WASHINGTON STATE
DEPARTMENT OF
ECOLOGY

Evaluating Standards for Protecting Aquatic Life in Washington's Surface Water Quality Standards

Temperature Criteria

Draft Discussion Paper and Literature Summary

Revised December 2002
Publication Number 00-10-070

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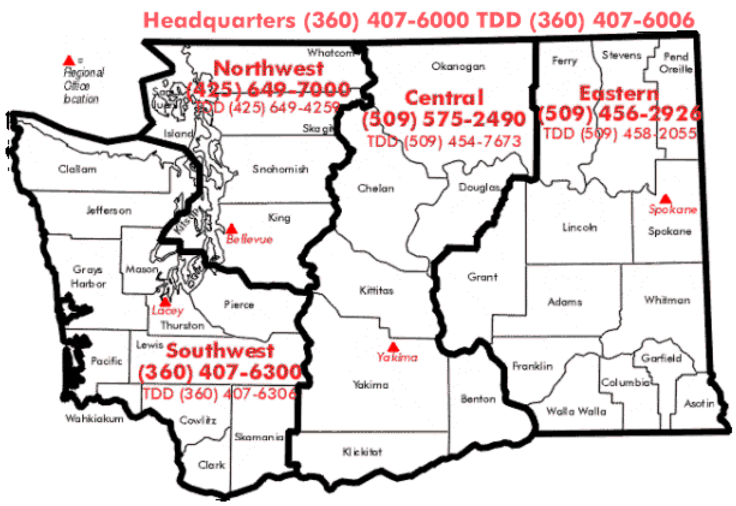

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Abstract

Maintaining proper temperatures in our natural waterways is vital to the long-term health of fish and other aquatic life. In response to critiques over the adequacy of Washington's existing temperature criteria for freshwaters, the Washington State Department of Ecology performed a comprehensive review of the available technical literature on the temperature requirements of our native fish and aquatic life. This document summarizes the findings of that review.

Part I of this document provides a brief history of the review effort. Part II of this document reviews the scientific literature and establishes technical recommendations for protecting the state's freshwater aquatic species. Based on previous reviews of the literature it was determined that freshwater species can be reasonably placed into four groups having similar sensitivity to temperature. These four groups, identified by key species, serve as the foundation for this review:

1) Native Char (bull trout and Dolly Varden);
2) Salmon, Steelhead, Cutthroat Trout, and Coastal Rainbow Trout;
3) Interior non-Anadromous Redband Trout (eastern Washington species); and
4) Warm Water Fish Species (e.g., dace, shiner, sucker, etc.).

Technical evaluations provide recommendations for temperature thresholds that protect the key life-stages of adult migration and holding, spawning, incubation, juvenile rearing, and smoltification. Recommendations are also made to avoid significant increases in the risks of warm water fish diseases and parasites.

Recommendations are also presented that may be instructive in trying to avoid detrimental effects from discrete site-specific human actions that may cause:

1) Thermal blockages to migration,
2) Short-term (7-day duration) lethality, and
3) Near instantaneous (1-2 seconds) lethality.

The temperature thresholds identified in this paper are ones which Ecology has high confidence represents the upper threshold temperatures that provide full protection for the species. As temperatures rise above these values, negative impacts to the health of fish and other aquatic life will rapidly escalate to levels detrimental to the health of aquatic communities. The metric used to express the technical recommendations (a 7-day average of the daily maximum temperatures) was chosen to better match the laboratory and field research results to an exposure period that reflects the risk of harm to aquatic species. The result of this process is the recommendation of temperature limits that better reflect the thermal requirements and limitations of the state's indigenous freshwater fish and aquatic life. There are still some notable areas where more research would improve confidence in specific recommendations (particularly for warm water species and for interior redband trout). It is clear however, that implementation of the temperature thresholds identified in

part II of this paper, wherever attainable would eliminate human warming of water temperature as a source of impairment to our native aquatic communities.

Part III of this document examines temperature data from rivers and streams around Washington. The information provided in this section can be used to assess the potential implications of selecting specific temperature values for use as state criteria.

Part I

Background and Project History

1. Background

The Washington State Department of Ecology administers the state's surface water quality standards (Chapter 173-201A WAC). These regulations establish minimum requirements for the quality of water that must be maintained in lakes, rivers, streams, and marine waters. This is done to ensure that all the beneficial uses associated with these waterbodies are protected. Examples of protected beneficial uses include: aquatic life and wildlife habitat, fishing, shellfish collection, swimming, boating, aesthetic enjoyment, and domestic and industrial water supplies.

As part of a public review of its water quality standards, the Department of Ecology convened a technical work-group to evaluate the water quality criteria established to protect freshwater aquatic communities. One of the recommendations of the work-group was that Ecology should re-evaluate the state's existing temperature criteria.

2. Current Temperature Requirements

The existing state surface water quality standards contain three separate single daily maximum temperature criteria limits that can be applied to rivers:

Class AA - 16°C
Class A - 18°C
Class B - 21°C
Lake Class - Temperatures are to be maintained at natural levels.

Class AA and Class A provide two different levels of protection for the same set of beneficial uses, and are intended to protect salmonid spawning, rearing, and migration. Class AA is predominately applied to forested upland areas, but Class A waters are designated broadly throughout the state. Class B, is designed only to protect salmonid rearing and migration, and was not intended to fully protect spawning. There are only a small number waterbodies in the state that have been assigned the Class B designation. With each class, the criteria are applied as the highest single daily maximum measurement of temperature occurring in the waterbody.

3. Organization of this Review Document

Part I: Provides a brief background discussion on the effort to revise the state's existing water quality criteria for temperature in freshwater systems.

Part II: Reviews available scientific research on the effects of temperature on aquatic life, with a particular focus on species occurring in Washington.

Part III: Summarizes the patterns of temperature in Washington's rivers using available continuous monitoring data.

Part II

The Effect of Temperature on the Freshwater Aquatic Life of Washington

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1. The Goal of this Technical Review

The primary goal of this paper is to identify temperature thresholds that if met would have a high probability of fully protecting Washington's freshwater aquatic communities. Full protection includes the reasonable prevention of both lethal and sublethal effects that may detrimentally affect the health, fecundity, and the ultimate wellbeing of naturally balanced indigenous populations. This review uses the available technical literature to determine temperature regimes that will fully protect the individual life-history stages of key species. This information is then combined into stream-wide temperature recommendations that will protect entire communities of aquatic life.

The following summarizes the findings pertaining to the protection of our state's native fish species. The technical recommendations are based on grouping together species having the same or nearly the same temperature requirements. This both simplifies the resulting recommendations and acknowledges that these species commonly occur together in the state's streams, rivers, and lakes. This approach results in establishing temperature threshold values for four different species groupings: 1) native char, 2) salmon and coastal trout, 3) non-anadromous interior redband trout, and 4) warm water fish species.

2. Summary of Thermal Requirements and Recommended Threshold Values

a) Native Char (Bull Trout and Dolly Varden)

Char require colder waters to be fully supported than the other fishes native to Washington. Char do not begin spawning until temperatures drop to 7-9°C, and subsequent egg incubation is harmed by continuous daily average water temperatures above 5-6°C. The same waters that are used for spawning are also used for tributary rearing by juvenile char. Tributary rearing waters that provide full support for char are best described by summer maximum temperatures at or below 13-15°C or average (7-day) daily maximum temperatures below about 12.5-14°C.

At age 2-3, char often move to lower more main stem waters to rear. This may be a pattern that more effectively uses the larger prey bases of larger stream and rivers, or just acts to disperse the populations in order to use wider resource areas. In any case, it is common to find char in waters where the summer maximum temperatures would appear unsuitable based on research focused on young juveniles and non-migratory (resident) populations. It appears that char will move into and out of these waters in a manner that avoids (or in response to) warm water temperatures. The temperatures noted in association with the movement varies but generally appears to be above those identified as necessary to fully protect the rearing of young juveniles. At this time, information is not available to either identify the historic patterns in specific Washington streams or identify with confidence temperature criteria appropriate for this migratory life-stage.

b) Salmon and Trout

Salmon and trout both have similar spawning and incubation requirements. In evaluating the temperature requirements of salmon and trout it is important, however, to remember that salmon begin spawning in the fall as temperatures are cooling and trout begin spawning in the spring as temperatures are warming. For simplicity, the following discussion follows the pattern of fall spawning fish:

In the weeks immediately preceding spawning, temperatures above 14-16°C can reduce the health of the eggs and sperm in adult fish. Constant temperatures in the range of 8-10°C and daily maximum temperature below 13-15°C are necessary to ensure that fertilized eggs have high survival success and the embryos develop into healthy emergent fry. Once the fry emerge, juvenile rearing will be fully supported in natural streams where the average temperatures do not exceed 13-15°C, and maximum temperatures do not exceed approximately 17-19°C. Once the fish have reached a critical size, they will begin the process of changing from parr to smolts. This is the critical physiologic process that allows these freshwater juveniles to adapt their systems for life in marine waters. Average temperatures greater than 15-16°C appear capable of stopping the process altogether, and average temperatures below 12-13°C appear necessary to fully support smoltification (particularly for the spring out-migration of steelhead). In early spring, overlapping the period of out-migration of many anadromous salmonids, adult smelt will be moving upstream to spawn. These fish have been found to have very low temperature thresholds.

While the information on these fish is somewhat limited, it appears that spawning success can be impaired by maximum temperatures above about 12-13°C, and adult mortality has been noted in association with water temperatures as low as 16°C. After a period of growth in the ocean, salmon and steelhead will begin their migrations back up to their natal streams to spawn. Migration can be impaired by experiencing average temperatures above about 15°C and maximum temperatures above about 18-20°C. Temperatures above 21-22°C have frequently blocked the migration of anadromous fish altogether; particularly where the fish have come from cooler waters. For both the rearing of juvenile fish and the migration of adult fish, warm water diseases can reduce survival. Average temperatures above 13-14°C and periods of maximum temperatures above about 17-18°C have been found to increase the risks of losses associated with warm water fish diseases and parasites. Extreme temperatures can be lethal to salmon and trout with exposure periods from a couple of seconds to a couple of hours. Single daily peak temperature of 24-25°C are capable of killing salmonids that have not been well acclimated to warm waters in advance of the exposure, and plumes of water warmer than 32-33°C can be lethal to passing fish in only 1-2 seconds regardless of their prior acclimation temperature.

The information reviewed for revising the state's temperature criteria generally suggests that non-anadromous interior forms of rainbow trout (often described as the subspecies of redband trout that occurs on the eastside of the Cascade mountains in Washington) have higher optimal temperature ranges than other subspecies of rainbow trout. However, the information was rather inconsistent on this point, and caution is warranted before allowing any significant departure from the temperature ranges determined healthy for the majority of the state's salmon and trout. It is recommended therefore that temperatures at the upper end of the range determined to fully protect salmon and trout in general be viewed as the warmest temperatures that will protect these interior redband trout. The available information suggests that acutely lethal temperatures are very similar for all subspecies and stocks of trout, and thus no sound basis exists for assuming that these fish would be better capable of resisting short-term spikes of temperature into the lethal range.

c) Warm Water Aquatic Life

A warm water fish community in Washington would be characterized by the presence of redside shiner; tui chub; margined, mottled, or piute sculpin; longnose or speckled dace, sucker, and northern pikeminnow. These fish are known to exist in our warmest waters, where they often out-compete introduced populations of rainbow trout. Insufficient information exists to develop individual water quality recommendations for these species, so it is recommended that they be considered broadly as a community. There is very little experiential data available that can be used to establish the fully protective upper temperature range for our warm water species in general, so these recommendations may need to be revisited periodically to determine if changes are warranted. Establishing criteria to protect our temperature tolerant non-salmonid fish species will also provide protection for desirable introduced warm water sport fish species such as bass and crappie. In general, Washington's indigenous warm water fish communities can sometimes thrive in waters that have summer maximum temperatures as high as 25-27°C; although, most appear to prefer waters below 20°C

d) Special Provisions to Prevent Acute Effects

The previous technical recommendations are designed to protect waterbodies in recognition of the way that temperatures change in nature over hours, days, and weeks. Discrete human actions, such as point source discharges, are capable of altering these normal temperature regimes and thus may require special consideration. For example, scheduled or emergency bypasses for maintenance at an industrial facility may require asking questions like: a) How much can temperature be raised for a single day or week?, or b) How hot can a discharge be within an authorized mixing zone? These questions require a departure from consideration of what are healthy stream conditions and instead must focus on what is tolerable for a discrete location and a limited duration of time. To assist in answering these inevitable questions, recommendations have been made for avoiding acute (short-term) lethality and barriers to migration.

For evaluating the effects of discrete human actions, a 7-day average of the daily maximum temperatures greater than 22°C or a 1-day maximum greater than 23°C should be considered lethal to cold water fish species such as salmonids. Discharge plume temperatures should be maintained such that fish could not be entrained (based on plume time of travel) for more than 2 seconds at temperatures above 33°C to avoid creating areas that will cause near instantaneous lethality. Barriers to migration should be assumed to exist anytime daily maximum water temperatures are greater than 22°C and the adjacent down-stream water temperatures are 3°C or more cooler.

3. Methodology and Considerations in Establishing Temperature Recommendations

This chapter discusses the methodology used and some of the underlying thoughts and concerns that went into establishing the temperature threshold recommendations contained in this paper.

a) The Multiple Lines of Evidence (MLE) Methodology

Scientific information comes in a wide variety of forms. These include:

- Laboratory testing where the temperature is held constant,
- Laboratory testing where the temperature is made to fluctuate at a set rate,
- Controlled field studies using either natural or artificial channels,
- Field studies where environmental variables such as shade are altered, and

- Field observational studies where the patterns of fish are observed in the wild.

All of these sources of information provide valuable insights, but it can be a challenging task to try and compare and contrast such different types of research. This has led many researchers to simplify their approach and select only a single type of research. This simplification, while understandable, can result in a loss of understanding. More importantly, however, it can result in a lost opportunity to demonstrate how well all of these very different types of studies correspond to one another. The key to using a diversity of information types is to convert the results into a common metric.

The multiple lines of evidence (MLE) approach used in this paper was developed as a means to use all of the available scientific information to support sound decision making. The MLE methodology was developed to provide a method for making recommendations that are transparent to the reviewer and that can be predictably modified when new information becomes available. The basic approach is rather simple. All the scientific information is sorted first by the life-stage (e.g., spawning, rearing, migration, etc.) or by some discrete environmental risk (e.g., lethality, smoltification, disease, etc.). The information is then sorted into different categories of study types. The following provides a simplified example of how this information can be categorized into independent lines of evidence (ILOE) for the life-stage of juvenile rearing:

Study types (ILOE): Constant temperature laboratory testing of growth
Fluctuating temperature laboratory testing of growth
Controlled field studies on growth
Studies on the distribution and health status of natural populations
Laboratory studies examining competition and predation
Field studies examining competition and predation

For each line of evidence the study conclusion are standardized into a standardized exposure metric and summarized as the range of individual study results. Depending upon the line of evidence, this range may be either the absolute range or the dominant range (e.g., 90th percentile of distribution of study results).

The standard metric for this temperature analysis is a 7-day average of the daily maximum temperatures (7DADMax). This metric was chosen primarily because:

1. Sublethal chronic biologic reactions generally take more than a week's exposure to become meaningful;
2. Small daily maximum temperature fluctuations beyond some "healthy" target level will not be biologically meaningful, but if a single daily maximum metric were chosen and then not attained such fluctuations would have regulatory repercussions; and
3. It is not as defensible to use weekly averages of the daily average temperatures alone because fluctuations about the mean temperature can be highly variable and extreme fluctuations will erase or diminish the benefits of otherwise healthy average temperatures.

To make the conversions to a standard metric, this analysis relies upon the conversion equations provided by Dunham et al. (2000) that are based on data from 752 stream sites located in the Western United States; particularly the Northwest. For converting the temperature research results for protecting bull trout and Dolly Varden (Washington's most cold water loving fish species), it is assumed that their habitat will have very stable temperatures. This analysis uses the assumption that summer average diel fluctuations are less than 2°C in char habitat. This is consistent with the state's information showing that colder streams (7DADMax <15C) have median average fluctuations of 2.1°C (90% between 1.1-3.6°C). It is also consistent with the commonly held belief that many of these waters are kept thermally stable due to a higher reliance on input from groundwater. For salmon and trout waters, the conversion is based on assuming that the summer average diel fluctuations are from 4-6°C. This is consistent with the state's data showing that warmer streams (7DADMax 15-19°C) have median average fluctuations of 1.2-5.3°C (90 percentile range – median 2.6°C). It also recognizes that the waterbodies used by salmon and trout have the most variable temperature regimes overall. The following table shows the adjustment calculations that were used to convert temperatures to a common metric.

Table 3.1. Conversion equations for standardizing duration of exposure scenarios. These are used to convert study results to the standard metric of a 7-day average of the daily maximum temperatures.

Convert from:	To a 7DADMax (°C)	Summer Average of the Diel Ranges (°C)
In Char Spawning Habitat:		
Summer max	Subtract 0.55	0-2
Summer mean	Add 2.00	0-2
Weekly mean (highest)	Add 0.93	0-2
Daily mean (highest)	Add 0.62	0-2
In Salmon and Trout Habitat:		
Summer max	Subtract 0.95	4-6
Summer mean	Add 4.64	4-6
Weekly mean (highest)	Add 3.18	4-6
Daily mean (highest)	Add 2.60	4-6

The metric adjustment step was also used where appropriate to put bounds on the potential correct estimate on each line of evidence. This bounding process was used where there was reasonable uncertainty about the duration of exposure that best represented the line of evidence and the related biological response. For example, growth studies are generally conducted for a relatively long period of time (e.g., 30-90 days), but significant changes in growth between different test temperatures are commonly obvious after the first week or two. Thus there is uncertainly whether the results of these tests should be applied as if they are summer average exposures or weekly average exposures. In the face of this uncertainty, conversions are made for both possible cases. The range produced by using these two adjustment factors creates a range within which the most probable correct answer would be expected to occur.

The results of this MLE process are presented in tabular form, and a range is produced by independently averaging both the lower and upper range values for each line of evidence. This creates a range within which the best estimate should be found. The midpoint of this range is considered to be the overall best estimate, unless overriding concerns with any particular line of evidence suggest another conclusion is warranted. In such a case, the suspect line of evidence is noted and either dropped entirely from the final range calculation, or is used as a basis for conditioning the recommendation. Table 3.2 shows a simplified example based on protecting the juvenile rearing life-stage of salmon and trout.

Table 3.2. Juvenile rearing of salmon and trout:

Line of Evidence (LOE)	7DADMax (°C)	Midpoint	Comments Regarding LOE
Laboratory Growth Studies at Constant Temperatures	x-z	y	Based on well controlled laboratory tests.
Laboratory Growth Studies at Fluctuating Temperatures	x-z	y	
Field Studies on Growth	x-z	y	
Predation and Competition	x-z	y	
Ranges Identified as Protective	x-z	y	Basis for estimates and intended metrics unclear.
Comparing Discrete Test Regimes	x-z	y	
Laboratory Temperature Preferences	x-z	y	
Swimming Performance and Scope for Activity	x-z	y	
Field Distribution of Healthy Populations	x-z	y	This estimate relies on the general upper range considered healthy, and temperatures above which coldwater species begin to loose dominance
Summary Statistics and Final Estimated Range:	**Ave(x)-Ave(z)**	**Midpoint**	

Based on previous draft reviews of the temperature requirements of Washington's native fish, it was determined the differences in thermal thresholds between species were generally slight. Only division into three species groupings (guilds) appears warranted (Hicks, 1998, 2000). Therefore, the multiple lines of evidence procedure was conducted separately in this current review only for the guilds of: 1) Char, 2) Salmon and trout, and 3) Warm water species.

b) General Thoughts and Observations

i) Adjusting Laboratory Data for Application to Natural Waters

Laboratory tests do not represent the full range of conditions that an organism will face in the natural environment. In most laboratory tests fish are exposed to a constant temperature environment, while in natural waters the temperature continuously fluctuates during each day, between days, and in seasonal trends of spring warming and fall cooling. In natural waters, fish must actively maintain position and seek food and shelter in the currents of rivers, succeed in the face of inter- and intra-species competition for both food and shelter, avoid predation, and resist disease. In laboratory studies, however, the fish are often in test chambers without substantial currents, fed food in pellet form, treated to prevent disease, and seldom need to compete or avoid predation. On the other hand, in laboratory tests, fish are often crowded into very small unnatural spaces, even Styrofoam cups, forced to perform using electrical stimulation or prodding, subjected to laminar artificial flows, and often fed unusual rations with large time intervals of starvation.

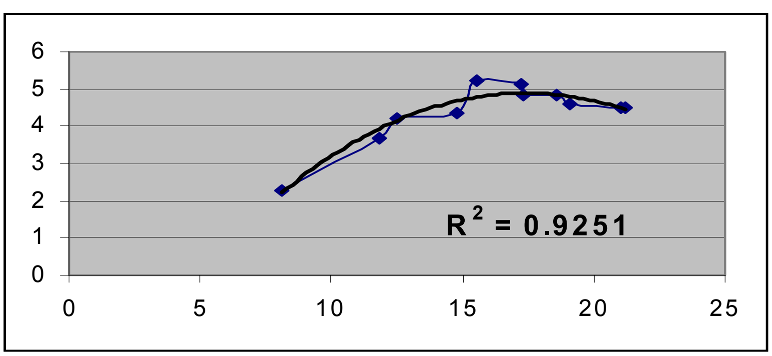
Because of the differences between laboratory conditions and the environmental conditions that fish face in the natural world, we must use caution in how we apply laboratory-derived data in setting ambient water criteria. We must ensure that the temperature regimes used in the laboratory tests are considered in any application to natural streams.

Growth Studies:

Most of the research on optimal growth temperatures is conducted with water kept at a constant temperature. Water quality standards, however, must apply to naturally fluctuating thermal environments. Since temperature directly effects the metabolism of the fish, a fish kept continuously in warm water will experience more metabolic enhancement than one which only experiences that same temperature for one or two hours per day. Thus, constant test results cannot be directly applied as a daily maximum temperature in a fluctuating stream environment. The literature examined for this paper strongly suggests that constant temperature test results can be used to represent daily mean temperatures (Hokanson et al., 1977; Clarke, 1978; Grabowski, 1973; Thomas et al., 1986; Hahn, 1977; and Dickerson, Vinyard, and Weber, 1999, and unpublished data, as cited in Dunham, 1999); at least in systems with moderate temperature fluctuations. Growth studies may be conducted for substantially varying periods of time (14 to 90 days) but generally encompass time-frames that would match reasonably well with periods of maximum summer temperatures (20-60 days).

For illustrative purposes we can examine the findings of Hokanson et al. (1977). This study compared specific growth and mortality rates of juvenile rainbow trout for 50 days at seven constant temperatures between 8°C and 22°C and six diel temperature fluctuations (sine curve of amplitude +/- 3.8°C about mean temperatures from 12°C to 22°C

Figure 3.1. Relationship between growth rates and mean temperature exposures. Based on Hokanson et al.(1977).



Plotting the growth rates against the mean temperatures for both the constant and fluctuating tests produced a characteristic normal distribution for growth rate and temperature (Figure 3.1 above). Thus a strong relationship appears between the daily mean temperatures in fluctuating tests and those in the constant tests. A pattern was demonstrated, however, where daily mean temperatures in the fluctuating tests at means of 12.5 and 15.5°C produced greater growth rates than comparable constant temperatures at 11.8 and 14.8°C. At the constant optimal temperature of 17.2°C and above, however, this pattern was reversed. This pattern led Hokanson et al. to suggest that the growth of rainbow trout appears to be accelerated at fluctuating treatments when the mean temperature is below the constant temperature optimum for growth and retarded by mean fluctuating temperatures above the constant temperature optimum. Hokanson et al. suggested that water quality standards (based on weekly mean values) should be set such that the average weekly temperature is below the constant test temperature producing maximum growth.

Like Hokanson et al. (1977), other researchers (Thomas et al., 1986; and Everson, 1973) have found that fluctuating temperature regimes actually enhance growth over what is found at constant temperature exposures; at least where the mean of the fluctuating regime is at or below that of the constant exposure test temperature producing optimal growth. The works by these authors also suggest that high peak temperatures may create stress which will harm growth even though the daily average temperature appears optimal. For example, Thomas et al. (1986) noted stress conditions occurring in cycles with daily peak temperatures of 20°C.

Variable Feeding Regimes:

Growth rates are related to both temperature and food rates. As temperature goes up, more food is necessary to supply basic physiological needs but also the efficiency goes up for utilizing excess foods. This relationship results in a situation where at maximum feeding rates fish will grow larger in warmer water, but at reduced feeding rates in the same warm water growth rates will suffer. In cooler waters, maximum growth rates are achieved at feeding rates well below those that produced maximum growth in the warmer waters. This relationship between feeding rates and temperature means that laboratory test results would need to be modified to account for the feeding regimes present in natural stream environments to be able to confidently set a very precise maximal growth temperature.

Numerous authors have demonstrated that food availability in the natural environment is well below that used in laboratory growth studies (Brett et al., 1982; Saski, 1966; Nedham and Jones, 1959; Wurtsbaugh and Davis, 1977; Ensign et al., 1990; Bisson and Davis, 1976; as cited in ODFW, 1992; Elliott 1975, McCullough 1975, 1979, Murphy and Hall 1981, Edwards et al. 1979, Vannote et al. 1980, Bisson and Bilby 1998, and James et al. 1998; as cited in USEPA, 2001, and others). As an example of the influence of feeding rates, McMahon, Zale, and Selong (1999) tested bull trout growth and found that at satiation (maximum) and 66% satiation ration levels growth was highest at 16°C, whereas at a 33% satiation ration growth rate was maximized at 12°C. Thus in waters of lower productivity, maximum growth may occur at temperatures well below those that produce optimal growth at high rations.

While the basic relationship between feeding rates and growth at various temperatures is well established, there is a problem with trying to apply an adjustment factor to laboratory test results. In the laboratory tests reviewed for this paper, feeding rates and regimes varied significantly. In addition, the nutritional value can be different between feeds, the size and type of food along with its method of presentation can influence the ability of fish to feed and consequently grow, and the specific starting size of the test fish will greatly influence growth rates. Given that the feeding regimes and test conditions were so highly variable, trying to make a standard adjustment to laboratory test results to try and match natural feeding regimes is problematic. Nevertheless, it is important that this factor be recognized when setting water quality criteria recommendations for juvenile rearing.

There are at least a couple of ways that this factor can be accounted for without having to develop complex growth models to test various temperature regime scenarios. The first is to make a standard 2-4°C adjustment downward to the temperature value determined optimal for growth at satiation feeding. The second is to apply the criteria to a relatively brief window of time (e.g., 2-3 weeks), even though the growth tests often lasted 4 weeks or more, and recognize that temperatures will need to be below this value most of the time in even the warmest years to result in compliance, thus virtually ensuring that temperatures will produce excellent growth overall. In assessing the risks associated with making such simplifying assumptions it is important to recognize that growth rates diminish on either side of the optimal temperature range. It is not substantially different to err slightly on the warmer side of optimal than it is to err on the cooler side of optimal, barring any other detrimental biologic responses. By extending just beyond the warmer side of optimum during the warmest period of the warmest years the fish will actually be experiencing a greater number of days in the optimum range over most years. In the recommendations of this paper, except where noted for testing that examined reduced feeding rates, temperatures that consistently resulted in maximum growth at satiation feeding were used to set the threshold value.

Incubation Studies:

Specific studies were not found that compared the effects of constant and fluctuating temperatures on incubating fish. However, it is assumed in this paper that that incubating fish generally respond to the daily mean temperature. This seems warranted given the strong basis provided through the use of the standardized “temperature unit” calculations in hatchery operations and in fisheries science in general. It is fortunate that many of the incubation studies were conducted with fluctuating water temperatures (highlighted in the discussions of individual species). This provided a good opportunity to generally check the effect of applying the results as average temperatures and to assess the risks of allowing higher daily maximum temperatures. Additionally, a natural safety factor often exists to protect egg incubation. Since salmonids bury their eggs in the gravel of the stream bed, they are buffered slightly from both daily maximum and daily minimum stream temperatures. The buffering of the stream bed gravel can effectively reduce the daily maximum temperature by at least 1-1.5°C (Crisp, 1990). While this natural safety factor is not accounted for in laboratory tests it is also not dependable. Therefore, in the recommendations of this paper no adjustment is made to account for this often occurring buffering effect. It is useful, however, when reviewing the potential risks of the recommendations in this paper to recognize that sudden and unseasonable rises in stream temperature during incubation will often not cause similar temperature exchanges in the egg pockets situated in the gravel.

Few studies examined the risk of short-term lethality to eggs from unusually high temperatures for individual species, so the few that were conducted are used broadly to suggest limits on daily maximum temperatures during the incubation period for all related species. Limits for daily maximum temperatures are also based on the results from controlled laboratory tests where the temperature regime experienced by the fish was started at varying high daily maximum temperatures and then allowed to fluctuate and fall in concert with the seasonal changes in the natural waters used to supply water for the tests. From these experiments it can be observed what temperatures at the start of the incubation tests are generally associated with reduced incubation performance, and what temperatures appear not to hinder incubation.

Lethality and Acute Effects:

The water quality standards must be applicable to a broad range of human activities. The standards must protect against both gradual basin-wide increases in temperature as well as localized shifts in daily maximum temperatures. Rapid or site-specific changes in temperature can be caused by unique human activities (such as industrial cooling waters, process wastewaters, and water releases from reservoirs). While localized extreme changes in water temperature are not as common as the gradual basin-wide changes, they do exist, and their regulation through discharge permits and water quality certification programs require careful application of biologically-based temperature standards. These localized point sources of temperature change are also those most capable of creating short-term lethality to aquatic life as they may discharge water significantly hotter or colder than the ambient water to which organisms are acclimated.

The incipient lethal level (ILL) is typically determined by exposing juvenile fish to constant temperatures and determining the test temperature that causes 50% mortality of test fish within typically a 7-day exposure period. It would not be appropriate to establish criteria that would allow 50% mortality, however, so the ILL value needs to be adjusted to a level that would not be expected to cause any mortality. The National Academy of Sciences (1972) and Coutant (1973) recommend subtracting 2°C from the LT50 value to determine a safe (no more than 1% mortality – an LT1) short-term temperature limit. Some reasons for extra caution in interpreting lethality studies include that:

1. The time above lethal levels appears cumulative (DeHart, 1974, 1975, and Golden, 1978);

2. Adults appear more sensitive than the juveniles which are most commonly tested (Coutant, 1970; Becker, 1973; Bouck and Chapman, 1975);
3. Individual stocks possess slightly different tolerance levels (Beacham and Withler, 1991);
4. Indirect acute effects are often cited to occur just below lethal levels (e.g., increased predation, feeding cessation, migration blockage); and
5. The range between no mortality and high mortality rates is often described by as little as 0.5°C (Charlon, Barbier, and Bonnet, 1970).

The selection of laboratory results for use in developing recommendations focuses on test fish that had previously been acclimated to reasonably cool water temperatures. This recognizes that fish migrating from cooler upstream tributaries or from marine waters may not be fully acclimated to warmer main stem summer river temperatures. It also helps to bridge the gap in protection that occurs when protecting fish from hot thermal discharges occurring in the late fall through early spring period when the ambient river temperatures are often very cold.

Although test results that determine lethal threshold temperatures are used as one line of evidence in this paper for recommending water temperature thresholds that will prevent acute (short-term) effects, the final recommendations are not based on just avoiding lethality. Temperatures that would result in any detrimental acute effect such as causing a barrier to adult fish spawning or migration take precedence in the recommendations. Thus, while a species may be able to survive in a laboratory environment at a given temperature, research may show that the temperature maximum would be unacceptable in natural waters.

ii) Minimum Temperature Thresholds

One issue not directly included in the technical recommendations at this time are recommendations for how cold a water body can be allowed to be due to human actions. It is well documented that unseasonably cold waters can be as detrimental to aquatic organisms as unseasonably warm waters. Sudden releases of very cold water can cause rapid lethality to unacclimated organisms, and waters substantially colder than what is optimal can decrease survival of eggs and embryos and detrimentally depress juvenile growth rates. Human activities, such as the removal of overhead vegetative canopies will increase long-wave radiative cooling causing potentially harmful drops in the natural winter low temperatures. This may encourage anchor ice, a result of streams freezing, that may cause additional damage to fish and their habitat as it causes super-cooling of the water and scours the channel during spring break-up (Jakober et al., 1998; Needham and Slater, 1944; Needham et al., 1945 Maciolek and Needham, 1952). It may be that thresholds for low temperature limits should be considered at some point in the future, and information is included in this paper to assist in setting site-specific limits for individual activities. However, to keep the focus of this paper on the area of greatest concern, that of high water temperatures, the issue of cold water limits is not being addressed at this time.

iii) Protection of Untested Species

The technical recommendations made in this paper are primarily based upon data obtained on the temperature requirements of our two native char, the five Pacific salmon, rainbow and cutthroat trout, smelt, mountain whitefish, several stream breeding amphibians, and numerous insect species. Rigorous scientific testing generally has not been done on most of the other aquatic species indigenous to Washington's waters. What references have been found for these other species tends to be of a more anecdotal nature; noting what the temperature was when spawning was observed, or indicating the temperature of a waterbody where a species was found. For some of these less well known indigenous species, however, direct testing of their temperature optima and lethal limits has occurred. Based on what temperature information has been found, both direct and indirect, these other species do not appear to possess more sensitive temperature requirements than the species that have been used to make temperature threshold recommendations in this document.

Many of the less well known aquatic species, which often occur together as a community, appear to thrive in waters which are at the upper margin of what is optimal for salmonids, and represent warm water fish communities indigenous to Washington. Recognition of these species has resulted in the recommendation that the state establish a unique level of use-support that can be assigned to our naturally warmer waters.

The warm waters that occur in the margins and slack-water areas of many rivers serve as important habitat to many species that prefer summer water temperatures somewhat warmer than what is healthy for the state's indigenous salmonids. These other species also commonly serve as food fish for salmonids and are important to the overall health of the system. Thus, these warmer stream margins should not be viewed as lost or unhealthy habitat, but as a necessary and natural adjunct to a healthy aquatic system. It is important to note that young salmonid fry also often initially rear in the shallow margins of rivers until reaching a size that allows them to habitat the more active channel, and that these young fry have been commonly shown to have slightly higher temperature preferences than older fry or juvenile fish.

4. Temperature Requirements of Char, Salmon, and Trout Species

In this chapter, the temperature requirements of the char, salmon, and trout species indigenous to the state of Washington are examined. Whenever the data allowed doing so, two temperature values are provided to define the upper end of the temperature range that is fully protective of each species' key life stages. This was generally done for the primary metric recommended which is a 7-day average of daily maximum temperatures. The approach taken recognizes that the upper fully protective endpoint is often more accurately described by defining a narrow range of temperature rather than a single value. The final selection of a single recommended value comes only after the needs of all of the species, their life-stages, and stressors are considered together [see Summary Section 4 g)].

a) Native Char Temperature Requirements

i) General Life History Information:

Bull trout (*Salvelinus confluentus)* and Dolly Varden (*Salvelinus malma*) are the only two species of char native to Washington (Hass and McPhail, 1991). Perhaps more than any other species, cold waters are critical to maintaining healthy populations of these native char. These two closely related species are difficult to taxonomically identify from one another in the field (Hass and McPhail, 1991). Cavender (1978) may have first recognized that what had previously been considered an interior form of Dolly Varden was in fact a distinct species, now referred to as the bull trout. Goetz (1989) suggests that bull trout may be more directly related to the Arctic char (*Salvelinus alpinus*), and in fact a sister to the Arctic char-Dolly Varden group. Spalding (1997) found that for Washington's Olympic Peninsula many of the anadromous char previously assumed to be Dolly Varden keyed out to be bull trout. While important to advancing scientific understanding, the historic problems with discriminating between these char appear to pose little practical problems in terms of setting water quality criteria. This is because Dolly Varden and bull trout are generally considered to have very similar biological requirements, and the management measures needed to protect both Dolly Varden and bull trout may be identical (WSDFW, 1994).

The Washington State Department of Fish and Wildlife considers the majority of native char stocks in the state as being "Vulnerable Populations" requiring special protection. Bull trout in particular have received considerable publicity in recent years because of their status as a threatened species under the federal Endangered Species Act. The results of a 12-month study evaluating stock status by U.S. Fish and Wildlife Service noted serious declines of bull trout populations statewide (USFWS, 1997). Rieman et al. (1997) examined the distribution and status of bull trout across 4,462 sub-watersheds of the interior Columbia River basin and the Klamath River basin and found that bull trout are more likely to occur and the populations are more likely to be strong in colder, higher-elevation, low- to mid-order watersheds with lower road densities. They noted that while bull trout were widely distributed across their potential range, strong populations may exist in only 6% of this potential range.

Upon hatch, char fry will either remain in the localized area or move downstream to larger streams or lakes to rear (Goetz, 1989; Williams and Mullen, 1992; Reiser et al., 1997). Movements to more suitable upstream waters has also been observed (Fraley and Shepard, 1989; Armstrong and Morrow, 1980, as cited in Goetz, 1989). Unless information clearly demonstrates that a stretch of water would not be used for summer rearing even under natural conditions, temperature criteria assigned to these migration paths should also be set to protect the rearing of char fry.

Some research suggests that age 0-1 juvenile char have cooler temperature preferences than age 1+ juveniles; however, there is little consistency in the values identified. The preference values for age 0-1 bull trout range from an average of 4.5°C (Ratliff, 1992), to maximum stream temperatures of 10°C and 13°C (Ratliff, 1987; and Martin et al., 1991). Resident forms of bull trout remain in or near their natal streams for their entire life. Fluvial and adfluvial forms may remain in the area of their natal stream for 1 to 3 years and then migrate significant distances to more productive waters for greater juvenile growth opportunities (Pratt, 1992; Ratliff, 1992; Riehle et al., 1997; Fraley and Shepard, 1989; Goetz, 1989); although, some stocks have also been observed to migrate to lakes or reservoirs immediately after hatching (Reiser et al., 1997). Sea-run (anadromous) forms will migrate hundreds of miles to take advantage of productive near-shore marine habitat (Goetz, 1989). Temperature standards would ideally be set in consideration of these various life-strategies.

The needs of resident forms may be slightly different from the various migratory forms. Juvenile bull trout and Dolly Varden have difficulty competing with several common salmonid species in warmer waters (Haas, 2001; McMahon et al., 1999). This may partially explain why researchers have observed young juvenile fish remaining in their natal stream for the first several years before moving downstream to warmer and more productive waters. It is plausible that the lack of significant competitors in their cold natal streams may compensate for the reduced productivity of these pristine environments. Since non-migratory resident bull trout must remain in and defend their natal habitat for their entire life, temperatures here should clearly favor bull trout over competing species such as chinook salmon and rainbow trout (Martin et al., 1991; Mullan et al., 1992; Ziller, 1992; Adams and Bjornn, 1997; WSDFW, 1994; Haas, 2001).

ii) Spawning Requirements

Field Observations of Spawning Initiation

Maximum temperatures should generally be below 12°C and on a fall season cooling trend at the time char enter their spawning streams (Fraley and Shepard, 1989). In a study on the Rapid River in Idaho, pairing behavior was noted to begin after average water temperatures dropped from 10 to 6.5°C (generally equivalent to a change in single daily maximum temperatures from 11-7.5°C) (Schill, Thurow, and Kline, 1994). In the same river, Elle and Thurow (1994) found that daily maximum water temperatures below 10°C influenced the movements of spawners both in and out of the Rapid River. While daily maximum temperatures may need to fall below 9 to 11°C (WSDFW, 1994) for redd construction to begin, no authors have been found to suggest spawning will begin at daily maximum temperatures above 10°C. Most place the temperature that triggers spawning below 9°C (Goetz, 1989; Pratt, 1992; Kramer, 1991; Fraley and Shepard, 1989), with the peak of spawning activity not occurring until stream temperatures falls below 7°C (James and Sexauer, 1997; Wydoski and Whitney, 1979). Reiser et al. (1997) suggested that a daily average temperature between about 6.8 to 8.1°C (generally equivalent to a single daily maximum range of 7.8-9.1°C) was necessary to initiate spawning activity. Temperatures above 8°C were noted by Kramer (1994) as appearing to cause spawning activity to temporarily cease in char in northwest Washington streams. The Washington Water Power Company (1995) studied the distribution of fish in the lower Clark Fork River in Idaho and found that bull trout spawning was confined to an artificial spawning channel created to mitigate the effects of the Cabinet Gorge Dam. Water temperatures in theses spawning areas were consistently cooler (5-7°C) than other areas of the channel, and during the period of redd construction bull trout used the area of the channel where the temperature was 11°C due to ground water seeps.

Bull trout are noted to begin spawning as soon as conditions are suitable and redds are constructed. Temperature may be the primary cue used by the fish to determine when to begin migratory movements (Elle and Thurow, 1994; Swanberg, 1997) as well as to initiate spawning (Kramer, 1994). It is important that temperatures at the initiation of spawning be within a range that would not hinder ovulation and would not cause obvious harm to offspring of any early spawning individuals.

The field observations and citations noted above are in strong concurrence that spawning behavior (pairing and redd construction) will not begin 7DADMax temperatures fall below 8.45-9.45°C, and that spawning itself will only be initiated once the daily maximum temperature falls below 7.45-8.45°C.

Laboratory Studies of Spawning Initiation

Only a single study was found that addressed the question of what temperatures are required to initiate spawning. In a study by Gillet (1991) ovulation in char was found to be completely inhibited at constant temperatures above 11°C and slowed down above 8°C as compared to fish held at 5°C. This would be correlated with 7DADMax values of 11.62-11.93°C and 8.62-8.93°C, depending upon the constant test exposures being treated as if they represent on-day average and seven-day daily average stream exposures. Transfers from 8°C to 5°C were found to stimulate ovulations. Gillet also found that exposure to temperatures of 8°C prior to ovulation were favorable to fecundity rates, and assumed based on their work that very cold water was only necessary during the last weeks before spawning. The work of Gillet suggests that for the closely related Arctic char, temperatures should be falling below 8°C to stimulate healthy spawning, and falling towards 5°C to ensure full survival of fertilized eggs (only 11, 8, an 5°C were tested, so specific incubation thresholds were not determined). Based on this one laboratory study it would appear that a 7DADMax of less than 8.62-8.93°C is necessary to allow healthy ovulation to occur in bull trout.

Summary on Spawning Initiation Requirements

There is strong agreement among both field and laboratory research and observations on the spawning requirements of bull trout. The weight of the evidence supports the position that initial spawning behavior (pairing and redd construction) is hindered by daily maximum stream temperatures above 9-11°C and that the act of spawning may be impaired by daily maximum water temperatures greater than 8-9°C.

Laboratory Studies on Incubation Success

Only a few studies were found that tested the incubation requirements of bull trout in the laboratory. Fredenberg (1992) reported that eggs from wild bull trout incubated at an average temperature of 3.1°C had egg survival averaging 97.4% from unfertilized egg to eye-up and 97.1% from unfertilized egg to hatch. Eggs were subsequently collected from the hatchery raised broodstock and incubated at an average temperature of 5.8°C (5.0°C minimum and 6.6°C maximum), and while no growth or survival data was collected the author suggested that it appeared normal. Fredenberg, Dwyer, and Barrows (1995) collected gametes from wild spawning bull trout from the Swan River drainage of northwest Montana during September of 1993 and 1994. Fertilized eggs were produced by paired matings and incubated in 1993 at approximately 3.1°C with a resultant 97.1% survival from green eggs to hatching. Eggs in 1994 were incubated at approximately 6.5°C with a resultant 95.5% survival.

