) conducted a study to determine the relation of water temperature to Ceratomyxosis in juvenile rainbow trout and coho salmon. Rainbow trout from the Roaring River Hatchery, and coho from Fall Creek Salmon Hatchery (both in Oregon) were used in this experiment. Groups of 25 fish exposed to *C. shasta* were transferred to 12.2°C water, and then were tempered to one of eight experimental temperatures from 3.9 to 23.3°C (2.8°C increments).

In the juvenile coho salmon experiment Udey et al. (1975) found that percent mortality increased progressively from 2% at 9.4°C to 22% at 15.0°C and 84% at 20.5°C. No deaths occurred in coho salmon maintained at 3.9 and 6.7°C, indicating that ceratomyxosis in coho can be suppressed by water temperatures of 6.7°C or below (Udey et al. 1975).

Tests conducted by Udey et al. (1975) on rainbow trout juveniles indicate that once infection is initiated, juvenile rainbow trout have little or no ability to overcome *C. shasta* infections at water temperatures between 6.7 and 23.3°C. Fatal infections varied from 75-86% at temperatures ranging from 6.7 to 15.0°C (Udey et al. 1975). Mortality in trout held at 20.5 and 23.3°C were lower (72% and 52% respectively) due to losses from *Flexibacter columnaris,* which occurred well before the onset of deaths caused by *C. shasta,* in spite of efforts to control it with terramycin (Udey et al. 1975). The results from Udey et al. (1975) also reflected no deaths occurred in juvenile trout held at 3.9°C.

Table 12: Effects of Temperature in Considering Disease and Salmonids

°C	Ich		Ceratomyxosis		Columnaris	Disease (general)	
26		21-26.7 Optimum temp. range for Ich, compilation of temps. from three references (3,4,5)					
25							
24	>24 Lifecycle takes less than 4 days (5)						
23	21-23.9 Life cycle takes as few as 3-4 days (5)		23.3 Juvenile coho salmon and rainbow trout time from exposure to death is 12.5 and 14 days respectively (9)	6.7-23.3 Juvenile rainbow trout have little or no ability to overcome infection, and mortality varied from 75-86% (9)	23.3 Juvenile spring Chinook mortality was 92%, and time from exposure to death was 2.3 days (13)		
22					22.2 Mortality is 100% in juvenile sockeye exposed to *C. columnaris* (10)		
21					>21.1 Temperatures at this level are associated with a 28-74% infection rate in Chinook (11)		
20	18.3-21.2 Serious outbreaks of Ich occur (4)	20 Lifecycle takes 1 week (6)	20.5 Mortality is 84% in juvenile coho exposed to *C. shasta* (9).		20.5 Mortality in juvenile steelhead and coho from Columnaris was 100%, and 70% in juvenile spring Chinook (13) 20.5 In juvenile steelhead and coho time from exposure to death was 1.6-1.7 days (13) 20 Average water temperature at which low virulence strains show signs of outbreak (3, 12)	>20.88 MWMTs over this value can result in severe infections and catastrophic outbreaks (1)	18-20 Temperature range which is associated with a high risk of disease in rearing juveniles and migrating adults (2)
19							
18							
17					17.8 Mortality rates were 52, 92, and 99% for juvenile spring Chinook, steelhead and coho respectively (13)	17.38 MWMT should not be exceeded to avoid serious rates of infection and mortality (1)	14-17 Temperature range which is associated with an elevated risk of disease in rearing juveniles and migrating adults (2)
16					16.1 Mortality is 30% in juvenile sockeye exposed to *C. columnaris* (10)		
15	>15.6 Associated with outbreaks in salmonid fingerlings, especially Chinook (3) 15.5 Lifecycle of Ich takes 2 weeks (5)		15 Mortality is 22% in juvenile coho exposed to *C. shasta* (9).		15.6 Average water temperature at which low virulence strains show signs of outbreak (3) 15 Mortality was 31, 56, and 51% for juvenile spring Chinook, steelhead, and coho respectively (13)		
14						14.38 MWMT will virtually prevent all warm water disease (1)	