McPhail and Murry (1979) tested incubation of bull trout at constant laboratory temperatures of 2, 4, 6, 8, and 10°C in a series of three replicate tests. In the one test lot that escaped high transit-related mortality during movement to the laboratory after fertilization, McPhail and

Murry (1979) found that survival was excellent (90-95%) at 2, 4, and 6°C, good (85%) at 8°C, and poor (20%) at 10°C. In the two other test lots, which experienced significant transit-related stress (40% egg mortality during transit), survival rates were noted to steadily decline from 2 to 4, to 6°C and drop to zero at 8 and 10°C. Similarly, constant test temperatures in the range of 7-11°C were reported to result in "poor" survival in hatchery culture by Brown (1985). McPhail and Murry (1979) noted that mortalities at low temperatures (<6.0C) typically occurred at blastopore closure, while at high temperatures (>8.0) mortality is associated with hatching. In studies on the related species of Arctic char, Humpesch (1985) reported optimal incubation to occur at 5°C.

The above studies generally found that constant temperatures in the range of 3.1-6.5°C capable of producing excellent (90-97.4%) survival of char eggs, with survivals equally high throughout the range. At temperatures 8 to 10°C survival rates may drop precipitously from 85% to 0%. The research suggests that a constant temperature of 6.5°C may most confidently define the upper limit for fully protecting incubation. This would be equivalent to a 7DADMax temperature of 7.43°C when correlated as if it were a one-week average daily exposure, and equivalent to a 7DADMax temperature of 8.5°C when correlated as if it were an incubation season-long average exposure (assuming a stable stream temperature with 0-2°C diel variation). Based on the above, the laboratory studies suggest full incubation protection will occur if the highest 7DADMax temperature during the incubation period does not exceed 7.43-8.5°C. It is important to note that this process is not trying to determine an acute threshold for eggs or embryos. It only identifies temperatures that can occur at the initiation of incubation that will fully protect native char incubation under a normal temperature regime (i.e., fall cooling trends).

It is important to note that even though 2°C has been shown to be suboptimal at a constant incubation temperature, natural seasonal declines in temperature down to 2°C in the incubation period are unlikely to reduce survival rates. Salmonids have been shown to undergo conditioning in the early stage of incubation that allows excellent survival at very low temperatures occurring later. Where the conditioning does not occur, and the eggs are incubated at an early stage at very low temperatures, significant reductions in survival have been noted (Murry and Beacham, 1986; Seymour, 1956). This assertion is also supported by work showing that newly hatched bull trout alevins are tolerant of temperatures near 0°C (Baroudy and Elliott, 1985) and that the lower limit for hatching in the related Arctic char is less than 1°C. Such conditioning, however, may not only protect embryos from later exposure to colder waters but may help increase tolerance for warm water fluctuations as well. Bebak, Hankins, and Summerfelt (2000) examined the hatching success and posthatch survival of three stocks of Arctic char and found that if incubation had been well initiated at a favorable (6°C) temperature then later transfers to waters as warm as 10-12°C still allowed for excellent hatch rates (90-98%). It is noteworthy, however, that they also found that survival rates post-hatch declined over time at both 10°C and 12°C.

Field Evidence on Incubation Requirements

Little evidence was found from field studies on the incubation requirements of bull trout or Dolly Varden. In one study that was reviewed, however, it was noted that bull trout redds in the upper Flathead River basin in Montana had mean temperatures that ranged from 2.1-5.4°C (Weaver and White, 1985). This season-long estimate of average field temperatures would correlate with a 7DADMax temperature range of 4.1-7.4°C. It is important to point out that just noting the average temperature of redds does not indicate whether it was healthy, and is not very useful for describing of the upper boundary for successful incubation. For this reason, only the upper half of the range will be used to represent this line of evidence, the next preferred option would be to not use this range at all to estimate incubation requirements. Based on the above discussion, field temperatures of bull trout redds should be considered to have an upper range of 5.75-7.4°C.

Conclusion on Spawning and Incubation

While spawning and incubation were discussed separately above, it is important to recognize they actually occur concurrently in the natural stream environment. Once spawning has occurred the eggs begin to incubate. The multiple lines of evidence created from the wide variety of field and laboratory studies can be brought together in support of selecting a temperature standard for application at the beginning of the spawning and incubation period. The focus on the temperature at the initiation of incubation is viewed as appropriate since temperatures will be at their highest at this time. They should also be on a trend of fall cooling that will soon reach temperatures that are naturally determined by the elevation and geographic location of the site. The interim conclusions from each line of evidence are summarized below:

Table 4.1. Spawning and Incubation requirements of native char.

Line of Evidence	**7DADM - Range (°C)**	**Median (°C)**
Field observations on spawning initiation	***7.45-8.45***	***7.95***
Laboratory studies on spawning initiation	***8.62-8.93***	***8.77***
Laboratory studies on incubation success	***7.43-8.5***	***7.97***
Field study on typical average redd temperatures in Montana	***5.75-7.4***	***6.57***
Best Estimate of Threshold	***7.31-8.32***	***mid. pt. 7.82***

The range of these independent lines of evidence is 5.75-8.93°C with a mean range of 7.31-8.32°C and an overall midpoint of 7.82°C. This strongly suggests that a 7-day average daily maximum temperature of 7.82°C will fully protect the spawning and incubation of char. In recognition that temperatures of 8.0°C have been noted as hindering spawning in char, it may not be advisable in this situation to select a spawning threshold value from the upper end of the range presented above. It is concluded that a 7-day average of the daily maximum temperatures of 7.5-8.0°C best represents the highest temperature that can occur at the initiation of spawning without causing detrimental effects to either spawning or subsequent incubation.

iii) Juvenile Rearing

Field Distribution Work Examining Fish Presence

Dunham et al. (2001) surveyed the distribution of juvenile/small bull trout (Note: small resident stock fish cannot be distinguished apart from juveniles of migratory stocks) in 6 basins (109 sites) in Washington state and found that summer maximum temperatures best defined their presence in streams. In their study, 95% of the bull trout were found in streams with temperatures above 12°C with an interquartile range of 13.3-14.7°C (with the median and mode both at 14°C). This is similar to a study by Rieman and Chandler (1999) who examined 581 sites throughout the Western United States and found that the majority of sites with juvenile/small bull trout had summer maximum temperatures of 11-14°C (95% were from waters with summer maximums less than 18°C). Goetz (1997b) surveyed 13 drainages in Washington and Oregon and was unable to find juvenile bull trout in streams with temperatures above 14°C. In a study in British Columbia, Hass (2001) found that the warmest study streams containing bull trout (resident juveniles or adults) had summer maximum temperatures of 16°C, which is similar to the findings of numerous other researchers that 15-16°C formed the upper temperature limit to bull trout (juveniles or adults) summer distributions (Fraley and Shepard 1989, Shepard 1985, Goetz, 1989, Pratt, 1992, Martin et al. 1991) and that a temperature of 15°C can trigger the out-migration of char from otherwise suitable habitat (Goetz, 1997). The general findings for bull trout discussed above are also supported by the work of Jensen (1981) who found that 14°C (as a 10-day mean) appeared to form a barrier to the distribution of the closely related Arctic char.

The above studies demonstrate that daily maximum temperatures in the range of 14-15°C (7DADMax 13.45-14.45°C) set the upper boundary for commonly finding juvenile/small bull trout. It is important to note that some researchers have both wider and narrow margins of distribution. Some authors have found that colder summer maximum temperatures (10-11.5°C) formed the general limits to bull trout distributions in specific watersheds (Ratliff, 1987). While other authors have reported finding juvenile bull trout at much warmer (17-20.5°C) temperatures (Brown, 1992; Goetz, 1989, Adams and Bjornn, 1997; Reiman and Chandler, 1999). It was noted by Adams (1999) that bull trout found at 20.5°C held in the coolest water available in the area (<17.2°C) and looked physically unhealthy. This point is made to remind the reader that the mere presence of a fish does not indicate that it is healthy or that the stream is capable of supporting healthy populations.

Field Work that Considered Dominance, Density, and Competitive Advantage

While studies that describe the stream temperatures associated with the presence of a species are a useful line of evidence, they cannot be used to say whether or not the population is in good health at the observed temperature regimes. Researchers have tried to answer the question of what is healthy for bull tout in field studies by identifying sites with high densities of bull trout, and by identifying temperatures beyond which bull trout begin to loose dominance over other competing species. Health has also been assessed more directly by evaluating the condition of the fish using standard bio-metrics.

Haas (2001) found that a 7-day average of the daily maximums of 11.6°C (correlating with a single daily maximum of 12.15°C) consistently determined the dominant presence and better condition of bull trout in 26 sites in the Columbia River drainage in British Columbia. Haas reasoned that bull trout populations would be supported by maintaining summer maximum temperatures below 13°C, and noted that rainbow trout were found to be dominant over bull trout and in better condition as summer maximum temperatures approached 14-15°C. This corresponds well to the Dunham et al. (2001) finding that 90% of the sites that did not have bull trout had summer maximum temperatures greater than 13.5°C (non-char sites had an interquartile range of 14.6-19.8°C and a median of 17°C). It also corresponds well with Williams and Mullen (1992) finding that rainbow trout excluded the first two age classes of bull trout at weekly average temperatures above approximately 11-12°C (correlating with single day maximums of 12.49-13.49°C). Williams and Mullan (1992) found that bull trout growth in the Early Winters Creek basin of northern Washington steadily increased with increasing temperatures at three synchronous test sites having annual maximum weekly average temperatures of 8.7, 10.3, and 11.7°C, respectively. The maximum weekly average of 11.7°C correlates to a 7DADMax of 12.63°C. Growth was not tested at any warmer sites, thus the 7DADMax temperature that would allow for optimal growth in this stream system was not identified, but would likely be greater than 12.6°C. Similarly, Martin et al. (1991) and Goetz (1989, 1997) concluded that bull trout are dominant in streams with summer maximum temperatures less than 13°C. Saffel and Scarnecchia (1999) examined 18 reaches of six streams and found that the density of bull trout increased with increasing maximum temperature below 14°C (range 7.8-13.9°C) and decreased with increasing temperature above 18°C (range 18.3-23.3°C). The highest densities were found in reaches with maximum summer temperatures between 10-13.9°C. In this work there were no study streams having summer maximum temperatures within the range of 14-18°C, so it cannot be said whether or not densities would have begun to decline just above 14°C. Kitano et al. (1994) found that brook trout and cutthroat trout coexisted with bull trout in the Flathead River basin in Montana in waters with a temperature range of 5.3-8.9°C in early September, but they provided no information on the relative health of these populations or on when competition would be impaired.

Based on the above works, it is reasonable to expect that streams with summer maximum temperatures of 12-14°C (7DADMax 11.45-13.45°C) will be capable of producing and maintaining strong populations of bull trout. Not all of the research examined, however, fully supports this assertion. Sexauer and James (1997) studied four bull trout streams in the Yakima and Wenatchee River watershed in central Washington that were selected because they were considered "healthy" and found summer maximum temperatures in the year the study was conducted ranged from 9-12.5°C. Further, Ratliff (1992) and Ziller (1992), reported that bull trout began to lose dominance as summer average temperatures rose above 7.9°C (correlating with single day maximums of 10.45°C).

The wealth of studies across the Northwest when considered in combination demonstrate some strong patterns of occurrence. Any study of a single basin or stream needs to be carefully considered prior to accepting its conclusions. For example, in the cold groundwater dominated Metolius River system in Oregon, Ratliff (1987) reported that bull trout were rarely found at temperatures above 10°C. While true, it is important to recognize that warmer waters are largely unavailable in this tributary system. Thus care should be exercised before concluding that 10°C has been shown to create a barrier to bull trout populations. Similarly, many of the studies were conducted over a single year, and thus the long-term relationship between the presence healthy populations and maximum ambient temperatures at the site is often not documented. So while Sexauer and James (1997) studied streams with healthy populations, they only reported temperatures from a single year. The actual temperature regime for these sites, which hold healthy char populations, may include years with warmer temperatures than those observed during the study year.

Summary of Evidence from Field Studies on Juvenile Rearing

A preponderance of juvenile/small bull trout in Washington may be found in streams with summer maximum temperatures between 13.3-14.7°C (7DADMax 12.75-14.15°C). This is reasonably consistent with surveys extending throughout the Western states that found most juvenile use to occur in stream segments with maximum temperatures not exceeding 14°C. It is also well supported by studies of in-stream growth, density, and competitive dominance which suggest healthy bull trout streams have summer temperatures that do not exceed 12-14°C. While field studies are a very useful line of evidence for developing temperature criteria, they can be strengthened by cross-checking the conclusions with laboratory findings.

Laboratory Studies Supporting Juvenile Rearing

In a controlled hatchery environment, Fredenberg et al. (1995) found that constant exposure to 8.3°C produced greater growth of bull trout at maximum rations than at lower test temperatures. This would be equivalent to a single-day maximum of 9.79°C (7DADMax 9.24°C) if the constant hatchery temperature is treated as it represented the warmest one-week average stream temperature; and a single-day maximum of 10.85°C (7DADMax 10.3°C) if it were equivalent to a summer season-long average stream temperature.

In a laboratory study, McMahon et al. (1998) found that growth was highest at a constant 12°C, but not significantly less at 14 and 16°C at maximum rations. Growth declined sharply at temperatures greater than 18°C and less than 10°C. In follow-up tests, the authors (McMahon et al., 1999) found that growth at maximum and at 66% of maximum rations were highest at 16°C, but that at 33% of maximum ration growth was maximized at 12°C. In modeling the available calories in low productivity streams (the ration used and the basis for its selection was not provided) against the growth observed in their tests, the authors suggested the optimum growth range of 12-16°C would shift to 8-12°C. McMahon et al. (2000) examined the growth of bull trout over a 60-day period in both constant and fluctuating temperature regimes. Peak growth at a moderately restricted ration (0.66) occurred at 12.4°C at a constant temperature and at a mean of 12.2°C in fluctuating treatments (+/- 3°C around the mean - giving a 60-day average daily maximum of 15.2°C). Peak growth at an unrestricted ration occurred at 13.2°C and at a severely restricted ration (0.11) occurred at 12.3°C. In this work the authors found that growth was higher in constant exposure tests overall, and opined this was due to the fluctuating temperatures increasing metabolism without increasing food intake. Similar findings were produced using the related Arctic char (Swift, 1975; as cited in Jensen, 1995; and Jobling, 1983) where maximum growth occurred at about 12-14°C (at satiation rations). These growth studies may help explain why Shepard et al. (1984) found that bull trout growth was slower in the middle fork of the Flathead River, Montana, even though it was warmer and more productive. The work of McMahon et al. (2000) suggest that an average temperature of 12-13°C can produce maximal growth under both severely restricted and satiation diets, respectively. A constant laboratory test temperature exposure of 12-13°C can be correlated with 7DADMax summer stream temperature maximums of 12.93-13.93°C based on correlations with the warmest one-week average stream temperature; and 7DADMax summer maximums of 14-15°C based on correlations with the summer season-long average stream temperature. There is reason to also believe that in some cases growth could be maximized, or not statistically different, at even higher constant temperatures. Their work also suggests that daily maximum temperatures of 15-16°C (7DADMax 14.45-15.45°C) may be producing thermal stress or excess metabolic demands that may hinder growth in juvenile char that are at otherwise healthy daily mean temperatures. This is supported by the findings of Bonneau and Scarnecchia (1996) who noted that temperatures above 15-16°C are associated with increased metabolic stress and swimming impairment in bull trout. The line of evidence produced using the above laboratory studies suggests that streams with 7DADMax temperatures not exceeding 12.93-15°C are likely to fully support the growth of juvenile char.

Laboratory Studies Examining Competition for Food

Brook trout are a species of char that have been widely introduced in the northwest that have often been cited as eliminating bull trout from their native habitat. McMahon et al. (1999), found that the presence of brook trout in sympatry (together) with bull trout resulted in significantly greater growth of brook trout and significantly lower growth for bull trout than occurred with either species in allopatry (alone), especially at constant water temperatures equal to or greater than 12°C. McMahon et al. (2000) examined bull trout and brook trout competition under two constant (11 and 17°C) temperatures. At a constant 11°C there were not significant differences in the growth of bull trout and brook trout in allopatry and sympatry. However, at the higher temperature (17°C) brook trout grew significantly more (a

2.5-times greater growth rate) than bull trout in both allopatry and sympatry.   observations were also made at temperatures of 8 and 16°C. When in the presence of brook trout, bull trout feeding rates declined 50% at 8°C and 64% at 16°C, whereas feeding by brook trout showed no change. The work of McMahon et al. (1999, 2000) suggests that as average water temperatures rise above 12°C bull trout may begin to loose their competitive ability against brook trout. It also points out the difficulty of trying to protect bull trout from displacement by brook trout since the brook trout are capable of significantly out-competing the bull trout even at very low temperatures (8°C).

In trying to correlate the laboratory studies on competition to stream temperatures, it is important to recognize that competition may be related as much to the absolute temperature at any point in time as much as a weekly or seasonal average temperature regime. However, since the effect of competition on the health of a species will not be determined by a portion of a single day allowing for detrimental competition, it is still considered reasonable to correlate average stream temperatures with the constant laboratory test temperature at which competition was not favored by water temperature (12°C). A single daily average and a weekly average are used below to represent the effects found with constant laboratory exposures and make conversions to a 7DADMax temperature metric. The above cited work suggests that a 7DADMax summer temperature of 12.62-12.93°C may best describe a stream which does not provide any thermal advantage in competition between bull trout and brook trout. It is important to remind the reader that the laboratory tests did not include constant temperatures within the range of 12-16°C making it difficult to determine if a threshold exists within this range above which most of the change in competitive ability occurs.

Summary of Laboratory Studies

The work of McMahon et al. (1999, 2000) suggest that a constant or average temperature of 12°C can produce maximal growth under even severely restricted diets. Their work also suggests that as water temperatures rise above 12°C bull trout begin to loose their ability to compete with brook trout. As noted above, the research on competition seems best viewed by comparison with a single week's average temperature, rather than as a single day of detrimental competition. So, while the range produced for the laboratory growth tests is compared as either weekly average temperatures or season-long average temperatures, the laboratory study on brook trout competition is only compared here as a weekly average temperature. After appropriately converting the constant laboratory test results to 7DADMax temperature metrics, the studies on growth and competition overlap each other. Growth should be maximized at a 7DADmax of 13.5-15.5°C and competition with brook trout should not be materially worsened at temperatures below 13.5°C.

Conclusion on Rearing

The multiple lines of evidence created from the wide variety of field and laboratory studies can be brought together in support of selecting a summer rearing temperature standard. The interim conclusions from each line of evidence is summarized below:

Table 4.2. Juvenile rearing of native char:

Line of Evidence	7DADM - Range (°C)	Median (°C)
Field studies on limit to where most commonly found	***13.45-14.45***	***13.95***
Filed studies on density, and dominance	***11.45-13.45***	***12.45***
Laboratory Growth Studies	***12.93-15***	***13.96***
Laboratory Competition Studies	***12.62-12.93***	***12.75***
Best Estimate of Threshold (averages)	***12.61-13.96***	***mid. pt. 13.29***

The range of these independent lines of evidence is 11.45-15°C with a mean range of 12.61-13.96°C and an overall midpoint of 13.29°C. This strongly suggests that streams having 7-day average daily maximum summer temperatures not exceeding 13.29°C are fully protective of juvenile/small bull trout rearing. After cross checking this conclusion against each independent line of evidence, no overriding factors of disagreement appear to exist. The slight conflict with the field studies on density and dominance, and the laboratory competition studies do, however, suggest that rounding the estimate down to the nearest 0.5°C increment, rather than up, may be more appropriate. It is therefore concluded that 13°C as a 7-day average of the daily maximum temperatures will fully support the life-stage of juvenile/small char rearing.

iv) Migratory Adult and Sub-Adult Char Populations

As noted previously, fluvial and adfluvial forms of char may remain in the area of their natal stream for 1 to 3 years and then migrate significant distances to more productive waters for greater juvenile growth opportunities (Pratt, 1992; Ratliff, 1992; Riehle et al., 1997; Fraley and Shepard, 1989; Goetz, 1989). The larger size of these migrants is generally believed to allow them to better compete for resources, and to make use of a larger prey base that includes the juvenile fish of other species. This is similar to the way the ocean is used by Pacific salmon to enable them to grow to significantly greater sizes than would be possible if they were to remain in freshwater tributaries. This may be a very important survival trait of these migratory populations, and serve to free up food resources in the tributary system for juvenile char. These adult and non-spawning sub-adult fish, may also move out of tributary systems to hold in lower main stem areas during the winter to avoid unsuitable winter conditions of ice and storm flows. In Washington, bull trout may migrate all the way from headwater streams to the Puget Sound to feed and rear. Relatively little is known about the temperature preferences and requirements of these migratory fish which makes setting temperature criteria for them problematic.

Heimer (1965) examined the use by Dolly Varden of an artificial spawning channel on the lower Clark Fork River in Idaho below the Cabinet Gorge Dam. The channel was constructed in an area where cool spring water would make the artificial channel cooler than the main stem river during part of the year. Temperatures in the majority of the spawning channel were between 8-11°C. The author noted that fish observed in the spawning area were consistently in the areas of cooler water. As river temperatures declined in the fall a portion of the fish in the spawning area left without spawning. These fish were presumably present because of the cooler waters, as the main stem temperatures in the Clark Fork River did not decline to below 13.9°C until after September 26th. The Washington Water Power Company (1995) also studied the distribution of fish in the lower Clark Fork River in Idaho and found that while main stem river temperatures were 18°C on September 28th temperatures in the adjacent channel used by bull trout for spawning was 11°C. These two studies when considered together suggest that bull trout will actively avoid rivers having fall water temperatures above 18°C. The strong contrasting temperatures between the river and the channel, the combination of spawning and non-spawning fish, competition with other salmonids also using the channel for refuge, and the lack of specific temperature metrics in association with char movements all combine to prevent using these studies to estimate a threshold response.

Swanberg (1997) found that bull trout residing in the lower Blackfoot River in Montana migrated out when daily maximum temperatures reached 18-20°C, and non-spawning sub-adult fish began returning once maximum temperatures declined to 12°C. The few fish that did not migrate were found in association with the confluence of a small cold tributary with a daily maximum temperature of 12°C. Elle and Thurow (1994) found that adfluvial bull trout in the Rapid River in Idaho began leaving the lower system in peak numbers seven out of nine years as the daily maximum temperatures began to exceed 10°C and returned as the temperature of the lower river declined to 10°C. These fish moved to lower main stem rivers to hold for the winter. Movements to avoid unhealthy winter conditions are common in salmonids, and Jakober et al. (1998) found that bull trout and westslope cutthroat trout in two drainages in Montana made extensive downstream movements as temperatures dropped precipitously in the Fall. These movements were most extensive in mid-elevation streams where frequent freezing and thawing led to anchor ice formation and super cooling (<0°C) of the water.

Several very import issues and questions need to be addressed prior to setting criteria to protect these adult and sub-adult fish. These include:

- Is it ecologically appropriate to base temperatures in salmon and steelhead strongholds on the temperature requirements of char?
- How, and should, populations that are in main stems to rear be separated from those that may be leaving inhospitable winter conditions in the tributaries?

- Is rearing protected only by maintaining favorable temperatures in these lower rivers year-round, or can migration out of the lower reaches during maximum summer temperatures be considered a normal and thus acceptable natural pattern?
- Should temperatures considered protective of these adult and sub-adult fish be based on assumptions of relative food abundance and lack of competition?

Until these questions are reasonably answered, there does not seem to be sufficient foundation in the research to confidently support recommending a temperature threshold value in lower main stem rivers that is colder than that appropriate for the protection of salmon and steelhead.

v) Lethality to Adults and Juveniles

As shown above in the discussion of juvenile rearing, waters that fully protect the health of native char will have temperatures well below those posing a threat of acute lethality. Thus, the conclusions that follow are intended for application in the evaluation of special projects. They can also be used as an aid in assessing the relative safety for char moving through main stem rivers predominantly protected for salmon and steelhead.

The only research found directly testing one of Washington's native char species (bull trout) was the works of McMahon et al. (1998, 1999) as published in Selong et al. (2001). McMahon et al. (1998, 1999) conducted 60-day lethality studies of juvenile bull trout. In their 1998 study, 98% survival occurred at temperatures between 7.5-18°C. Mortality was 21% at 20°C over the 60-day test period, but was 100% within 24 hours at 26°C, within10 days at 24°C, and within 38 days at 22°C. In the 1999 study, survival was 46% at 21°C and 53% at 20°C, with the time to 50% mortality varying from 10-days at 23°C to 24 days at 22°C. Using the data from both the 1998 and 1999 studies, the authors determined a 60-day UUILT (Ultimate Upper Incipient Lethal Temperature) of 20.8°C for juvenile bull trout and estimated that a 7-day UILT (Upper Incipient Lethal Temperature) would be 23.5°C (Selong et al., 2001).

The work of McMahon et al. (1998, 1999) and Selong et al. (2001) strongly suggest that lethality will be prevented at constant temperature exposures of 18-19°C or less. This assertion comes from two sources of information. The first is that in tests at a constant 18°C there was at least 98% survival over a 60-day exposure. The second is derived by using the 60-day UUILT of 20.9°C. After applying the adjustment factor recommended by the USEPA (Brungs and Jones, 1977) to change from a temperature that kills 50% of the exposed fish to a temperature that is unlikely to kill any fish. The non-lethal temperature estimate would change to a constant 18.9°C (20.9°C minus 2°C). Constant temperatures of 18-19°C would be correlated to 7DADMax temperatures of 21.18-22.18°C and 1-day maximums (1DMax) of 22.13-23.13°C when treated as if they were based on weekly temperature exposure. When treated as if they were based on a season-long exposure (which may be justified in this case since the laboratory tests were 60 days long) these values change to 22.64-23.64°C (7DADMax) and 23.60-24.60°C (1DMax). This line of evidence suggests that acute mortality will be prevented in acclimated fish by maintaining 7DADMax temperatures below 21.18-23.64°C or 1-day maximum temperatures below 22.13-24.6°C.

While a constant temperature exposure would generally be similar to an average temperature in a natural stream, daily maximum temperatures above the lowest determine lethal concentration (20.9°C with a 60-day exposure) will begin to accumulate lethal stress. To avoid exposure to temperatures that create lethal stress altogether (would eventually cause lethality if exposure period is sufficient) daily maximum temperatures should not exceed 20.9°C (7DADMax 19.95°C). Since this is not an estimate of a threshold beyond which acute mortality would be expected, it should only be viewed as a line of evidence for establishing a lower-bound estimate of temperatures that would avoid lethality and severe stress.

Using the data of Selong et al. (2001) we can also estimate the general risk of mortality from multiple days of exposure in the potentially lethal range. By assuming that temperature exposure in the lethal range is additive (DeHart, 1974, 1975; Golden, 1978), and by examining the potential lethal dose that occurs with each hour spent over the lowest lethal level (20.9°C), the risk of mortality can be reasonably described. The equation in Selong et al. (2001) giving the relationship between exposure temperature and time to mortality (LC50) can be used to estimate the number of hours that would need to be spent at each daily temperature increment (one-hour intervals used herein) above the an ultimately lethal temperature (20.9°C) to cause mortality (LC50). Using this approach, the number of daily cycles of temperature that would occur before causing mortality can be predicted. Based on this technique, bull trout in a stream with a daily average temperature of 20.9°C (21°C) and a diel range above the daily mean of 4.13°C would be expected to experience high mortality (LC50) in approximately 10 days or less. In streams with mean temperatures 19 and 18°C, high mortality (LC50) would occur after 54 and 163 days of repeat exposure, respectively. This approach to evaluating the risk of mortality is only useful in assessing relative risk. Nevertheless, it provides a good support for the position that weekly average temperatures of 18-19°C and summer peak daily maximum temperatures of 22-23°C (7DADMax 21.05-22.05°C) pose little risk of creating acutely lethal conditions in char populations.

While having relatively sensitive optimal temperature limits, adult and juvenile char do not appear unusually sensitive to acute temperature limits. With acclimation, juvenile and adult char are very tolerant of temperature extremes in a laboratory environment – capable of withstanding temperatures of –1.2°C (below zero) for up to 5 continuous days and having upper lethal temperature limits similar to, but towards the lower end, of that for juvenile Pacific salmon (Selong et al. 2001).

Table 4.3. Temperature induced lethality of in native char.

Line of Evidence	7DADMax (°C)	Midpoint (°C)
Direct laboratory observation of no mortality, and conversion of LC50 to no effects temperature using Brungs and Jones (1977).	21.18-23.64	22.41
Laboratory estimate of temperature exerting lethal stress	19.95	19.95
Modeling risk associated multiple day exposures to fluctuating temperatures	21.05-22.05	21.55
Best Estimate of Threshold	*20.73-21.88*	*mid. pt. 21.31*

The range of the independent lines of evidence discussed above is 19.95-23.64°C with a mean range of 20.73-21.88°C and an overall midpoint of 21.31°C. This strongly suggests that not allowing single daily maximum temperatures to exceed 21.31°C (7DADMax of 21.35°C) will prevent acute lethality in char populations. Based on the above it is concluded that an annual highest single-day maximum temperature not exceeding 21°C will prevent direct lethality to Washington's juvenile native char.

It is important to point out, however, that only juveniles of one stock of bull trout were tested. Juvenile Dolly Varden, other stocks of juvenile bull trout (Beacham and Withler, 1991), and adults of either species could be somewhat more (or less) sensitive (Coutant, 1970; Becker, 1973; Bouck and Chapman, 1975). It would be unwise to assume that temperatures at the upper end of the range identified above are of equal merit for consideration as an acute criteria until more stocks have been tested. The data cited below by Ugedal et al. (1994) lend further support for being cautious about assuming the upper end of the predicted range would be fully protective.

Support for the above findings can be found in research on related species of char (Arctic char and Arctic grayling). The estimated LT50 (lethal to 50% of test population within 7 days) values for a variety of char species at acclimations of 5-20°C generally group between 21.5-24°C. Lohr et al (1996) determine a 7-day LC50 of 23-25°C for juvenile Arctic Grayling; Lyytikainen et al. (1997) determined a 14-day LC50 of 23-24°C for juvenile Arctic Char; and Baroudy and Elliott (1994) determine a 7-day LC50 of 21.5-21.6°C for Arctic char fry and parr. These ranges were determine primarily by varying the acclimation temperatures. In a modified CTM test, the authors also found that fry and parr experienced 10-minute LT50 values of 24.79-26.57°C at acclimation temperatures from 10 to 20°C. Ugedal et al. (1994), in conducting a 104-day growth test using Arctic char, found that when water temperature rose from an initial 12-13°C (daily mean) to a brief 20°C (average temperature for approximately 10 days) before falling again a slight increase in mortality (approx 5%) occurred during the period that water temperatures reached 20°C.

Some additional information from studies with these related species are worth noting here. At full acclimation to temperatures of 15-18°C, sudden exposure to 29°C water produce LC50 values within 2-4 minutes in Arctic char (Lyytikainen et al., 1997). At an acclimation of 15°C a test temperature of 26°C produced LC50 results in just 44 minutes. Baroudy and Elliott (1994) found that the Arctic char alevins had 7-day UILTs of 18.67, 19.67, 20.83, and 20.79°C at acclimation temperatures of 5, 10, 15, and 20°C. Alevins experience 50% mortality within ten minutes at 23.33, 25.09°C, and 25.39°C at acclimation temperatures of 5, 10, and 15°C.

Research useful for estimating daily maximum temperatures that will protect developing embryos and alevins was only found for Arctic char (Baroudy and Elliott,1994). Since the work of Baroudy and Elliott was based on a non-indigenous species of char, and tested only the short-term effects to the alevin life-stage it is insufficient for setting an acute lethality threshold for char incubation. It can be used, however, to demonstrate that incubation of char is more sensitive then juvenile rearing, and to suggest that daily maximum temperatures would likely need to remain below 16.7°C to prevent acute lethality to char alevins. This estimate was made by subtracting 2°C from the LC50 value determined at an acclimation temperature appropriate for incubation (5°C) to convert to a temperature that should not produce any short-term mortality (USEPA, 1977).

b) Salmon and Trout

i) General Life History Information

<u>Chinook Salmon</u>

Chinook salmon (*Oncorhynchus tshawytscha*) are found in most of the larger streams of the Columbia River drainage, and the coastal and Puget Sound drainages. Juvenile chinook salmon spend about a year in fresh water before smolting and migrating to the Pacific, where they generally remain from three-four years before returning to their natal streams to spawn. Adults begin the ascent of coastal streams in late May and early June and principally spawn through September. Chinook salmon are primarily divided into two stock types, based on the season they initially return to fresh waters. These are spring-run and fall-run stocks, but in some areas a third, summer-run, stock may be identified. Spring run fish begin entering freshwaters from May through June, and typically hold in deep pools and at the mouths of cool tributaries until the fall rains begin and stream levels go up sufficiently to allow them to reach their upriver spawning sites. These spring run fish tend to spawn higher in the watersheds than the fall run stocks. Fall chinook migrate up the streams in August and September and spawn as soon as the spawning grounds are reached when water temperatures are between 5.6-14.4°C. Eggs hatch in about two months and the young remain in the gravel for two-three weeks prior to emerging. Juveniles remain in freshwater from a few days to three years. Usually, juvenile fall chinook feed for a short time and then migrate to the ocean, whereas most juvenile spring chinook remain in the stream for one year before migrating (Wydoski and Whitney, 1979). In Washington, 96 of the 98 chinook stocks assessed began spawning after August 1, and 96 of 98 had midpoints in their spawning periods that were after August 23. After emerging from the gravel, chinook fry may remain in freshwater from just a few days to up to 3 years. Usually, fall chinook feed for a short time and then migrate to the ocean, whereas most juvenile spring chinook remain in the stream for one year before migrating to the ocean (Wydoski and Whitney, 1979).

Coho Salmon

Coho salmon occur all along the Pacific coast. While fourth in abundance of the Pacific salmon, coho provide the dominant harvest of sport fisherman (Wydoski and Whitney, 1979). In Washington, spawning adults are found in most streams of the upper and lower Columbia River drainage, and in the coastal and Puget Sound drainages. Coho spend their first (one to two) years in freshwater before becoming smolts and migrating to the ocean. Spawning generally occurs from September through December; although, a late run of large fish is known to spawn in January in the Satsop River. Like all Pacific salmon, adult coho die after spawning. Young hatch in 6-8 weeks depending on water temperature and emerge in about two-three weeks. Fry congregate in schools in the pools of the stream. Ruggels (1966; as cited by Chapman and Bjornn, 1969) found that coho did not use substrate as cover in the winter, and Hartman (1965) found that coho tended to lie near or on pool bottoms in aggregations.

Chum Salmon

Chum salmon are found in streams of the Puget Sound and coastal drainages, and up the Columbia to the Wind River (upstream from the Bonneville Dam). Spawning often occurs just at the head of tidewater. Upon emergence from the stream gravel, chum salmon fry begin to migrate to the ocean. Juveniles migrate to the ocean between March and June where they spend six months to four years. In Washington, chum salmon spawn primarily from October to December. Redds occur in medium or fine gravel in the stream riffles. Most of the high mortality from the fertilized egg to early fry state (70 to over 90%) is reported to occur during the embryonic stage due to suffocation from silt. Eggs hatch in two weeks to four and one-half months depending upon the temperature. Newly hatched fry (alevins) absorb their yolk sac in 30-50 days, again depending on temperature. Fry are usually in fresh water for only a few days after emerging from the gravel. They migrate downstream at night from April through June (Wydoski and Whitney, 1979). Little information was found on which to base a recommendation for juvenile rearing temperature limits for chum salmon; however, this is not a major concern. Considering that juvenile chum may only spend a few days in freshwaters, the temperature threshold established for the pre-emergent stages of development should result in cool waters remaining during the out-migration period. Thus even without a specific juvenile rearing criterion the freshwater portion of the juvenile life-stage will be fully protected. If unique situations appear to demand that a separate rearing standard be applied, the temperature threshold established to protect other Pacific salmon smolts during sea-water adaptation should be applied.

Pink Salmon

Pink salmon are the most abundant of the Pacific Salmon. Pink salmon ascend rivers along the Pacific coast; and in Washington, the Stillaguamish, Skagit, Snohomish, Puyallup, and Nooksack are the top producing watersheds. Pink salmon are similar to chum salmon in spending only a brief time in fresh water as juveniles and adults. Spawning in Washington occurs chiefly during August and September, usually near the mouths of streams, but sometimes spawning occurs far up into large rivers, such as the Skagit. Females usually dig redds in a riffle area with small to medium size gravel, but they occasionally spawn in the tail section of pools. In Alaska, a large percentage of pink salmon spawn in the intertidal areas. Eggs usually hatch in thee-five months, depending upon water temperature. The alevins and fry remain in the gravel for as long as several months at low temperatures in northern waters before emerging (Wydoski and Whitney, 1979). Washington state appears to be at the southern end of the range for streams that support consistently exploitable spawning runs of pink salmon. Pink salmon have a two-year life cycle which is so invariable that fish running in odd-numbered calendar years are effectively genetically isolated from those that run in even years (Bonar et al., 1989).

Sockeye Salmon

In Washington, populations of sockeye travel up the Columbia River to the headwaters of the Salmon River in Central Idaho. Populations also use Quinalt Lake on the Olympic Peninsula, Baker Lake, lakes Washington and Sammamish in the Puget Sound drainage, and Osoyoos Lake and Lake Wenatchee east of the Cascade Mountains. Sockeye differ from the other species of salmon because they require a lake environment for part of their life cycle. Although spawning typically occurs in the gravel of streams some may spawn along lake shores in areas where ground water percolates through the gravel. Eggs hatch in six-nine weeks. The young remain in the gravel for another two-three weeks. Newly emerged fry move from the spawning stream into the lake associated with the stream. Young sockeye live in the pelagic zone of the lake for one to two years years before migrating to the sea where they will remain for two years before returning to freshwaters to spawn (Wydoski and Whitney, 1979).

Steelhead

Steelhead is the popular name given to the anadromous form of *O. mykiss*. The anadromous form is found in coastal rainbow and interior redband trout groups and occurs from southern California to Alaska (Behnke, 1992). Steelhead populations can be broadly divided into spring-, summer-, fall- and winter-run stocks, depending upon the time the fish re-enters freshwater. Spring and summer-run fish enter fresh waters typically from May through August and move upstream to hold over until the following spring to spawn. Fall runs typically enter from September through November and spawn in the spring. Winter-run (December-March) steelhead may spawn soon after entering fresh waters. In general, summer-run steelhead spawn further upstream in the watershed than the fall- or winter-run fish. With a spring spawning stock, protection is achieved by not encouraging spring water temperatures to warm above fully protective levels during the spawning and incubation periods. Juvenile steelhead may remain in freshwaters for one to seven years before emigrating to sea, depending upon the stream temperature and the latitude, although, most stay in fresh water for two years (Wydoski and Whitney, 1979; Mullan et al., 1992). Mullan et al. (1992) note that summer-run stocks tend to remain longer in freshwater than winter-run steelhead, presumably because the colder temperatures of the headwaters streams preferred by summer-run steelhead retards their growth rate.

Rainbow Trout

The name rainbow trout is commonly applied to represent any or all of the members of *Oncorhynchus mykiss*. However, *O. mykiss* in Washington can be further divided into resident coastal rainbow trout; resident interior redband trout; and steelhead, the anadromous form of the coastal rainbow and redband trout. Coastal rainbow trout populations extend from Alaska to Mexico, and non-anadromous, or resident, populations occur throughout the entire range (Behnke, 1992). Redband trout are found east of the Cascades and in the Columbia River basin, and Behnke suggests that that the native redband trout of each basin has its own peculiarities and could probably be separated into several new subspecies. Behnke also notes that in the desert basins of the western states, the redband trout has evolved adaptations to live in extremely harsh environments characterized by great extremes in water temperature and flow.

Cutthroat Trout

In Washington, native cutthroat trout can be separated into coastal cutthroat (*Oncorhynchus clarki clarki*) and west-slope cutthroat trout (*Oncorhynchus clarki lewisi)*. Coastal cutthroat exhibit anadromous, potamodromous stream dwelling, potamodromous lake-dwelling, and headwater stream-resident life-history forms; while west-slope cutthroat exclude anadromous populations (Trotter, 1998). Behnke (1992) suggests that cutthroat trout enjoy a selective advantage over non-native trout in many high-altitude headwaters; presumably because they function better in colder waters. He notes that native cutthroat are quickly eliminated from waters where non-native trout become established. Cutthroat are displaced from preferred habitat in the presence of rainbow trout and coho salmon. The aggressive interaction of these other species may be heightened by warmer water temperatures and thus the displacement of cutthroat is lessened by cooler water temperatures (Pauley et al., 1989; Trotter, 1989; and Mullan et al., 1992).

Coastal cutthroat trout (*Oncorhynchus clarki clarki*) occur all along the Pacific coast from southern California to Alaska. Though rarely found more than 16 km inland, it is considered the most abundant of the cutthroat subspecies (Trotter, 1998). Sea-run cutthroat live to a maximum age of about ten years, as compared to resident forms which may live for only 4 to 5 years (Behnke, 1992).

In Washington, sea-run cutthroat may re-enter fresh water for spawning anytime from July through March (Pauley et al., 1989). Early-entering stocks in Puget Sound and Hood Canal typically occur from July through November with the peak in September and October. Late-entering migration peaks in December and January but continues through March (Trotter, 1989; Pauley et al., 1989). In southeast Alaska, Jones (1977; as cited in Pauley et al., 1989) found that migration began at 10-12°C and peaked at 9-10°C.

Pauley et al. (1989) suggests that prior to smolting and entering saltwater, sea run cutthroat juveniles may migrate up and downstream several times. They further suggest that in Washington and Oregon, downstream movement is reported to take place from March to June, but peaks in mid-May. They note that in southeast Alaska, juveniles have been reported to experience a peak of out-migration when water temperatures are between 4-6°C. Cutthroat parr may migrate to sea from ages one to six, but age two to four may be most common (Trotter, 1989; Pauley et al., 1989).

Stream resident forms of coastal cutthroat spend most or all of their life in or very near their natal streams (Trotter, 1989). In spring when water temperatures reach 5-6°C, mature resident cutthroat move onto the spawning gravel. Trotter (1989) suggests that potamodromous forms of coastal cutthroat do not move into spawning tributaries until very late winter or spring rather than in autumn to early winter as for anadromous fish. Similar to stream resident forms, they are reported to begin spawning as the water temperature increases to 5-6°C, which may occur from February through June. Lake-dwelling potamadromous coastal cutthroat first spawn at age 3 or 4, and then spawn almost every year thereafter for the remainder of their lives in the inlet and outlet streams of the lake (Trotter, 1989). Few sea-run cutthroat trout sexually mature before age 4, and not all returning fish spawn their first year back in freshwater (Trotter, 1989). Fish that do spawn, may return (39-41%) to spawn a second time, and some (12%) may return for a third spawning (Trotter, 1989; Pauley et al., 1989).

West-slope cutthroat trout, the interior form, have been found to spawn in April and early May with a peak around mid-April in Montana (Fraley et al., 1981). Trotter (1999) found an introduced population of west-slope cutthroat initiating spawning around June 1 at a temperature of 7°C in the Tolt River in Washington, and a natural population initiating spawning on June 29 at a temperature of 11°C in a stream in the upper Yakima River basin in Washington. Newly emerged fry move to low velocity stream margins, backwaters, and side channels adjacent to the main-channel pools and riffles (Pauley et al., 1989; Trotter, 1989). Trotter (1989) suggests that these young fish may move downstream to the main stem as early as the winter of their first year, but more generally later in the spring. With the onset of winter freshets, the fish may again move back into the tributaries. Older fish may migrate to sea where they will remain for two to five months concentrating in bays, and estuaries along the coast gaining weight before returning to fresh waters. It is considered unusual for cutthroat to over-winter in salt waters (Pauley et al., 1989). Fry of potamadromous forms may spend the first 1-3 years in the tributaries before commencing a lake-ward migration. These potamadromous fish may over-winter in the lower main stem of the river while anadromous fish are in the marine waters (Trotter, 1989). Pauley et al. (1989) cite research showing that while in freshwaters, cutthroat adults are associated with the deeper pools and slower velocity waters, while the fry are found in shallower, faster areas.

ii) Spawning Requirements

Field and General Observations on Spawning Temperatures:

The authors that have provided the following general observations of spawning temperatures rarely provided the associated temperature metric. Thus it is not clear most of the time whether or not they were referring to a range of daily average temperatures or a range of daily maximum temperatures. Other confounding factors include that the authors do not always make it clear that they are separating pairing and redd construction activity with actual spawning, and generally do not provide a copy of their methodology to use in determining if the temperatures were recorded at the site of spawning at the time spawning was taking place. For these reasons, the following information on temperatures at which spawning commonly occurs should be used cautiously.

Chinook Salmon

The technical literature reviewed for this paper notes a wide range of temperatures associated with the spawning of chinook salmon (5.6-17.7°C) (Seymour, 1956). The majority of these temperature observations, however, cite maximum temperatures below 14.5°C [Bell, 1986 (literature Summary); Piper et al., 1982; Wydoski and Whitney, 1979]. In the Hanford reach and in the Snake River in Washington, redd construction began as weekly mean temperatures dropped to 15.9°C and averaged 13.6°C during the weeks of spawning initiation from 1993-1995 (Groves and Chandler, 1999).

Coho Salmon

Coho salmon (*Oncorhynchus kisutch*) tend to spawn later and at lower water temperatures than the other Pacific salmon. In Washington, 79 of the 82 stocks of coho salmon assessed begin spawning after September 22, and 80 of 82 have midpoints in their spawning periods that occur after November 1. Spawning activity in coho may typically occur in the range of 4.4-13.3°C [Bell, 1986 (literature summary); Piper et al., 1982; Chambers, 1956, as cited in Andrew and Green, 1960; Gribanov, 1948, and Briggs, 1953, as cited in Sandercock, 1991].

Chum Salmon

Chum salmon are reported to spawn between 1-12.8°C, with a range of 7-10.5°C being most consistently identified [Beacham and Murray, 1986; Bell, 1986 (literature summary)]. In Washington, 65 of the 68 stocks of chum salmon (*Oncorhynchus keta*) assessed begin spawning after September 1, and 65 of the 68 stocks have midpoints in their spawning ranges that occur after October 8.

Pink Salmon

In Washington, 10 of the 12 pink salmon (*Oncorhynchus gorbuscha*) stocks assessed begin spawning after September 1, and 10 of 12 have midpoints in their spawning periods which occur after September 22. Spawning typically occurs between 7.2-14°C (Bonar et al., 1989), and may be optimally supported at temperatures from 7-12.8°C [Sheridan, 1962; Bell, 1986 (literature summary)]. This potential optimum range coincides well with an identified peak in spawning activity at 10°C identified by Sheridan (1962).

Sockeye Salmon

In Washington, 8 of the 8 stocks of sockeye salmon (*Oncorhynchus nerka*) assessed begin spawning after September 7, and 8 of 8 have midpoints in their spawning ranges that occur after October 3. Temperatures to support spawning activity in sockeye salmon have been identified as ranging from 7.2-12.2°C (Piper et al, 1982), with a preferred range between 10.6-12.2°C (Bell, 1986, literature summary). Chambers (1956; as cited in Andrew and Geen, 1960) reported that sockeye spawn on the falling portion of the cycle at 12.8 to 8.3°C. Andrew and Geen (1960) reported that spawning temperatures of sockeye in the Fraser River range from 7.2 to 12.8°C with a peak at about 10°C.

Steelhead Trout

In Washington, 101 of the 105 spring spawning steelhead stocks assessed ended spawning before July 1 (91 of the 105 ended prior to June 15), and 101 of 105 have midpoints in their spawning periods that occur before May 7. Spawning occurs primarily in the spring as water temperatures are rising. Bell (1986, literature summary) noted that spawning has been observed at temperatures ranging from 3.9-21.1°C. Hunter (1973; as cited in Swift, 1976) noted the preferred temperatures for spawning range from 4.4-12.8°C.

Rainbow Trout

Both the coastal rainbow and the redband trout spawn in the spring, stimulated by rising water temperatures. Behnke (1992) suggests that along the Pacific coast a water temperature of about 3-6°C may initiate spawning activity, but that actual spawning does not occur until the temperatures reach 6-9°C. While this spawning activity would typically occur from late December through April, in some very cold headwater streams local temperatures may delay spawning until July or August for some stocks. Bell (1986, literature summary) set the range for spawning at 2.2-18.9°C; and Piper et al. (1982) concluded that rainbow trout spawning should occur between 10-12.8°C.

Cutthroat Trout

Bell (1986, literature review) has suggested that the spawning range is 6.1-17.2°C. Fraely et al. (1981) evaluated the spawning habitat of west-slope cutthroat trout in Montana. They found that the better spawning streams had maximum temperatures of 11-13°C and mean monthly maximum temperatures that exceeded 10°C only during July and August. The poorer quality spawning streams had higher maximum summer temperatures, with two having 18°C and 19°C as the average maximum temperatures during July.

Cutthroat trout spawn in the spring, stimulated by a rising water temperature. While temperatures of 3-6°C may initiate spawning activity by coastal cutthroat from late December through April, actual spawning may not occur until temperatures reach 6-9°C. Spawning may extend from December through May in Washington, but peaks in February (Trotter, 1989; Wydoski and Whitney, 1979; Pauley et al., 1989; Behnke, 1992). Sea-run cutthroat tend to spawn close to deep pools (Pauley et al., 1989) in low gradient areas of small tributaries (Wydoski and Whitney, 1979; Trotter, 1989) where they may avoid competition for rearing area with steelhead and coho salmon. Pauley et al. (1989) suggest that searun cutthroat travel farther upstream to spawn than either steelhead or coho salmon where they rear sympatric with resident cutthroat populations. While cutthroat home very precisely to their natal streams to spawn, immature fish may migrate from marine waters to non-natal areas to feed (Pauley et al., 1989).

Summary of Reported Spawning Temperatures: While both salmon and trout have been occasionally cited has having a spawning range that extends as high as 17.2-17.8°C (7DADMax 16.35-16.95°C), these are uncommon citations and are sometimes described as poorer quality spawning streams. Generally, maximum temperatures below 12.8-14.5°C (7DADMax 11.95-13.65°C) appear to most consistently define the thermal conditions under which spawning will be initiated in the fall spawning Pacific salmon. Spring spawning species such as Steelhead trout and cutthroat trout commonly begin spawning as temperature warm above 4-6°C. Most authors reviewed place the late spring spawning temperature range, or define quality spawning stream summer maximum temperatures, as being 12.8-13°C (7DADMax 11.95-12.15°C). Thus for all salmonids, temperatures below 12.8-14.5°C (7DADMax 11.95-13.65°C) are generally viewed as the upper limit for spawning. For the purpose of this analysis, the studies are being treated as if they were representing the daily maximum temperature, unless the author suggested otherwise. This interpretation by itself could be viewed as being biased towards the protective side. However, it is reasonable in light of the way temperature ranges are typically used in the literature (as extreme point estimates), and in light of the fact that the temperature ranges are not typically related to an estimate of reproductive success.

Prespawning Effects of Temperature:

The effect of temperature exposure prior to actual spawning can effect the development of viable offspring and needs to be considered in setting a temperature standard. It has been found that temperature can effect both the health of the spawners and their potential reproductive success prior to the act of spawning. One of the ways in which temperature affects the health of spawners is by increasing the risk of mortality from warm water diseases (Schreck et al., 1994; Bumgarner et al., 1997; and ODFW, 1992) prior to spawning (disease is discussed separately in this paper). Another way that warm water affects the success of spawners is through its effect on the health of the unfertilized eggs as well as the maturation timing of adult salmon. This information is important to setting temperatures in both spawning streams and along the final migratory route taken by adult spawners.

Chinook Salmon

Several researchers have examined the effects of holding mature adult chinook prior to spawning at warm temperatures. Holding mature adults at warm temperatures has been found to the reduce the survival of eggs (Hinze, 1959; as cited in CDWR, 1988). Rice (1960) found that holding broodstock at temperatures above 15.6°C reduced survival of eggs to the eyed stage by 12.7% as compared to holding broodstock at 8.3-15.6°C (mean 11.95°C). Adult immigrants held at temperatures greater than 15.6 or less than 3.3°C were also found to produce eggs that are less viable in a study by Hinze, Culver, and Rice (1956; as cited in CDWR, 1988). The greatest survival (95%) was from adults taken at temperatures in the range of 11.7-12.2°C. Berman and Quinn (1989) cite a personal communication with the manager of the Kalama State Fish Hatchery as finding egg moralities of 50% or more from adults held in river waters fluctuating from 14.4-19.4°C (mean 16.9°C). The current supervisor of the Kalama Falls Hatchery, Ron Castaneda, notes that they still attribute some increased losses to holding temperature around 15.6-17.8°C; although, they have not had conditions of mortality as high as 50%. Similarly, Marine (1992; as cited in USEPA, 2001) noted that conventional hatchery practice is to consider chinook broodstock stressed at temperatures above 15°C, and noted that survival declines dramatically in holding ponds when temperatures exceed 17°C. M. Everson with the Oregon Department of Fish and Wildlife is cited in a personal communication by Marine (1992; as cited in USEPA, 2001) as acknowledging that wild spring chinook in the lower Rouge River exhibited high prespawning mortality in 1992 when water temperatures ranged from 18-21°C. The information cited above suggests that average temperature exposures of 15.6-17°C are associated with reduction in reproductive success. Average temperatures of approximately 12°C were associated with high survival rates.

Sockeye Salmon

Andrew and Geen (1960) noted that average daily temperatures in excess of 12.8°C during the spawning period appear to increase the numbers of female sockeye salmon that die unspawned. In one year when the average daily water temperatures at the peak of spawning ranged from 12.8-15.6°C (mean 14.2°C), spawning success was only 45%.

Steelhead and Rainbow Trout

Smith et al. (1983) and Piper et al. (1982) cite work demonstrating that adult brood-fish should be held at temperatures below 12.2-13.3°C prior to spawning to produce good quality eggs, while holding temperatures above 13°C have been found to reduce invivo post-ovulatory egg survival (Flett et al., 1996, and Billard and Gillet, 1981; as cited in Billard, 1985). Temperatures of 18°C or higher have been found to reduce the volume of male sperm, and a temperature of 20°C has found to cause a drop in egg fertility invivo to 5% after four and one-half days (Billard and Breton, 1977). But at 10°C, fertility of the eggs held in the hen trout remained high. Steroid biosynthesis has been noted to be suppressed in rainbow trout testes at 17°C (Manning and Kime, 1985; as cited in Macdonald et al., 2000). Saki et al. (1975; as cited in De Gaudemar and Beal, 1998) found that embryonic and post hatching survival in *O. mykiss* decreased significantly if they remained ripe in the body cavity for more than 5-7 days after ovulation, and fertility could approach zero after two weeks (Stein and Hochs, 1979; as cited in De Gaudemar and Beal, 1998). To avoid invitro damage to the eggs of steelhead and rainbow trout it appears that constant temperatures should be maintained below 12.2-13.3°C.

Summary on Prespawning Effects: A consistent finding among the studies reviewed was that average temperatures greater than 12-13°C (7DADMax of 13.48-14.48°C when study results are treated as daily average, and 13.96-14.96°C when treated as a weekly average) (conversion assumes a diel variation of 2-4°C) pose a real risk of reducing spawner viability, and that high losses can occur when average temperatures exceed 14°C (7DADMax 15.48-15.96°C) in the weeks immediately prior to spawning. An important consideration is that the viability of the eggs in ripe fish will decline both with time held in utero and with increasing temperatures above 12°C, thus temperatures should be suitable for spawning within a few days of when ripe adults arrive on the spawning grounds to avoid losses. It seems most appropriate to treat the laboratory test results that were based on constant test exposures as daily average and weekly average temperatures (both are used to create the likely range within which the best estimate would occur) when converting to the standardized 7DADMax metric used in this analysis. This is because the period of time that exposure would be effecting ripe eggs and adult fish in spawning condition would be around one to four weeks. Thus to avoid prespawning losses of eggs the highest 7DADMax temperature should not exceed 13.48-14.96°C. Given that the effect of concern is a lethal endpoint (rather then sub-lethal such as a reduction of growth) it would be most advisable not to assume the upper end of this range is fully protective.

Incubation and Pre-emergent Development

Chinook Salmon

Once spawning has taken place, the eggs of chinook salmon hatch in about 2 months and the young remain in the gravel for 2-3 weeks prior to emerging. Many researchers have tested incubation survival at constant exposure to various test temperatures. Complete mortality (100%) has been noted at incubation temperatures from 13.9 to 19.4°C (Donaldson, 1955; Garling and Masterson, 1985; Seymour, 1956; Eddy, 1972, as cited in Raleigh, Miller, and Nelson, 1986). Significant mortality (over 50%) has been noted at constant incubation temperatures from 9.9 to 16.7°C (Donaldson, 1955; Seymour, 1956; Burrows, 1963, and Bailey and Evans, 1971; as cited in Alderdice and Velsen, 1978; Hinze, 1959; as cited in Healy, 1979). A constant incubation temperature of 8°C produced more robust alevin and fry than constant exposure to either 4 or 12°C in a study by Murry and Beacham (1986), and Velsen (1987) compiled data showing that the best survival (>92.9%) occurred between 7.2-9.6°C. Heming (1982), however, found good survival at both 10°C and 12°C. Heming tested the survival in both incubation trays and artificial redds. Survival rates declined as the temperatures increased from 6 to 8, 10, and 12°C. The greatest survival (91.7-98%) occurred at 6 and 8°C, but it was still very good (90.2-95.9%) at 10°C. Incubation at 12°C consistently had the lowest survival (84.6-89.3%). Heming also tested survival rates from incubation to hatching against survival rates from hatching through complete yolk absorption. His work suggests higher incubation temperatures may create a metabolic energy deficit for pre-emergent salmon that increases mortality. Once alevin have hatched and absorbed their yolk sacs they will need to make a transition to active feeding. Heming and McInery (1982) found that temperatures of 6, 8, and 10°C resulted in an average survival of 98.4% during this transitional period, while 12°C was associated with a decrease in survival to 89.2%. Heming (1982; as cited in Beacham and Murray, 1986) found the maximum conversion of yolk to tissue weight occurred at 6°C or below. Seymour (1956) noted a 9-fold increase in abnormalities in fry incubated at 15.6°C and higher when compared to those incubated between 4.4-12.8°C. Seymour also noted that fry incubated at 4.4°C emerged larger than those reared at higher temperatures, however, subsequent fry growth was maximized at 12.8°C. Considered together, the work of the authors cited above strongly suggest that constant temperatures above 8-9°C or below 5°C may reduce the survival of chinook salmon embryos and alevins. A constant 10°C has been shown to produce mixed results with some authors finding high survival rates and others noting significant losses. While constant temperatures of 11-12°C can still result in good success, the results are consistently less than what is produced at lower temperatures.

Some researchers have tried to mimic the naturally fluctuating and falling temperatures actually experienced by incubating eggs, or have made stepwise reductions in the incubation temperatures as incubation progressed. Initial incubation temperatures from 15.6-16.7°C have been associated with significant to total losses of young fish through the incubation to early fry development phase (Healy; 1979; Brice, 1953; CDWR, 1988; Jewett, 1970; as cited in CDWR, 1988). Rice (1960) found that source waters declining from 15.6-8.3°C resulted in satisfactory egg development, though did not provide survival rates and may not have considered survival through to the fry stage. Johnson and Brice (1953) found survival to often exceed 90% where initial water temperatures (as a daily mean) were below 12.2°C. Healy (1979) found that highest survival (97%) occurred in creek water where the daily maximum reached 12.8°C only a few times during the first two weeks of development; but also noted that survival was still very good (90-94%) where the initial daily maximum temperatures were between 12.8-14.2°C. Olson and Nakatani (1969) found 53.7-88% survival in egg lots started at 12.5°C, experiencing a brief increase to 14.7°C (daily mean) in the first week, and then quickly dropping back to 12-12.5°C and assuming a seasonal downward trend in temperature (test water paralleled both diel and seasonal fluctuations – and no control lots were provided). Olson and Foster (1955) found the greatest survival at an initial test temperature (daily mean) of 11.6°C (92.2%), but reported no appreciable differences in survival rates at initial test temperatures of 13.8, 15, and 16°C (89.9-83.9%) (test water paralleled seasonal daily average temperatures). Seymour (1956) tested four geographically distinct stocks of chinook. Taking into consideration both mortality and growth rate, the optimum temperature was estimated as 11.1°C for eggs and fry. The mortality rate was considered low at all stages of development for lots reared between 4.4°C and 12.8°C (daily mean). Lots with initial temperatures of 18.3° had the highest mortality (11, 24, 40, and 100%). In the cyclic and fluctuating temperature tests reviewed here, having temperatures at the beginning of incubation that are below 11-12.8° (daily mean) are typically associated with excellent survival rates. This range compares well with the optimal temperature range of 8-12°C recommended by the Independent Scientific Group (1996).

Donaldson (1955) transferred eggs to more optimal (10-12.8°C) constant incubation temperatures after various periods of exposure to higher temperatures. He found that tolerance to temperature exposure varies with the stage of development. He also found 20% mortality could be induced by exposing eggs to 19.4°C for one day, 18.3°C for thee days and 17.2°C for less than ten days. Donaldson's work lends further support to the observations made by other authors such as Jewett (1970; as cited in CDWR,1988) that the latent effects of holding eggs at higher than optimal temperatures continues through the period of absorption of the yolk sac, thus using mortality estimates at the time of hatching underestimate the total temperature induced mortality. Donaldson found the developmental stages associated with the greatest percentages of temperature induced mortality were: 1) the time up until the closure of the blastopore (200 T.U.); 2) the period just previous to and during hatching; and 3) when fry are adapting themselves to feeding. He also found that when eggs were exposed to test temperatures (17.2, 18.3, and 19.4°C) past the eye pigmentation stage (350 T.U.) the time necessary for complete hatching doubled, and the frequency of common abnormalities increased with both the higher temperatures and longer exposures. Donaldson's work also suggests that a week or more exposure at an average of 17°C would likely cause at least moderate mortality (20%), even if the water were quickly and substantially cooled after that initial exposure. Murry and Beacham (1986) found that initial incubation at 4°C reduced survival even with later transfer (at completion of epiboly) to warmer waters (8°C and 12°C). Transfers after epiboly or completion of eye pigmentation from 4 to 12°C and from 12 to 4°C also caused an increase in alevin mortality. The authors also found that a decreasing temperature regime produced longer and heavier alevins and fry. Combs (1965) found that eggs developed to the 128-cell stage at 5.8°C could then tolerate 1.7°C for the remainder of the incubation period with only moderate losses. Mortality of 14.5% was observed with a transfer time of 72 hours, while only 3.3% mortality occurred with a transfer at 144 hours. These three works taken together suggest that the effects of suboptimal initial incubation temperatures may not be nullified by later changes in the temperature regime to more optimal levels; that sudden changes in temperature at either early or later stages of development, regardless of the direction of that change, can be harmful to pre-emergent life stages; and that initial incubation at optimal temperatures may condition eggs and embryos such that they can withstand very low winter temperature regimes. Neitzel and Becker (1985) also conducted work on the effects of short-term increases in temperature that can be used to support daily maximum temperature criteria. Neitzel and Becker (1985) used chinook salmon to try and determine the effects of short term de-watering of redds by hydropower facilities. Neitzel and Becker found that sudden increases in temperatures from 10°C to above 22°C for 1-8 hours significantly reduced survival of cleavage eggs in chinook salmon. Controls held at 10°C experienced very low mortalities (less than 2%). Mortality in treatment groups was 8-10% at 22°C after 2 hours exposure, and was 22% after a one-hour exposure at 23.5°C. They further found that decreasing the temperature from 10°C to near freezing (0.0°C) for up to 24 hours did not increase mortality in eggs, embryos, or alevin.

Considering the work of Donaldson (1955) and Neitzel and Becker (1985) together allows a reasonable estimate of temperatures that would avoid causing acute effects to eggs and embryos. Donaldson found that a constant 24-hour exposure to 19.4°C caused modest lethality. This is relatively comparable to Neitzel and Becker's findings that, a 1-8 hour exposure to 22°C caused moderate lethality. Adjusting this range (19.4-22°C) by a reduction of 2°C would be expected to reduce the likelihood of any mortality occurring at all, and produces a single daily maximum or one-hour duration limit of 17.4-20°C to fully protect incubating eggs and embryos from acute lethality.

While there is some disagreement, the literature is very consistent overall regarding the optimal incubation requirements for chinook salmon. To provide full protection from fertilization through initial fry development for chinook salmon, average daily temperatures should remain below 11-12.8°C at the initiation of incubation, and the seasonal average should not exceed 8-9°C throughout the incubation-through-emergence period. To protect eggs and embryos from acutely lethal conditions the highest single day maximum should not exceed 17.5-20°C.

<u>Coho Salmon</u>

Embryo survival is consistently maximized in tests conducted at constant temperature exposures between 2.5-6.5°C, and is only slightly less successful between 1.3-10.9°C (Dong, 1981; Tang et al., 1987; Murry et al., 1988; Velsen, 1987). Davidson and Hutchinson (1938; as cited in Sandercock, 1991) suggested the optimum temperature for egg incubation is from 4-11°C. Mortalities tend to become moderate (21-26%) between 11-12.5°C, and between 12.5°C and 13.5°C mortalities of 50% can be expected. Above 14-14.4°C, tests commonly report at or near 100% mortality. Alevin survival may be excellent (97%) between 1.3-10.9°C (Dong, 1981; Tang et al., 1987), and the most robust fry are at incubation temperatures between 4-8°C (Dong, 1981; Murry et al., 1988). Alevin mortalities of 51-59% occur at 12.5°C (Dong, 1981), and 100% mortality occurs at 14-14.4°C (Dong, 1981; Murry et al., 1988).

From the studies discussed above we can be relatively confident that egg survival would be consistently maximized at exposure to constant temperatures between 2.5-6.5°C, but may still be excellent for many stocks at temperatures between 1.3-10.9°C. Alevin and fry survival and health may be optimized at exposure to constant temperatures between 4-8°C, but survival may remain excellent up to 10.9°C. Based on the preceding, the incubation of coho salmon should be fully support by maintaining the average temperature throughout the incubation period should at or below 8-10°C.

There is no information available that suggests coho salmon embryos and alevin would be more sensitive to short term (daily peak) increases in temperature than any other Pacific salmon. The one study reviewed that looks at short term temperature changes for coho was that by Tang et al. (1987). In that study, incubation temperatures were increased from 10.2 to 17°C and lowered from 10.2 to 4°C for eight hours. In neither test did these modest changes result in any statistically significant increase in mortality. Additionally, one field study reported coho alevins surviving very "substantial" daily peak temperatures with no clear change in later juvenile abundance (summer peak stream temperatures of 24 and 30°C were noted; although, its is highly unlikely the eggs were actually exposed to these temperatures and were most likely protected by placement in groundwater seeps) (Hall and Lantz, 1969). Since no clear basis has been found for setting a daily peak temperature specific to coho incubation, it is suggested that the daily maximum value chosen for chinook be considered appropriate for coho salmon as well.

Pink Salmon

The range for successful incubation has been suggested to be from 4.4°C to 13.3°C (Bonar et al., 1989). Murray and Beacham (1986) reported excellent survival (91-97%) with initial fertilization occurring at constant 14°C and a 0.5°C drop in temperature every three days down to 5°C. When they allowed temperatures to drop further to 4 and 2°C survival was reduced. Murray and McPhail found survival of 94% from fertilization to emergence at 5°C, and Beacham and Murray (1986) found the greatest survival for 5 stocks and 21 families of pink salmon tested at 8°C. Velsen (1987) compiled data that showed the best, though highly variable, survival (generally >89.5%) occurred between 8-13°C. Survival decreased at an incubation temperature of 11°C in a test by Murray and McPhail (1988), and was 50% at 15-15.5°C (Beacham and Murray, 1990). Temperatures of 5-8°C produced the largest alevins in a study by Murray and McPhail (1988), and 8°C produced the longest (Beacham and Murray, 1986) and fry heaviest (Murray and McPhail, 1988). Konecki et al. (1995) incubated embryos from ten western Washington populations and found significant variation (1-3 weeks) in incubation rates – suggesting that some differences in temperature optimums may occur between stocks.

Survival of the alevin life-stage was found to be generally excellent (>97%) for 21 families of pink salmon tested at temperatures ranging from 4-12°C (Beacham and Murray, 1986). Survival to emergence was reported as low at 14°C (Murray and McPhail, 1988). Examining low incubation temperatures, Beacham and Murray (1986) found that temperatures of 4°C consistently resulted in the lowest survival for 5 stocks and 21 families of pink salmon, and in a 1990 study found 50% mortality at 5°C. Complete mortality has been found at an incubation temperature of 2°C (Murray and McPhail, 1988; Beacham and Murray, 1990; Bailey and Evans, 1971). Murray and Beacham (1986) transferred embryos in a late stage of development from 8°C to 1°C and found that while northern stocks had 100% survival, southern stocks experienced moralities ranging from 38-60%.

Based on the research cited above, constant temperatures in the range of 4.5-12°C, and a constantly declining temperature regime beginning at 14°C are capable of producing excellent and perhaps optimal survival rates of incubating pink salmon. However, a constant temperature of 8°C appears to produce the most consistently optimal results; and while tests up to 12-13.3°C were found to produce excellent results, several tests found temperatures of

11-12°C to produce lower survival and smaller fry. Further, in natural streams the temperatures will not dependably decline at a steady rate, and constant temperatures of 15-16°C have resulted in high mortality. In consideration of all of these issues it should be assumed that constant temperatures in the range of 8-10°C represent upper range for fully supporting the embryonic development of pink salmon. Therefore, to fully protect the incubation of pink salmon the daily average temperature at the initiation of incubation should be maintained below 12-14°C and the average temperature throughout incubation through emergence should be not exceed 8-10°C.

Chum Salmon

Incubation survival from fertilization to emergence is variable, but can be excellent anywhere from 4-12°C (Murray and Beacham, 1986; Beacham and Murray, 1985). In the initial period of embryonic development temperatures in the range of 8-12°C produce the highest survival. However in later stages of incubation, temperatures in the range of 5-8°C produce the best survival as well as the largest and heaviest alevin and fry (Beacham and Murray, 1986). Temperatures of 12°C in the later developmental stages can result in heavy losses in some stocks (Beacham and Murray, 1985; Beacham and Murray, 1986). The optimal temperature range for conversion of yolk to tissue weight was estimated to be from 6-10°C (Beacham and Murray, 1986), and optimal respiration efficiency has been estimated to range from 11-12.5°C for prolarvae and larvae (Zinichev and Zotin, 1988). Constant incubation at temperatures of 14°C and 16°C as well as at 2.5°C have been associated with embryonic mortalities of 50% (Beacham and Murray, 1990). The alevin stage of development (late), however, was shown to have very high survival rates when exposed to temperatures as low as 2°C. Beacham and Murray (1987) found that 10°C resulted in higher growth and survival (96%) of emergent fry. Fry survival rates were 62% at 13°C, and 73% at 16°C.

Based on the literature reviewed, constant incubation temperatures from 4-12°C can produce excellent and incubation results; however, some researchers have noted reductions in survival occurring at the ends of this range. Constant incubation temperatures in the range 6-10°C would be most consistently fully protective for chum salmon. Average temperatures at the initiation of incubation should not exceed 11-12°C to allow for the full protection of developing eggs. To provide for the full protection of the period of development from incubation through emergence in chum salmon, the daily average temperature at the beginning of the incubation period should not exceed 11-12°C and the seasonal average temperature should not 8-10°C.

Sockeye Salmon

Murray and McPhail (1988) and Combs (1965) report that sockeye salmon are more tolerant of low incubation temperatures and less tolerant of high incubation temperatures than the other Pacific Salmon. At constant exposure, Combs (1965) reported that temperatures within the range of 4.4-12.7°C produced similarly high survival rates (85.8-90.9%), with the highest occurring at 5.8°C. Combs found incremental increases in mortality of 53-67% occurred when the temperature was lowered from 5.8 to 4.4°C or raised from 12.7 to 14.2°C. Velsen (1987) found that while survival rates were highly inconsistent between 1.1-15°C, the best survival generally occurred between 3.1-5.8 (generally >90%), with fair survival (>70%) occurring in the range of 2.1-12.7°C, and survival rates consistently poor (17-76%) above 14°C. Murray and McPhail (1988) found that survival was highest at 8°C (79%) but only 40% at both 11 and 5°C. Andrew and Geen (1960) reported that in the first two years of a four year field study, eggs initially incubated at temperatures of 7.2°C had lower survival than those initially incubated at 10, 12.8, and 15.6°C. In a follow-up experiment the following two years, they found that eggs exposed to temperatures of 15.6 to 16.7°C for "short periods of time" suffered severe losses during the period of exposure, and that temperatures of 16.7-18.3°C caused extensive losses both during and following the exposure. In a study by Craig et al. (1996) the temperature range of 8-10°C resulted in the optimum 1:1 male to female sex ratio in offspring; although, the study design really only allows the conclusion that temperature in the early stage of development affects sex determination.

In the studies cited above, constant temperatures in the range of 4-12.7°C produce variable but oftentimes excellent survival rates in sockeye salmon; but that the range 6-10°C appears most consistently optimum. Severe losses have been noted at and above 15.6°C, even with short term exposure under fluctuating field conditions, and poor survival occurred at constant temperatures of 14-14.2 and above. Taken together this information suggests that daily average temperatures in the early incubation period should not exceed 11-12.7°C, and the average temperature throughout the period of incubation to emergence should not exceed 8-10°C to fully protect the incubation success of sockeye salmon.

Steelhead and Rainbow Trout

Fuss (1998) considered the range 5.6-11.1°C as being optimal for steelhead egg survival in the Washington State hatchery program, and Bell (1986) suggests that 10°C is the preferred hatching temperature for steelhead eggs. Rombough (1988) found less than 4% embryonic mortality at 6, 9, and 12°C, but noted an increase to 15% mortality at 15°C. Alevin mortality was less than 5% at all temperatures tested, but alevins hatching at 15°C were considerably smaller and appeared less well developed than those incubated at the lower test temperatures. Redding and Schreck (1979) similarly found that emergent fry were larger at 12°C than at 16°C.

Velsen (1987) compiled data on the incubation survival of both anadromous (steelhead) and non-anadromous rainbow trout that showed survival was consistently high (>92%) between

4-9°C, and fair (>78%) between 3-15°C, but very poor (7%) above 16°C. Kamler and Kato (1983) tested incubation survival of rainbow trout at 9, 10, 12, 14, and 16°C. They found the highest survival of eggs at 10°C and 12°C, slightly lower survival at 14°C, and abrupt drops in survival at both 9°C and 16°C. Survival to the swim-up stage in two strains of rainbow trout had 94-98% survival at 7°C, 72-95% at 4°C, and <12-41% survival at 2°C (Stonecypher and Hubert, 1994). Kwain (1975) found the lowest mortalities of rainbow trout occurred at 7 and 10°C, and Kashiwagi et al. (1987; as cited in Taylor and Barton, 1992) found optimal hatching occurred at 10°C. Humpesh (1985) found that optimal hatching (>90%) occurred between 7-11°C in rainbow trout, and Alekseeva (1987; as cited in Taylor and Barton, 1992) suggested that optimal incubation occurs with temperatures rising from 5.3-10.5°C. Constant temperatures 10-12°C commonly form the upper end of the temperature range that provides excellent support for the incubation and hatching of anadromous and non-anadromous forms of *O. Mykiss*. Losses become moderate at temperatures of 14-15°C and severe above 16°C. Maintaining a seasonal average temperature of 7-10°C appears to provide for the most consistent occurrence of optimal survival and development in *O. Mykiss*. Thus, it can be reasonably concluded that the average temperature throughout the development of *O. Mykiss* should not exceed be 7-10°C, and the maximum daily average temperature at the time of hatching should be maintained below 11-12°C.

Statewide spawning dates were not found for non-anadromous rainbow trout. In the absence of such information, it is suggested that dates associated with the anadromous forms of *O. mykiss* be considered if need arises to set dates of application for the spawning and incubation criteria.

Cutthroat Trout

Eggs of sea-run cutthroat incubate for 6-7 weeks before they hatch and the alevin remain in the gravel for about another 2 weeks before they emerge (Trotter, 1989; Pauley et al. 1989). Fry may emerge from March through June, depending on the location and time of spawning, but peak emergence occurs in mid April (Trotter, 1989; Wydoski and Whitney, 1979).

Pauley et al. (1989) cite studies demonstrating that the optimum temperature for incubation is 10-11°C. Bell (1986) has suggested that the range for hatching of cutthroat trout eggs is from 4.4-12.8°C. Smith et al. (1983) found that west-slope cutthroat trout eggs held in creek water with a fluctuating temperature of 2-10°C had significantly better survival than eggs held at a constant 10°C. Stonecypher and Hubert (1994) found that survival to swim-up stage in Snake River cutthroat trout was 95% at 7°C, approximately 87% at 4°C, and less than 16% at 2°C. Hubert and Gern (1995) found 68.6% survival in a control population held at 7°C when testing the effects of lowering incubation temperatures in the early stage of development. Mortality rates were no different from controls when temperatures were lowered to 3°C at least 13-15 days after fertilization but were higher if the cooling took place sooner.

It is somewhat problematic to set standards for the incubation of cutthroat trout that can be reasonably applied statewide. As a spring spawning species that often spawns high in the watershed, cutthroat trout have a very broad period of spawning when examined statewide. Stocks that exist in lower or warmer watersheds will spawn as early as February when temperatures rise above 6°C, while stocks that exist in high elevation snow fed streams may need to wait until late June or July for waters to be sufficiently warm (6-11°C) to allow successful spawning. Were it not for risk of egg loss due to late winter and spring freshets, one could suggest that the spring spawning strategy is relatively unencumbered by changes in the temperature regime. While earlier spawning subjects cutthroat eggs to higher risks of physical damage, the earlier hatch also places surviving resident fry in a good position to maximize summer growth and thus increase their survival opportunities over the following winter. It may well be that the superior growth obtained in the oceanic phase of anadromous forms may make minor differences in weight gains from earlier emergence of less value, but this relationship remains to be tested. In general, specific stocks will have tailored their spawning and emergence periods to optimize both incubation survival and early fry growth. Significant changes in the temperature regime, such as earlier spring warming will bring unknown risks to individual populations. Therefore, while a fully protective temperature regime is suggested in this document for cutthroat trout, it would be best tailored to the historic patterns of spawning found in specific stocks. To initiate spawning in most stocks the water temperatures must at least warm to daily maximums of 6-7°C, though some stocks may not begin spawning until temperatures reach 11°C. Specific studies on incubation survival suggest, however, that incubation may be optimized with constant temperature exposures in the range of 7-11°C; although, the data suggests their could sometimes be incubation losses at constant water temperatures of 10-11°C. Statewide, most cutthroat spawn in mid-February and hatch by the end of March. It is suggested that in the absence of more watershed-specific information April 1 could be used to compare the incubation threshold recommendations statewide. Given that the studies reviewed create some contradictions, it is believed that the middle portion of the possible fully protective range should be considered most defensible for use in setting any final recommendations. To fully protect the period of incubation through emergence in cutthroat trout, the available information suggests that the average temperature throughout the entire development period should not exceed 8-9°C, and the daily average temperatures should not exceed 11-12°C until after emergence.

Summary of Laboratory and Field Studies on Incubation Success: Across all species of salmonids examined, full protection would be achieved by maintaining an overall average temperature throughout the period of incubation through emergence of 8-9°C, and by not exceeding 12-12.8°C as a daily average temperature at the initiation of incubation in fall spawning stocks and at the time of emergence in spring spawning stocks (see Table 4.4, below).

Table 4.4. Constant or average temperature exposures estimated to allow for full protection of the incubation of individual salmon and trout species.

Species	Daily Average Temperature at Initiation	Seasonal Average Temperature
Chinook	11-12.8	8-9
Coho	----	8-10
Chum	12-14	8-10
Pink	11-12	8-10
Sockeye	11-12.7	8-10
Steelhead/Rainbow	11-12	7-10
Cutthroat	11-12	8-9
Summary	***11.16-12.58 (mid. 11.87)***	***7.86-9.71 (mid. 8.79)***

Converting these temperatures to a standardized 7DADMax metric will facilitate the comparison with other lines of evidence on this life stage. It seems appropriate to assume the overall average temperature (based on constant temperature exposure throughout the incubation period) represents a seasonal average (which gives a 7DADMax of 11.29-12.29, and the initial incubation temperature (based on tests that allowed temperatures to cool during incubation and that recorded temperature as a daily average) is represented best as either a daily average (7DADMax 13.48-13.77°C) or a weekly average (7DADMax 13.96-14.76°C) (conversions are based on assuming stream diel temperature ranges of 2-4°C).

Table 4.5. Spawning and incubation requirements of salmon and trout.

Line of Evidence	7DADM - Range (°C)	Median (°C)
General observations on spawning initiation (generally field observations)	11.95-13.65	12.8
Prespawning effects (lab and field studies)	13.48-14.96	14.22
Incubation success (as highest 1 week period)	13.48-14.76	14.12
Incubation success (as a average across the entire life-stage)	11.29-12.29	11.79
Best Estimate of Threshold	***12.55-13.92***	***mid. pt. 13.24***

The range of these independent lines of evidence is 11.29-14.96°C with a mean range of 12.55-13.92°C and an overall midpoint of 13.24°C. This suggests that to fully protect salmon and trout during the period from incubation through emergence, temperatures should not exceed a 7-DADMAx of 13.24°C. After cross checking the conclusion against each independent line of evidence, no overriding factors of disagreement appear to exist. The largest disagreement is with the season-wide estimate of incubation success, however, this seems well counterbalanced by the estimate of initial incubation temperatures relating to full protection. The similarity between species for each line of evidence, and the similarity between each of the lines of evidence lend greater credibility to the overall estimate of a temperature regime that will fully protect the salmonids from incubation through emergence.

To protect eggs and embryos from acutely lethal conditions that may arise under unique situations, the highest single day maximum should not exceed 17.5-20°C. (Note: the conversion estimates would have been raised by 1.12,1.22, and 1.35°C for the daily average, weekly average, and seasonal average estimates, respectively, if it were assumed the streams would have an average seasonal diel fluctuation of 4-6°C rather than 2-4°C, however, a lower range seems more appropriate for use in the incubation period).

iii) Juvenile Rearing

General Introduction:

Attaining good growth is very important to the survival of young salmon. In a study by Burrows (1963), it was found that doubling the weight of sockeye salmon fingerlings released from a hatchery resulted in a tripling of the adult return rate. However, in determining temperatures that will fully protect juvenile salmonids, growth is not the only endpoint of concern. It is important to note that disease, predation, and smoltification concerns are all important issues that need to be considered. Additionally, when considering growth rates, it is important to distinguish between studies conducted under constant and cyclic temperature regimes, and to recognize that the feeding rates used in testing will affect the results of the test. As food becomes more limited, the temperature that provides for optimal growth declines. As food becomes more plentiful, fish can grow larger in warmer waters. Since most tests are conducted at high to very high rations, the results must be cautiously applied to natural stream environments where food availability can be more limiting.

Laboratory Growth Studies Conducted at Constant Temperatures:

<u>Chinook Salmon</u>

In constant temperature experiments conducted at high feeding rates, maximum growth tends to be associated with temperatures in the range of 15-19°C (Hillman, 1991; Cech and Myrick, 1999; Brett et al., 1982; Banks et al., 1971). Banks et al. (1971) found that growth was similar at 15.6°C and 18.3°C, with 15.6°C being slightly higher in 2 of 4 test lots. In the two lots where 18.3°C produced better growth; however, the fish in this warmer water showed higher rates of disease incidence. Temperatures above 19°C were associated with reduced feeding and growth, as well as increased problems with disease. Marine and Cech (1998, as cited in USEPA, 2001) found that growth was substantially reduced at 21-24°C when compared to 13-16°C. Brett et al. (1982) estimated that under natural ration levels the optimum of 19°C would be reduced to 14.8°C and no growth would be possible at 21.4°C. Seymour (1956) studied three Washington and one California stock of chinook salmon and concluded that the general optimum temperature for growth and survival of chinook fingerlings was 14.4°C. Zaugg and Wagner (1973) found that at the end of a 16-week test, growth was roughly 27% greater at 12°C than at 8°C. Based on the foregoing works, maximum growth should be expected with constant exposure at 15.6-19°C. The increase in growth above 15.6°C, however, was inconsistently greater, and under natural rations the maximum growth rate may decline by as much as 4.2°C (14.8°C).

Coho Salmon

Maximum growth of coho fed to satiation in the laboratory occurred at constant 17°C in a study by Shelbourn (1980).

Sockeye Salmon

Brett et al. (1969; as cited in USEPA, 2001) found that optimum growth occurs at 15°C on unrestricted rations, but when the feeding rate was reduced to 1.5% of body weight/day the optimal growth rate lowered to 10°C and growth was zero at 15°C. Brett and Glass (1973) noted that 10°C resulted in the most efficient use of food and that the reduction from 15 to 10°C created a 33% reduction in the demand for food. Brett and Groves (1979) note that at temperatures below 10°C food conversion efficiency rises most rapidly from the base level (maintenance ration) and reaches peak efficiency at an intermediate ration. This relation changes progressively with rising temperature such that at 17°C and above the highest efficiency occurs on a maximum ration diet. They note that for sockeye salmon, over the complete range of tolerable temperatures maximum food conversion efficiency occurs at 11°C. Brett (1971; as cited in USEPA, 2001) found swimming capacity, metabolic scope, growth on excess rations, and ingestion were maximized at 15°C, and that 15°C was also the final preferendum temperature. Wurtsbaugh and Davis (1977) found that optimum growth occurred at 16.5°C on full rations. Donaldson and Foster (1941; as cited in Brett, Hollands, and Alderdice, 1958) discovered that growth in young sockeye tends to be poor to none-at-all at temperatures above 21°C and below 4°C. Brett (1956) noted that sockeye juveniles may cease feeding entirely when temperatures reach 21°C. Temperatures in the range of 4-7°C have been associated with poor growth (Brett, 1956). The foregoing works suggest that maximum growth may occur at constant temperatures of 15-16.5°C under unrestricted rations, but that under severely restricted rations the point of maximum growth may decline as much as 5°C (to 10°C).