Table 12 (continued):Effects of Temperature in Considering Disease and Salmonids

°C	Ich	Ceratomyxosis		Columnaris	Disease (general)
13			6.7-23.3 Juvenile rainbow trout have little or no ability to overcome infection, and mortality varied from 75-86% (9)		12-13 Temperature range which minimizes the risk of disease in rearing juveniles and migrating adults (2)
12				12.8 After 7 days of infection mortality is 60-100% (majority of tests 100%) (12)	
				12.2 Mortality was 4-20% in juvenile spring Chinook, steelhead, and coho respectively. Time from exposure to death ranged from 7.6-12.2 days (13).	
11		10-11 *C. shasta* appears to be come infective (4)			
10	10 Lifecycle takes more than 5 weeks (5)	<10 Steelhead show evidence of *C. shasta* in ~38 days (8)			
9		9.4 Juvenile coho time from exposure to death is 146 days, mortality is 2% (9)		3.9-9.4 No mortality in spring Chinook, steelhead, or coho from Columnaris (13)	
8					
7	7 Lifecycle takes 20 days (6)				
	<7 Lifecycle takes more than 5 weeks (7)				
6			6.7 Juvenile rainbow trout time from exposure to death is 155 days (9)		
			3.9-6.7 No mortality in Juvenile coho exposed to *C. shasta* (9)		
5					
4					
3					

References

1 WDOE 2002 (reviewed many literature sources to make assessments of temperature needs)
2 USEPA 2003 (reviewed many literature sources to make assessments of temperature needs)
3 Bell 1986 (reviewed many literature sources to make assessments of temperature needs)
4 CDWR (1988)
5 Piper et al. (1982)
6 Nigrelli et al. (1976, as cited by Dickerson et al. 1995)
7 Durborow et al. (1998)
8 Leitritz and Lewis (1976)
9 Udey et al. (1975)
10 Ordal and Rucker (1944, as cited by Pacha et al. 1970)
11 USEPA 1999 (reviewed many literature sources to make assessments of temperature needs)
12 Pacha et al. (1970)
13 Holt et al. (1975)

Columnaris
The importance of temperature on infections of Columnaris has been demonstrated in numerous laboratory studies. Ordal and Rucker (1944, as cited by Pacha et al. 1970) exposed juvenile sockeye salmon to *C. columnaris* and studied the effect of temperature on the disease. In these studies, the overall mortality ranged from 30% in fish held at 16.1°C to 100% in those held at 22.2°C (Ordal and Rucker 1944, as cited by Pacha et al. 1970). USEPA (1999) cites studies that conducted surveys of Columnaris infection frequency on Chinook in the Snake River in July and early August of 1955-1957, which revealed 28-75% of fish infected when water temperature was >21.1°C.

Low virulence strains of Columnaris show signs of outbreak when average water temperatures are over 20°C (Bell 1986, Pacha et al. 1970). Bell (1986) states that outbreaks of high virulence strains occur when average water temperatures reach 15.6°C, and Pacha et al. (1970) found mortalities of 60-100% (majority of tests 100%) occur at temperatures of 12.8°C after 7 days of infection. With regard to strains of higher virulence, while these strains are capable of beginning infection and producing disease at water temperatures as low as 12.8°C, the disease process becomes progressively slower as the water temperature is lowered (Pacha et al. 1970).