Steelhead and Rainbow Trout

Olson and Tempelton (undated manuscript; as cited in USEPA, 1973) reportedly found that the most favorable range for steelhead growth was between 5-17°C, with a physiological optimum in the vicinity of 15°C. The amount of food necessary to maintain the fishes' weight increased rapidly as temperatures rose above 12°C with no growth occurring at approximately 23°C despite the presence of excess food. It was suggested that the most efficient growth, within the consumption ranges believed to occur in nature, is at the temperature of 5-14°C in the early spring, 11-14°C in early summer, 14-17°C in late summer, 11-17°C in fall, and 5-8°C in winter. Behnke (1992) cites work showing that rainbow trout reduce and finally cease feeding as temperatures rise to between 22-25°C, often well below the lethal temperature.

Cech and Myrick (1999) tested winter-run steelhead from the American river in California at three different temperature (11, 15 and 19°C) and ration levels that varied from 82% to 100% of satiation. They found that while a 12% reduction in feeding rate resulted in a statistically significant reduction of growth at 19°C, the growth rate was still higher than that observed at any feeding levels at 11°C and 15°C. This suggests that the maximum growth rate under more moderate level of feeding would likely occur between 15-19°C.

Behnke (1992, citing Dwyer et al. 1981, 1983a, 1983b) suggested that the optimum temperature for the growth and food assimilation in salmonids occurs between 13-16°C. Taylor and Barton (1992) recommended temperature criteria for Alberta in British Columbia of 12-19°C as a 7-day average. In a review on rainbow trout, Moyle (1976) opined that the optimal temperature for growth and the completion of most life history stages was 13-21. The optimal temperature range was cited by Bell (1986) as being 12.2-18.9°C with the most optimal set at 13.9°C. Piper et al. (1982) in a hatchery management review paper set the optimal at 10-16.7°C. Mckee and Wolf (1963; cited in Wedemeyer et al., date absent from copy) are reported to have found 13°C to be optimal.

Behnke suggests that redband trout from an Oregon desert basin have been demonstrated to have an optimum feeding temperature at some untested temperature higher than 19°C (citing unpublished work from the U.S. Fish and Wildlife Service, Cultural Development Center, Boozeman, Montana). This was contrasted to work done at the same research facility on other forms of rainbow trout that showed growth optimum feeding peaked at 10-16°C. Behnke (1992) suggests that the work done to date demonstrates that the desert redband have a functional feeding temperature that is higher than rainbow trout that have evolved in less harsh environments of temperature and water flow. Kaya (1978) compared an introduced population of interior rainbow trout from the Firehole River in Montana to two hatchery strains. Temperatures in the Firehole River at times reach summer maximums as high as 29.5°C due to thermal springs. The planted stock has been living in the river for approximately 20 generations, yet it was found that neither the functional feeding temperature or the upper incipient lethal temperature had increased in comparison to the hatchery stocks.

Reimers (1957) found that raising water temperatures (from 9.4 to 16.7°C) at the conclusion of starvation testing, increased metabolic demands sufficiently to cause mortality in the weakened fish, and found that fish that began the trials as well nourished hatchery rainbow trout survived better than stream-conditioned wild brown trout. This was to point out the importance of beginning the winter period with good energy reserves.

Hokanson et al. (1997) found that a constant exposure to 17.2°C produced the greatest growth rates in trout fed to satiation over a 30-day test period. Maximum growth was estimated to occur between 15-20°C (mean 17.5°C) by Cho and Kaushik (1990; as cited in

Dockray et al., 1996). Sadler et al. (1986) found that growth and food conversion efficiency were greater at 16°C as compared with 10°C. Myrick and Cech (2000) found that the growth rates of two strains of rainbow trout from California tended to increase as temperatures increased from 10 to 19°C, with the significant increase occurring from 10-14°C, and to decrease to near zero as temperatures increased from 19 to 25°C. They also found that while the growth of the two strains was similar at low temperatures, the hatchery strain grew much better then the wild strain when exposed to temperatures in the upper range (22 and 25°C). The authors noted that the increasing trend in food consumption and growth rates for the two strains between 14-19°C, suggests the optimal temperature lies between these to temperatures. Huggins (1975) suggested older fish sometimes demonstrate more intermediate temperature preferences. While the conclusions of the foregoing authors are highly variable, the estimates at the low end of the range all come from recommendation papers or indirect citations. For this reason, preference is being given the conclusions of research papers directly reviewed. It is therefore estimated that growth may be maximized at temperatures as high as 17.2-19°C under satiation rations.

Cutthroat Trout

Pauley et al. (1989) cite research concluding that the optimal temperature for juveniles is 15°C, and that equilibrium and ability to swim is lost between 28-30°C. Hickman and Raleigh (1982; as cited by Barton, 1996) suggest that the optimal range for cutthroat trout is 12-15°C. Data reviewed by Carlander (1969; as cited in Gresswell, 1995) suggest optimum water temperatures between 4.4 and 15.5°C for Yellowstone cutthroat trout. A temperature of 15-15.5°C is consistently cited as optimal for the growth of cutthroat trout.

Table 4.6. The following summarizes the conclusions from laboratory tests where the fish were exposed to constant test temperatures:

Species	Temperature (°C)	Feeding Rate	Comments	Author
Chinook	15.6 and 18.3	Satiation	Highest growth each in 2 of 4 tests, Higher disease at 18.3	Banks et al., 1971
	19	Satiation		Brett et al., 1982
	14.8	60% of satiation	A 4.2C reduction from max at satiation feeding	Brett et al., 1982
	14.4	Satiation	Three Washington and one Calif. stocks	Seymour, 1956
Coho	17	Satiation		Shelbourn, 1980
Sockeye	15	Satiation		Brett et al., 1969
	10	1.5% body	A 5C reduction from	Brett et al.,

		wt.	max at satiation	1969
	16.5	Satiation		Wurtsbaug and Davis, 1977
	17	Satiation	Highest growth efficiency	Groves, 1979
Steelhead	15	Satiation		Olson and Tempelton
	19	Satiation and 88%		Cech and Myrick, 1999
	13.9	Satiation		Bell, 1986
	13	Satiation		Mckee and Wolf
Redband	19	Satiation	Maximum may be higher	Behnke, 1992
Rainbow	17.2	Satiation		Hokanson et al., 1997
	17.5	Satiation		Cho and Kaushik, 1990
	19	Satiation		Myrick and Cech, 2000
	15	Satiation	Based on peak of plotted results	Grabowski, 1973
Cutthroat	15	Satiation		Pauley, 1989
	17.5	Satiation	Based on peak of plotted results	Clarke, 1978
Summary	*16.41(mean)*	*Satiation*	*Range 13-19*	

Optimal growth rates under high feeding levels have been found at constant temperature exposures from 13-19°C with a mean of 16.41°C. However, most studies group the estimate more narrowly, between 14-17.5°C (15.75°C). When feeding is reduced substantially, however, the temperature that will allow for maximum growth has been noted to decrease by 4-5°C. Thus under natural feeding regimes, where food availability is more restricted during the high temperature months of summer, maximum growth rates would be more likely to be obtained at a constant temperatures of 11-13.5°C (assuming a 4°C reduction due to restricted feeding). If treated as either a weekly average or summer average temperature regime this constant temperature range would be converted to estimated 7-DADMax temperature ranges of 14.18-16.68°C (15.43) and 15.64-18.14°C (16.89), respectively.

Ranges Identified in the Literature as Optimal for Growth:

The upper end of the ranges estimated as optimal for growth in the literature ranged from 15-21°C with a midpoint of 18°C (Table 4.7). It was not always clear from the literature why the authors chose the specific ranges that were recommended, whether or not they had tried to set the ranges to maximum growth, or what temperature metric (i.e., daily average, daily maximum, etc.) they were associating with their recommended ranges. Thus, this line of evidence should be considered with caution.

Table 4.7. A summary of the ranges identified in the literature as producing optimal growth conditions

Species	Estimated Optimal Range	Comments	Author
Steelhead and Rainbow Trout	14-17	Estimate for the late Summer regime	Behnke, 1992
	10-16	Growth optimum feeding	Behnke, 1992
	5-17		Olson and Templeton
	13-16		Dwyer et al., 1981, 1983a, 1983b
	12-19	Recommended 7-day average criteria	Taylor and Barton, 1992
	13-21		Moyle, 1976
	12.2-18.9		Bell, 1986
	15-20		Cho and Kaushik, 1990
	14-19	Optimal temperature lies between 14-19	Myrick and Cech, 2000
Cutthroat Trout	12-15		Raleigh, 1982
	4.4-15.5		Carlander, 1969
Summary	*Upper Range: 15-21 (18)*		

Comparison Test Regimes with Better Growth:

The results in the table 4.8 below should only be used to generally support other studies since they did not determine specific temperatures that resulted in maximum growth. These results suggest, however, that constant temperatures above 21°C and below 10°C may be detrimental to growth, and that constant temperatures in the range of 12-14.5 are generally favorable. When feeding is reduced substantially, however, the temperature that will allow for similar levels of growth may be decreased substantially (4-5°C). Thus under natural feeding regimes, where food availability is more restricted during the high temperature months of summer, maximum growth rates would be more likely to be obtained at a constant temperatures of 8-10.5°C (assuming a 4°C reduction due to restricted feeding). If treated as either a weekly average or summer average temperature regime this constant temperature range would be converted to estimated 7-DADMax temperature ranges of 11.18-13.68°C (12.43) and 12.64-15.14°C (13.89), respectively. This line of evidence when viewed on its own merits suggests that relatively good growth will occur with 7DADMax temperatures of 11.18-15.14°C as compared with temperatures significantly (4°C or more) warmer or colder.

Table 4.8. Tests Comparing Growth at Only Two Contrasting Temperatures:

Species	Better growth	Worse growth	Feeding Ceased	Author
Chinook	13-16 (14.5)	21-24 (22.5)		Marine and Cech, 1998
	12	8		Zaugg and Wagner, 1973
Sockeye		<4 and >21, poor to no growth		Donaldson and Foster, 1941
		4-7	21	Brett, 1956
Steelhead and Rainbow Trout			22-25	Behnke, 1992
		23 no growth		Olson and Templeton, 1973
	16 better conversion efficiency	10		

Laboratory Growth Studies – Fluctuating Temperatures:

Chinook Salmon

Neilson and Green (1985) found that in comparing fluctuating to constant test conditions, that growth was enhanced through naturally cyclic temperature regimes, suggesting that food utilization in fluctuating environments may be higher (although it should be noted that this is not a consistent finding among authors). Marine (1997) conducted a 2.5 month test on Sacramento River hatchery stocks under satiation rations and a fluctuating temperature regime (13-24°C) that generally followed the seasonal pattern of the source water. Marine concluded that his work suggests the upper optimum for growth is about 18°C (approx. range 17-20°C). Fish reared at the next highest range (21-24°C), however, experienced significantly less growth than those reared in the control group (13-16°C). Hillman (1991) conducted tests in a controlled laboratory stream environment with chinook salmon. He found that chinook salmon production was 1.2 times greater in cold than warm water (i.e., a 20% reduction in weight when reared at 18-21°C (mean 19.5°C) when compared with 12-15°C (mean 13.5°C) when fed twice per day in experimental channels). The two works cited above suggest 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).

Coho Salmon

In a controlled study by Everson (1973), test fish were subjected to different fluctuating temperature regimes. The greatest growth occurred in coho at the lowest test regime of 12.1-20.8°C (median 16.5°C). Everson also found that juveniles fed moderate rations and subjected to higher fluctuating test temperatures did not reach sizes typical of smolts at the time of downstream migration.

Sockeye Salmon

Biette and Geen (1980, as cited in USEPA, 2001) tested growth under variable rations (4-6.9%) and fluctuating temperature regimes similar to what the fish voluntarily experience in a lake (fluctuating two times per day from 5-9°C to 12-18°C)(approximate mean 11°C). In this work, sockeye grew as well or more rapidly under the natural feeding and temperature regime than at constant temperatures from 6.2-15.9°C (mean 11.05°C); however, at satiation rations growth was better under the constant temperature regimes. Clarke (1978) found that under-yearling sockeye salmon exposed to diel thermocycles are able to acclimate their growth to a temperature above the mean of the cycle. Specific growth in weight on the 7-13°C (mean 10°C) cycle over 42 days was equivalent to that on a constant 11.4°C, and on the 5-15°C (mean 10°C) cycle it was equivalent to a constant 13.9°C. Clarke found that growth was greater at the 5-15°C cycle than at a 7-13°C cycle. In constant exposure testing on maximum rations, growth was linear over the range of 7.5-17.5°C. The work of Clarke suggests that maximum growth would be produced at constant temperatures of 17.5°C.

Steelhead and Rainbow Trout

Grabowski (1973) tested three constant temperatures (8, 15, and 18°C) and one fluctuating temperature regime (8-18°C, mean 13°C) over eight weeks with juvenile steelhead on maximum rations. The author found that steelhead grew best at the constant 15°C and second best in the fluctuating with its mean of 13°C. When the author plotted the data using the midpoint of the fluctuating test as a surrogate for a constant test condition, it showed almost linear growth from 8 to 15°C with a steep drop as the temperature approached 18°C. The percentage weight gains at 8 and 18°C were very similar and both substantially lower than the similar gains obtained at the mean of 13°C and the constant 15°C.

Wurtsbaugh and Davis (1977) studied the effects of ration size and temperature on the growth of juvenile steelhead trout through a series of laboratory and field studies. In 25-day laboratory tests, creek water was used as a control, and was heated 3 and 6°C above its natural fluctuating (dielly and seasonally) temperature to create two alternative test conditions. From this work, the authors concluded that trout growth would be enhanced by average seasonal rearing temperature increases to approximately 16.5°C under satiation feeding, but if the food of wild fish is limited, any substantial temperature increase would result in decreased growth. By examining the fish fed at rates more comparable to those observed in a natural creek, the maximum growth rates observed occurred at mean temperatures of 13.3°C in the Fall test (1.7%/day compared to 1.3%/day at 16.4°C) at 15.2°C in the Spring test (1.6%/day compared to 1.4%/day at 12.6°C), and at 16.2°C in the summer test (1.2%/day compared to 1.1%/day at a mean of 19.5°C). It is worthy of emphasizing that while the summer growth at a mean of 19.5°C (range of 16-23.9°C) was only slightly less than growth at 16.2°C under moderate laboratory rations (7.9 and 6.8%/day, respectively), at the next lowest ration tested (6.0%/day) growth rates at 19.5°C fell sharply to 0.1%/day. The authors calculated that maintenance requirements of the fish increased more than three-fold (2.2-7.4%/day) over the temperature range of 6.9 to 22.5°C.

Dockray et al. (1996) conducted a 90-day test in which temperatures were allowed to fluctuating with the natural regime of the city source water, which followed the pattern of Lake Ontario, plus 2°C to test the potential effects of global warming. The authors found that during the first 50 days of the 90-day test that the temperature increase of 2°C was beneficial to growth up to daily average of 18°C, after which further increases in the daily temperature inhibited long term growth. In a follow-up study, Linton et al. (1998) noted that rainbow trout fed to satiation continued to feed and grow at a mean temperature of 20.5°C, that a 30% reduction in food intake occurred at 22°C, and that juvenile fish continued to feed near their thermal maximum. Linton et al. (1998) found that increasing the temperature regime by 2°C over the natural (base) level for Lake Ontario trout resulted in increased spring and early summer growth that was lost in the latter part of the summer due to suppression of appetite and growth. Mortality rates increased from 6 to 13.1% in the warmer test water during the late summer in the first summer of testing when the mean monthly base temperature in August was 23°C. Mortality was almost nonexistent through the following summer which had a mean August base temperature of 18°C. The threshold temperature for the cessation of feeding, and subsequently growth, differed from >20°C to <20°C over the two summers, and thus also fish size and age. Hokanson et al. (1997) found that a constant exposure to 17.2°C produced the greatest growth rates in trout fed to satiation over a 30-day test period. Increased mortality was observed at temperatures in excess of this growth optimum. They also noted that in fluctuating temperature experiments that growth was accelerated where the mean temperature is below the constant temperature optimum (17.2°C), and growth was retarded by mean fluctuating temperatures above this optimum. The highest growth rate in the fluctuating temperature environment occurred at a mean of 15.5°C (range of 11.7-19.3°C). A statistically non-significant decrease occurred at a mean of 17.3°C (range of 13.5-21.1°C). Through their work the authors also concluded that rainbow trout acclimate to some value between the mean and the maximum daily temperatures. The foregoing works suggest that maximum growth will be obtained at average daily temperatures between 15.5 and 18°C.

<u>Cutthroat Trout</u>

Dickerson et al. (1999, and unpub. data; as cited in Dunham, 1999) found that Lahontan cutthroat growth rates in a test with temperatures fluctuating from 20-26°C (mean of 23°C) were similar to groups of fish held at a constant 23°C, and after two weeks was not significantly different from fish held at a constant 20°C.

Table 4.9. Growth studies conducted in laboratory test waters with fluctuating temperature exposures.

Species	Temperature (range and mean)	Results	Feeding level	Comments	Author
Chinook	13-16 (14.5) 17-20 (18.5) 21-24 (22.5)	Optimal 17-20, with 13-16 having significantly better growth than 21-24	Satiation	2.5 month test following source water regime	Marine, 1997
	12-15 (13.5) 18-21 (19.5)	12-15 significantly better than 18-21	Satiation	18-21 had 20% less growth and 12-15	Hillman, 1991
Coho	12.1-20.8 (16.5)	Greater growth than higher regimes tested	Satiation	Juveniles fed moderate rations did not reach typical size of smolts	Everson, 1973
Sockeye	5-9 to 12-18 (approx 11)		Variable from 4 to 6.9% body weight	Grew more rapidly under natural feeding regime and fluctuation temperatures than at constant 11.05C, but constant better under satiation feeding.	Biette and Geen, 1980
Cutthroat	7-13(10) 5-15(10)	5-15(10) had greater growth than 7-13(10)	Satiation		Clarke, 1978
Steelhead and Rainbow	8-18 (13)	Better growth in a constant 15	Satiation	Weight gains similar at 8 and 18 and both	Grabowski, 1973

Trout		than the fluctuating 8-18 (13)		substantially lower than at 13 and 15.	
		16.5 average seasonal temp considered to enhance growth	Satiation (6.8%/day)	Heated creek water (3 and 6C) followed natural regime for 25 days	Wurtsbaugh and Davis, 1977
		16.2 summer average seasonal considered to enhance growth under natural feeding	Restricted to rates seen in control stream (1.2%/day)	Heated creek water (3 and 6C) followed natural regime for 25 days	Wurtsbaugh and Davis, 1977
		Increases beneficial up to daily average of 18	Satiation	Fluctuated with source water plus 2C over 90 days.	Dockray et al., 1996
	11.7-19.3 (15.5) 13-21.1 (17.3)	Highest growth rate in 11.7-19.3 (15.5), with non-significant decrease in 13-21.1 (17.3)		60 day test	Hokanson et al., 1997

The results of these fluctuating temperature tests is highly variable due at least in part to the high variability in test methodology. Better growth conditions varied from regular daily ranges of 5-15°C to 11.7-19.3°C over the course of the studies (typically month-long studies), to a monthly (described as seasonal) average of 16.5°C, and a highest daily mean of 18°C in a seasonally (90-day) rising temperature regime. This could be simplified and viewed as a range of 10-16.5°C as a monthly average and a maximum daily average of 18°C. Treating the monthly average as either a weekly average or a summer average, to bound the potential best range, would result in a 7DADMax of 13.16-19.68°C (16.42) and 14.64-21.14°C (17.89), respectively. Thus the 7DADMax temperature that would result in maximum growth would most likely occur between 13.16-21.14°C (17.15).

Field Studies on Growth:

Chinook Salmon

In studying growth in a natural stream, Bisson and Davis (1976; as cited in ODFW, 1992) reported that juvenile chinook grew faster in a stream where temperatures peaked at 16°C compared with a stream where temperatures peaked at 20°C.

Coho Salmon

Averett (1969; as cited by Everson, 1973) proposed that August-September stream temperatures should fluctuate between 11-17°C (mean 14°C) for optimal growth. Holtby (1988) reviewing a long term study of coho in an experimentally harvested watershed determined that coho had likely benefited from changes in maximum stream temperature from 12°C to 15°C (which would be approximately equal to a maximum weekly average of 14.56°C). Similarly, Thedinga and Koski (1984) found that smolt size and condition factor was greater in years in which stream temperatures fluctuating annually from 4-13.5°C than in years with temperatures of near 0 to 11-12°C. They associated greater smolt return rates with this greater growth. In a field study by Martin et al. (1984) the stream having the lowest growth was the warmest surveyed, and had average monthly temperatures of 12-17°C and peak monthly temperatures of 21-26 through the summer months. The foregoing does not provide a basis for estimating a maximum growth temperature, but can be used to support the position that weekly average temperatures of 14-15°C would be more beneficial to growth under natural conditions than lower temperature regimes. It also suggests that extreme daily fluctuations and daily maximum temperatures of 21-26°C can be detrimental to growth even under natural conditions.

Steelhead and Rainbow Trout

De Leeuw (1982) found that stream temperature increases that raised the summer maximum temperature from 12°C to 16.5°C were associated with an increase in growth rates in three streams in British Columbia, Canada.

Bisson and Davis (1976; as cited in Li et al., 1994) found that streams with daily maximum temperatures in the range of 16-23°C had greater standing crops of trout than streams with warmer maximum temperatures (26-31°C). Ebersole et al. (2001) found that in tributaries to the Grande Rhonde River in Oregon, rainbow trout density declined as mean daily maximum temperatures (for the two week period prior to survey) warmed above 16°C; reaching zero at approximately 24°C. While the decline in fish density was highly variable in the range of 16 to 20°C, it was a steady decline with very low densities at temperatures above 20°C.

Cutthroat Trout

Temperature increases in general are not always found to restrict cutthroat populations. Aho (1976) found coastal cutthroat preferring an unshaded section of stream in the Cascade mountains of Oregon. Density was twice as high and biomass was 49-65% greater in the unshaded section. He suggested that earlier fry emergence in the warmer unshaded section probably played a role in creating the greater fish weights. The highest weekly mean temperature was 14°C in the unshaded area, with the highest one hour temperature being 17°C. This compared to a daily maximum temperature of 14°C in the shaded section. Cutthroat were the only fish species present in the study stream so any relationship to potential competition could not be evaluated. Martin (1985) studied the affect of removing the vegetative canopy along a 1000 meter section of a third order stream on the Olympic Peninsula used only by cutthroat trout. Fish density increased in the upper 500 meter treatment reach in comparison to the 200 meter control section established just above the treatment reach. Summer daily maximum temperatures in this upper treatment ranged from 13.8°C at the boundary with the control section to about 16.1°C at the bottom of this upper treatment section 500 meters downstream. In the second treatment reach, which extended from 500 to 1000 meters below the control section, the average fish weight increased but density went down. Temperatures in this reach changed from 16.1°C at the upper boundary of the treatment reach to 17.3°C at the lower boundary of the lower treatment reach. The daily maximum temperature was 15.2°C in the midpoint of the upper treatment reach where fish density increased.

Martin (1984) in studying a small upper watershed creek on the Olympic Peninsula found that higher water temperatures during the summer caused metabolism and thus food consumption to increase in a population of cutthroat trout. He found that growth rates declined from a spring high to a low in the winter, and was below the maximum possible during periods of optimum water temperature. Food consumption followed the seasonal trend in food abundance and was limited by the available food supply.

Table 4.10. Summary results from growth studies conducted in the field.

Species	Better growth	Worse growth		Author
Chinook	16 (daily max)	20		Bisson and Davis, 1976
Coho	15 (daily max)	12		Holtby, 1988
	4-13.5 (annual ranges)	0-12	Size and condition factor	Thedinga and Koski, 1984
		12-17 (average monthly)	Lowest growth stream Had peak temperatures of 21-26	Martin et al., 1984
Steelhead and Rainbow Trout	16.5 (daily max)	12		De Leeuw, 1982
	16-23 (daily max)	26-31	Greater standing crops	Bisson and Davis, 1976
	Greater than 16		Density declined	Ebersole et al.,

	(mean daily)		above 16 and was zero at 24. Steady decline above 20	2001
Cutthroat	14 (weekly mean) 17 (daily max)		Site with highest weekly mean of 14 had twice the biomas. Highest one hour temperature was 17.	Aho, 1976
	15.2 (difference along reach 13.8-16.1) (daily max)	16.7(difference along reach 16.1-17.3)	Density increased in reach at 15.2, density declined but average size increased at 16.7.	Martin, 1985

In the field studies cited above, daily maximum stream temperatures from 15-17°C were consistently cited in association with streams having better standing crops of fish. This temperature range would be approximately equal to a 7DADMax range of 14.05-16.05°C. It is important to recognize that most of these studies did not evaluate stream temperatures just one or two degrees higher than those found to have better growth. Thus the conclusion is somewhat restricted to the statement that under natural feeding and temperature regimes salmonid populations will be fully supported at 7DADMax temperatures from 14-16°C.

Predation and Competition Involving Juvenile Fish:

Chinook Salmon

In examining the effect of temperature upon predation rates of juvenile chinook, Marine (1997) found that striped bass predation upon the juvenile fish was very intense in their intermediate test at 17-20°C (mean 18.5°C). Hillman (1991) examined the interaction between chinook salmon and redside shiner in both the Wenatchee River in Washington and in controlled laboratory streams. Immigration of shiners began as river temperatures reached 15°C and as their numbers increased the shiners were able to push the chinook out of the most favorable portions of the river for feeding. Similarly, in the laboratory tests Hillman found that chinook production was 1.2 times greater in cold water (12-15°C, mean 13.5°C) than warm water (18-21°C, mean 19.5°C – resulted in a 20% reduction in weight) in alloparty. In sympatry, shiners affected the distribution, activity, and production of chinook in warm water, but not in cold water. Based on the preceding, average temperatures in the range of 13.5-15°C favors the cold water chinook salmon over common non-salmonid competitors. Average temperatures of 18.5-19.5°C would place the chinook salmon at a significant disadvantage for occupying and defending important habitat.

Steelhead and Rainbow Trout

Juvenile competition, particularly with warm water and non-salmonid species, is a concern that is sometimes expressed in association with warm summer rearing temperatures. Reeves et al. (1987) found that steelhead production was decreased by 54% in the presence of redside shiner in waters in the range of 19-22°C (mean 20.1°C), but was not reduced in cooler waters (12-15°C, mean 13.5°C). They also noted that production of steelhead in a fluctuating 19-22°C waterway was less than half of that in a fluctuating 12-15°C waterway. While warmer waters favor redside shiner over steelhead, colder waters may favor other species. It has been suggested, for example, that in cooler waters brook trout can out-compete juvenile steelhead. In trying to explain the patterns of species distributions observed in the upper Columbia river tributaries, Mullan et al. (1992; using the work of Cherry et al., 1975) note that sympatry occurs between *O. mykiss* and brook trout in the range of 15-18°C (mean 16.5°C), that temperatures above 18°C favors *O. mykiss*, and that temperatures less than 15°C favors brook trout. They also note, however, that under natural food rations, the level of optimal competition is likely to be lower. Cunjak and Green (1986) found that rainbow trout were able to compete better with brook trout at 19°C than at either 8 or 13°C. In tests of the interaction between rainbow trout and bull trout in the Columbia River drainage in British Columbia, Haas (2001) found that rainbow trout do particularly better than bull trout when maximum temperatures approach 14-15°C. Trying to set temperature threshold recommendations that will prevent a competitive advantage with an introduced coldwater salmonid, however, is not viewed as appropriate given the extensive overlap of their preferred thermal ranges. Based on the preceding, it appears that average temperatures of 20°C or warmer place steelhead at a competitive disadvantage over warm water competitors like redside shiner, while average temperature of 13.5°C or less do not.

Cutthroat Trout

DeStaso and Rahel (1994) found that Colorado cutthroat trout competed nearly equally with brook trout at 10°C, but at 20°C the brook trout were dominant. Schroeter (1988; as cited in Dunham, 1999) found that Lahontan cutthroat were equal competitors with brook trout at 15°C. Nilsson and Northcote (1981) found interestingly enough that in sympatry the presence of more aggressive rainbow trout actually resulted in higher growth rates in cutthroat trout than the growth rates shown by the cutthroat in allopatry.

Summary on Competition and Predation

Trying to set temperature standards that will prevent competition with an introduced cold water species is not viewed as appropriate give the extensive overlap of their preferred thermal ranges with Washington's native cold water species. It is more appropriate to focus this discussion on temperatures that allow coolwater or warmwater species to out-compete our native salmon and trout. Table 4.11 below summarizes the studies on competition and predation. The literature suggests that as average river temperatures increase to about 15°C competitors begin to gain a competitive edge that becomes very significant as the average temperature reaches 18.5-20°C. In converting these average ranges they may best represent either daily average or weekly average temperatures. This results in an estimate that as the 7DADMax temperature exceeds 17.60-18.18°C (17.89) coolwater species will begin to displace juvenile salmon and trout from the best feeding habitats, and that the impact on growth would be severe at 22.05-23.18°C (22.62) even if such displacement did not occur.

Table 4.11. Studies on predation and competition with salmon and trout.

Species	**Increased predation or competition**	**Type of Study**		**Author**
Chinook	17-20 (18.5)	Laboratory	Intense increase in predation from striped bass	Marine, 1997
	15 (average)	Field	Redside shiner immigrated and began to push out juvenile salmon	Hillman, 1991
	18-21 (19.5)	Laboratory	Redside shiner caused a 20% reduction in weight compared to competition at 12-15 (13.5)	Hillman, 1991
Steelhead and Rainbow Trout	19-22 (20.1)	Laboratory	Redside shiner caused a 54% reduction in production compared to competition at 12-15(13.5)	Reeves et al., 1987
	Less than 15 favors brook trout		Sympatry with brook trout 15-18 under satiation rations.	Mullan et al., 1992
	8-13		Brook trout are better able to compete	Cunjak and Green, 1986
	Below 14 (maximum temperatures)		Bull Trout	Haas, 2001
Cutthroat Trout	20 and above		Colorado cutthroat are in sympatry with Brook trout at 10	DeStaso and Rahel, 1994
			Lahontan cutthroat equal with brook trout at 15	Schroeter, 1998

Temperature Preferences in the Laboratory:

Chinook Salmon

Brett (1951; as cited in Ferguson, 1958) reportedly found that the final preferendum temperature for chinook is 11.7°C. Sauter and Maule (2000) found that the mean temperature preference of fall chinook decreased from a high of 17.77 to a low of 11.12°C during smoltification, while yearling spring chinook salmon showed no change in their preference for a mean temperature of 16.69°C.

Coho Salmon

Piper et al. (1982) suggested that maximum temperatures between 9.4-14.4°C are optimal or selectively preferred by juvenile coho; however, Bell (1986) suggested the preferred range for coho is 4.4-9.4°C. Konnecki, Woody and Quinn (1995) studied two groups of coho and found that the preference temperature changed with the parental stock used. Coho from parental stock originating from cold ground water supplied streams preferred 9.6°C (range 6-16°C), while those from stock originating from warmer streams preferred 11.6°C (range 7-21°C).

Chum Salmon

Juvenile chum salmon reportedly prefer temperatures between 11-14.6°C, and are considered to be optimally maintained at 13-13.5°C (Kepshire, 1971; as cited in Brett, 1979). Ferguson (1958) suggests that the final temperature preferendum for chum salmon is 14.1°C. In a 1952 study, Brett found that juvenile sockeye avoided temperatures above 15°C and selected 12-14°C when provided an opportunity.

Pink Salmon

Bell (1986) and Bonar et al. (1989) suggest pink salmon prefer waters in the range of about 5.6-14.5°C, while Ferguson sets the final preferendum at 11.7°C and Brett (1952) determined pink salmon acclimated to temperatures below 15°C select temperatures in the range of 12-14°C.

Sockeye Salmon

Ferguson (1958) used earlier work by Brett (1951) to determine that the final preferendum for sockeye was 14.5°C. Brett (1971; as cited in USEPA, 2001) found swimming capacity, metabolic scope, growth on excess rations, and ingestion were maximized at 15°C, and that 15°C was also the final preferendum temperature.

Steelhead and Rainbow Trout

Hahn (1977) compared the preference decisions of fry and yearling steelhead exposed to three constant (8.5°C, 13.5°C, and 18.5°C) and one fluctuating (8-19°C) temperature regime. Hahn found that as many fish remained in the fluctuating regime (which has a mean of 13.5°C) as in the constant 13.5°C regime; twice as many fish remained in the fluctuating regime compared with the constant 18.5°C; and twice as many remained in the constant 8.5°C as in the fluctuating regime. By inference, Hahn concluded that twice as many fish preferred a constant 13.5°C to a constant 18.5°C, and twice as many preferred a constant 8.5°C to a constant 13.5°C. Hahn's work suggests that juvenile steelhead may have a preference for water temperatures between 8.5-13.5°C. It also suggests that the daily average temperature may roughly equal a constant exposure test scenario for the purpose of translating laboratory tests into water quality criteria.

Ferguson (1958) cites 13.6°C as the final preferendum temperature for rainbow trout. The work of Li et al. (1993; and 1994) and Li et al. (1991; as cited in Spence et al., 1996), studying interior populations of rainbow trout, suggest that while rainbow trout showed no avoidance reactions when stream temperatures were below 20°C, they actively avoided staying in waters warmer than 23-25°C. McCauley and Huggins (1975) found that five large (150-250 grams) rainbow trout had a preferred mean temperature of 16.7°C, and that the fish actively cycled between 13.8°C and 18°C. The work and literature citations of Kwain and McCauley (1978) (citing Huggins 1978 Garside and Tait, 1958, Christie as reported in Fry, 1971, and McCauley et al., 1977) support the position that rainbow trout temperature final preferendum decline from 17-21°C in first six months of life to eventually centering on 13°C as overyearlings. McCauley and Pond (1971) found that underyearling rainbow trout showed a preference for 17-20°C in laboratory tests.

Summary of Laboratory Temperature Preference Studies

The results of preference testing depends upon acclimation temperature, length of test, breadth of temperature gradients used, and age of fish. Fish will actively cycle between temperature regimes during the test period, which is typically one hour in length, and their time spent in different temperature zones is used to determine where they spent most of their time (preference is in essence the mode of the distribution). While the range of temperatures through which fish commonly cycled during the tests extended from 4.4-21°C, preferred temperatures ranged from 9.6-17.7°C. The majority of the preferred temperatures were from 11.6-16.7°C (see Table 4.12, below). These preferred tests would best relate to a daily mean temperature. A daily mean of 11.6-16.7°C would be roughly equivalent to a 7DADMax of 14.2-19.3°C (16.75).

Table 4.12. Results of laboratory studies examining temperature preferences.

Species	Preferred	Preferred	Comments	Author

	temperature	Range		
Chinook	11.7		Final preferendum	Brett, 1951
	17.7 to 11.12		Fall Chinook decrease in preference during smoltification	Sauter and Maule, 2000
	16.69		Spring chinook	Sauter and Maule, 2000
Coho		4.4-9.4		Bell, 1986
		9.4-14.4 9		Piper et al., 1982
	9.6	6-16	Parental stock from colder water	Konnecki et al., 1995
	11.6	7-21	Parental stock from warmer water	Konnecki et al., 1995
Chum		11-14.6		Kepshire, 1971
	14.1			Ferguson, 1958
		12-14		Brett, 1952
Pink		5.6-14.5		Bell, 1986 and Bonar et al., 1989
	11.7			Ferguson, 1958
		12-14	Acclimated below 15	Brett, 1952
Sockeye	14.5		Used work of Brett, 1951	Ferguson, 1958
	15		Final preferendum	Brett, 1971
Steelhead and rainbow trout		8.5-13.5		Hahn, 1977
	13.6		Final preferendum	Ferguson, 1958
			Actively avoided 23-25	Li et al., 1991, 1993, and 1994
	16.7	13.8-18	Cycled between 13.8-18	McCauley and Huggins, 1975
		17-21	First six months of life.	Kwain and McCauley, 1978
	13		Overyearlings	Kwain and McCauley, 1978
		17-20	Underyearlings	McCauley and Pond, 1971

Swimming Performance and Scope of Activity:

Coho Salmon

In tests on swimming performance, Griffiths and Alderdice (1972) and Brett et al.(1958) found that optimum swimming performance in juvenile coho salmon occurred at a combination of acclimation and test temperatures near 20°C. Griffiths and Alderdice reported that above 20°C swimming performance experienced a marked reduction. Delacy et al. (1956) and Paulik et al. (1957) also studied the swimming performance of coho salmon. They found that coho could recover to approximately to 31% after a one-hour rest and to 70% within three hours of exhaustive swimming effort, and recover fully overnight. They also noted that eggs taken from coho salmon repeatedly fatigued in their testing exhibited normal fertility and survival. A significant swimming performance decrement was associated with pre-test activity of the salmon, and salmon that swam longer before fatigue required more recuperation time; suggesting that the salmon are highly susceptible to fatigue. Beamish (1978; as cited in USEPA, 2001), in a literature review indicated that coho reach a maximum speed at approximately 17-18°C.

Sockeye Salmon

Brett (1971; as cited in USEPA, 2001) found swimming capacity, metabolic scope, growth on excess rations, and ingestion were maximized at 15°C, and that 15°C was also the final preferendum temperature. In tests on physiological performance, juvenile sockeye reach their maximum swimming speed at 15°C (Brett and Glass, 1973; Brett et al., 1958). Brett et al. (1958) noted that the capacity of young sockeye to stem a normal river current of 1.0 ft/sec. for more than an hour is limited to a relatively small temperature range of 12.5-17.5°C. Beamish (1979; as cited in USEPA, 2001) found that sockeye reached maximum speed at 15°C.

Mcdonald et al. (2000) used field studies to conclude that optimal swimming performance occurs at 17°C and that a 20% reduction occurs at 21°C. Brett (1983) in discussing the energetic needs of sockeye suggested that the protected environment of a growth-metabolism tank or hatchery pond may not correspond well with the search-attack-avoid-escape patterns of real life. An attack or escape episode involving 20 second burst speed was shown, in terms of energy expended, to be equal to that of 15 minutes of active metabolism (maximum sustained swimming speed) or about 3 hours of basal metabolism (cites Brett and Groves, 1979). Brett suggests the additional energy requirements of real life cannot be disregarded; nor can it be conceived as incessantly present. Hinch and Bratty (2000) found that Fraser River sockeye used a “burst and then sustained” swimming pattern to negotiate obstacles, and that fish that maintained the “burst” phase too long failed to negotiate significant obstacles and often dropped back downstream failing to complete their migration. This work showed two important facts, the first being that sockeye may be near the limits of their performance while migrating through rapids and that fatigue can result in the permanent loss of the migrants, and that fish may use techniques to perform better in the field than in laboratory experiments. That such stressors may be additionally selective against individuals is also likely. The work by Hinch and Rand (1998) and others has shown that males suffer more swimming impairment then females and that small fish must expend more energy than larger fish.

Steelhead and Rainbow Trout

Cech and Myrick (1999) found that winter-run steelhead swimming velocities increased slightly with an increase in temperature from 11°C to 15°C and decreased slightly with an increase in temperature from 15°C to 19°C. Dickson and Kramer (1971) found that the maximum scope of activity occurred at 20°C in rainbow trout.

Cutthroat Trout

Dwyer, and Kramer (1975; as cited in Dunham, 1999; and Gresswell, 1995) found the greatest scope for activity in cutthroat trout to be at 15°C.

Table 4.13. Studies examining swimming speed and maximum scope for activity.

Species	**Maximum performance**	**Prolonged performance**		**Author**
Coho	20		A marked reduction occurred above 20	Griffiths and Alderdice, 1972
	20			Brett et al., 1958
	17-18		Literature review	Beamish, 1978
Sockeye	15			Brett, 1971
	15			Brett and Glass, 1973
	15			Brett et al., 1958
		12.5-17.5	Capacity to stem normal current for more than one hour limited to range of 12.5-17.5	Brett et al., 1958
	15			Beamish, 1979
	17		Based on field studies. 20% reduction at 21	Mcdonald, 2000
Steelhead and	15			Cech and

rainbow trout				Myrick, 1999
	20		Maximum scope for activity	Dickson and Kramer, 1971
Cutthroat	15		Maximum scope for activity	Dwyer and Kramer, 1975,
	15		Maximum scope for activity	Gresswell, 1995

Maximum swimming speed and maximum scope for activity have been noted at temperatures ranging from 15-20°C (17.5) in salmon and trout. The short-term tests that were used to base most of these estimates on, and the real time effects of temperature (the effect of temperature is essentially immediate on swimming performance) suggests these estimates may best transfer to some daily maximum metric. The biological consequences of having a short-period of each day not allowing for maximal performance is difficult to ascertain. However, the works of Brett (1958) and Mcdonald (2000) were designed to better transfer swimming performance estimates to the field, and suggest a more narrow temperature range (12.5-17.5°C, and 17°C, respectively) of temperatures. Based on these factors it seems reasonable to assume that exposure to temperatures above 17-17.5°C may have detrimental biological consequences in cases where overcoming predators and river obstacles is necessary. Since these temperature effects are not apparently affected by average exposures, it is believed that a 7DADMax of 17-17.5°C should be considered the upper temperature regime that will fully protect the swimming performance of salmon and trout in riverine environments.

Field Distribution Restrictions in Juvenile Fish:

<u>Chinook Salmon</u>

In the work of Torgersen et al. (1999) fish from portions of the John Day River basin in Oregon were found strongly associated with cool water segments in the middle fork where temperatures ranged from 22-24°C along its length, but were much less related to temperature fluctuations in the cooler north Fork where temperatures ranged from 15-22°C along its length. In an unpublished report to the USEPA and the National Science Foundation (1999) Torgersen, Baxter, Li, and McIntosh further discuss the spatial distribution of fish in the John Day. They noted that the cross-over point where cold water fish no longer dominate over warm water fish occurred where afternoon temperatures reached 17°C. The general range for chinook salmon has been suggested as extending from 0.0-0.6°C to 25°C, with an optimal or preferred range extending from 6.7-10°C to 13.9-14.4°C (Bell, 1986; Piper et al., 1982).

Coho Salmon

In trying to determine the cause for coho losses from streams on the west side of Mount St. Helens, Martin et al. (1986) found that summer mortality was correlated with both high monthly average temperatures and maximum August diel fluctuations. One creek experiencing high mortality exceeded 25°C for 10 days in one year and 30 days in the next. Bisson et al. (1988) found that growth remained positive in streams that exceeded 24.5°C, but that at about 22°C the coho seek out cool water areas. Hall and Lantz (1969) found no statistically significant change in coho abundance in a clear-cut test stream where maximum summer temperatures were increased from 16.1-16.6°C to 24-30°C, even though cutthroat trout populations experienced a decline of 75%. In a study of salmonid distributions in a coastal Oregon river drainage, Frissell, Nawa, and Liss (1992) found that cutthroat, coho, and chinook salmon dropped out in sequence as daily maximum temperatures increased, with rainbow trout being the only species found in waters exceeding 23°C. An abrupt loss of coho and chinook was found to occur between 21 and 23°C, and while small numbers of coho were found in the warmer waters, they were always found in association with small cool pockets of otherwise warm reaches.

Chum Salmon

Juvenile and adult chum salmon have been observed in waters with temperatures ranging from 0-25.6°C (Bell, 1986). Bonar et al. (1989) considered 10.1°C to be the optimal temperature for adults in marine waters.

Pink Salmon

Pink salmon are noted as being found in temperatures ranging from 0-25.6°C (Bell, 1986), while Sheridan (1962) has stated that the range in Alaskan waters extends from 7.2-18.3°C. Welch et al. (1995) determined that the upper thermal boundary for the offshore marine occurrence of pink salmon was 10.4°C.

Sockeye Salmon

While sockeye salmon are noted to occur within the range of 0.6-21°C (Piper et al., 1982), the range of temperatures under which they perform optimally may be more restricted. The optimal temperature for juvenile rearing was identified 10-15°C by Piper et al. (1982), and 10.6-12.2°C by Bell (1986).

Steelhead and Rainbow Trout

Frissel et al. (1992) studied the distribution of rainbow trout and found that while they could be found in water temperatures over 23°C, there was a general threshold response for age 1+ fish above 22°C and for age 2+ fish above 21°C.

The work of Li et al. (1993; and 1994) and Li et al. (1991; as cited in Spence et al., 1996), studying interior populations of rainbow trout, suggest that while rainbow trout showed no avoidance reactions when stream temperatures were below 20°C, they actively avoided staying in waters warmer than 23-25°C. While the works of Li et al. (1991, 1993, and 1994) were conducted on interior populations of trout (likely to have been redband trout), Behnke (1992) reported finding redband trout in the desert basins of southern Oregon and northern Nevada that regularly encounter temperatures that kill other trout. Trout in these intermittent desert streams were found actively feeding in water of 28.3°C.

Kaya et al. (1977) found that daily maximum temperatures exceeding 25°C caused rainbow trout to move out of the main stem of the Firehole River in Montana. These fish would move into tributary streams that averaged 6-10°C lower in temperature. Behnke (1992) in a review of the Kaya (1978) study concluded that thousands of years of adaptation to a desiccating environment have enabled the Oregon desert redband trout to feed at high temperatures, but 60-70 years seem too few to have allowed the planted rainbow trout to expand their functional feeding temperature in the Firehole River. While there are observations of redband trout feeding and surviving at relatively high temperatures for a salmonid (28°C, Behnke 1992; 27.4°C, Sonski 1986 and 27°C, Bowers et al. 1979 as cited in USEPA, 2001), it is unclear whether temperatures were measured at the location of the stream where the fish were found. These trout may rely on microhabitats or thermal refugia to maintain populations in desert environments (Ebersole et al. 2001). Thus it may not be appropriate to use these observations to conclude that such temperatures are not harmful. However, the basis for the argument that interior redband may have warmer optimum limits then the coastal rainbow stocks seems likely, even if it is not well established in the literature. It is believed that the upper range of what is sometimes found as fully protective for rainbow trout should be applied specifically to these interior non-anadromous redband trout.

Cutthroat Trout

Bell (1986) used a review of the literature to conclude that the range for cutthroat trout was from 0.6-22.7°C, and the preferred range was from 9.4-12.7°C. Hall and Lantz (1969) found a 75% reduction in a cutthroat trout population in response to experimental logging of riparian canopies in three coastal streams. Prior to treatment, these streams had monthly average temperatures ranging from 6.1-12.8°C and maximum temperatures ranging from 16.1-16.6°C. In the treatment stream experiencing the greatest canopy removal, daily maximum temperatures increased to 24 and 30°C in the two years following treatment. These results compared well with the work of Frissell et al. (1992) who studied the distribution of salmonids in a small coastal river system in southwest Oregon. They found that cutthroat, coho, and chinook salmon dropped out in sequence as maximum temperatures increased, with rainbow trout the only species present in waters exceeding 23°C. Cutthroat were absent, and coho salmon rare in segments exceeding 21°C. While Varely and Gresswell (1988; as cited in Gresswell, 1995) reported that Yellowstone cutthroat are found in geothermally heated streams with ambient temperatures of 27°C, they report these fish are found associated with cooler thermal refuges. Varley and Gresswell (1988) suggested that the optimum water temperature for Yellowstone cutthroat trout is from 5.5-15.5°. Kelly

(1993: as cited in Gresswell, 1995), however, reportedly found that cutthroat were excluded from a tributary to the Yellowstone River because summer water temperatures often exceeded 22°C. Dunham et al. (unpub.; as cited in Dunham, 1999) found Lahontan cutthroat appear to have distributional limits that correspond closely to maximum water temperatures of 26°C. Pauley et al. (1989) suggest that cutthroat trout are not usually found in waters where the maximum temperature exceeds 22°C even though they may tolerate brief periods of temperatures as high as 26°C.

Table 4.14. Summary of information on the field distribution of salmonid and trout in relation to temperature.

Species	Temperature for range	Optimal or preferred range		Author
Chinook	15-22		Range of river temperatures where fish not found in association with refugia	Torgersen et al., 1999(a)
	17 (daily max)		Point where warm water fish begin to dominate	Torgersen et al., 1999(b)
	0.0-0.6 to 25	6.7-10 to 13.9-14.4	General observed range	Bell, 1986, and Piper et al., 1982
Coho	22		Begin to seek out refugia	Bisson et al., 1988
	24-30 (daily max)		No change in abundance with rise from 16.1-16.6 to 24-30	Hall and Lantz, 1969
	21-23 (daily max)		Abrupt loss in coho	Frissel et al., 1992
Chum	0-25.6		General observed range	Bell, 1986
		10.1	Optimal in marine water	Bonar et al., 1989
Pink	0-25.6		General observed range	Bell, 1986
	7.2-18.3		In Alaska	Sheridan, 1962
	10.4		Upper thermal boundary in marine water	Welch et al., 1995
Sockeye	0.6-21	10-15	General observed range	Piper et al., 1982
		10.6-12.2		Bell, 1986
Steelhead and rainbow trout	22 (age 1+) 21 (age 2+)		General threshold	Frissel et al., 1992

			response	
	27, 27.4, 28.3		Redband trout found actively feeding	Bowers, et al., 1979, Sonski, 1986, and Behnke, 1992
	25 (daily max)	15-19	Caused rainbow trout to move from main stem	Kaya et al., 1977
	23-25	20	Redband actively avoided 23-25, but not 20	Li et al., 1991, 1993, and 1994
Cutthroat trout	0.6-22.7	9.4-12.7	General observed range	Bell, 1986
		16.1-16.6 (daily max)	Increase from 16.1-16.6 to 24-30 resulted in a 75% population reduction	Hall and Lantz, 1969
	21 (daily max)		Absent in segments exceeding 21	Frissel et al., 1992
	27	5-15.5	Yellowstone cutthroat found in river at 27 in association with refugia	Varley and Gresswell, 1988
	22		Yellowstone cutthroat reported to be excluded above 22	Kelly, 1993
	26 (daily max)		Lahontan cutthroat distributional limits	Dunham et al., 1999
	22 (daily max)		Seldom found above	Pauley et al., 1989

While some authors report finding salmon and trout in the range of 24-30°C, most found that their presence was dependent upon cold water refugia. The general pattern of the findings cited above seems to suggest that daily maximum river temperatures of 21-22 will create a distributional limit to finding salmon and trout, and that healthy populations are more likely to be found within the range of 10-19°C. Most authors, however, place the optimal range below 17°C and Torgersen et al., (1999b) additionally found that warm water species begin to dominate above 17°C. Thus based on this line of evidence, a 7DADMax of 16.05°C should be considered the limit for finding strong populations of salmon and trout, and river temperatures above a 7DADMax of 20.05-21.05°C should be considered to create a thermal barrier to the general summer distribution of salmon and trout. Beyond this temperature barrier, the presence of salmon and trout may be primarily dependent on the availability of cold water refugia. There is reason to suspect that redband trout may have slightly higher temperature ranges than the other native salmon and trout. The information is scant and should be used with caution, but it suggests that the healthy distribution of redband trout may be better described by 18.05°C as 7DADMax, and 22.05°C may more appropriately describe the thermal barrier for redband populations.

General Findings and Recommendations Found in the Literature:

Chinook Salmon

The Independent Scientific Group (1996) concluded that juvenile chinook salmon rearing is optimal where temperatures are maintained in the range of 12-17°C; and suggests 15°C is most optimal.

Coho Salmon

Servizi and Martens (1991) found that susceptibility to sediment toxicity increased by 33% at 18°C, and Shelbourn (1980) determined that hypo-osmoregulatory capacity is optimized at 14°C.

Steelhead and Rainbow Trout

Bell (1986) recommended that temperatures generally be maintained in the range of 7.3-14.5°C for optimal rearing of juvenile steelhead.

Conclusion on Juvenile Rearing of Salmon and Trout:

Table 4.15. The multiple lines of evidence for juvenile rearing of salmon and trout.

Line of Evidence	**7DADMax (°C)**	**Midpoint**	Comments
Laboratory Growth Studies Conducted at Constant Temperatures	14.18-18.14	16.16	Based on well controlled laboratory tests.
Ranges Identified in Literature as Optimal for Growth	15-21	18	Basis for estimates and intended metrics unclear.
Comparison Test Regimes With Better Growth	11.8-15.4	13.6	Maximum growth temperatures were not determined, only favorable growth compared to one other significantly warmer or cooler temperature.
Laboratory Growth Studies in Fluctuating Temperature Regimes	13.16-21.14	17.15	Based on well controlled laboratory tests.
Field Studies on Growth	14.05-16.05	15.05	Regime with better standing crops. Specific temperature limits were not determined.
Predation and Competition	17.60-18.18	17.89	Displacement of juvenile salmon and trout
Temperature Preferences in the Laboratory	14.2-19.3	16.75	Mode of distribution of fish cycling between temperature zones
Swimming Performance and Scope for Activity	17-17.5	17.25	Based primarily on controlled laboratory studies.
Field Distribution - Healthy	16.05	16.05	Basis and methodology generally unclear for most literature estimates. Thus this estimate relies on the general upper range considered healthy, and temperatures above which coldwater species begin to loose dominance
Best estimate of threshold	***14.78-18.08***	***mid. pt. 16.43***	

Using all nine lines of evidence cited above, the upper limit to defining a healthy summer rearing temperature would occur within the range of 14.78-18.08°C as a 7DADMax, with an overall mean of 16.43°C. While each line of evidence has unique strengths and weaknesses, the second and third lines of evidence are particularly questionable. The second line of evidence consists of technically unsubstantiated recommendations of specific authors, and the range produced in the third line of evidence is driven by comparisons tests that only compared and contrasted two very different test regimes (e.g., only compared 8 to 12) without any effort to identify maximum growth. Without these two very weak lines of evidence, the range within which favorable juvenile rearing would be expected changes to a 7DADMax of 15.18-18.05°C (16.62°C). Since both estimates would round out to the same ½ degree value, it is recommended that a 7DADMax of 16.5°C be considered fully protective of juvenile rearing.

iv) Juvenile Winter Holding

<u>Chinook Salmon</u>

Temperature declines below 1.1-5°C can cause fish to become dormant and move into the substrate. Once fish have initiated hiding behavior, it may take temperatures rising again to above 7°C to bring them back out (Chapman and Bjornn, 1969). While this natural behavior is a healthy response for winter survival, unseasonably cold discharges causing water temperatures to unseasonably fall below 5-7°C need to be avoided. Dropping the temperature to 2.5°C for even a few days may result in mortality to chinook that were acclimated to a river temperature of 15°C (Brett, 1956). To avoid initiating unseasonable hiding behavior, to avoid lethal effects, and to encourage strong growth rates the daily low temperature should typically exceed 7°C during the growing season.

<u>Steelhead and Rainbow Trout</u>

After steelhead fry emerge from the gravel they move to the slow moving waters of the stream margins, shifting to faster and deeper waters as they grow larger (Chapman and Bjornn, 1969). Martin et al. (1991) and Wydoski and Whitney (1979) note the importance of cover to juvenile steelhead. Large woody debris, substrate, and turbulence are all identified as important habitat for young juveniles. Temperature is believed to affect the habitat selection and migration of juveniles. Mullan et al. (1992) found that fry emigrate from cold headwater streams to down-stream reaches to rear in warmer waters. Chapman and Bjornn (1969) found that young steelhead may move downstream in the fall to over-winter in larger streams. Chapman and Bjornn (1969) found that 5-5.5°C marked the boundary between activity and inactivity in steelhead, with fish entering the substrate. They found that steelhead emigration could be stopped by warming the water from 7.2°C to 11-12.2°C. Mullan et al. (1992) suggest that while steelhead juveniles may reside in the dark frozen snow covered tributaries near 0°C for up to 5 months, 6°C may form the boundary that allows winter growth to occur.

Some controlled field studies have shed some light on the winter rearing habits of rainbow trout. Rainbow trout actively feed at very cold temperatures (0-0.6°C) even under ice covered streams. Their winter feeding habits are primary controlled by the availability of food. They consume dislodged insects, and feed on insects that emerge at more moderate temperatures (4.4°C or more). Winter mortality is likely due to a combination of factors including insufficient food supply, and physical damage from snow slumps and ice scour (Needham and Jones, 1959; Needham and Slater, 1944; Maciolek and Needham, 1952; and Reimers, 1957).

Cutthroat Trout

Jokober et al. (1998) found that westslope cutthroat trout made extensive migrations downstream to escape winter conditions that resulted in supercooling (<1°C) of the water and anchor ice formation.

v) Adult Migration

Barriers to Migration of Salmon and Trout:

Chinook Salmon

After spending 3-4 years in the ocean mature chinook salmon begin their return migrations to freshwaters to spawn. Temperatures can create serious problems for migrating salmon. In addition to posing the threat of direct lethality to adult spawners, temperatures can create blockages that stop migrating fish, create conditions that result in high mortality of spawners from disease, and reduce the overall fitness of migrants. Since migrating salmon do not feed in freshwaters they must enter freshwater with sufficient fat and muscle reserves to supply their metabolic requirements up to and through the act of spawning. The increased active and basal metabolic demands caused by traveling and holding in warmer waters uses up stored energy reserves at a more rapid rate. This can result in a decrease in the quality and quantity of eggs as well as an overall reduction in the fitness of the adult fish that need to migrate and negotiate obstacles, excavate and guard redds, and complete the act of spawning. Berman and Quinn (1991) demonstrated that in the months prior to spawning, spring run chinook actively sought out cool water refuges in the Yakima River, in Washington. These fish were able to maintain average internal temperatures 2-5°C below the ambient river condition, which may have reduced their metabolic demand by 12-20%. Mcdonald et al. (2000) found that chinook salmon in the Fraser River in Canada suffered unusually large losses (25%) where mean daily river temperatures frequently exceeded 20°C and reached a high of 23°C. The most widespread concern with warm temperatures is from prespawning mortality due to an increased incidence of diseases. These diseases can directly kill or impair healthy fish, or act secondarily through infection of the minor wounds that normally occur in migrating fish. Disease is a serious concern and is discussed and incorporated separately in the recommendations of this paper.

Daily maximum temperatures rising above 21-22°C are widely cited as causing barriers to migrating chinook salmon (Stabler, 1981; Bumgarner et al., 1997; Hallock, Elwell, and Fry, 1970; Thompson, 1945, as cited in Snyder and Blahm, 1971; Don Ratliff, 1977, as cited in Stabler, 1981; Fish and Hanavan, 1948, and Major and Mighell, 1967, as cited in USEPA, 1971; and Alabaster, 1988, as cited by USEPA, 2001). Hallock, Elwell, and Fry (1970) suggested that maximum temperatures of 18.9°C in association with low dissolved oxygen levels (5ppm) created a partial block of migrating chinook salmon. However, some authors note chinook not showing avoidance for temperatures as high as 24.4°C (Gray, 1990; Dunham, 1968; as cited in CDWR, 1988). However, Thompson (1945; as cited in Snyder and Blahm, 1971) suggested that it was the difference in temperatures that stopped chinook from migrating from the Columbia to the Snake River. Differences were 17.2:21.7°C and 22.2:26.1°C when blockages occurred, with migration resuming when the difference approached 1.6°C. Similarly, Gray (1990) suggested that incremental increases of 9-11°C formed a barrier to migration. Temperatures above 20-21°C are certainly stressful for chinook salmon. Sauter and Maule (1997) reported cessation of feeding as well as thermoregulatory behavior in sub-yearling fall chinook held between 18-20°C, with exposure to 20°C for several hours inducing heat shock proteins (Sauter et al., in review, and M. Hargis, personal comm.; as cited in Sauter and Maule, 1997). In a field study by Frissel, Nawa, and Liss (1992), it was found that maximum water temperatures in a coastal river system in Oregon were linked to the presence or absence of various species of salmonids. While it was noted that cutthroat were absent and coho salmon rare or absent in segments exceeding 21°C, chinook dropped out completely only at 23°C; although, their presence in such waters was associated with positioning in small cool pockets in otherwise warm reaches. Some authors have suggested criteria for the protection of migrating chinook salmon. Piper et al. (1982) considering this important life stage suggested that 7.2-15.6°C was necessary to protect upstream migration and maturation. Bell (1973; as cited by Everest et al., 1985) suggested that temperatures should be within the range of 3.3-13.3°C for spring chinook, 13.9-20°C for summer chinook, and 10.6-19.4°C for fall chinook. Support for assuming a general 20-21°C threshold for salmon migration can also be found in the technical literature on lethality studies. As summarized below, temperatures of 20-22°C, particularly at lower prior acclimation temperatures, can be directly lethal to chinook salmon (Brett, 1956; Brett et al., 1982; Coutant, 1970; Beacham and Withler, 1991; Becker, 1973; Orsi, 1971; as cited in CDWR, 1988) with a 7-day exposure. It also appears from the available evidence that adults may be more sensitive than the juveniles which are most typically tested (Becker, 1973). Based on the technical literature, it is concluded that to prevent a risk of causing blockage of migrating chinook salmon daily maximum temperatures should not exceed 21-22°C, particularly when the migrating fish will be acclimated to lower (2-6°C) water temperatures as they travel upstream.

Many runs of chinook will need to hold or travel during the summer when stream temperatures are at a maximum in the lower and mid-elevation rivers. Therefore, criteria to protect migration should be set to protect against chronic sublethal effects as well as acute effects such as blockages and lethality. While chinook adults can almost certainly withstand occasional daily peak temperature cycles up to 22°C, the general condition encountered by these migrating fish should approach more optimal conditions. This will avoid unhealthy levels of stress and utilization of stored energy reserves. It is concluded that summer daily maximum temperatures during migration should generally remain within or below the range identified previously as fully protective for juvenile chinook salmon rearing, and single daily maximum temperatures be maintained below 20-21°C wherever possible.

Where fish may hold in waterbody segments for long periods of time prior to spawning, as is commonly the case for spring chinook, special protection may be warranted on a case-specific basis. To protect adult fish that are holding throughout the summer, temperature limits should be established that recognizes these fish are living off their stored energy reserves and may be in a ripe condition in the later portion the summer or early Fall. Three physiological endpoints seem especially relevant in guiding the selection of an appropriate summer holding criteria. The first is the preferendum values (constant 11.7°C, and a range of 6.7-14.4°C), the second is the fully protective rearing threshold (an average of 14-15°C, and a 7-day average of the daily maximum temperatures of 16.5°C) and the third is the temperature regime identified to protect eggs invivo in ripe females (weekly average temperatures below (13-15°C). In consideration of these factors it is concluded that where chinook are holding over the summer, the average water temperatures should be maintained below 13-14°C and the 7-day average of the daily maximum temperatures maintained below 16-17°C.

<u>Coho Salmon</u>

While adults can migrate through waters warmer than considered fully protective for juvenile rearing, the same thresholds which produce metabolic stress with juveniles are likely to produce stress in adults that can lead to lethal and sublethal effects. Beschta et al. (1987) suggested as a basis for water quality criteria that upstream migration occurs between 7.2-15.6°C. Studies with other species support the work of Thomas et al. (1986) in showing that adults may actually be somewhat more temperature sensitive than juveniles. Sensitivity is enhanced in adults through the fact that they do not feed during their freshwater migration and must rely on their stored fat and muscle reserves to see them through the spawning process. The stress of higher temperatures not only influences the health of the spawner, but to some extent it also can effect the quality of unfertilized eggs carried by the hen salmon. In tests evaluating the effects of holding ripe adult coho at warm temperatures, Bouck et al. (1970; as cited in USEPA, 1971) found no apparent adverse effects to eggs in utero caused by prolonged exposure to 16.7°C. Flett et al. (1996), however, found that adults migrating through waters often warmer than 20°C experienced reduced quality and more rapid deterioration of eggs. For these reasons it would be prudent to maintain temperatures close to the range considered fully protective for juvenile coho (i.e., 7DADMax temperatures below 16.5°C) over the migration routes used by adult spawners.

Chum Salmon

Studies were not found that establish a specific basis for setting adult upstream migration temperature threshold. Beschta et al. (1987) has suggested as a basis for establishing water quality criteria that upstream migration is protected by keeping water temperatures in the range of 8.3-15.6°C. While adults can certainly withstand much higher temperatures for short periods of exposure without directly lethal effects, the potential of warm waters (above 14°C) to reduce the number of viable eggs, as shown in other fish species, should be cause for some caution. Since chum salmon spawn just above tidewater and have very short migrations in most watersheds, their time in migration and thus the potential for sublethal effects appears at least somewhat naturally mitigated in most cases. Recommendations to prevent barriers to migration and to protect other mature Pacific salmon spawners ripe with eggs should also be applied for chum salmon.

Pink Salmon

Unlike most Pacific salmon, the pink salmon that occur in Washington have relatively short migrations and concerns over disease and over depleting energy reserves are less than with the other salmon. However, migrating adults will pass through the lower reaches of major rivers near the period of maximum seasonal temperatures and disease is still a concern that should be considered in setting any final temperature recommendations (discussed and incorporated separately). It is also worthy of consideration that pink salmon have lower maximum sustained swimming speeds than sockeye salmon (20% less) and require more energy to support the same speed (30% higher) (Brett, 1982; as cited in Brett, 1995). While no specific recommendation is warranted for pink salmon migration, the literature reviewed herein suggests that caution should be exercised in applying the upper end of the optimal range to waters that may support longer than typical migrations or periods of holding by pink salmon.

Sockeye Salmon

Migration exerts a tremendous strain on salmon. Idler and Clemens (1959) found that female sockeye salmon in the Fraser River may use between 91.4-96% of their body fat reserves, and 53-61% of their protein reserves from the time of entrance to completion of spawning. As noted by Brett (1983), migration and egg production uses up most of the energy stored from ocean feeding and leaves “all too slim a safe margin of energy reserves”.

Linley (1993; as cited in Quinn et al., 1997) reportedly found that populations with arduous migrations show lower levels of reproductive output (ovary weight) than populations with shorter migrations. At a constant 16.2°C, depletion of fat reserves and reproductive organ abnormalities were noted by Bouk (1977), and Gilhousen (1990) found that high prespawning mortalities were associated with adult salmon migrating through waters having daily maximum temperatures between 17.5-19°C. Temperatures above 15.5°C (as an apparent daily average value) were also noted by Gilhousen (1990) as being linked to higher prespawning mortality from columnaris disease in adult Fraser River sockeye salmon.

Mcdonald et al. (2000) in a comprehensive study of the migratory success of Fraser River sockeye in relation to temperatures found that during unusually warm years (mean daily temperatures above 20°C) hormonal and stress indicators suggested that fish were suffering significant physical stress and maturation impairment. Temperature conditions detrimentally effected the ability of the fish to migrate successfully through rapids. Poor spawning success, poor egg quality and viability, and senescent death prior to spawning were all observed. The authors reference unpublished laboratory work of Dr. Craig Clarke showing that laboratory exposure to 19°C over a two-week period significantly depressed hormones controlling maturation, but exposure to 15°C did not. This was noted as consistent with findings with rainbow trout showing that temperatures of 17°C can reduce steroid synthesis in rainbow trout testes (citing Manning and Kime, 1985). Mcdonald et al. (2000) suggested that the upper threshold for successful reproduction of migrating sockeye salmon occurs with mean daily temperatures at the lower Fraser River (Hells Gate) between of 18-22°C. The authors also note that field studies suggest the temperature for optimum swimming endurance is 17°C and that a 20% reduction occurs at 21°C. The authors conclude that migration blockages, susceptibility to disease, impaired maturation processes, increases to stress parameters, reduced efficiency of energy use, and reduced swimming performance all become more hazardous as daily mean temperatures exceed 17°C.

Paulik (1960) found that sockeye subjected to daily swimming tests did not live as long as control fish, and postulated that as migrating salmon move upstream their swimming capacity declines such that performance is progressively reduced. DeLacy et al. (1956) using eggs from coho salmon and steelhead trout found, however, that the viability of sex products did not seem to be affected by repeated exhaustive testing.

Welch et al. (1995) found that the upper thermal limit to the off-shore occurrence of sockeye salmon was 8.9°C, and 8.9°C was found to be the maximum holding temperature in lakes by migrating adults (Wydoski and Whitney, 1979).

Quinn and Adams, 1996; as cited in Quinn et al., 1997) note that in the Columbia River, based on passage data at Ice Harbor Dam, migration usually ceases at temperatures above 21°C. Fish and Hanava, (1948; as cited by USEPA, 1971) found that during an extremely warm year (1941) sockeye were observed congregating in small previously unused cold tributary creeks when the temperature in the Columbia rose to 21.7-23.9°C. Major and Mighell (1966) noted that entry of sockeye from the Columbia River into the Okanogan River, was blocked when rising or stable daily average temperatures were above 21.1°C, but that migration would resume if temperatures were falling. Hatch et al. (1992) found that when water temperatures reached daily average temperatures of 22.8°C, all migration of sockeye salmon ceased, that the bulk of the migration occurred below 22.2°C, and that surges of migration occurred when temperatures fell to below 21.1°C.

Constant or daily average temperatures in the range of 15.5-17°C have been found by numerous authors to cause excessive depletion of energy reserves and prespawning losses, and 17°C has been set as the limit beyond which detrimental physiologic effects would become hazardous. Since maximum temperatures in the range of 17-19°C have also been identified in association with increased losses in migrating sockeye, caution should be exercised in selecting daily maximum values. Based on the available research, temperatures should not exceed a maximum 21-day average of 14-15°C, and the 7-day average daily maximum temperatures should not be greater than 16-17°C to support the migration of adult sockeye salmon. This temperature range is generally associated with an absence of prespawning mortality and will avoid high losses of stored energy reserves. To reduce the potential for causing blockages to migrating fish, the single daily maximum temperatures should not exceed 21-22°C, particularly when the migrating fish are acclimated to lower (2-6°C) water temperatures as they move upstream.

<u>Steelhead Trout</u>

Most fish returning to Washington's streams are believed to have been at sea for 2 years. Fish that have been at sea for three years make up 18.5-33% of the returning fish, and only a few are at sea for 4 years (1-3.9%). The largest steelhead are generally those with the longest oceanic phase (Wydoski and Whitney, 1979).

Snyder and Blahm (1971; as cited in Monan et al., 1975) found that temperatures of 23.9°C created a barrier to the migration of steelhead trout from the Columbia to the Snake River that remained until temperatures declined to nearly 21.1°C. Strickland (1967; as cited in Stabler, 1981) also noted that steelhead destined for the Snake River do not leave the relatively cooler waters of the Columbia River until the Snake cools to 21°C or lower. Fish and Hanavan (1948; as cited in Stabler, 1981 and USEPA, 1971) reported that steelhead trout entered minor typically unused tributaries and died there when the temperatures in the Columbia River ranged from 21.6 to 23.8°C. On the Deschutes River in Oregon, nearly all steelhead reportedly stopped migrating past Pelton Dam when the water in the ladder averaged between 20-21°C and the water below the dam was 13-14°C (Don Ratliff, personal communication, as cited in Stabler, 1981). Stabler (1981) noted that Fessler (1977) and Everest (1973) found that steelhead halt their migration and will enter nonparent streams when water temperatures exceed 21°C. While not a study on migration, Nielsen et al. (1994) found temperatures of 22°C elicited an avoidance reaction in steelhead trout. They noted that foraging began to decline when stream temperatures reached approximately 22°C; although, it was noted that juvenile steelhead were seen actively feeding in surface waters with ambient temperatures up to 24°C. Fish moved to cool portions of stratified pools when temperatures exceeded 22°C, but not at or below 22°C, and would return to their original stream territories once ambient stream temperatures fell to about 23°C. Based on the above referenced studies, daily average temperatures of 21-24 are associated with avoidance behavior and migration blockage in steelhead trout.

Support for assuming 21-22°C creates significant enough stress in steelhead as to create a potential barrier to migration is also found in lethality studies of Coutant (1970) and Becker (1973). Citing what appears to be the same study, these authors concluded that the incipient lethal temperature for migrating adult steelhead was near a constant 21-22°C. They noted that adults appear to be more susceptible to high temperatures than are juveniles, which are typically used in lethality studies.

Concerns over disease may warrant restricting temperatures to levels well below that which would result in direct barriers to migrating steelhead. Diseases of native fishes is discussed and incorporated separately in this paper. In setting a criteria for the full protection of migration, it is also important to consider chronic and sublethal effects caused by warm waters. Migrating spring and summer steelhead will be passing through during the peak temperatures of summer as they move upstream to holding areas where they will wait until the following stream. While often repeat spawners, steelhead still rely on their muscle and fat reserves to hold them over through to the completion of spawning and return to the ocean. In addition to concerns over disease, the metabolic demands of swimming, negotiating obstacles, and supplying the basal metabolic requirements while holding leaves little reserves left for digging redds and spawning once they reach their spawning streams. The warmer the water the more energy will be required to survive until spawning is completed and thus the greater chance that fitness will be affected and that higher pre- and post-spawning mortalities will occur. For these reasons it would be unwise to assume that any temperature regime that does not form a blockage to migration or cause direct lethality will fully protect migrating steelhead.

Where fish may hold in waterbody segments for long periods of time prior to spawning, as is common for spring and summer run steelhead, daily maximum temperatures should not exceed the range previously identified as fully protective for juvenile rearing. At this point in the life-stage of the adults when feeding is not occurring, even cooler waters would be preferable. Based on the preceding, it is estimated that to fully protect the adult migration of steelhead trout the 7-day average of the daily maximum temperatures should not exceed 17-18°C. Single daily maximum temperatures should not exceed 21-22°C.

Cutthroat Trout

Gresswell (1995) suggests that cutthroat generally migrate when temperatures approach 5°C (citing Varely and Gresswell, 1988, Byorth, 1990, and Thurow and King, 1994). In one cutthroat stream into Yellowstone Lake maximum daily water temperatures at the time of peak spawning ranged from 10-14.2°C over a 13 year period (USFWS, unpubl. data; as cited in Gresswell, 1995).

Migrations of resident and potamadromous cutthroat trout occupy largely the same habitat used for juvenile rearing. Thus for these forms, there is little specific basis for establishing a specific migration criteria higher than the fully protective range identified for juvenile rearing. The anadromous forms of cutthroat, unlike the Pacific salmon, may make numerous journeys to the marine waters and back again. Thus they may need to repeatedly pass through any suboptimal temperature regime, however, since they may feed on their return migrations through fresh waters, they may be subject to less sublethal stress effects than the Pacific salmon. It is recommended that any standard applied to protect the anadromous migration of the Pacific salmon also be applied to cutthroat trout. Such a temperature value would likely be protective if the 7-day average of the daily maximum temperatures seldom exceeded 17-18°C and the single daily maximum temperature does not exceed 21-22°C.

Table 4.16. Barriers to migration of salmon and trout:

Species	Barrier to Migration	Comment	Author
Chinook	21-22 (21.5)		Stabler, 1981; Bumgarner et al., 1997; Hallock, Elwell, and Fry, 1970; Thompson, 1945, Ratliff, 1977, Fish and Hanavan, 1948, Major and Mighell, 1967, and Alabaster, 1988
	18.9 (maximum)	Partial blockage associated with low (5ppm) oxygen levels	Hallock et al., 1970
	17.2:21.7 and 22.2:26.1	Temperature differences that caused blockage	Thompson, 1945
	9-11 (change)	Temperature differences that formed blockage	Gray, 1990
Sockeye	21	Migration ceases	Quinn and Adams, 1996
		Congregated in cold tributaries when main stem reached 21.7-23.9	Fish and Hanava, 1948
	21.1	Blocked migration into tributary unless temperatures were falling	Major and Mighell, 1966
	22.8 (daily average)	Bulk of migration occurred below 22.2 and surges occurred when temperatures fell to below 21.1	Hatch et al., 1992
	23.9	Barrier until tributary temperature declined to nearly 21.1	Snyder and Blahm, 1971
	21	Barrier for entry into tributary	Strickland, 1967
Steelhead	21.7-23.9 (22.8)	Congregated in cold tributaries when main stem reached 21.7-23.9	Fish and Hanava, 1948
	20-21 (20.5)	Average temperature causing blockage when fish were coming from water of 13-14	Ratliff, Personal communication
	21		Stabler, 1981

Temperatures of 21-22°C are commonly cited as creating barriers to migration. While some researchers have found that fish will travel through waters as warm as 24°C, this is generally uncommon. Temperatures below 21°C have also been noted as causing blockages, but again this is generally uncommon and has been in association with fish encountering significant changes in temperature or encountering high temperatures in combination with low (stressful) oxygen levels. Most of the authors reviewed were not clear about the metric, but most appeared to be referring to the daily average temperature. Some, however, may have been referring to the absolute temperature at the time of measurement, and thus would be assessing something closer to the daily maximum temperature. To bound the estimate on the temperatures creating migratory blockages, the commonly cited literature range for blockage should be treated both as potentially related to the daily maximum temperature or the daily average temperature. This would result in the estimate that the 7DADMax temperature threshold that would generally prevent migration blockages would occur within the ranges of 20.05-21.05°C or 23.6-24.6°C, respectively. This would create a potential range within which migration blockages may occur of a 7DADMax of 20.05-24.6°C (22.1°C). The acute nature of blockages, the undescribed temperature metrics reported by most authors, and the general trait of larger rivers such as the Columbia River being more thermally stable suggests the upper range of this estimate may underestimate the effects of temperature in the field.

While barriers to migration have a direct effect on adult migrants, warm temperatures can harm migrants in many other important ways. These include prespawning mortality, decreased migratory performance, reduced fecundity and egg viability, and increased disease rates that affect both the spawners and their offspring. For this reason any criteria set to protect adult migration should consider more than just the temperature that creates a barrier to migration.

Average daily temperatures of 15.5-20°C have been most frequently associated with prespawning mortality, thermal stress, and reduced reproductive success in adult migrants both in laboratory studies and natural streams. Concerns over the effect of temperature on egg-carrying females was discussed previously in the section on reproductive success. Some examples are included in this evaluation of migratory effects that represent ambient river studies conducted at the lower reaches of main stem rivers. This is because these studies better fit with the concept of protecting migratory pathways than studies done specifically on ripe females. The studies examined here are typically expressed as a daily average exposure, which would be approximately equal to a 7DADMax of 18.1-22.6°C (20.4°C). Considering the lethal endpoints under consideration here, it is suggested that only the lower portion of this range should be considered potentially acceptable. For these reasons, it is concluded that to protect migrating fish from prespawning losses in main stem rivers the 7DADMax temperatures should not exceed 18.1-20.4°C (19.25). It is important to note that females carrying ripe eggs would be expected to have egg losses at these temperatures, and so it is important not apply this temperature estimate in headwater rivers where migrating fish are likely to be carrying ripe eggs.

Table 4.17. Migratory effects to salmon and trout other than barriers.

Species	Prespawning Mortality or Egg Loss	Migration Criteria Estimates	Migration Stressors	Comments	Author
Chinook	20 (mean) 23 (max)			River temperature associated with high (25%) losses	Mcdonald et al., 2000
			18-20	Thermo-regulatory behavior in sub-yearling fall Chinook at 18-20 and heat shock proteins within several hours at 20	Sauter and Maule, 1997
		7.2-15.6			Piper et al., 1982
		3.3-13.3 (spring) 13.9-20 (summer) 10.6-19.4 (fall)		Migration recommendation for different runs	Bell, 1973
Coho		7.2-15.6			Beschta et al., 1987
	>20			Reduced quality and rapid deterioration of eggs in utero in migrants	Flett et al., 1996
	16.7 (no effect)			No apparent adverse effects to eggs in utero	Bouck et al., 1970
Chum		8.3-15.6			Beschta et al., 1987
Sockeye			16.2	Depletion of fat reserves and reproductive organ abnormalities at 16.2	Bouck, 1977
	17.5-19.5 (maximum)			High prespawning mortalities in river. Temperatures greater than 15.5 (daily ave) higher mortality from columnaris disease	Gilhousen, 1990
	20 (average)		20 (average)	Mean daily river temperatures above 20 resulted in signs of significant stress, poor spawning success, prespawning mortality, and poor egg quality	Mcdonald et al., 2000
			19 (constant)	Laboratory exposure over two weeks at 19 depressed maturation, but 15 did not.	Clarke, Personal comm.
	18-22 (mean daily)			Threshold of Fraser Rv. at mouth for successful reproduction	Mcdonald, 2000

<u>Holding of Adult Spawners</u>: It is important to recognize that many stocks of salmon do not migrate directly through to their spawning streams, but instead hold in upper main stem rivers throughout the warmest period of the summer until the fall when they ascend the tributaries and begin spawning. This section has not included an evaluation of the temperature requirements of these holding areas. Because adult fish do not feed while they are holding, maintaining cold waters are expected to be especially important to reduce metabolic demands and stress in areas used for over-summer holding. It is concluded that the temperature determined previously for the protection of juvenile rearing (7DADMax 16.5°C) also be considered for application to these holding areas, at a minimum. Or alternatively, temperatures should be maintained at levels determined previously to prevent prespawning losses to eggs (7DADMax 14.2°C).

vi) Lethality to Adults and Juveniles

Constant Laboratory Exposure Studies:

<u>Chinook Salmon</u>

Beacham and Withler (1991) transferred juvenile chinook salmon from 14°C saline water to a series of test temperatures and noted genetic differences in the resistance times of southern versus northern stocks. They also found that 55% mortality occurred within three days after transfers to saline waters with temperatures as low as 20.3-21.5°C. They found 87% mortality occurred within 2 days at 22.4°C. In tests using adult "jack" chinook salmon the authors established an upper incipient lethal temperature of 21-22°C. Orsi (1971; as cited in CDWR, 1988) found that 50% mortality in fingerlings acclimated to 15.6°C occurred within 48 hours at 21.1°C, however, by slowly acclimating fish to 21.1°C the author raised the lethal endpoint to 24.7°C. Becker (1973) noted that tests conducted with Jack chinook salmon produced 50% mortality at 21-22°C (this was likely the same tests conducted in Coutant, 1970, in which case the acclimation was at best the prevailing temperature of the Columbia River). Brett et al. (1982) found that 21.5°C was the lethal limit of spring chinook acclimated previously at 10°C and that minor increases in mortality (up to 5%) occurred at 20°C. Brett (1956) found that acclimations of 5, 10, 15, and 20°C produced 50% mortality at test temperatures of 21.5, 24.3, 25, and 25.1°C. Brett et al. (1982) established the lethal level to be 25°C at an acclimation of 20°C. Snyder and Blahm (1971), however, reported no mortality in chinook subjected to a change from 10 to 21.1°C over a 3-day test.

Some authors have noted temperatures that result in almost instantaneous lethality to chinook salmon. Orsi (1971; as cited in CDWR, 1988) found that fingerlings acclimated to 21.1°C suffered complete mortality when exposed to 31.1°C water for 4-6 minutes, and 50% mortality occurred in fish acclimated to 18.3°C and exposed to 28.3°C from 4-6 minutes. In a study by Snyder and Blahm (1971) a temperature of 26.7°C has resulted in mortalities beginning after just 100 seconds of exposure and complete mortality after 4 minutes, while at

32.2°C it only takes 4 seconds for mortality to begin and complete mortality after 11 seconds. Further, Gray (1990) found that temperature plumes above 25.1°C caused spasmodic muscle contractions in passing chinook salmon. Gray (1990) cited research showing that juvenile salmonids are more susceptible to predation at 10-20% of the thermal dose causing loss of equilibrium.

<u>Coho Salmon</u>

In constant exposure tests, the upper lethal levels producing 50% mortality in juvenile coho was 25°C at an acclimation temperature of 20°C (DeHart,1974; Brett, 1956), but at an acclimation of 5°C, Brett (1956) found the lethal level declined to 22.9°C. McGeer, Baranyi, and Iwama (1991) exposed stocks from six hatcheries to a 1°C/hour increase in temperature and found the point of 50% mortality ranged from 23.8-24.4°C. While all test fish survived up to 23°C none survived beyond 25.5°C. While juvenile coho are reasonably tolerant to short-term peaks in temperature, adults may be far less tolerant. Using migrating adult fish taken during the summer from the Columbia River, Coutant (1970, and Becker, 1973) determined the lethal limit to be 21-22°C.

<u>Chum Salmon</u>

Chum acclimated to cold waters (5°C) have an upper lethal temperature of 21.8°C, which increase to 22.6 and 23.1°C at acclimation temperatures of 10 and 15°C (Brett, 1956). In work by Snyder and Blam (1971) it was found that 50% mortality occurred in less than 50 minutes to a test population transferred from 15.6°C to 26.7°C. A transfer from 15.6°C to 29.4°C resulted in 50% mortality in only 60 seconds, and at 32.2°C it only required 15 seconds to cause 100% mortality. Lethal low temperatures range from 6.5°C and 4.7°C at acclimation temperatures of 20°C and 15°C, to 0.5°C at a 10°C acclimation.

<u>Pink Salmon</u>

Brett (1952) found that pink salmon could not be acclimated to 24°C and were unable to survive for one week at 25°C. Brett (1952) found that at acclimations of 5°C the LT50 occurred within one hour of exposures to 22.5°C and 23°C. With acclimation to 10°C the LT50 also occurred at 22.5°C, and at an acclimation of 20°C, it occurred at 23.9.

<u>Sockeye Salmon</u>

Bouck and Chapman (1975) found that adult sockeye could not survive long periods at 20°C or 22°C, and determined that the LT50 for these temperatures occurred at 11.7 days and 3.2 days, respectively. At the lower acclimation temperatures of 5 and 10°C, Brett found that juvenile sockeye had lethal levels of 22.2°C and 23.4°C in a week-long test. At acclimations between 15-23°C, the LT50s for juvenile sockeye were variable within the range of 24-24.8°C (Brett, 1952; Beschta et al., 1987; Servizi and Jensen, 1977). Brett (1952) determined the lower acutely lethal temperatures for juvenile sockeye salmon. He found that at acclimations of 15 and 20°C the temperatures that produced 50% mortality in a one week test were 4.1 and 4.7°C, and that fish acclimated to 10°C had a lower lethal level of 3.1°C.