Holt et al. (1975) performed a study on the relation of water temperature to Columnaris in juvenile steelhead trout and juvenile coho and spring Chinook salmon. Tests were performed on groups of 25-35 fish at eight temperatures ranging from 3.9°C to 23.3°C (2.8°C increments). At 20.5°C mortality was 100% in juvenile steelhead trout and coho salmon, 70% in juvenile spring Chinook salmon, and at temperatures 23.3°C juvenile spring Chinook mortality was 92% (Holt et al. 1975). Mortality rates were 52, 92, and 99% at 17.8°C for juvenile spring Chinook, steelhead trout, and coho salmon respectively, and mortality dropped to 31, 56, and 51% at 15.0°C (Holt et al. 1975). At 12.2°C mortality varied from 4 to 20% among juveniles of the three species, and at temperatures of 9.4°C and below, no deaths due to the experimental infection with *F. columnaris* occurred (Holt et al. 1975). Holt et al. (1975) state that these results indicate that under the conditions of these experiments Columnaris disease was completely suppressed by water temperatures of 9.4°C or below.

In general, data from laboratory studies indicates that as water temperatures increase, the time to death decreases (Pacha et al. 1970). With juvenile steelhead trout and juvenile coho and spring Chinook salmon as the temperature increased above 12.2°C, the disease process was progressively accelerated, resulting in a minimum time to death at 20.5 or 23.3°C and a maximum at 12.2°C (Holt et al. 1975). In these juvenile salmonids Holt et al. (1975) found the mean time to death decreased from 7.6-12.2 days at 12.2°C to 1.6-1.7 days at 20.5°C for juvenile coho and steelhead, and 2.3 days at 23.3°C for juvenile spring Chinook (Holt et al. 1975).

Selection of TMDL Temperature Thresholds
As a result of this literature review, Regional Water Board staff has selected chronic and acute temperature thresholds for evaluation of Klamath River basin stream temperatures. Chronic temperature thresholds (MWMTs) were selected from the USEPA document *EPA Region 10 Guidance For Pacific Northwest State and Tribal Temperature Water Quality Standards* (2003), and are presented in Table 13. The Region 10 guidance is the product of a three-year interagency effort, and has been reviewed by both independent science review panels and the public. Acute lethal temperature thresholds were selected based upon best professional judgment of the literature, and are presented in Table 14.

Table 13: Temperature Thresholds-from USEPA 2003

Life Stage	MWMT (°C)
Adult Migration	**20**
Adult Migration plus Non-Core[1] Juvenile Rearing	**18**
Core[2] Juvenile Rearing	**16**
Spawning, Egg Incubation, and Fry Emergence	**13**

[1] Non-Core is defined as moderate to low density salmon and trout rearing usually occurring in the mid or lower part of the basin (moderate and low not defined).
[2] Core is defines as areas of high density rearing (high is not specifically defined).

Table 14: Lethal Temperature Thresholds

Lethal Threshold (°C)			
Life Stage	**Steelhead**	**Chinook**	**Coho**
Adult Migration and Holding	**24**	**25**	**25**
Juvenile Growth and Rearing	**24**	**25**	**25**
Spawning, Egg Incubation, and Fry Emergence	**20**	**20**	**20**

In some cases it may be necessary to calculate MWATs for a given waterbody, and compare these to MWAT thresholds. USEPA (2003) states that for many rivers in the Pacific Northwest the MWMT is about 3°C higher than the MWAT (USEPA 2003, as cited by Dunham et al. 2001and Chapman 2002). Rather than list MWAT thresholds in this document using the 3°C difference suggested above, the Regional Water Board will consider stream temperatures within an individual watershed. Thus the Regional Water Board will calculate both MWMTs and MWATs for a given waterbody, and characterize the actual difference between these temperature metrics for the watershed using an approach similar to that used in Sullivan et al. (2000). Once this relationship is understood, MWAT thresholds for each life stage can be identified for a specific watershed, and compared to the watershed MWATs.

The freshwater temperature thresholds presented in this section are applicable during the season or time of year when the life stage of each species is present. Periodicity information is not discussed in this document and will be presented in the watershed-specific TMDLs. Where life history, timing, and/or species needs overlap, the lowest of each temperature metric applies.

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