Steelhead and Rainbow Trout

In evaluating the effect of high water temperature on steelhead, Nielsen et al. (1994) found that the upper lethal temperature is approximately 24°C for juvenile steelhead. Redding and Schreck (1979) subjected juvenile steelhead previously acclimated to 12°C to a rapid rise (6.25 hours) to 26.5°C where it was maintained for the duration of the test. All fish died within 20.5 hours. In a separate test the temperature was held at 26°C, and all fish died within 31 hours. Coutant (1970; and Becker, 1973), however, examined the upper lethal temperatures for adult steelhead taken at peak migrating temperatures from the Columbia River in Washington. Coutant concluded from his work that the incipient lethal temperature for migrating adult steelhead was closer to 21-22°C. Most laboratory studies use juveniles of the larger species of fish due to the difficulty of handling adult salmon and steelhead in laboratory tanks. It has been noted previously that adult Pacific salmon may have lower incipient lethal levels than that for juveniles, and it could be that this relationship may hold true for steelhead as well.

Temperatures as low as 23°C have been found to produce 50% mortality (LT50) in rainbow trout with a week's constant exposure in fish previously acclimated to very cold (4°C) waters (Sonski, 1982; Threader and Houston, 1983, as cited in Taylor and Barton, 1992), with the lethal temperature rising to 24°C in moderately cold water (6-11°C) acclimated fish (Black, 1953; Stauffer et al., 1984; Bidgood, 1980, as cited in Taylor and Barton, 1992). However, at most acclimation temperatures likely to be encountered during the spring through fall seasons (12-20°C) lethal levels are consistently in the range of 25-26°C (Bidgood and Berst, 1969; Hokanson et al., 1987). With cautious acclimation to temperatures in the range of 23-24°C, rainbow trout may not experience LT50 level effects until temperatures are held for a week at 26°C (Charlon et al., 1970, as cited in Grande and Anderson, 1991). Even with careful acclimation, 27°C results in high or complete mortality in less than 24 hours (Charlon, Barbier, and Bonnet, 1970), and temperatures of 29-30°C result in 50% mortality in periods of 1-2 hours (Kaya, 1978; Craigie, 1963, and Alabaster and Welcomme, 1962; as cited in Taylor and Barton, 1992). Some authors conducted critical thermal maximum (CTM) tests on rainbow trout. In this type of test, water temperatures are continuously increased at a rapid rate until the test fish either loose equilibrium or die completely. CTM values at prior acclimations of 10 to 25°C ranged from 27.6 to 32°C, respectively, in testing by Myrick and Cech (2000).

Cutthroat Trout

Heath (1963) subjected sea-run cutthroat to a cyclic temperature regime of 10-20°C and calculated a critical thermal maximum (CTM) of 29.77. At constant acclimations of 10, 15, and 20°C, the corresponding CTM values were 27.63, 29.06, and 29.88°C. De Staso and Rahel (1994) reported at CTM of 28°C at some unknown acclimation temperature. Pauley et al. (1989) cite research concluding that equilibrium and ability to swim is lost with a rise in temperature to 28-30°C. Feldmuth and Eriksen (1978, as cited in McIntyre and Rieman, 1995) estimated that the CTM for westslope cutthroat trout was 27.1°C, a value lower than those estimated for brook trout (29.8°C), brown trout (29.6°C) and rainbow trout (31.6°C). Golden (1976) tested the temperature tolerance of zero age coastal cutthroat stocks from western Oregon. In CTM tests where the temperature is rapidly increased until the fish die or loose equilibrium, acclimation to 10 and 23°C yielded CTM values of 28.03 and 30.62°C. At a fluctuating equilibriums of 7.8-10°C and 13-23°C the CTM values were 27.64 and 30.31°C.

Golden (1978) tested the lethality of significantly fluctuating temperature regimes with cutthroat trout. Incipient lethal levels (ILL) were 25.5°C and 25.7°C for fish acclimated to 23°C and a fluctuating regime of 13-23°C, respectively. Golden estimated losses in one week of 10% or less at a fluctuating cycle of 13-27°C.

Vigg and Koch (1980) measured the lethal limits of two stocks of Lahontan cutthroat in three water types and found that alkalinity profoundly influences the results. In waters with alkalinity of 1,487 mg/l the lethal range was 18.5-20.2°C, in waters with alkalinity of 357 mg/l the range was 20.2-21.1°C, and at an alkalinity of 69 mg/l the lethal range was 21.8-23.0°C for the two species. Kramer (1975; as cited in Vigg and Koch, 1980) found they were able to hold a Humboldt River strain of cutthroat at 24°C for two weeks without any mortality, but with feeding inhibition.

Dickerson et al. (1999, and unpublished data as cited in Dunham, 1999) tested the lethal tolerance levels of Lahontan cutthroat. Survival was 100% at 24°C but declined to 35% at 26°C. At 28°C mortality was complete in 48 hours.

Were it not for the studies of Lahontan cutthroat trout by Vigg and Koch (1980), it would be easy to conclude that cutthroat trout would only be expected to have 50% mortality (LT50) over a one week's exposure to constant temperatures above approximately 24°C. While it is clear that in many cases no mortality would occur as a consequence of short term exposure to infrequent daily maximum temperatures as high as 26°C, the data of Vigg and Koch (1980) suggest more caution may be warranted. They calculated LT50 values of 20.2-21.1°C and 22-23°C using two stocks of cutthroat and two water sources with alkalinity levels comparable to what is regularly found in Washington. More work is needed to clear up the question of whether native stocks demonstrate lower lethal thresholds in natural waters with high alkalinity levels, prior to assuming the data of Vigg and Koch (1980) to be anomalous.

Table 4.18. The following summarizes the results of laboratory tests subjecting salmon and trout to constant test temperatures. The column on acclimation provides the temperature to which the fish were acclimated to prior to being moved to the test temperature, and the endpoint reported is the percent of mortality that occurred at each lethal temperature level (LT).

Author or Study	Species	Acclimation Temp. (°C)	Temperature of Test	Time to Endpoint	Endpoint Reported	Comment

			(°C)	(seconds)		
Beacham and Withler, 1991	Chinook	14	20.9	259200	LT55	LT55 in 3-days with transfers to 20.3-21.5 (mean 20.9°C).
		14	22.4	172800	LT87	2 days
		14	21.5	604800	LT50	Adults 7-day 21-22 (mean 21.5°C).
Orsi, 1971	Chinook	15.6	21.1	172800	LT50	2 days
		21.1	24.7	172800	LT50	2 days
		18.3	28.3	300	LT50	4-6 minutes
		21.1	31.1	300	LT100	4-6 minutes
Becker, 1973 and Coutant, 1970	Chinook	Summer ambient	21.5	604800	LT50	Adults 7-day 21-22 (mean 21.5°C)
Brett, 1982	Chinook	10	21.5	604800	LT50	Spring run
		10	20	604800	LT5	Spring run
		20	25	604800	LT50	Spring run
Snyder and Blahm, 1971	Chinook	10	21.1	259200	LT0	3-days - no mortality
		10	26.7	100	LT1	100 seconds
		10	26.7	240	LT100	4 minutes
		10	32.2	4	LT1	4 seconds
		10	32.2	11	LT100	11 seconds
Brett, 1956	Chinook	5	21.5	604800	LT50	
		10	24.3	604800	LT50	
		15	25	604800	LT50	
		20	25.1	604800	LT50	
DeHart, 1974	Coho	20	25	604800	LT50	
Brett, 1956	Coho	20	25	604800	LT50	
	Coho	5	22.9	604800	LT50	
Becker, 1973 and Coutant, 1970	Coho	Summer ambient	21.5	604800	LT50	Adults 7-day 21-22 (mean 21.5°C)
Brett, 1956	Chum	5	21.8	604800	LT50	
	Chum	10	22.6	604800	LT50	
	Chum	15	23.1	604800	LT50	
Snyder and Blam, 1971	Chum	15.6	26.7	3000	LT50	50 minutes
		15.6	29.4	60	LT50	60 seconds
		15.6	32.2	15	LT100	15 seconds
Brett, 1952	Pink	5	22.5	3600	LT50	1-hour LT50 at both 22.5 and 23°C.
		10	22.5	604800	LT50	
		20	23.9	604800	LT50	
			24			Could not be acclimated to 24°C or survive one-week at 25°C.
Brett, 1952	Sockeye	5	22.2	604800	LT50	
		10	23.4	604800	LT50	
Bouck and Chapman, 1975	Sockeye		20	1010880	LT50	Adults -11.7 days
			22	276480	LT50	Adults – 3.2 days
Brett, 1952; Servizi and Jensen, 1977	Sockeye	15-23	24-24.8 (24.4)	604800	LT50	

Nielsen, Lisle, and Ozaki, 1994	Steelhead		24	604800	LT50	Upper lethal temperature for juveniles
Redding and Schreck, 1979	Steelhead	12	26	73800	LT100	Complete mortality in 20.5 hours with rapid rise to test temperature
		12	26	111600	LT100	Complete mortality in 31 hours with immediate transfer to test temperature
Becker, 1973 and Coutant, 1970	Steelhead	Summer ambient	21.5	604800	LT50	Adults 7-day 21-22 (mean 21.5°C)
Sonski, 1982	Rainbow Trout	4	23	604800	LT50	
Threader and Houston, 1983	Rainbow Trout	4	23	604800	LT50	
Black, 1953	Rainbow Trout	6-11	24	604800	LT50	
Stauffer et al., 1984	Rainbow Trout	6-11	24	604800	LT50	
Bidgood, 1980	Rainbow Trout	6-11	24	604800	LT50	
Bidgood and Berst, 1969	Rainbow Trout	12-20	25-26	604800	LT50	
Hokanson et. al., 1987	Rainbow Trout	12-20	25-26	604800	LT50	
Charlon et al., 1970	Rainbow Trout	23-24	26	604800	LT50	
Charlon, Barbier, and Bonnet, 1970	Rainbow Trout	High	27	86400	LT50-LT100	High to complete mortality in less than 24 hours
Kaya, 1978	Rainbow Trout	High	29-30	3600-7200	LT50	1-2 hours
Craigie, 1963	Rainbow Trout	High	29-30	3600-7200	LT50	1-2 hours
Alabaster and Welcomme, 1962	Rainbow Trout	High	29-30	3600-7200	LT50	1-2 hours
Golden, 1978	Cutthroat Trout	23	25.5	604800	LT50	
		13-23	25.7	604800	LT50	Fluctuating acclimation regime
Vigg and Koch, 1980	Cutthroat Trout - Lahontan		18.5-20.2 (19.35)	604800	LT50	Alkalinity 1,487 mg/l – two stocks of Lahontan and two water sources
			20.2-21.1 (20.65)	604800	LT50	Alkalinity 357 mg/l – two stocks of Lahontan and two water sources
			21.8-23.0 (22.4)	604800	LT50	Alkalinity 69 mg/l – two stocks of Lahontan and two water sources
Kramer, 1975	Cutthroat Trout		24	129600	LT0	No mortality in two weeks using Humboldt River strain of cutthroat
Dickerson et al., 1999	Cutthroat Trout - Lahontan		24	604800	LT0	Lahontan

				26	604800	LT35	Lahontan
				28	172800	LT100	2-days – complete mortality in Lahontan

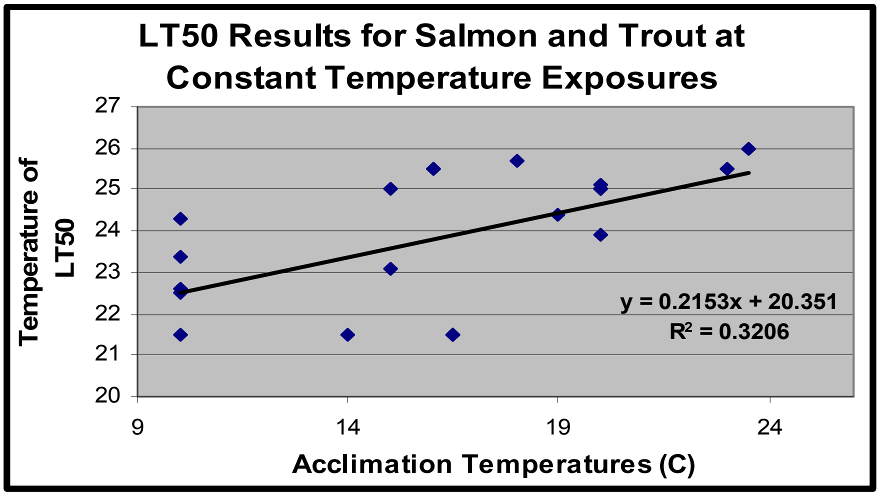
Typical Constant Laboratory Exposures Producing Fifty-Percent Mortality:

The results from constant temperature testing that resulted in fifty-percent mortality in 3-12 days of exposure (shown in the table above) can be used to assess weekly temperatures that will not result in excess lethality. Of the 38 tests assessed, 90% of the values were between 20.5-25.6°C, the inter quartile range was 21.9-24.6°C, and the median was 23.1°C. The 5th and 95th percentiles for the distribution are used herein to calculate expected thresholds to avoid the possibility of using anomalous extreme data points. Converting from an LT50 to an LT1 estimated mortality rate (by subtracting 2°C) suggests a constant exposure to a temperature above 18.5-23.6°C for a period of a week or more may result in the direct mortality to salmon and trout. Converting the constant laboratory test exposure estimate to a field exposure regime is especially difficult for this form of lethality data. Because the exposure times necessary to cause lethality reduce as temperatures continue to increase above the incipient lethal limit it is not appropriate to treat the laboratory results as weekly average temperatures. However, using the results directly as 7DADMax thresholds would overstate the risks since the time spent above the threshold will be only a small portion of each day while the original tests exposed fish to these temperatures for 24-hours per day. Thus a more defensible estimate would be one that falls between these two approaches rather than using the specific values contained in either. Treating the constant laboratory exposure as a weekly average temperature would result in the estimate of a 7DADMax of 21.68-26.78°C (24.23), and using it directly would result in the estimate of a 7DADMax of 18.5-23.6°C (21.05). Using these two approaches to bound the estimate results in the expectation that mortality will occur as 7DADMax temperatures exceed 21.05-24.23 with the best estimate expected to be the midpoint of the distribution (22.64°C).

Regression of Constant Laboratory Exposures Producing Fifty-Percent Mortality:

Although, the relationship between acclimation temperatures and test temperatures resulting in 50% mortality is strong within individual studies, the relationship is weak when all of the various studies are combined for analysis. This is illustrated in figure 4.1 below.

Figure 4.1. Combined lethality data for all salmon and trout species (based on 7-day LT50 estimates) from Table 4.18 above.



Acclimation Temperature (°C)	Combined LT50 for all Salmonids(°C)	Estimated LT1 with NAS Adjustment (°C)
10	22.50	20.50
12	**22.93**	**20.93**
14	**23.37**	**21.37**
16	**23.79**	**21.79**
18	24.23	22.23
20	24.66	22.66

The regression equation in figure 4.1 above, can be used to predict temperatures at which significant lethality (50%) would be expected with a constant exposure for 7-days at various prior acclimation temperatures. Since the results are based on 50% mortality, they should be adjusted to better reflect temperatures that would not directly kill fish. The USEPA recommends that states subtract 2°C from LT50 results to obtain an estimate that would result in 1% or less mortality (LT1) under the same exposure assumptions. Fish acclimate to ambient temperatures approximately equal to the average temperature, and often fish that are migrating from the ocean or from cooler tributary systems will not be fully acclimated to warm prevailing temperatures in main stem rivers. For this reason, acclimation temperatures from 12-16°C may best represent the condition of migrating fish during the summer period (yielding LT1 estimates of 20.93-21.79°C). Juvenile fish that reside within a system, may be acclimated to warmer temperatures. However, even resident fish will not be as fully acclimated as those used in tests to estimate an ultimate incipient lethal temperature (the absolute highest LT50 that can be produced with slow and careful laboratory acclimation). Based on the foregoing, a constant temperature exposure for 7 days would be expected to cause no more than LT1 levels of mortality at temperatures of 20.93-21.79°C. Converting the constant laboratory test exposure to a field exposure regime is especially difficult for this form of lethality data. Because the exposure times necessary to cause lethality reduce as temperatures continue to increase above the incipient lethal limit it is not appropriate to treat the laboratory results as weekly average temperatures. However, using the results directly as 7DADMax thresholds would overstate the risks since the time spent above the threshold will be only a small portion of each day while the original tests exposed fish to these temperatures for 24-hours per day. Thus the more defensible estimate would be one that falls between these two approaches, rather than containing values from either. Treating the constant laboratory exposure as a weekly average temperature would result in the estimate of a 7DADMax of 24.11-24.97°C (24.54) using it directly would result in the estimate of a 7DADMax of 20.93-21.79°C (21.36). Using these two approaches to bound the estimate results in the estimate that mortality will occur as 7DADMax temperatures exceed 21.36-24.54 with the best estimate expected to be the mean of the distribution (22.95°C).

Modeling Lethality of Fluctuating Temperature Regimes:

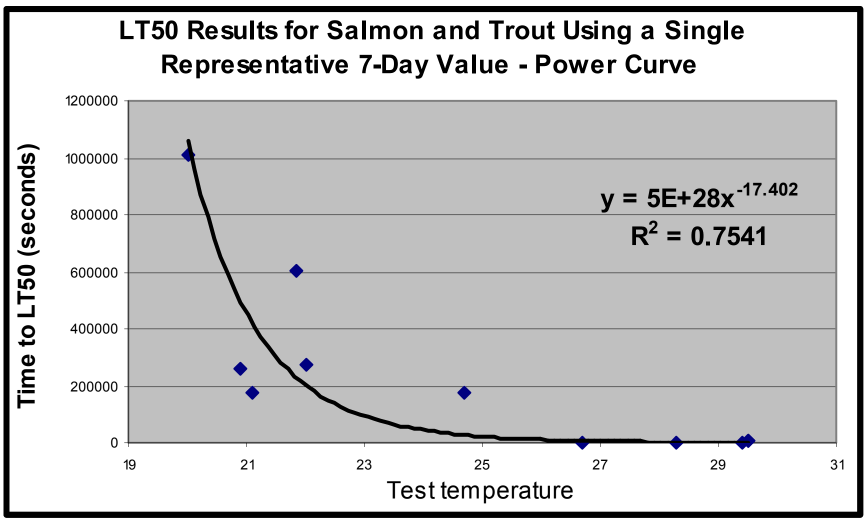
The concept of resistance time is very important to estimating potential lethality. It is well demonstrated that it is the time spent above a lethal threshold that determines whether or not short term lethal effects will occur. Different peak temperatures (e.g., 22, 24, 27, 30°C), may all be lethal to an organism, but the organism can likely withstand these temperatures for variable lengths of time. A population of fish may be able to withstand 21°C for 7 days of constant exposure without any mortality, but have 50% of the population die after 2 days at 24°C. At 27°C 50% mortality may occur after less than 2 hours of exposure, and at 30°C, complete mortality may occur in just a few minutes.

In considering the effect of repeated hot days, it is important to incorporate the potential for cumulative effects over a series of days. DeHart (1974) found that lethal effects occur in relation to the area of the temperature time curve that is above a fish's incipient lethal level (ILL); an accumulation of thermal effects occurs over periods of several days when the daily temperature cycle fluctuates above the incipient lethal level; and the time above the incipient lethal level influences the thermal resistance time independent of the lower temperatures experienced in fluctuating tests. In other words, the ability of a fish to resist a single day's exposure to a lethal temperature may not be sufficient, and fifteen minutes spent at 4°C over the ILL is of more consequence than the same time spent at 2°C over the ILL.

The results from laboratory lethality tests conducted at constant temperatures can be used to estimate lethality under fluctuating temperature conditions. This can be done by creating a simple model of the time to mortality using the laboratory studies of a duration of 7-days or less from table 4.18 above. Each temperature value is assigned a lethality indices which represents the proportion of a lethal exposure that occurs within a single day. Lethal loading stress is assumed to be cumulative such that the model can predict the number of consecutive days until 50% mortality will occur under any combination of diel temperature fluctuations. Because of the great variability in 7-day LT50 values, only a single representative value is used to represent this particular exposure period. A constant temperature of 21.85°C was chosen to represent an 7-day LT50 temperature, which represented the 25th percentile of the distribution of LT50 values. Alternatively, 23°C was considered since it represents both the regressed LT50 value at the lower expected acclimation temperature and is the median of the distribution of LT50 results. However, taking this alternative approach would have risked extrapolating the estimate beyond 50% of the actual test endpoints, and would not well incorporate the observed pattern of adult fish showing greater lethality at similar temperatures as juveniles who are the subjects of most of the tests.

Figure 4.2 below shows a power curve regression of the LT50 data with a single representative value included to moderate the variability in the tests conducted for seven days. The equation of the regression line can be used to predict fifty percent lethality rates at any given duration of exposure. This equation (y = 5E+28x-17.402) is used herein to model lethality under fluctuating temperature environments.

Figure 4.2. Regression of LT50 data with a single composite value for all 7-day tests.



Temperature of Test (°C)	Time to LT50 Endpoint (seconds)
29.4	60
28.3	300
26.7	3000
29.5	5400
29.5	5400
29.5	5400
21.1	172800
24.7	172800
20.9	259200
22	276480
21.85	**604800**
20	1010880

If it is assumed that fish are acclimated to a series of temperatures (representing the daily mean of a fluctuating environment) then the number of days until fifty-percent mortality would be expected can be estimated (See table 4.19 below). Since the 7-day exposure tests were composited using the 25th percentile of the 7-day LT50 values, the estimates would generally suggest that most (75% or more) stocks would have a greater degree of protection. The results of this modeled analysis suggest that at acclimation temperatures in the range of what can be expected in natural streams during the summer months (15-20°C) fifty-percent mortality may occur to some stocks with a 7-day exposure at daily maximum temperatures of 22.13-22.47°C (22.3). This estimate is then converted to a temperature range that would be unlikely to result in any mortality (an estimated LT1) by subtracting 2°C. This results in the estimate that direct mortality will be prevented if the 7DADMax temperature is maintained below 20.13-20.47°C (20.3).

Table 4.19. Modeled results showing the days to LT50 at various daily mean and daily maximum temperatures and assuming a 4.13°C per day change in temperature.

Daily mean	Daily Max	Days to LT50
15	22.13	6.802
16	22.13	6.81
17	22.13	6.836
18	22.47	6.911
19	22.13	7.12
20	22.13	7.743

Laboratory Studies with Fluctuating Temperatures:

Coho Salmon

DeHart (1974) reported that a cyclic temperature regime having 6 hours a day over 25°C produced 50% mortality in 1.5 cycles. In a 20-day test with highly fluctuating daily temperatures (5-23°C) having an average of 11°C, however, Thomas et al. (1986) found no increase in mortality. Acclimated age-0 and age-2 fish did not begin dying until the diel temperature range reached 4-25°C. Thomas et al. also reported that juvenile coho were able to feed and grow in fluctuating temperatures that approached their upper lethal limits. The studies of DeHart (1974) and Thomas et al. (1986) suggest that daily maximum temperatures of 25°C produce a risk of direct mortality, the level of that mortality may vary substantially but can be as high as 50%. The levels of fluctuations in the Thomas et al. work were so great as to significantly limit the time fish spent above temperatures that can be lethal with longer-term exposure. Converting the LT50 estimate at 25°C to an LT1 estimate by subtracting 2°C (USEPA recommendation), yields the prediction that daily maximum temperatures below 23°C should prevent direct lethality in coho salmon over short-term (one-week or less) exposures. The safety of taking this approach is also supported by the direct evidence of Thomas et al. (1986) where daily maximums of 23°C (diel range 5-23°C) did not result in an increase in mortality.

Steelhead and Rainbow Trout

Under fluctuating temperature test conditions, rainbow trout have been found to experience 50% mortality in a week of daily cycles from 21-27°C (Lee, 1980). If 2°C is subtracted to reduce the level of mortality from 50% to 1% or less, this would change the daily maximum temperature to 25°C to prevent direct mortality.

Cutthroat Trout

Golden (1976) tested the temperature tolerance of zero age coastal cutthroat stocks from western Oregon. It was found that seven diel cycles of 13-27°C resulted in 0-20% mortality. However, by increasing the peak temperature in the cycle 0.5°C (13-27.5°C) mortalities increased to 50-90% within 1 to 1.5 cycles. In CTM tests where the temperature is rapidly increased until the fish die or loose equilibrium, acclimation to 10 and 23°C yielded CTM values of 28.03 and 30.62°C. At a fluctuating equilibriums of 7.8-10°C and 13-23°C the CTM values were 27.64 and 30.31°C. Golden (1978) tested the lethality of significantly fluctuating temperature regimes with cutthroat trout. Incipient lethal levels (ILL) were 25.5°C and 25.7°C for fish acclimated to 23°C and a fluctuating regime of 13-23°C, respectively. Golden estimated losses in one week of 10% or less at a fluctuating cycle of 13-27°C. Golden (1978) found that high mortality could still occur with temperatures as high as 25.5-25.7°C at constant exposures, even for cutthroat acclimated to high (23°C) daily maximum temperatures. The work of Golden (7976, 1978) suggests that 50% mortality can occur and temperatures from 25.5-27°C even where fish have been well acclimated to warm waters. After converting this range to one in which 1% or less (LT1) mortality would be expected (by subtracting 2°C) it would be expected that direct mortality could be avoided by maintaining daily maximum temperatures below 23-25°C. Since many of the test fish were carefully acclimated to warm waters prior to testing, the upper end of this range may pose greater risks to migratory stocks.

Dickerson et al. (1999, and unpublished data as cited in Dunham, 1999) tested the lethal tolerance levels of Lahontan cutthroat. Survival was 100% at 24°C but declined to 35% at 26°C. At 28°C mortality was complete in 48 hours. In a separate test of fluctuating (20-26°C) and constant (13, 20, and 23°C) temperatures no mortality occurred. Dunham (1999) concluded from a review of the literature that Lahontan cutthroat can survive weekly exposure to daily temperature fluctuations of 20-26°C, including 1-hour exposures to temperatures of up to 26°C.

The works of Dickerson (1999) and Golden (1976, 1978) can be used to support the position that cutthroat trout may be capable of tolerating daily maximum temperatures as high as 23-26°C (24.5) for up to a week of exposure without experiencing direct mortality. However, without the non-indigenous Lahontan cutthroat data the estimate of lethality would change to 23-25°C (24°C) and should be viewed as a more defensible estimate of lethality in Washington’s cutthroat trout populations.

Summary of fluctuating lethality studies: In many of the fluctuating exposure studies reviewed, the laboratory test water had high diel fluctuations (14°C). These fluctuations are greater than what would often occur in natural waters and acts to significantly limit the amount of time spent each day spent above incipient lethal levels. The studies also included fish that were pre-acclimated to relatively warm temperatures, and thus some natural migratory stocks may be at slightly higher risks. The works also included a non-indigenous species of cutthroat that is widely found in desert environments and which may have different lethal thresholds than Washington's native cutthroat. Thus caution should be exercised in using the results from this line of evidence. Based on the fluctuating laboratory tests cited above, daily maximum temperatures above 23-25°C should be considered capable of causing direct mortality to salmon and trout. Since even very slight (0.5°C) temperatures increases in the daily maximum temperature have been shown to produce significant increases in mortality in this range, these values may best be treated as single daily maximum thresholds. However, the single daily maximum range of 23-25°C can also be converted to the standard metric of a 7DADMax temperature (by subtracting 0.95°C). This approach yields the estimate that to avoid direct mortality the 7DADMax temperature should remain below 22.05-24.05°C (23.05).

Field Studies of Lethality:

<u>Chinook Salmon</u>

The previously mentioned studies of lethality were predominantly conducted in a laboratory environment. Baker et al. (1995), however, modeled the escapement of smolts from the lower Sacramento River and determined an upper lethal temperature of 23°C. Burck (1993) used live-box tests with juvenile chinook salmon, and found that daily maximum temperatures in the range of 25.5-26.6°C were lethal to all of the test fish after a single daily cycle of exposure (daily minimums ranged from 13.3-16.1°C). Daily maximums in the range of 23.8 to 25.5°C (minimums ranging from 11.1-13.3°C) resulted in 80% mortality over the four-day test period. No mortality occurred in the three controls that had daily maximum temperatures from 14.4-17.2°C. While 50% mortality occurred in one treatment with maximums of 20.5-21.6°C, no mortality occurred in four other treatments with daily maximums in the range of 20.0-22.7°C. We can roughly compare Burck's data with values found in standardized laboratory tests using chinook salmon. If we assume the temperature midway between the daily maximum and the daily average is the acclimation temperature, then these live-box tests generally demonstrated that at an acclimation temperature of 20.6°C the lethal temperature was 25.6°C, and at an acclimation of 18.3°C the lethal level was 24.7°C. At an acclimation temperature of 16.5°C, however, there was inconsistent but typically complete survival at up to 21.6°C.

High mortality has been observed in fish held in rivers with daily maximum temperatures of 23.8-25.5°C over a four-day period. Reducing this range by 2°C would convert it to a range for daily maximum temperatures at which mortality would not be expected. This would yield the range of 21.8-23.5°C (22.65). This range was derived from daily maximum temperatures over a four day exposure period. This range can be used to create a range that is based on a 7DADMax temperature metric. The estimate can also be bounded by treating the range as if it were representing either the 7DADMax temperature directly (7DADMax 21.8-23.5°C) and also as if it represents the single daily maximum temperature (since it may have been the warmest day that triggered the mortality) and converting (subtracting 0.95°C) that value to a 7DADMax estimate (20.85-22.55°C). This approach suggests that direct mortality would be prevented by maintaining the 7DADMax temperature below 20.85-23.5°C (22.18).

Steelhead and Rainbow Trout

Sonski (1983) noted having success with culturing rainbow trout in ponds that that reached a summer maximum of 28.9°C, and Chandrasekaran and Subb Rao (1979) noted that rainbow trout in India were largely able to survive in rearing ponds with months having daily maximum temperatures in the range of 26-29°C. Neither of these works estimated lethality directly and cannot reasonably be used to suggest safe temperature ranges for rainbow trout. They can however be used to suggest that losses can sometimes be moderate (acceptable from a fish culturing standpoint) at temperatures that reach highs of 26-29°C.

Summary of field studies: Only two of the four citations actually provide estimates of lethal temperature ranges. These two studies both can be used to support the estimate that lethality should be expected as the 7DADMax temperature exceeds 20.85-23.5°C (22.18). The rearing pond observations that were also reviewed suggest that mortality rates sometimes may not become significant in cultured rainbow trout even though daily maximum temperatures may reach 26-29°C.

General Measures of Lethal Stress:

Cutthroat Trout

Titus and Vanicek (1988; as cited in Muoneke and Childress, 1994) reported that mortality of cutthroat trout caught and released by angling was less than 2% at temperatures below 17°C but rose to 49% as the temperature neared 21°C.

Summary of Lines of Evidence on Lethality:

Table 4.19. Direct lethality to salmon and trout with short-term exposure (7-days).

Line of Evidence	7DADMax (°C)	Midpoint (°C)	Comments
Ninety percentile range of constant laboratory tests with 1% or less mortality estimated.	21.05-24.23	22.64	Based on the 5th and 95th percentiles of the distribution of 7-day LT50 results at acclimations from 5 to 23°C.
Constant laboratory tests regression of 1% or less mortality estimate.	21.36-24.54	22.95	Regression of all of the lethality data for acclimations between 12 and 16°C.
Modeled exposure to fluctuating temperatures based on constant laboratory tests.	20.13-20.47	20.3	Assumes a steady diel fluctuation of 4.13°C per day for a 7-day period. LT50 converted to an LT1 by subtracting 2°C.
Fluctuating laboratory exposure studies.	22.05-24.05	23.05	Generally based on high diel fluctuations and including a non-indigenous form of cutthroat trout.
Field Studies with Fluctuating exposures	20.85-23.5	22.18	Based primarily on a study of chinook held a range of temperature exposures in a NW river.
Best estimate of threshold	***21.09-23.36***	***mid. pt 22.23***	

The absolute range is a 7DADMax of 20.13-24.54°C, with a mean range of 21.09-23.36°C, and with an overall midpoint of 22.23°C. The lower end of this range is based on the results of several studies using different species in a controlled laboratory environment at moderate acclimation temperatures. This gives it greater weight than if only one species was tested or the results came from only one study at low acclimation temperatures. Extra caution is warranted because actual exposure periods greater than 7-days at very near but not exceeding the estimated lethal threshold can exert a cumulative stress (lowering the temperature that would cause lethality over the longer period of exposure). For these reasons, the lower half of the potentially protective range (21.09-22.23°C, midpoint of 21.66) should be considered to be a more confident estimate for statewide use. Therefore, to prevent direct lethality it is concluded that the 7DADMax should be maintained below 21.66°C, or single daily maximum (adding 0.95 for conversion) temperatures maintained below 22.61°C.

Near Instantaneous Lethality

In the previous discussion the period of exposure was selected to represent a reasonable chronic field exposure (i.e., a 7-day duration). Higher temperatures, however, will exert lethal stress in much shorter periods of time, such that at some temperature lethality will occur almost instantaneously. Since wastewater can sometimes be discharged at very high temperatures (33-40°C) there is a need to ensure that lethal barriers are not permitted to occur in Washington's waters.

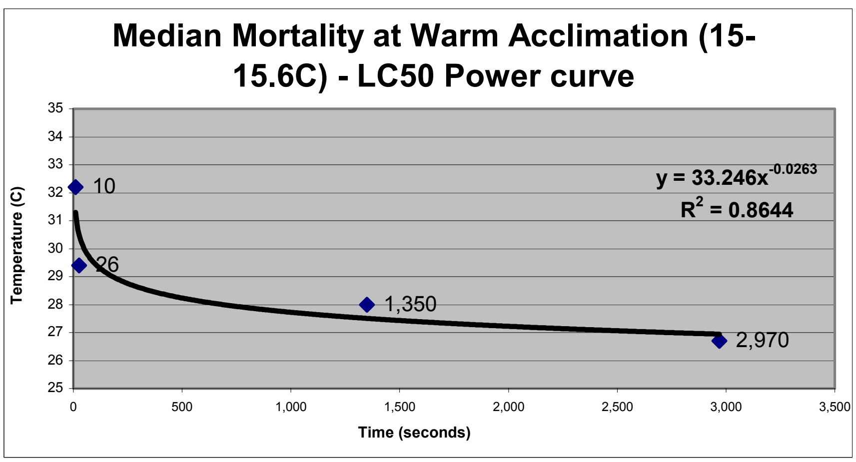
Data is available on exposure periods from 4 to almost 4,000 seconds have been used to evaluate the risk of instantaneous high water temperatures. The purpose of this analysis is to determine if a limit should be placed on the temperature of water discharged to waters of the state. The premise of such a restriction would be that at a given high temperature fish passing through the plume of hot water will be immediately killed.

Data is available for numerous fish species with the tests conducted a various acclimation temperatures and recording several important mortality endpoints (see table below). These endpoints ranged from when deaths began in the test population (herein described as the LC1) through where 50 percent of the population had died (LC50) to where 100 percent mortality (LC100) occurred. Also included are the results of a study that recorded the points where short-term exposures caused an identifiable increase in mortality due to increased predation.

The complete data set was examined by separating out different acclimation ranges and different endpoints, by only looking at endpoints with significant mortality occurring in less than 10 minutes, and by lumping all the data together to examine the general endpoint of lethality. This process was used as a form of sensitivity analysis to gain better confidence and understanding of the strength associated with extrapolating beyond the lowest tested endpoint duration of 4 seconds. It is assumed here that extrapolation to a 1 second exposure duration represents instantaneous exposure and thus should be used to define instantaneous lethality. The power curve that best represented the data was used to create the extrapolation equation used in the following discussion. The following is intended to provide a general understanding of the analyses that were conducted, but does not represent an exhaustive description.

Separation by acclimation temperature and by test endpoints resulted in predicted 1 second LC1 (deaths beginning) to LC100 (all dead) values ranging from of 32.76°C to 34.32°C at moderate acclimation temperatures of 15-15.6°C. The 1 second endpoints at cold acclimation temperatures (9-10°C) ranged from 32.45°C to 34.34°C. Since sensitivity to temperature is well demonstrated to be dependent upon prior acclimation temperature, this analysis is believed to be the most appropriate. In extrapolation from a single study using rainbow trout at an unknown acclimation temperature, it was found that increased predation rates may occur with a 1 second exposure to 33.47°C. Since all of these data sets were small, analyses were also made that lumped together the acclimation temperatures. This resulted in an estimated 1 second LC1 (deaths beginning) to LC100 (all dead) values ranging from 32.59°C to 34.69°C. In examining only the LC50 endpoints that occurred within 4 minutes or less, it was estimated that the 1 second LC50 (50% dead) would occur at 34.69°C. And when examining all of the available short term mortality data together, to create the largest data set for extrapolation, it was predicted that some mortality will occur with a 1 second exposure of 33.18°C. The point of this discussion is to demonstrate that the estimations cluster between 32.5 to 34.6°C, a very narrow range. Taking the midpoint of this range to further improve confidence in using an extrapolation would suggest that an almost instantaneous exposure to temperatures of 33.5°C or greater will likely result in at least some mortality to passing fish. Given that 100% mortality has been demonstrated at 32°C in 11 seconds at low acclimation temperatures (9-10°C) and 50% mortality in 8 seconds, and that mortality has been noted at low acclimation temperatures to begin in 4 seconds the estimate should not be considered overly conservative. The fact that greater sensitivity can be expected at even lower winter and early spring acclimation temperatures (4-8°C), and the fact that lethal exposures are cumulative with all temperatures above the lethal threshold, suggests temperatures greater than 33°C should not be allowed where that water would result in the entrainment of fish for a duration of 1 second or longer. For this reason, discharges with temperatures greater than 33°C should be evaluated for possible risks of creating a lethal barrier to organisms. The changing velocity and temperature of the discharge plume should be examined to ensure that time spent at or above 33°C does not exceed 1 second (it should generally be assume the organism is entrained and is moving along with the plume in the analysis).

Figure 4.20. The following is an example of one of the data subsets examined:



Acclim. Temp. (°C)	Temperature of Test (°C)	Time (sec.)	Endpoint of Test	Predicted Endpoint Temperatures
15.6	26.7	2,970	LC50	26.94052
15	28	1,350	LC50	27.505
15.6	29.4	26	LC50	30.51586
15.6	32.2	10	LC50	31.29244
	Predicted	2		32.64542
	Predicted	1		33.246

The following table summarizes the data used for the analysis of lethality.

Table 4.21. Summary of data used to determine risk of near instantaneous lethality.

Author or Study	Species	Acclimation Temp. (°C)	Temperature of Test (°C)	Time to Effect (seconds)	Endpoint Reported
Snyder and Blahm, 1971	Chum	15.6	26.7	2,640	LC1
		15.6	26.7	2,970	LC50
		15.6	26.7	3,960	LC100
		15.6	29.4	15	LC1
		15.6	29.4	26	LC50
		15.6	29.4	60	LC100
		15.6	32.2	6	LC1
		15.6	32.2	10	LC50
		15.6	32.2	15	LC100
		10	26.7	100	LC1
		10	26.7	240	LC50
		10	26.7	2,220	LC100
		10	32	4	LC1
		10	32	8	LC50
		10	32	11	LC100
Coutant, 1972(a)	Chinook	15	28	1,350	LC50
	Rainbow	17-19	30.5	900	LC50
Lyytikainen, Koskela, and Rissanen (1997)	Char	15	29	120	LC50
		18	29	240	LC50
Baroudy and Elliott, 1994	Char	5	23.3	600	LC50
		5	24.1	600	LC50
		5	25.7	600	LC50
Groves and Mighell, 1970	Salmon	9	30	10	LC16
		9	30	35	LC100
Coutant, 1972(b)	Rainbow		30	33	Increased Predation
			28	120	Increased Predation
			26	1,920	Increased Predation

c) Temperature Influenced Fish Diseases

Temperature affects both the occurrence and severity of many diseases and infections important to fish and other aquatic life. While some diseases are associated with holding fish at very cold temperatures, and some are prevalent across the full spectrum of temperatures occurring in Washington's waters, many are facilitated by temperatures within or slightly above the fully protective temperature range for the growth of our native fishes. This discussion is limited to those diseases that are known to cause illness in populations of wild fish that are facilitated by temperatures at the upper end of the physiologically protective range of our indigenous fish. The intent is to identify where a stream temperature standard may need to be set below this upper end to prevent, or at least reduce the severity of, disease outbreaks in natural fish populations. It must be recognized, however, that temperature standards by themselves will not eliminate the risk of disease in fish. Besides warm water diseases, native fishes are harmed by numerous very important cold water fish diseases, such as bacterial kidney disease. It is of course reasonable that most fish pathogens thrive in cold waters here in the northwest since the pathogens themselves have evolved along with our native fishes.

Fish diseases can be divided into four types of infections: 1) bacterial, 2) viral, 3) fungal, and 4) parasitic. Regardless of the type of infection, temperature affects both the virulence of the disease as well as the immune system of the host fish. When environmental conditions are optimal for the disease it grows more rapidly and is often more virulent. If the environmental conditions are more optimal for the disease then they are for the fish, then there is a greater likelihood that the disease will be able to overcome the host's defense systems and create serious illness (Wedemeyer and Goodyear, 1984). Just as each disease causing organism has an optimum temperature range, they also have lethal boundaries or limits of activity. If the temperature is above or below these thresholds, the disease causing organism will be unable to reproduce or grow, and thus will be unable to affect disease in fish. Catastrophic outbreaks of many bacterial diseases are associated with water temperatures that are optimal for the bacterium but above the optimal temperature for the infected fish.

While some diseases will have thresholds of temperature above or below which the disease organism is unable to grow, most diseases are able to grow at some temperature that occurs during the year in Washington's waters. The primary goal, therefore, cannot be to set standards at which diseases organisms will not exist. A complicating factor in evaluating diseases is that most have multiple, sometimes hundreds, of strains. Individual strains can have significantly different characteristics for optimal infection and virulence. Since researchers often do not specify specific strains examined, this creates variability in research results that may very well just be the consequence of testing different strains. Further, native fish differ in susceptibility to these diseases both by subspecies and by individual stock (Li et al., 1987, and others).

The focus of this effort is to identify pathogens that: 1) occur in freshwaters; 2) are enhanced by increasing water temperatures in the upper optimal range of our native fishes (roughly 14-18°C); and 3) have been associated with serious outbreaks of disease in indigenous wild fish populations.

In reviewing the literature, only three diseases appear to meet all three criteria, these are two parasites (*Ichthyophthirius multifillis* and *Ceratomyxa shasta*) and columnaris disease. While numerous other diseases are documented to be influenced by warming temperatures, these others tend to be primarily problems associated with intensive fish culturing facilities, or are associated with species and temperatures not common in our natural waters. Since there is little suggestion that any of these other diseases pose a significant threat to the welfare of our native fishes, they will be used only broadly to discuss how temperatures influence the health of fish and in support of the findings for the two specific diseases discussed below.

Ichthyophthiriasis. Post (1987) notes that the etiological agent for ichthyophthiriasis is the largest protozoan found on fishes. Occurring on both hatchery and wild fish (Bell, 1986), ichthyophthiriasis is considered one of the most prevalent diseases of fishes (Post, 1987). Bell (1986) notes that outbreaks in fingerlings often occur at temperatures above 15.5°C, and the optimum temperature for the organisms is 25-27°C. Post (1987) notes that temperatures over 12-15°C are more suitable for reproduction, and that disastrous losses have occurred in trout culture where water warms to near 20°C.

Ceratomyxiasis Shasta. An obligate parasite widespread in the Northwestern U.S. where anadromous salmonids return from the ocean to spawn. While not important to adult fish, *C. shasta* may be devastating to very young salmonids (Post, 1987) and is a parasite of concern for northwest salmonids (Bartholomew, Rohevec, and Fryer, 1989; and Conrad and Decew 1961; as cited by Hoffman and Bauer, 1971). Bartholomew, Rohevec, and Fryer (1989) note it is important because it not only causes losses in hatchery-reared and wild juvenile salmonids but also contributes to prespawning mortality in adult salmon.

Infections of *Ceratomyxa shasta* are temperature dependent (Yamamoto and Sanders 1979, and Udey et al. 1975; as cited in Bartholomew, Rohevec, and Fryer, 1989). Udey et al. (1975) found that rainbow trout exposed to the infective stage of *C. shasta* and held at water temperatures of 6.7 to 23.3°C had little or no ability to overcome the infection, and that the mean time from exposure to death was directly correlated to temperature (about 155 days at 6.7°C and 14 days at 23.3°C). In rainbow trout the disease process was suppressed at 3.9°C; however, when the infected fish were subsequently transferred to water at 17.8°C, many died. Mortality in exposed rainbow trout was greater than 92% at temperatures above 12.2°C, 84-75% at 9.4-6.7°C, and zero at 3.9°C (Fryer and Pilcher, 1974). In juvenile coho salmon mortality was 92-100% at 20.6°C and above, 57-59% at 17.8°C, 13-31% at 15-12.2°C, and 4-0% at 9.4°C and lower.

Evidence suggests that only salmonids are susceptible to *C. shasta* infections, but that susceptibility may vary within species. Juvenile salmonids originating from waters containing the infective stage of the parasite have been found to be more resistant than strains from areas free of the infective stage (Johnson 1975, Zinn et al. 1977, Buchanan et al. 1983, and Hoffmaster 1985; as cited in Bartholomew, Rohevec, and Fryer, 1989). Sanders et al., (1970; as cited in Li et al., 1987) reported that infected coho show an increasing susceptibility as temperature rises: mortality below 10°C is 2% at most, 22% at 15°C, and 84% at 20.5°C. In contrast, mortality of infected juvenile steelhead trout can be as high as 80% and is independent of temperature. Ratliff (1983) studied the infective stage of *Ceratomyxa shasta* in the Deschutes River of central Oregon and found that *C. shasta* emanates from the bottoms reservoirs, and that the infective period began in the spring when river temperatures were between 6.9 and 8.6°C. The author noted that based on his observations *C. shasta* spores are more likely observed when test fish are held during the incubation period at 10°C rather than at warmer temperatures. Waters where infected fish have been found do not necessarily contain the infective stage of the parasite (Johnson et al. 1979; as cited in Bartholomew, Rohevec, and Fryer, 1989), and even in the Columbia River Basin where infected fish migrate and distribute spores throughout the drainage, the infective stage has not been demonstrated in many tributaries. The authors (Bartholomew, Rohevec, and Fryer, 1989) suggest that the geographic isolation of the disease supports the position that presence of the spores is insufficient to cause transmission and disease, and that a yet unidentified factor (perhaps an intermediate host) is required for the completion of the life cycle of this parasite.

Columnaris Disease. There is little doubt that columnaris disease is the most important warm-water disease for our native salmonid populations. Frequent and catastrophic losses to natural populations throughout the Pacific northwest are well document throughout the literature. For this reason, the prevention of human-caused additional losses from columnaris disease should be considered a critical element in setting temperature standards for the state of Washington.

In evaluating the research it is important to recognize that there are probably at least 1,200 strains of columnaris in Washington, and that strains can be categorized as possessing low, medium, and high levels of virulence (Pacha, 1961). High virulence strains are infective and capable of producing high rates of mortality at low temperatures, while low virulence strains are problematic only at higher temperatures (Bell, 1986). Since only a handful of authors categorized the strains they were evaluating, care must be exercised in broadly applying the conclusions of any one study. Table 4.22 below summarizes the results noted in the literature.

The milestones of 12-13, 15-16, 18-20°C are cited extensively in both field and laboratory research, and show generally consistent levels of increasing risk of columnaris disease. In field studies it has been noted that as river temperatures rise to about 10-12.8°C, researchers begin isolating columnaris strains from water (Fujihara and Nakatani, 1970). Temperatures above 13°C were associated with the occurrence columnaris in thirteen species of fish collected from the Columbia River watershed (Fujihara and Huntgate, 1970). In the Fraser River in Canada it was found that prespawning mortality of sockeye was eliminated by maintaining average temperatures on the spawning grounds of 12.8°C (Colgrove and Wood, 1966). This finding was generally supported by the work of Johnson and Brice (1952, as cited in Colgrove and Wood, 1966) that exposed four species of salmonids to columnaris for six months and found that no mortalities developed when daily maximum temperatures were 12.8°C or less. At maximum temperatures of 15.6-18.3°C, mortalities increased to 0.7-15.5% in three species but remained zero in the fourth, and at maximum temperatures 18.3-21.1°C all four species showed high mortalities (37.5-82%). These results are supported by other researchers studying columnaris under natural environmental conditions.

The spread of columnaris throughout the Columbia River basin has been noted to be linked to the water temperatures occurring during individual years. In warmer years, columnaris disease is widespread throughout the entire basin, but in cooler years, the first major exposure occurred at McNary Dam and the warmer tributaries (Pacha and Ordal, 1970). A difference of heating or cooling natural river water 2.2°C from its natural (17.7-21.7°C) condition was shown to increase and decrease mortality rates in naturally exposed fish (Fujihara, Olson, and Nakatani, 1971). While the decrease resulted in only a modest decrease (4.2%) in mortality (6.2 versus 10.4%), the increase resulted in a more substantial increase (19.5%) in mortality (29.9 versus 10.4%).

At river temperatures of about 15°C isolation of columnaris cultures is typically quite successful (Ordal and Pacha, 1963; Pacha and Ordal, 1970), with 15°C found also to be a demarcation point between high (54%) and moderate (22%) levels of infection in the crowded spawning channels of the Columbia River. Scrap fish collected from waters throughout the Columbia River basin were found to exhibit the disease when warmed to 16.7°C (Pacha and Ordal, 1970). At river temperatures above 18.8°C strains of low and intermediate virulence can be readily isolated from fish (Pacha, 1961; Bell, 1986). Major outbreaks are said to almost always occur during periods in which the water temperature was 18.3-21.1°C (Pacha, 1961), and an average mid-summer river temperature of 20.3°C was associated with a catastrophic outbreak in sockeye salmon in the Columbia River (Fish, 1948).

Laboratory tests generally confirm what has been found through these field or controlled channel studies. A complication is created by looking strictly at mortality rates from these laboratory tests. Fish are generally injected with or exposed to high doses of the pathogen, and some are inoculated with high virulent strains while others with low or intermediate virulent strains. Putting aside these general problems with comparing laboratory test results we can see the same basic patterns emerge as were found in field research. Constant temperatures of less than 12°C result in low to no infections or mortalities (Fryer and Pilcher, 1974; Post, 1987; Fujihara and Nakatani, 1970; Ordal and Pacha, 1963). Constant temperatures of 15-18°C have produced a wide range of mortalities, but is most characterized by moderate (typically 20-60%) to heavy (80-100%) mortality. In this range, authors that have made the distinction have shown high virulence strains to be commonly associated with the highest mortality (see table 4.22 for references). At constant temperature exposures of 20-23.6°C, mortalities of infected fish are consistently very high (70-100%) (Ordal and Rucker, 1944; Fryer and Picher, 1974; Fish and Rucker, 1943; as cited in Ordal and Pacha, 1963; Holt et. al., 1975).

Table 4.22. Summary of literature findings for columnaris disease.

Approximate Temperature Range or Direction	Categories of Effects of Interest noted in the literature associated with the temperature range	Citation from the Literature
<12	Seldom infectious; difficult to isolate in the field; and low (0-8%) fatalities experimentally infected fish.	Fryer and Pilcher, 1974; Post, 1987; Fujihara and Nakatani, 1970; Ordal and Pacha, 1963
13	Organism begins to be isolated in the water and fish; not associated with measurable prespawning mortality; moderate (0-20%) to high (20-100%) mortality in experimentally infected fish.	Holt et al., 1975; Fryer and Pilcher, 1974; Fujihara and Nakatani, 1970; Johnson and Brice, 1952 as cited in Pacha, and Colgrove and Wood, 1966; Fish, 1944; USEPA, 1976; Fujihara and Huntgate, 1970; Colgrove and Wood, 1966
14.4	Average river temperature not leading to disease.	Colgrove and Wood, 1966
<15-15.6	Rarely a problem; mortality from low virulence strains decline; incidence of disease in river declines to 22%.	Amend, 1970; as cited in Austin and Austin; Johnson and Brice, 1952 and Rucker, 1944 as cited in Pacha, 1961; Garnjobst, 1945, as cited in Colgrove and Wood, 1966; Fujihara and Olson, 1962, as cited in Colgrove and Wood, 1966
15-16.7	Moderate (31-56%) mortalities become more consistent. in infected test fish; disease appears in Scrap-fish after temperature elevation; epizootics in aquarium.	Holt et al., 1975; USEPA, 1976; Fryer and Pilcher, 1974; Pacha and Ordal; Colgrove and Wood, 1966, as cited in Pacha and Ordal, 1970; Post, 1987
15.6-16	Moderate (60%) mortality of injured fish; high mortality (80-100%) from high virulence strains; prespawning mortality 63-81%, two week average temperature necessary to initiate pathological effects in river; moderately high (30-64%) mortality in infected test fish.	Post, 1987; Pacha and Ordal, 1970; Colgrove and Wood, 1966; Fish, 1944; Ordal and Pacha, 1963; Ordal and Rucker, 1944, as cited in Pacha and Ordal, 1970
>15-15.6	Easy to isolate in the field; associated with seasonal mortality in hatcheries; mortality and morbidity become factors in natural waters; outbreaks of high virulence strains; initiated mortalities in migrating sockeye; disease incidence in river becomes high (54%).	Ordal and Pacha, 1963; Fujihara and Nakatani, 1970; Post, 1987; Bell, 1986; Colgrove and Wood, as cited by Gilhousen, 1970; Fujihara and Olson, 1962, as cited in Colgrove and Wood, 1966
13-18	Low (0.6-7.7%), moderate (20-50%), and high (60-100%) mortality in exposed test fish. Known virulent strains resulting in highest mortality.	Fryer and Pilcher, 1974; Johnson and Brice, 1952, as cited in Pacha, 1961; Pacha and Ordal, 1970
15.6-18.3	Low (0.7-15.5%) mortality in three species of	Johnson and Brice, 1952, as cited

	salmonids	in Colgrove and Wood, 1966
15.9-19.9	Fluctuating river temp with low (6.2%) mortality.	Fujihara, Olson, and Nakatani, 1971
17-18	Mortality sometimes moderate (37- 50%) but mostly very high (99-100%) in infected test fish; explosive infections; high mortality from all strain types.	Fryer and Pilcher, 1974; Holt et al., 1975; USEPA, 1976; Pacha and Ordal, 1970
17-21.7	Fluctuating river temp with 10.4% mortality.	Fujihara, Olson and Nakatani, 1971
<18	Deaths greatly diminish.	Ordal and Pacha, 1963
>18	Mortality high from all strains, low and moderate strains isolated.	Johnson and Brice, 1952, and Rucker, 1944, as cited in Pacha, 1961
18-22	Mortalities moderate to high (37.5-82%) in infected fish; most outbreaks; fish found releasing columnaris; Epizootics.	Johnson and Brice, 1952, as cited in Colgrove and Wood, 1966, and as cited in Pacha, 1961; Fujihara and Nakatani, 1970; Amend, 1970, as cited in Austin and Austin, 1987; and Davis, 1922, Nigrelli and Hunter, 1945, Isom, 1960, and Johnson and Brice, 1952, as cited in Pacha, 1961
19.9-23.9	Fluctuating river temp with 29% mortality.	Fujihara, Olson and Nakatani, 1971
20-21	Outbreaks of low virulence strains; mortality high (70-100%) in infected test fish, catastrophic outbreak, 28-75% morbidity in river population; outbreaks in physically stressed fish; serious epidemics.	Bell, 1986; Ordal and Pacha, 1963; Pacha and Ordal, 1970; Fish, 1948; Holt et. al., 1948; Fryer and Pilcher, 1974; Post, 1987; Fish, 1944
22.2-23.6	Mortality 100% in infected test fish; summer maximum associated with devastating outbreak.	Ordal and Rucker, 1944, as cited in Pacha and Ordal, 1970; Fish, 1948; Fryer and Pilcher, 1974
25-37	Optimum growth temperature for organism.	Garnjobst, 1945, as cited in Colgrove and Wood, 1966; Pacha, 1961; Post, 1987

Based on a review of the available literature, it is concluded that for columnaris, Ceratomyxiasis Shasta, and Ichthyophthiriasis, as well as for warm-water induced diseases in general, the following general statements hold true:

1. Average temperatures below 12-13°C significantly and often completely eliminate both infection and mortality;
2. Average temperatures above 15-16°C are associated with often serious rates of infection and noticeable mortality; and
3. Average temperatures above 18-20°C are commonly associated with very severe infections and often catastrophic outbreaks of many fish diseases.

Treating these ranges as either daily or monthly average temperature may best bracket the exposure periods associated with the spread of disease causing organisms. Adding 0.58°C and 3.18°C, respectively, converts a maximum summer daily and monthly average temperatures to estimated 7DADMax temperature metrics. This approach yields the following estimates (Table 4-24):

Table 4.24. Warm water disease risk to salmon and trout.

Disease Incidence Level	7DADMax (°C)	Midpoint (°C)
Virtual elimination of warmwater disease effects	12.58-16.18	14.38
Avoiding serious rates of infection and mortality	15.58-19.18	17.38
Severe infections and catastrophic outbreaks	18.58-23.18	20.88

To reduce the risks of serious infection and mortality from warm water mediated bacterial and parasitic diseases, it is concluded that the 7-day average of the daily maximum temperatures (7DADMax) should not exceed 15.58-19.18°C (17.38). This approach will provide safe harbor for resident species and critical life stages as well as serving to reduce or eliminate disease-caused prespawning mortalities in migrating fish. When average river temperatures exceed 20°C, or 7DADMax temperatures exceed 20.88°C, explosive infection rates and the risk of catastrophic population-level outbreaks in natural populations become a serious concern.

The research evaluated in this paper has focused on protecting cold-water fish communities. Therefore, the above conclusions may not be applicable, and are therefore not recommended for application, to any designated habitat for warm water fish-species. Information on the disease threats to native warm water fishes was not discovered during the review of the available literature. For warm water fish habitat it is recommended that temperatures be maintained within the range of what otherwise is expected to produce healthy warm water fish communities. By maintain the general health of these species it will also increase their resistance to potential diseases.

d) Smoltification and Sea Water Adaptation

Smoltification is the name given to the physiological, morphological, and changes that occur in anadromous fish as they prepare to leave fresh waters for life in saline marine waters (Clarke and Hirano, 1995; Wedemeyer, Saunders, and Clarke, 1980; Sauter and Maule, 1997, 1999). The greatest concerns at this stage of life would be that: 1) parr fail to migrate because of temperatures that are too warm (Clarke, Shlebourn, and Brett, 1981), 2) that they will migrate but not be fully capable of living in marine waters (Marine, 1997), or 3) that delays in smoltification could require that juvenile fish remain in the estuarine environment longer and experience enhanced predation.

Pennel and Barton (1996) provided an excellent summary of the process of smoltification: In marine and estuarine waters the salinity in the water surrounding the fish is greater than the salinity of the internal body fluids. The gradient produced tends to draw out the water from the body of the fish while salts from the surrounding water diffuse inward. The lost water can be replaced by drinking the saline marine water but salt must be removed from the body to prevent detrimental accumulation. The process of removing sodium ions from the blood takes place in through special cells in the gills. Sodium ions are transported from the area of high concentration of the cells to the external environment down a concentration gradient via sodium channels. Energy to drive the sodium pump comes from the conversion of adenosine triphosphate (ATP) to adenosine diphosphate (ADP), a reaction catalyzed by the enzyme sodium/potassium adenosine triphosphatase (Na^+/K^+-ATPase). In order to maintain neutrality, Cl- diffuses directly from the chloride cell into the apical space and external environment, with the activity of the chloride cell probably under hormonal control (Pennel and Barton, 1996). A major change that occurs during smoltification is a dramatic increase in the number and activity of chloride cells in the gills. An increase in Na^+/K^+-ATPase activity indicates chloride cell activity and monitoring this activity is one of the useful smolt indicators. changes such as saltwater preference and migratory behavior (Folmar and Dichoff 1980; as cited in Pennel and Barton, 1996) often become evident as the juvenile fish become smolts. A performance monitoring method to evaluate functional smolts is the saltwater challenge test. The saltwater challenge test is used to determine if smolts are capable of regulating their blood Na^+. Fish are placed into a known concentration of salt water and blood samples are taken from fish 24 hours later for Na^+ analysis. If the fish are capable of regulating blood Na^+ levels to <170 meq/l, they are considered as functional smolts (Pennel and Barton, 1996).

This ability to regulate and maintain the osmotic gradient across a fish's body surface, whether the fish is exposed to the hydrating conditions of fresh water or the dehydrating conditions of sea water, is referred to as osmoregulation. While salmonid stocks that move to the estuarine environments early as young fry or juveniles (chum, pink, some populations of coho, and to some extent ocean-type chinook) tend to develop a more rapid tolerance to saline waters, those that have an extended period of freshwater residence as juveniles (coho, sockeye, and stream-type chinook) possess a limited capacity for ionic regulation in hyperosmotic media prior to reaching the smolt stage (Clarke and Hirano, 1995).

While the evidence suggests that smoltification is triggered by endogenous rhythms (Hoar, 1988; Wagner, 1974); growth (Ewing et al., 1979), photoperiod (Folmar et al., 1982 Wagner, 1974), and temperature all critically influence the timing, extent, and success of the transition process. Temperature influences smoltification in at least two primary ways. The first is that juvenile fish must generally reach a critical size to be capable of successfully smolting (Clarke and Shelbourn, 1985; Mahnken and Waknitz, 1979). The second is that temperature affects critical enzyme activities that control the ability to excrete salts from the blood – and thus to be able to live for an extended period in saline waters (Zaugg and Wagner, 1973; Wagner, 1974; Wedemeyer, Saunders, and Clarke, 1980; Duston, Saunders, and Knox, 1991).

Laboratory and field work associating temperature with the smoltification of salmonids has to date focused on steelhead trout, chinook salmon and coho salmon, all species that have a considerable period of fresh water rearing prior to moving to marine waters. The following summarizes the studies reviewed on these species:

Steelhead Trout

In Washington, migratory smolts usually move to sea during April through June, with a peak about mid April (Wydoski and Whitney, 1979). Zaugg et al. (1972), Zaugg and Wagner (1973), and Adams, Zaugg and McLain (1973) suggest that temperatures higher than about 12-13°C may alter the juvenile migratory behavior and physiological condition of steelhead trout. In their work these authors found that fish held at 15°C and 20°C experience high rates of mortality with subsequent transfer to sea water (30ppt). The authors also noted that smolts held at 10°C were unable to maintain high NaK-ATPase activity throughout the smolt season since at the beginning of the season the increase in activity for this group was similar to that in the 6.5°C group. Steelhead maintained at 6.5 or 10ºC, however, experienced an elevation of Na+, K+-stimulated ATPase activity and assumed the characteristic slender, silvery appearance of smolts. Adams, Zaugg, and McLain (1975) evaluated winter and summer steelhead trout metamorphosis at six different growth temperatures ranging from 6 to 15ºC. Salt water survival in 35% sea water at 10ºC was used to determine the extent of transformation. The highest temperature where a transformation was indicated was 11.3ºC. By April fish reared at 6ºC had elevated ATPase levels typical of smolts or migratory animals and showed 92% survival in sea water. Ten and 11.3ºC-reared fish showed a short-lived elevation in ATPase in mid-April alone concurrently with 100% sea water survival at that time. Only in 6ºC-reared animals did the salt water survival ability continue into May. Zaugg (1981) found exposures of fish to 13°C resulted in a delay in migration, fewer total fish attempting migration, and lower gill Na^{+}-K^{+} ATPase activity. Wagner (1974) found that parr-smolt transformation in steelhead appears to be based on endogenous rhythm. Wagner also found a tendency for fish reared at a normal temperature cycle (6.9-18.6°C) to migrate in greater numbers than those that experienced a constant temperature regime (12.3°C). This was consistent with Wagner (1971) where fish reared under constant photoperiods and normal temperatures also migrated in greater numbers than fish receiving a similar photoperiod but a constant temperature. Zaugg (2001) summarized a study done in 1977 assessing the effect of barging and trucking on the state of smoltification in Dworshak steelhead. Smolts held in water below 10°C had no trouble in maintaining elevated ATPase activities, whether of hatchery or wild origin. However, barged two-year old steelhead smolts held in the Columbia River water (12.5-13.6°C) reverted to parr-like gill ATPase activities within approximately 2 weeks (from May 6 to May 21). Smolts held in water below 10°C retained a smolt-level gill ATPase activity at least through June 8 when the experiment was terminated. Zaugg (2001) summarized the work reported by Dr. H.W. Lorz in December, 1974, to the Annual Northwest Fish Culture Conference. Three groups of winter steelhead were reared at the laboratory under normal photoperiod but different constant temperatures (8, 12, and 16°C). Only the fish reared at 16°C did not show an increase in ATPase activity during April. Samples of the fish were released into a small coastal stream. The fish reared at 16°C did not migrate at the same rate as those fish reared at lower temperatures, with a portion of these fish showing a three week delay. However, measurements from downstream migrants showed that the ATPase activity had increased during this three to four week period. This study supports the position that there is a close relationship between elevated gill Na+ K+ stimulated ATPase activity and seaward migratory movement; as well as providing information on the deleterious effect of elevated temperature on parr- smolt transformation. In a second part of this study, two groups of steelhead were maintained in laboratory tanks, one with water at 8°C and the other at 16°C into May. At the time when elevated enzyme activity was observed in the fish held at 8°C, enzyme activity remained low and unchanged in fish held at 16°C. Fish held at 16°C were then subjected to six different temperature regimes (0/24, 4/18, 6/16, 10/12, 14/18, 24/0) (time at 8°C /time at 16°C). The fish maintained at 24hr/day at 16°C failed to develop elevated ATPase activity as did also the fish held in 4/18, 6/16, 10/12, 14/18. Only the fish held for 24 hours per day at 8°C exhibited an increase in ATPase activity, which occurred in the 5th week.

Chinook salmon

Once juvenile chinook grow to an appropriate size they will migrate to the ocean (Ewing et al., 1979; Clarke and Shelbourn, 1985). Out-going migrations typically occur during the first and second years of life (Wydoski and Whitney, 1979) but since success is related to smolt size, some fish will not be ready until their third year. Clarke and Shelbourn (1985) found that optimum regulation of plasma sodium concentrations in ocean-type fall chinook salmon occurred with transfer from 13.8ºC fresh water to 10.2ºC sea water. They also noted that severe descaling in their freshwater holding tanks occurred in groups of smolts reared at 16 or 17°C, as well as with groups transferred from 8-12°C freshwater to 14°C seawater. Marine (1997) conducted laboratory tests on fall run chinook salmon from Sacramento River hatchery stocks to determine the chronic effects of varying temperatures from 13 to 24°C on growth and smoltification patterns (Na^+-K^+ ATPase activity and seawater challenges). The control test was 15°C (fluctuated from 13-16°C), the intermediate was 18.5°C (17-20°C), and the extreme was 21.5°C (21-24°C). The author concluded that both acceleration and inhibition of chinook smolt development may occur at temperatures above 17°C and significant inhibition of gill ATPase activity and associated reductions of hypo-osmoregulatory capacity may occur when chronic elevated temperatures exceed 20°C. Wedemeyer (1980; as cited in USEPA, 2001) noted that Fall chinook undergo a greater desmoltification rate at 15°C than coho do at that temperature range. Clarke, Shelbourn, and Brett (1981) found that while acclimation to brackish water (15-20ppt) had little effect on osmoregulatory performance of coho and chinook reared at 10°C, it did maintain performance in chinook at 15°C to the end of the experiment. The authors also found a dramatic regression of hypo-osmoregulatory capacity of chinook smolts held in fresh water at 15°C from week 7 to week 13. However, no such loss was observed in fish rear in 10 or 15ppt salinity. Marine (1997)found that smolts from the control (13-16°C) lot experienced higher ATPase levels and broader time periods of elevation, and better survival in seawater challenges than smolts reared in the warmer test lots (17-20°C and 21-24°C). The possibility that temperatures above 17°C exerts stress on migrating smolts is further supported by the work of Connor, Burge, and Bennett (1999; as cited in USEPA, 2001) that found sub-yearling chinook move into the main current of the Columbia River to avoid increasing near-shore temperatures, with this effect becoming significant above 17°C. It is further supported by the work of Sauter and Maule (1997, 1999) which found cessation in feeding behavior in smolting fall chinook at temperatures above 18°C and a decreased temperature preference (from 17.7 to 11.2°C). Exposure to water temperatures of 20°C for several hours induced heat shock proteins (Sauter et al., in review, and M. Hargis, personal comm.; as cited in Sauter and Maule, 1997). Zaugg (2001) summarized studies done by Bill Muir of the NMFS. It was observed that tagged yearling spring chinook salmon subjected to advanced photoperiod schedules and a 10-day exposure to elevated water temperatures (11-12°C) prior to release at the Dworshak hatchery migrated more rapidly and were detected in greater numbers at downstream dams than controls or fish exposed only to advanced photoperiods (no increase in water temperature). Dr. Zaugg notes that it appears that this level of temperature increase might actually benefit chinook and coho salmon, and that steelhead smolts appear to be the most sensitive to elevated temperatures. Roper and Scarneccia (1999; as cited in USEPA, 2001) found that approximately 50% of the spring chinook emigration occurs in the range of 12.5-15°C and the upper tail of this run is generally complete before 20°C in exceeded. Connor, Burge, and Bennett (1999; as cited in USEPA, 2001) note that as temperatures increase above 17°C, sub-yearling chinook rearing in near-shore areas of the Columbia River on their way to the ocean can be forced to enter the main current to avoid increasing temperatures along river margins. This is an indication that their may be indirect effects on smolts caused by warmer waters in addition to the direct effect on smoltification patterns.

<u>Coho salmon</u>

Zaugg and McLain (1976; as cited by Zaugg, 2001 and) found that ATPase reached a maximum one month earlier in fish reared at 10°C than those reared at 6°C, and that activity rose even earlier at 15°C but was only transitory in those held at 20°C. Cold water (6°C) was also found to preserve the elevated activity while higher temperatures (10 and 15°C) caused decreases after an initial accelerated increase. Additionally, Clarke and Hirano (1995) noted; however, that diurnal and seasonal temperature cycles may alter the timing of smolting. Juvenile steelhead trout reared on a simulated seasonal temperature cycle (6.9-18.6°C) exhibited greater migratory behavior and more pronounced elevation of gill sodium, potassium-activated $Na^{+}K^{+}$-ATPase activity than those reared at constant 12.3°C (Zaugg and Wagner 1973, and Wagner 1974). Adams et al. (1975; as cited in USEPA, 2001) found that 15°C was linked to impairment of smoltification, ability of smolts to migrate, and survival during smolt migration in coho salmon. Zaugg (2001) noted that in coho salmon that had reverted to parr and were subsequently released still migrated to the lower Columbia River very rapidly, and migrants captured there showed elevated ATPase levels. Although, ATPase levels were low at the time of release in June and July, these fish were capable of regenerating smolt level enzyme activities during migration in the warm waters of the Columbia during June and July. Migrants in the June and July releases migrated more rapidly than those released in May when ATPase activities were elevated in the holding ponds, and they had the greatest rate of survival to adults.

Discussion on Smoltification Studies:

Zaugg (2001) has noted that there is considerable risk in using the results obtained from temperature experiments conducted in the laboratory in predicting what may occur in the natural environment with similar temperatures. Fish held in confined conditions fail to undergo full smolt development. Once released from the confined environments, normal smolt development occurs as downstream migration proceeds. He noted that while his earlier work suggested an upper limit of 12-13°C existed for migrating steelhead based on confined laboratory conditions, we must now use some degree of caution in applying this suggested upper limit to the natural waters. He noted that once fish are actively migrating downstream and are in the process of transformation, it may take substantially warmer waters to make them revert. In a discussion on the use of the available research to set temperature criteria, Dr. Zaugg supported the premise that it may be most important to ensure that temperature conditions in the tributaries and headwater systems allow for the initiation of the smoltification process. However, it must be recognized, however, that not all migratory juveniles will have a long journey to marine waters, and not all will be able to hold in an estuarine environment if smoltification is not satisfactory upon arrival at the mouth of the tributary. Thus some caution must be exercised in assuming that the process of migration will be sufficient to allow smolts to successfully transition for life at sea. The laboratory results for steelhead trout strongly suggest that a constant exposure to temperatures greater than 12-13°C may hinder ATPase activity, and that temperatures greater than 15-16°C may disallow development altogether in multiple species. These results were obtained in tests conducted at constant temperatures, and would best be represented by weekly or monthly average temperatures. This position is supported by the work showing that steelhead trout reared on a simulated seasonal temperature cycle (6.9-18.6°C – mean 12.79°C) exhibited greater migratory behavior and more pronounced elevation of gill sodium, potassium-activated Na^+K^+-ATPase activity than those reared at constant 12.3°C. Treating the constant temperatures as a weekly average temperature results in the suggestion that a 7DADMax limit of 15.18-16.18°C may be necessary to allow normal ATPase development in smolts, and that a 7DADMax of 18.18-19.18°C may prevent or stop smoltification entirely.

To protect the smoltification capability of juvenile salmonids, it is concluded that the 7-day average of the daily maximum temperatures (7-DADM) should not exceed 15.18-16.18°C. Except for the Columbia and Snake Rivers this temperature threshold is viewed as appropriate for application throughout the entire juvenile migration path. These two major rivers are cited as exceptions because they provide a significant migratory time and terminate in a large estuary; both features that have been well demonstrated to assist in the full development of successful smolts, even under temperature conditions determined adverse in laboratory testing.

e) Miscellaneous Indigenous Species

With the possible exception of two amphibian species, the tailed frog and the torrent salamander, and two fish species, the mountain whitefish and the smelt, no other aquatic organisms have been identified that appear as sensitive overall to temperature increases as the native salmonids and char. This paper has focused on protecting species sensitive to temperature increases, however, it is important to remember that some of our native populations thrive in waters warmer than what is fully protective for salmonids (Wydoski and Whitney, 1979; Black, 1953; Li et al., 1993; Reeves et al., 1987; Cech, Mitchell, and Wragg, 1984, and others).

For the water quality standards to be fully protective in the ecological sense, they must recognize the continuum of temperature changes from upstream to downstream and between ecoregions and waterbody forms. The water quality standards should acknowledge that certain waters that are naturally not fully protective for salmonids may be ideally suited for other native species. It is appropriate that some of these naturally warmer waters have separate standards that consider more accurately the warm water tolerant communities that have historically existed.

i) Sensitive Amphibians

Three stream dwelling amphibians are of concern when it comes to temperature alterations. These are the *Rhycotriton* species (3 species of torrent salamanders), the *Dicamptodon* species (Pacific and Copes giant salamanders), and *Ascaphus truei* (tailed frog).

Rhyacotriton species are found in temperatures ranging from 5.9-10.9°C, and eggs have been found at 8-9°C then taken to the lab and incubated successfully at 8-9°C. Like most amphibians, *Rhyacotriton* can withstand high daily peak temperatures. When acclimated in a laboratory to temperatures of 13-14°C, *Rhycotriton* has a critical thermal maximum (CTM) of 27.8-29°C (Kelsey, 1998). Welsh and Lind (1996) suggest that suitable temperatures for Rhyacotriton are from 6.5-15°C, with highest abundance of salamanders occurring in a narrow range of about 8-13°C. The authors, using unpublished data developed while conducting critical thermal maximum testing, note that signs of thermal stress were noted at 17.2°C.

Dicamptodon species have larvae noted to develop at 12-16°C in the field. Larvae may develop for 2 years prior to becoming adult salamanders. Adults spawn in the spring when waters are warming, but may also spawn in the fall. While the Pacific giant salamander becomes a terrestrial salamander, the Copes giant salamander does not (Kelsey, 1998).

Ascaphys truei is typically found in waters from 4.4-14°C. Embryonic development can occur between 5-18°C. Tadpoles from 1-2 years old prefer waters around 5-8°C, but 3-4 year olds prefer waters of 12-16°C. *A. truei* larvae have a critical thermal maximum of 28.9-30.1°C and adults of 23-24°C; when both are acclimated at 23°C. The nine day LT50 for tailed frog larvae was determined to be 23°C. Tadpoles may develop from 1 to 4 years, depending on the individual stream, before metamorphosis (Kelsey, 1998). Hawkins et al (1988) found that variations in tadpole densities were high at maximum stream temperatures below 18°C and below that temperature substrate size and imbeddedness characteristics determined dispersal patterns. The authors suggest that low densities in nonforested watersheds may be better explained by the sensitivity of adults to desiccation rather than the effect of moderately warm water temperatures.

As noted by Hawkins et al. (1988) tailed frog (*Ascaphus truei)* tadpoles appear to be particularly well suited to life in swift streams. The body is streamlined and ventrally flattened, and the mouth is modified into a powerful suctorial disc. Tadpoles use the oral sucker to cling to rock surfaces, move against the flow of water, and scrape periphyton from streambed surfaces. Diatoms are apparently the main food source for these tadpoles (Metter, 1964; as cited by Hawkins et al., 1988). In most West Coast streams, eggs hatch in late summer and tadpoles transform to adults almost exactly two years later (Metter, 1967; as cited by Hawkins et al., 1988).

Claussen (1973) found that adult *A. truei* had an incipient lethal temperature limit of 24.1°C after 45 hours of exposure and 25.8°C after 7.3 hours, and that adults preferred temperatures of 16.5-18°C in laboratory tests conducted on wet sand. Claussen reported the adult frogs were kept in good health in the laboratory in terrariums kept at room temperature (19-24°C) for many months. Brown (1975; as cited by Hawkins, 1988) reportedly found that 18.5°C was the upper limiting temperature for egg development. De Vlaming and Bury (1970; as cited by Hawkins, 1988) are reported to have found that age 1+ tadpoles preferred 5-8°C and age 2+ tadpoles preferred 12-16°C, and that both cohorts avoided temperatures greater than 22°C and 50% of 1+ animals died within 29 days at 23°C.

Welsh (1990) studied the distribution of *A. truei* over a three year period at stream sites in the Pacific Northwest and found temperature to be an excellent predictor of tailed frog abundance. Higher numbers of tailed frogs occurred in streams with lower temperatures and the highest stream temperature at which he had observed tailed frogs was 14.3°C. Welsh suggested his work showed that while tailed frogs were found at maximum temperatures as high as 18°C, their densities began increasing only at stream temperatures below about 14.3°C and were characteristically highest in waters with temperatures below 12°C.

Hawkins et al (1988) sampled small streams near Mt. St. Helens, Washington between 1985-1987 and found that streams with little forest cover and maximum temperatures near 20°C had few *A. truei* while streams in completely or partially forested basins with maximum stream temperatures less than 18°C had relatively high tadpole densities. Variation in density within streams with maximum temperatures below 18°C were not associated with temperature differences but were instead associated with substrate size and embeddedness characteristics. In the Hawkins et al. (1988) suggest that while their work does not substantiate the opinion that adverse effects occur up to 20°C on tadpole density, temperatures in this range are within the critical limits found by other authors and their results should be used with care. Hawkins, Feminella, and Crisafulli (unpublished status survey) found that in the streams around Mt. St. Helens, Washington, maximum tadpole densities were associated with mean maximum summer water temperatures of 16°C and note that since 1988 tadpole densities have been consistently higher in nonforested (warmer) than in forested (cooler) streams. Crisafulli (personal communication) noted that the ability of tailed frog to thrive in the deforested areas of the volcano's blast zone may be related to the generally cool moist weather that is experienced in that region of the state which helps avoid desiccation of adult frogs. The concern being that work done in other regions associating tailed frog abundance to stream temperatures may be measuring the association of cool moist mature forest conditions to temperature rather than accurately gauging the importance of the specific stream temperatures to tailed frog health. Since flow, sediment, and riparian area conditions well all tend to be more favorable in the cooler headwater areas, this may confound efforts to gauge the importance of temperature compared with these other commonly associated factors.

Larvae of all of these stream breeding amphibians rely primarily on the perennial flows of 1st and 2nd order streams (mostly Type 4 and 5, but also some smaller Type 3 streams). Their rates of growth, and thus time prior to metamorphosis, is affected by temperature and food. Warmer waters within their tolerance range may speed up development (Kelsey, 1998).

The paucity of controlled research data on the temperature requirements of amphibians, and the potentially strong conflicts among the existing research, makes establishing a temperature standard aimed at ensuring their protection somewhat problematic. With lethal tolerances as high as most salmon and trout, the reported distributional associations with temperature must be considered with caution. Since these amphibians commonly occur high in the drainage, often at and above the upper limits of many fish species, they are typically able to associate with shallow groundwater dominated seeps and springs. Stream breeding amphibians, particularly the torrent salamanders and the tailed frog, may in fact have lower optimal temperatures than salmon and trout, but at this point the scientific information is not strong enough to reach this conclusion and does not suggest that establishing a species-specific temperature limits are clearly warranted. There is clearly a need for more controlled studies on the temperature requirements of our stream breeding amphibians, and the question of whether more stringent temperature standards needs to be set for these species should be revisited periodically to ensure that new information and understandings are taken into account in setting and revising water quality standards.

ii) Other Sensitive Fish Species

Smelt and mountain whitefish were identified through the literature as possessing sensitive temperature limits. The studies on smelt indicate they have a lower lethal temperature limit than do the salmonids and a lower optimum temperature preferendum. Longfin smelt (*Spirinchus thaleichthys*) was identified as having a limit of occurrence of 18.3°C by Wydoski and Whitney (1979). This corresponds well to acute exposure testing using the Eulachon smelt (*Thaleichthys pacificus*) by Snyder and Blahm (1971) who found a change from 10 to 18°C resulted in 50% mortality to adults in less than one hour, and 50% mortality occurring in 26 minutes at an exposure of 21°C. While temperature increases from 10°C to 13°C and 15°C, did not induce mortality over a 50-hour holding time, none of the females exposed to the higher test temperatures deposited their eggs. USEPA (1971) notes that in temperature studies on the eulachon, Smith and Saalfeld (1955; as cited in USEPA, 1971) reported the fish entered the Columbia River when the temperature was between 2 and 10°C but they migrate up to and beyond the Cowlitz River (RM 68) when the Columbia is approximately 4.4°C. The smelt run was delayed five weeks from entering the Cowlitz River because of low water temperatures during December 1968 and January 1969 (Snyder, 1970; as cited in USEPA, 1971). Eulachon eggs appear to be more tolerant than adults to temperature increases. The eggs can withstand a temperature of 14°C from a base temperature of 4 to 8°C without appreciable mortalities (Parente and Ambrogetti, 1970; as cited in USEPA, 1971), but a 3°C increase halts maturation of adult females. In tests in 1968 and again in 1969, it was observed that female smelt exposed to water heated 3.9°C above river temperatures were reluctant to spawn. Adult female smelt are less tolerant of temperature changes than other fish. Bell (1986) in a general review on the temperature requirements of fish suggested that the range for smelt was 3.8-12.7°C, and the preferred spawning range was 7.2-8.3°C. The spawning range identified by Bell, closely matches that observed for longfin smelt in the Cedar River in Washington. Wydoski and Whitney (1979) suggest that spawning occurs primarily in late February (with a range of mid-January to mid-April) when the river was between 4.4-7.2°C. They also note a British Columbia stock that hatches at 9.4-10.6°C approximately 25 days after spawning. Given that adult spawners and outgoing juveniles may be in fresh waters as late as March to mid-April, and their temperature requirements may be more strict than most salmonids, the protection of smelt is an important consideration in setting water quality standards. In waters supporting smelt, it is estimated that the 7-day average of the daily maximum temperatures should not exceed 12-14°C prior to May 1; with no single daily maximum temperature greater than 16°C to fully protect reproduction. This will allow most stocks to spawn and have the newly hatched juveniles return to the sea (or lake where a landlocked population) under tolerable temperature conditions.

Information on the temperature requirements of the mountain whitefish (*Prosopium williamsoni* Girard) is more limited to that for the smelt. Eaton et al. (1995) calculated that a weekly mean temperature of 23.2ºC was the 95th percentile of the distribution of mountain whitefish in field studies and suggested this value as a measure of the species temperature tolerance. Wydoski and Whitney (1979) and Daily (1971) note that mountain whitefish are found in both streams and lakes throughout the state of Washington, generally in large streams with average temperatures of 8.8 to 11.1°C. Whitefish are generally nocturnal autumn spawners that spawn from October into December and at temperatures below 4.4 to 5.5°C have been associated with spawning activity (Brown, 1952; as cited by Daily, 1971). Mountain whitefish eggs require low temperatures for optimum development. They hatch in about 5 months at 1.7°C and in about 1 month at 8.9°C (Sigler and Miller 1963, and Simon 1946; as cited in Davis, 1971). Daily (1971) noted that adult mountain whitefish are reported to prefer pool and meadow areas of cool streams where water depths exceed three feet. Sigler (1951) and La Rivers (1962) are cited by Daily (1971) as suggesting high water temperatures limit whitefish to elevations above 4,500 feet in California, Nevada, and Utah.

Northcote and Ennis (1994) note that mountain whitefish are often the most abundant sport fish species in many rivers of western North America (Sigler and Miller 1963, and Brown 1971; as cited in Northcote and Ennis, 1994). Hagen (1970; as cited in Northcote and Ennis, 1994) found that in Phelps Lake spawning began in September at temperatures over 11°C but may extend into November at near 7°C. Spawning starts in late September in the Sheep River and extends to mid-October at temperatures varying daily from 8 to 0°C (Thompson and Davies, 1976; as cited in Northcote and Ennis, 1994). Other authors reportedly found spawning at temperatures as high as 9°C and as low as near zero, but usually in the 3 to 5°C range. Brown (1952; as cited in Northcote and Ennis, 1994) found that in the west Gallatin River, Montana, fish do not spawn until water temperatures drop below 5.5°C with peak spawning activity later in higher elevation tributaries at temperatures just over 2°C. Rajagopal (1975, 1979; as cited by Northcote and Ennis, 1994) studied the developmental rate of mountain whitefish eggs and gave 6°C as the upper optimal temperature for successful development. At temperatures between 9 and 11°C some hatching occurred but there were high levels of mortality and abnormality; all eggs died at temperatures of 12 and 15°C.

The information is not sufficient to justify setting a separate criteria for mountain whitefish, and since mountain whitefish occur in general along with salmon and trout in our streams and lakes, any assignment of criteria to protect these other salmonids would also be used to protect mountain whitefish populations. Based on the above cited literature findings, it appears that mountain whitefish have summer growth tolerances similar to the Pacific salmon and trouts, but they may have spawning requirements that are more sensitive. The generally late spawning habits of the mountain whitefish assist in their protection; however, human actions that cause uncharacteristic seasonal warming may cause harm to mountain whitefish during their incubation. In waters used for the incubation of mountain whitefish, average temperatures during incubation should be maintained at or below 6°C. The strength of the literature findings is not sufficient for setting a separate temperature threshold for mountain whitefish. It can, however, be used in support of setting incubation criteria for the Pacific salmon and trout. Treating this average temperature as either a weekly average or season-wide average temperature helps bound the estimate for an incubation threshold and allows conversion to the standard 7DADMax metric used in this document. Taking this approach results in the estimate that to fully protect mountain whitefish incubation the 7DADMax temperature should be maintained below 7.47-10.64°C (9.1).

iii) Stream Macroinvertebrates

Only a relatively small number of studies were found that tested the thermal tolerance of stream macroinvertebrates. Most of the species examined have thermal limits higher than the Pacific salmon and trout species found in Washington (Sprague, 1963; Nebeker and Lemke, 1968; Moulton et al., 1993; Sherberger et al., 1977, as cited in Beschta et al., 1987; Craddock, 1970 and Hair, 1971, as cited in USEPA, 1971). However, two sets of studies were found that suggest individual species may sometimes as sensitive, and in some cases more sensitive, as our indigenous salmonids.

Gaufin and Hern (1971; as cited in Moulton et al., 1993) reported a range of 21.7 to 30.1ºC in mean lethal level (median lethal temperature) for six species of caddisflies held at 6.4ºC. The lowest lethal level 21.7ºC was observed for *Parapsyche elsis* Milne, (Hydropsychidae) an inhabitant of cold, fast-flowing mountain streams while the highest lethal level (30.1ºC) was recorded for *Hydropsyche sp.* collected from a marsh-lake outflow.

USEPA (1971) conducted 96-hour lethality studies to examine the heat tolerance of late instar larvae of 15 species of aquatic insects and one species of amphipod. USEPA reported that a marked difference in sensitivity was apparent in the different species. A mayfly, *Cinygmula par* Eaton, died at 11.7°C and was the most sensitive of all the species tested. This species is found in very cold clear mountain streams. The freshwater shrimp, *Gammarus limnaeus* Smith, proved to be surprisingly sensitive to temperature increases, with 50% lethality at 14.5°C. *Ephemerella doddsi* Needham, a small, widely distributed mayfly characteristic of cold turbulent streams in the Intermountain Region, was also very sensitive with a TLm (median lethal threshold) value of 15.4°C. A lotic species of mayfly, *Hexagenia limbata* Guerin, was much more tolerant than other mayflies tested with a TLm of 26.6°C. Considerable difference existed between the three stoneflies tested. *Isogenus aestivalis* (Needham and Claassen) was quite sensitive, 50% dying at 16°C, while *Pteronarcella badia* (Hagen) and *Pteronarcys californica* Newport, two closely related species survived increases to 24.6 and 26.6°C, respectively. Six species of caddis flies were tested and clearly reflected thermal differences in their habitat requirements. *Parapsyche elsis* Milne, which is largely restricted to cold, fast flowing mountain streams, had a TLm of 21.8°C while *Hydropsyche* sp. Taken from a slow flowing stream draining a marshy lake was very tolerant with a TLm of 30.1°C. In long-term (12-30 days) thermal bioassays of five aquatic insects, the stonefly *Pternorcella badi* was most sensitive with 50% mortality occurring at 18.1-20.5°C within 24-30 days (its 96-hour TLm was 22.55°C). *Ephemerlla grandis* Eaton experienced 50% mortality in 12 days at 21.5°C (its 96-hour TLm was also 21.5°C). *Pteronarcys californica* Newport experienced 50% mortality in 25 days at 20°C (its 96-hour TLm was 27°C). None of the three most sensitive species tested in the 96-hour tests (*C. par, E. doddsi, and G. limnaeus*) were included in these long-term tests.

Summary of macroinvertebrate temperature requirements: While few studies have been conducted to test the thermal limits of macroinvertebrate species, those that have been reported in the literature suggest that individual species may be significantly more sensitive than the salmonids and other fish examined in this review document. Tests reviewed focused only on mortality as an endpoint, so any sublethal effects of temperature on macroinvertebrates (such as reproductive impairment) remain undocumented. For the lethality testing, even short term exposure (4-days) resulted in 50 percent mortality at constant temperatures from range of 11.7-16°C, with three of the four species having LT50 values between 14.5-16°C. These sensitive species are all ones that naturally occur in high mountain streams. For the purpose of this analysis the lowest value will be assumed to be anomalous, and the range of 14.5-16°C will be used to represent the range for sensitive species. For the other macroinvertebrates tested, 4-day LT50 values (21.5-30.1°C) were above those typically found for salmonid species. These two groups of macroinvertebrates are treated separately in this analysis, since one best represents species that would be found in headwater regions and the other best represents those which would be found at lower altitudes and in more main stem stream areas. Treating both groups of species as if their corresponding laboratory tests correlate as if they were either daily average or weekly average temperatures (and then converting to a 7DADMax metric) bounds the estimate for an appropriate field-based temperature criteria. Conversions assume that summer diel temperatures average 4-6°C (similar to what was previously assumed for salmon and trout). Based on the above information and recommended conversion methodology, a temperature threshold can be estimated that will prevent lethality in macroinvertebrates. Headwater assemblages of macroinvertebrates should be expected to experience 50 percent mortality if the 7DADMax temperature exceeds 15.08 – 19.18°C (17.13) [the lower end of the range would decrease to 12.38°C (midpoint 15.78) if the most sensitive species tested were included]. Main stem and lower elevation assemblages of macroinvertebrates should be expected to experience 50 percent mortality if the 7DADMax temperature exceeds 22.08-33.28°C (27.68) – although, greater confidence should be placed on the lower portion of this range (22.08-27.68°C, with a median of 24.88) because the range of macroinvertebrate species tested was not limited to those that would occur in waters inhabited by salmonids (typical mid to lower elevation rivers in Washington). To prevent any mortality the temperatures associated with 50 percent mortality should be decreased by 2°C, similar as was explained previously for converting lethality studies for salmonids. To protect macroinvertebrates from lethal effects in cold water stream assemblages the 7DADMax temperature should not exceed 13.08-17.18°C (15.13) in headwater streams, and not exceed 20.08-25.68°C (22.88) in the low lying streams.

f) Miscellaneous Indigenous Fish Species

The following graphical summary includes only those species for which temperature information was available. In many cases the information pertains only to their general habitat associations and life-history traits. Information is not adequate to propose temperature thresholds for any of these species; however, the information is useful in evaluating whether the temperature thresholds recommended to protect the native salmonids and char also appear protective of these other species.

Western Brook Lamprey	**10** (Spawn peak, May)
Pacific Lamprey	**12.8** (Too cold for incubation) **15.6** (Successful incubation) **15---25** (Successful incubation)
White Sturgeon	**8.9---17.2** (Spawn, May-July) **10---18** (Spawning) **14** (Optimal Incubation) **14** (Most spawning occurred) **17.2-17.8** (summer occupation) **18** (Elevated embryonic mortality) **18---20** (Limited spawning occurs) **20** (Complete embryonic mortality)
Eulachon Smelt	**2---10** (River temp during spawning migration) **<- 13** (Successful egg deposition) **18** (Rapidly lethal to adults)
Longfin Smelt	**18.3** (Limit to occurrence) **4.4---7.2** (Spawn, primarily February) **9.4-10.6** (Eggs hatch)
Smelt (general)	**7.2-8.3** (Preferred spawning) **8.3** (Optimal hatch)
Mountain Whitefish	**8.8---11.1** (Average temp of habitat) < - **23.2** (95% of distribution) **6** (Upper optimal incubation)
Chiselmouth	**17 - >** (Spawn in summer)
Redside shiner	**6.7--23.9** (Range) **10 - >** (Spawn, April-July) **12.8------------------20** (Summer preference) **19--------22** (Fluct. better than 12-15) **25** (24 hr LT50 at 9-11C acclimation)

	27.6 (24 hr LT50 at 14C acclimation)
Longnose Dace	**11.7 --- >** (Spawn, June-early July) **12.8---21.2** (Prefers) **19.4---30** (Found over two years)
N. Pikeminnow	**16.1---24.4** (Prefers) **18.3** (Spawn, late May-July, hatch) **29.3** (24 hr LT50 at 19-22C acclimation)
Tui Chub	**12.8---15.6** (Spawn, May-June)
Peamouth	**12.2 - >** (Spawn, late May-early June) **26.6** (24 hr LT50 at 14C acclimation) **27** (24 hr LT50 at 11.5C acclimation)
Lake Chub	**13.9** (In streams) **18.9** (Spawn, Apr-Jun, lakes)
Speckled Dace	**17.8—18.9** (Eggs hatch)
Largescale sucker	**29.4** (24 hr LT50 at 19C acclimation)
Sucker (generic ref.)	**11.7---21.7** (Prefers)
Longnose Sucker	**5 - >** (Spawn, early spring)
Mtn. Sucker	**12.8---21.1** (Summer preference) **11.1---18.9** (Spawn, June-July)
Burbot	**1.7** (Spawn, Jan-Feb) **21.2** (Final preferendum)
T-S. Stickleback	**17.8** (Spawn, May-Aug, hatch) **26** (LT50 in 6 days)
Shorthead Sculpin	**< - 15.6** (Prefers) **23.8** (Found)
Piute Sculpin	**15 - >** (Frequents) **25** (Found) **12.2** (Spawn, May-June)
Prickly Sculpin	**10---17.8** (Typical) **24.1** (24 hr LT50, 18-19C acclimation) **27.8** (Found)
Margined Sculpin	**12.8---18.9** (Typical)
Mottled Sculpin	**12.8---18.3** (Preferred)

	15.6---23.3 (Found over two years)
	16.5 (Preferred)
	21.1 (Found)
	10---15.6 (Spawn, Feb-June, hatch)
Riffle Sculpin	**< - 15.6** (Prefers)
	22.2 (Found)
	< - 27.8 (Survive in lab)
Reticulate Sculpin	**10---17.8** (Typical)
	25.6 (Found)
Starry Founder	**11.1** (Ave. temp., spawn late Nov-Feb)

Although the temperature preferences of most of these species appears to overlap that of the upper end of the fully protective temperature range for rainbow trout, some of these species will thrive in waters warmer than what is fully protective for rainbow trout. Species such as dace and redside shiner may actually rely on their ability to tolerate warmer water to maintain strong populations where they exist in sympatry with rainbow trout or other salmonids.

g) Summary of Temperature Requirements for Indigenous Aquatic Life

i) Cold Water Species

The following table summarizes the individual conclusions made previously to protect the state's cold water aquatic habitats. For the two salmonid guilds examined, the life-stages are presented along with other thermal stressors that would influence the health of these life-stages (e.g., disease, and interactions with other associated community and prey species). This approach is useful in identifying what temperature criteria would be most appropriate to provide for a fully protective thermal environment. The conclusions are provided as summary statements in Table 4.25 below.

Table 4.25. Ranges within which lie temperatures likely to fully protect specific species and life-stages.

Requirements by Species Guild and Life Stage	7DADMax Temperature Range (°C)	Midpoint of Range (°C)
Bull Trout and Dolly Varden (Char)		
Char spawning and incubation	7.31-8.32	7.82
Char juvenile rearing	12.61-13.96	13.29
Disease - Virtual elimination of warmwater disease effects in salmon and trout	12.58-16.18	14.38
Macroinvertebrate lethality in headwater streams	13.08-17.18	15.13
Char lethality (7-day exposure)	20.73-212.88	21.31
***Summary**: Temperatures (7DADMax) should be below 7.5-8°C at the time of spawning for char and below 13-13.5°C outside of the incubation period. This temperature regime will also provide full protection from warm water disease and support sensitive headwater species of macroinvertebrates.*		
Salmon and Trout Waters		
Spawning and Incubation		
Salmon and trout spawning and incubation	12.55-13.92	13.24
Reproduction of Smelt (prior to May 1)	12-14	13
***Summary**: Temperatures (7DADMax) should be below 13-13.5°C at the time of spawning for salmon and trout. This temperature should also fully protect the reproduction of smelt and other non-salmonid species.*		
Juvenile rearing		

Salmon and trout juvenile rearing	15.18-18.05	16.62
Juvenile smoltification (typically ends prior to late June-late August when summer temperatures peak)	15.18-16.18	15.68
Macroinvertebrate lethality in headwaters	13.08-17.18	15.13
Disease - Virtual elimination of warmwater disease effects	12.58-16.18	14.38
Disease - Avoiding serious rates of infection and mortality	15.58-19.18	17.38
Macroinvertebrate lethality in main-stems	20.08-25.68	22.88
***Summary**: Temperatures (7DADMax) should be below 16-16.5°C to fully protect juvenile rearing of salmon and trout. However, in lower portions of rivers where smoltification interference is less likely, the natural macroinvertebrate community would not be expected to include the most sensitive taxa, the waters tend to be more productive for food organisms, and where holding by ripe adult fish is naturally uncharacteristic; slightly warmer temperatures (17-17.5°C) may still be fully protective of the indigenous aquatic community during the summer rearing period. In waters supporting the eastside redband trout, a 7DADMax of 17.5-18°C should also be considered fully protective.*		
Adult migration		
Direct Lethality (7-day) to salmon and trout	21.09-23.36	22.23
Direct lethality (7-day exposure) to char (recognizing use by migratory populations).	20.73-21.88	21.31
Barriers to migration in salmon and trout	20.05-24.6	22.1
Non-barrier migratory effects	18.1-20.4	19.25
Disease - Avoiding serious rates of infection and mortality	15.58-19.18	17.38
Salmon and trout juvenile rearing (used here as a general sign of low thermal stress)	15.18-18.05	16.62
***Summary**: Adult migrants are likely to be detrimentally impacted at a 7DADMax above 17-19°C; and barriers to migration and direct mortality should be expected when 7DADMax temperatures exceed 21.5-22°C. One day maximum temperatures for which lethality should be expected to begin would be 22.5-23°C.*		
Adult holding prior to spawning		
Prespawning effects	13.48-14.96	14.22
Disease – Virtual elimination of warmwater disease effects.	12.58-16.18	14.38
***Summary:** Locations in streams where adult migrants hold the week or two just prior to spawning should have temperatures not exceeding a 7DADMax of 14.5°C to avoid prespawning losses of adults or potential offspring.*		

ii) Warm water Species

Water quality standards must be applied in some fashion to all types of waterbodies; however, some waters will naturally have higher temperatures than what would support healthy populations of salmonids. A natural warm water fish community in Washington would be characterized by the presence of redside shiner; tui chub; margined, mottled, or piute sculpin; longnose or speckled dace, sucker, and northern pikeminnow. These fish are known to exist in some of Washington's warmest waters, where they often out-compete introduced populations of rainbow trout.

Insufficient research information exists on these species to allow a similar analysis as was provided previously for the state's cold water species. The following conclusions of authors who have studied the thermal habitat and tolerances of Washington's indigenous warm water species are provided to support establishing appropriately protective criteria:

Redside Shiner (*Richardsonius balteatus*)

Found in streams and lakes throughout Washington, redside shiners are found in ponds, lakes and irrigation ditches with summer water temperatures of about 12.8 to 20°C. However, they have been found at water temperatures as cold as 6.7°C and as high as 23.9°C. The fish move about in schools and tend to stay in vegetation when in shallow areas. They move to near-shore areas in the spring and remain there until July, when they move to the deep water zone; by August, when the surface waters become warmer they descend into deeper water. During September and October some movement from deep to shallow water occurs as the near-shore temperatures decrease. Between October and May the shiner probably stay in deep water. Spawning takes place in the spring and early summer (April - July). Movement to the inlet and outlet streams in British Columbia occurs when the temperatures first exceed 10°C. Spawning occurs at night over the gravel bottom of streams or in vegetation along the lake shoreline (Wydoski and Whitney, 1979).

Reeves et al. (1987) used laboratory streams to determine that the production of redside shiner increased by 30% when moved from a temperature regime of 12-15°C to one fluctuating between 19-22°C. Black (1953) measured the upper lethal temperature values for fish captured from lakes in southern Okanogan Valley of British Columbia. The upper temperature (°C) at which 50% of the fish died in 24 hours was estimated for redside Shiner (*Richardsonius balteatus*) as 25°C (9-11°C), 27.6°C (14°C) (with the approximate acclimation temperature being given in brackets).

Chiselmouth (*Acrocheilus alutaceus*)

In Washington this species is found in the upper Columbia River (east of the Cascade Mountains) and its tributaries. It inhabits both streams and lakes. It prefers the warmer areas of streams in moderately fast to fast water. Although chiselmouth are also found in lakes, they migrate into tributary streams to spawn. Spawning occurs in late June and early July in British Columbia when water temperatures exceed 17°C. This species may serve as a major link in the food chain from the primary production of plants to piscivorous fish (Wydoski and Whitney, 1979).

Longnose Dace (*Rhinichthys cataractae*)

Found throughout Washington, this dace inhabits the swift-running water of streams. it prefers summer temperatures of 12.8-21.1°C. Spawning occurs in the late spring or early summer (June and early July) on gravel bottoms of shallow riffles when the water temperature reaches 11.7°C. Fry hatch in 7-10 days at about 15.6°C (Wydoski and Whitney, 1979). Stauffer et al. (1976) studied the distribution of longnose dace (*Rhinicthys cataractae*). They found 14 specimens at water temperatures of 20.6-26.7°C one year, and 32 specimens at 19.4-30°C the following year.

Northern Pikeminnow (*Ptychocheilus oregonensis*)

In Washington it is found in the Columbia River system and coastal and Puget Sound drainages. Northern pikeminnow inhabit lakes and areas of slow to moderate currents in streams. They prefer the highest temperatures (20-22.8°C) that occur in Lake Washington. Spawning occurs from late May through July, with a peak in Washington of early July. The eggs hatch in 7 days at 18.3°C and the young become free swimming in 14 days (Wydoski and Whitney, 1979). Bell (1986) in a review on the temperature requirements of fish stated that the range for northern pikeminnow was from 16.1-24.4°C. The hatching temperature is around 18.3°C. Black (1953) measured the upper lethal temperature values for fish captured from lakes in southern Okanogan Valley of British Columbia. The upper temperature at which 50% of the fish died in 24 hours was estimated as 29.3°C (with the approximate acclimation temperature being 19-22°C). Based on field observations, northern pikeminnow have also been reported to prefer temperatures of about 16-22ºC (Dimick and Merryfield 1945; as cited in Vigg and Burley, 1991).

Tui Chub (*Gila bicolor*)

In Washington this species is found primarily in the central part of the state, east of the Columbia River. Tui chub migrate to shallow water in spring, but stay in the deeper water during the winter. Tui chub first spawn in their third year of life. Spawning occurs in May and June (when water temperatures are between 12.8-15.6°C) in areas with many aquatic plants. The eggs hatch in about 2 weeks; the larvae are well developed at hatching and the yolk sac has already been absorbed. Tui chub often overpopulate and compete with trout (Wydoski and Whitney, 1979).

Peamouth (*Mylocheilus caurinus*)

Peamouth occur in much of the Columbia River system and are also found in the Coastal and Puget Sound provinces. It is tolerant of salt water. In Lake Washington, young peamouth inhabit very shallow water in spring, summer, and fall; and deep water during the winter. Peamouth in Lake Washington grew fastest when the lake was most eutrophic, but their growth declined after the sewage was completely diverted from the lake. Spawning occurs in late May and early June in streams and along lake shores on a gravel and rubble bottom when water temperatures warm to about 12.2°C. Eggs hatch in 7-8 days at 12.2°C (Wydoski and Whitney, 1979). Black (1953) measured the upper lethal temperature values for fish captured from lakes in southern Okanogan Valley of British Columbia. The upper temperature at which 50% of the fish died in 24 hours was estimated as for Peamouth (*Mylocheilus caurinus*) as 27°C (10°C) and 27.1°C (14°C) (with the approximate acclimation temperature being given in brackets).

Leopard Dace (*Rhinichthys falcatus*)

In Washington it is found in the upper Columbia River and in the Similkameen River, which flows into the Okanogan and then into the Columbia. Leopard dace usually inhabit slower and deeper water than that preferred by long-nose dace. Spawning probably occurs in July and August (Wydoski and Whitney, 1979). Black (1953) measured the upper lethal temperature values for fish captured from lakes in southern Okanogan Valley of British Columbia. The upper temperature (°C) at which 50% of the fish died in 24 hours was estimated for leopard dace (Rhinichthys falcatus) as 28.3°C (with the approximate acclimation temperature being 14°C).

Speckled Dace (Rhinichthys osculus)

It is common throughout Washington. This species inhabits the colder waters of streams with currents ranging from slow to swift, and sometimes is found in lakes. Spawning occurs from June through August, peaking in late June. Eggs hatch in 6 days at 17.8 to 18.9°C (Wydoski and Whitney, 1979). Li et al. (1993) studied stream enhancement works in the John Day Basin of Oregon. The authors noted that speckled dace continued to feed when temperatures reached as high as 33°C. Baltz, Moyle, and Knight (1982) studied the distribution of riffle sculpin (Cottus gulosus) and speckled dace (Rhinichthys osculus) in a California creek. While both species occupied the same physical habitat types in the stream, riffle sculpin were confined to the upper reaches of the creek. In testing the swimming performance, metabolic rates, and competitive interactions between these two species they concluded that competitive interactions between dace and sculpin for preferred microhabitat were mediated by temperature with sculpin showing dominance in the cooler water and dace showing dominance in warmer water. The highest daily maximum temperatures in the upper portion of the creek was 29°C (though the data would suggest that daily maximum temperatures are more commonly below 24-26°C) and in the lower portion of the creek reached 32°C (temperatures approaching 32°C appears to be common in the lower portion of the stream). In studying prey selection the authors found that high proportion of the dace had empty stomachs. The swimming performance of dace increased significantly with temperature, but performances at 15 and 20°C were not significantly different thus poor swimming performance at cooler summer temperatures probably was not a factor contributing to dace displacement in upstream riffles.

Largescale Sucker (*Catostomus macrocheilus*)

Found throughout Washington in both lakes and streams. Spawning occurs during April or May (Wydoski and Whitney, 1979). Black (1953) measured the upper lethal temperature values for fish captured from lakes in southern Okanogan Valley of British Columbia. The upper temperature at which 50% of the fish died in 24 hours was estimated for large scale sucker (*Catostomus macrocheilus*) as 29.4°C (with the approximate acclimation temperature being 19°C).

Piute Sculpin (*Cottus beldingi*)

In Washington this sculpin is found east of the Cascade Mountains, in the Columbia, Yakima, Snake, and Walla Walla rivers and their tributaries. It inhabits streams that have a slight to moderate gradient, and is found in riffle areas among rubble and large gravel. It often frequents water warmer than 15°C and has been found at 25°C. Usually it is found in the lowlands but has been collected as high as 4,000 feet in Oregon. Piute sculpin in Lake Tahoe spawn in May and June at temperatures of about 12.2°C (Wydoski and Whitney, 1979).

Margined Sculpin (*Cottus marginatus*)

In Washington this species is found in the Walla Walla, Touchet, and Tucannon rivers. It has been collected in streams with temperatures of 12.8-18.9°C, but have also been found as high as 23.9°C. In Oregon it is associated with rainbow trout, speckled dace, longnose dace, and the Piute sculpin. It may have a similar life history as the reticulate sculpin (Wydoski and Whitney, 1979).

Summary on Temperature Requirements of Indigenous Warm Water Species:

Insufficient information exists to develop individual water quality thresholds for each of these native warmwater species, so it is recommended that they be considered broadly as a community. The lack of available experiential data for which to base sound recommendations on combined with the conflicts that are presented in what is available, strongly suggest that these recommendations may need to be revisited periodically to determine if changes are warranted. Establishing criteria to protect our temperature tolerant non-salmonid fish species will also provide protection for desirable introduced warm water sport fish species such as bass and crappie. In general, Washington’s indigenous warm water fish communities thrive in waters that have summer maximum temperatures as high as 25-27°C, although most seem to prefer waters below 18-20°C.

Warm Water Habitat Recommendation: It is recommended that in waters supporting communities of indigenous warm water fish, the highest moving 7-day average of the daily maximum temperatures should not exceed 20°C.

To avoid conflicts with the thermal requirements of cold water fish, it should probably be explicitly specified in the regulation that: *"The Warm Water Aquatic Life category may only be applied to waters that do not have self-reproducing populations of, or serve as migration corridors for, indigenous salmonids or char. It is appropriate only where the dominant species under natural conditions would be temperature tolerant indigenous non-salmonid species such as dace, redside shiner, chiselmouth, sucker, and northern pikeminnow; and which may also be serving as habitat for introduced warm water tolerant sport-fish species such as bass and crappie."*

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Part III

Ambient Temperatures of Washington's Streams and Rivers

<u>and</u>

Proposal for Protecting the Spawning and Early Tributary Rearing of Char

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Ambient Temperatures of Washington's Streams

Introduction

As described in Part two of this document, salmonids require colder temperatures during spawning and incubation than during rearing. Spawning and incubation usually occur in the fall, winter, and spring. One of the main decisions when establishing temperature criteria is whether to apply two criteria (one during rearing and a colder one during spawning/incubation) or only one criterion that is more reflective of rearing and relies on natural seasonal cooling to protect spawning and incubation.

In other words, can a single criterion be developed that will protect rearing and spawning/incubation? This section describes the physical characteristics of streams in Washington in order to help make that decision.

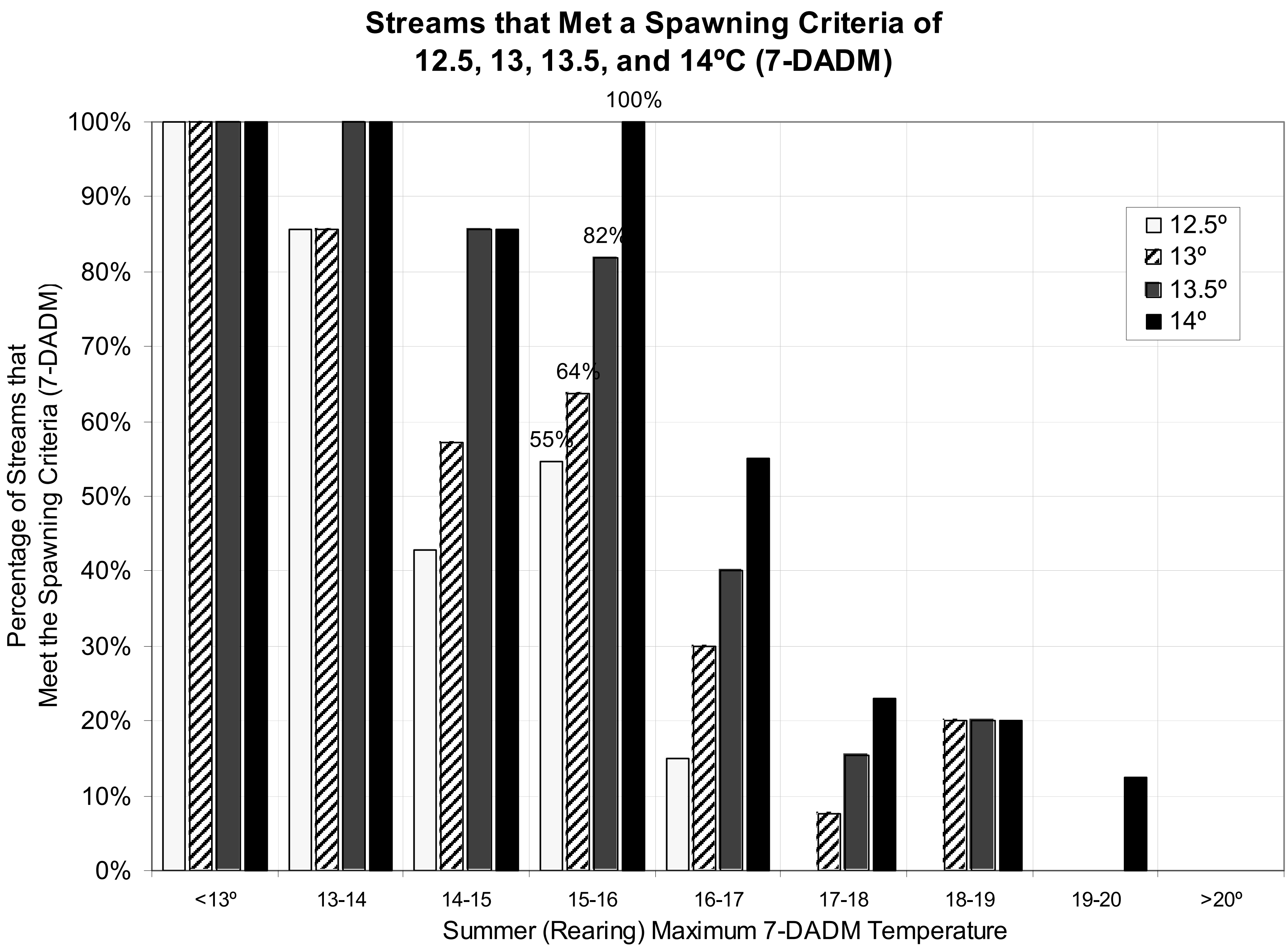
Comparison of Summer Rearing Temperatures and Spawning/Incubation Temperatures

The crux of whether or not to apply separate spawning/incubation criteria is a comparison of summer rearing temperatures and the spawning/incubation temperatures. Before a single rearing criterion can be used, the question must be asked "Will a single rearing criterion protect spawning and incubation when it occurs?"

In order to answer this question, Ecology gathered continuous temperature data from a variety of sources. Ecology obtained data from 126 sites over various years (a large percentage of the data was from 2000 and 2001). The data came from a variety of sources (Ecology, WDFW, USFS, and USGS) and a variety of streams from across the state. Given the relatively small sample size, Ecology made no attempt to make the data representative with respect to the year the monitoring occurred, elevation, geography, stream temperature, stream size, stream type, or any other factor. Although the sites do not proportionately represent water bodies in Washington, they do provide a broad sample of water body types.

Ecology used the WDFW Salmonid Stock Inventory (SaSI) to determine when spawning occurred. Sites with no temperature data during the spawning/incubation period were excluded.

The following chart shows how streams with different summer maximum 7-DADMax temperatures cooled down by the time spawning began. The multiple lines of evidence approach (described in Part 2 of this document) showed that the water temperature at spawning should be less than 12.5-14ºC (7-DADM). During non-spawning and non-incubating times, the temperature should be less than 16-17.5ºC (7-DADM). These temperatures fully protect salmonids.


Streams that Met a Spawning Criteria of
12.5, 13, 13.5, and 14ºC (7-DADM)
Percentage of Streams that
Meet the Spawning Criteria (7-DADM)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
100%
82%
64%
55%
12.5º
13º
13.5º
14º
<13º
13-14
14-15
15-16
16-17
17-18
18-19
19-20
>20º
Summary (Rearing) Maximum 7-DADM Temperature

Summer (Rearing) Maximum Temperature Ranges (7-DADMax in ºC)	Number of Sites with Data
<13º	12
13-14º	7
14-15º	7
15-16º	11
16-17º	20
17-18º	13
18-19º	5
19-20º	8
>20º	23

Looking at the streams with a summer 7-DADMax of 15-16ºC, one can see that 55% of those streams were 12.5ºC (7-DADMax) or less by the time spawning occurred, 64% were 13ºC or less, 82% were 13.5ºC or less, and all of the streams were 14ºC or less. As the summer temperatures decreased, a higher percentage of streams reach temperatures of 12.5-14ºC (7-DADMax) during spawning. As the summer temperatures increased, a lower percentage of streams reached temperatures of 12.5-14ºC (7-DADMax) during spawning.

For streams with a summer 7-DADMax of 16-17ºC, one can see that only 15% of those streams were 12.5ºC (7-DADMax) or less by the time spawning occurred, 30% were 13ºC or less, 40% were 13.5ºC or less, and 55% were 14ºC or less.

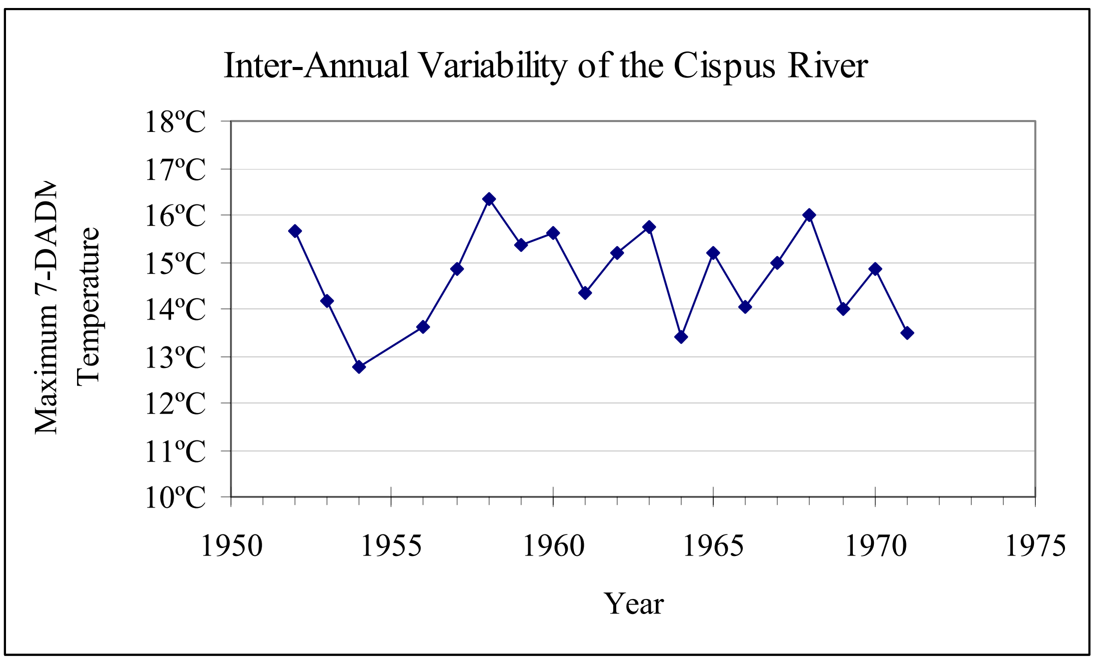
These data show that a single criterion of 16ºC 7-DADMax would have protected spawning in many, but not all streams. Before drawing conclusions about the protectiveness of a single criterion, two additional factors should be taken into account. These factors are inter-annual variability (how the maximum temperature of a water body varies from year to year) and spatial variability (how the temperature of a water body varies as it flows downstream).

Inter-Annual Variability

Most of the data just described was from one or just a few years. An important issue to address when setting temperature criteria is how maximum river temperatures fluctuate from year to year, also known as inter-annual variability. Unfortunately, there is very little continuous temperature data over a long period of time (i.e. ten or more years). It is not known how much of the inter-annual variability in the historic record is due to natural conditions (i.e. climate and rainfall) and how much is due to human activity (i.e. canopy shade reduction).

To illustrate inter-annual variability, consider the Cispus River. The USGS had a monitoring station on the Cispus River near Randle, Washington from 1952-1971. The Cispus River is in Lewis and Skamania Counties and is a tributary of the Cowlitz River. Other rivers have similar, but not identical, inter annual variability. A lack of data, especially on the east side, makes a more robust, statistical look at inter-annual variability impossible. The following table and chart show how the maximum 7-DADMax river temperature varied from year to year in the Cispus River:

Year	Maximum 7-DADMax Temperature (ºC)	Year	Maximum 7-DADMax Temperature (ºC)
1952	15.6	1963	15.7
1953	14.2	1964	13.4
1954	12.8	1965	15.2
1955	incomplete	1966	14.0
1956	13.6	1967	15.0
1957	14.8	1968	16.0
1958	16.4	1969	14.0
1959	15.3	1970	14.9
1960	15.6	1971	13.5
1961	14.4	1972	incomplete
1962	15.2		



While during the hottest years the Cispus River reached 16ºC, during the colder years the river typically stayed below 13-14ºC.

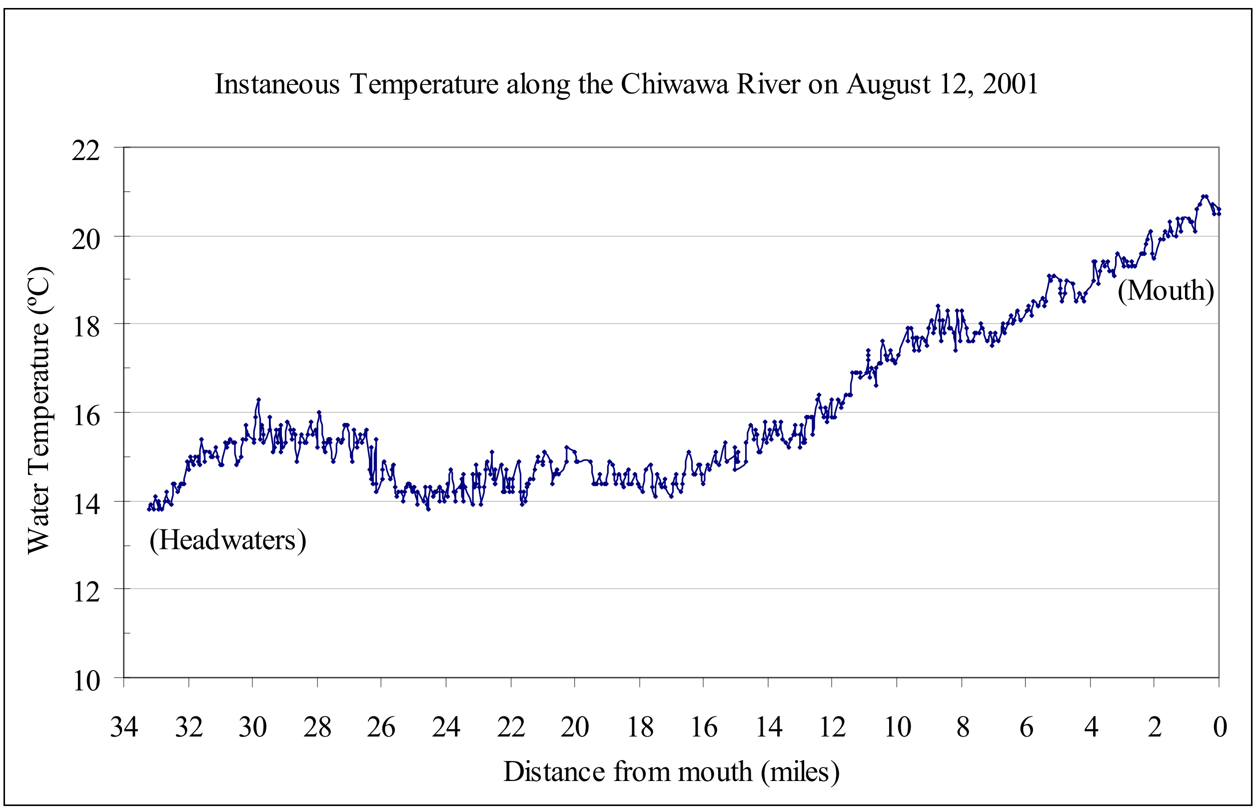
When deciding if a one criterion standard is protective enough, it is important to keep inter-annual variability in mind. While a water body might have a low probability of protecting spawning/incubation during warm years, during colder years it would be have a much higher probability of protecting spawning/incubation.

Spatial Variability

In general, streams warm as they flow downstream. The temperature criteria apply throughout the entire length of the stream, including the furthest downstream point. This means that in order to meet the temperature criteria at the furthest downstream point, upstream areas will have to be cooler than the criterion. How much a stream changes temperature as it flows downstream – spatial variability – is quite different for each water body and depends on the characteristics of the individual water body.

To illustrate spatial variability, consider the Chiwawa River, a tributary of the Wenatchee River in Chelan County. On August 12, 2001, the temperature along the Chiwawa River was measured. The temperatures were instantaneous measurements, not 7-DADMax, so they should not be compared with the proposed criteria. However, they are still useful for illustrating the effects of spatial variability. Other rivers have different spatial variability, but the Chiwawa River can be used as an example. A lack of data makes a more robust, statistical look at spatial variability impossible.

The following chart shows the river temperature generally increasing as the river flows downstream from the headwaters to the mouth.



As the chart shows, the river stayed between 14ºC and 16ºC for many miles. Over the last about 17 miles, the river warmed steadily. While some of this warming is probably due to human influences, some of it is also naturally occurring. As this example shows, in order for the entire river to meet a criterion, most of the river would be cooler than the criterion.

When deciding if a one criterion standard is protective enough, it is important to keep spatial variability in mind. While a water body might have a low probability of protecting spawning/incubation at the lowest downstream point, it would have a higher probability of protecting spawning/incubation further upstream.

Proposal for Protecting the Spawning and Early Tributary Rearing of Char

Introduction

The existing water quality standards do not have temperature criteria that fully protect char. This document describes the proposal to designate certain waters as char habitat for the purpose of applying a fully protective temperature criterion.

The goal is to fully protect the spawning and early juvenile rearing of char. Ecology investigated three methods of identifying waters used by char:

1. **Known spawning and early juvenile rearing streams.** Unfortunately, there is no comprehensive survey of known spawning and early juvenile rearing areas and finding spawning and rearing areas used by these reclusive fish has proved to be very difficult. There are entire populations of char where the spawning areas are completely unknown. Even in areas of extensive study, not all the spawning and early juvenile rearing areas have been identified. Using this method to identify streams for protecting spawning and early juvenile rearing of char would likely result in many streams with char populations not being protected in the water quality standards until they were identified.
2. **Entire watersheds where char are present**. Every water body in the entire watershed that is accessible to char would be protected, regardless of its likelihood of being a spawning or early tributary rearing water body. Even lower main stem rivers with their very warm temperatures and low likelihood of providing suitable habitat would have to meet very stringent temperature requirements.
3. **All stream segments in watersheds used by char that have the basic physical characteristics of known char spawning and early tributary rearing streams.** This option avoids applying the temperature criteria to streams that would not likely be used by char, but also does not depend on actually proving in advance that char are using each of the qualifying streams. The physical characteristics that were found to best define char spawning and early tributary rearing waters are addressed below.

Data

The Washington Department of Fish and Wildlife (WDFW) has compiled information on bull trout habitat. They recently released a database that identifies known spawning areas. This data set combines the knowledge from biologists working for WDFW, USFWS, Tribes, and others. The data are current as of November, 2001. There are no databases of known early tributary rearing areas. However, based on what is known of the biology of char, they would most typically be in the same general locations as the known spawning areas. It is important to note that where site knowledge demonstrates that this early tributary rearing occurs at locations away from the spawning grounds, then the proposed methodology will allow these areas to be protected in future rulemakings.

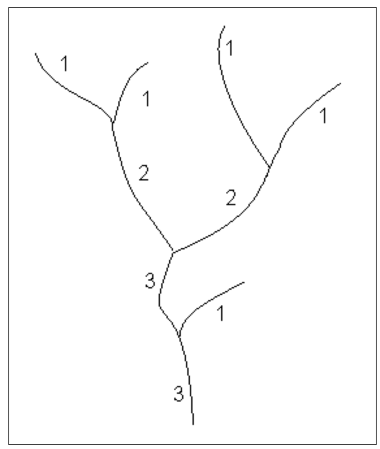
This database (often referred to as the "bullchar" database) forms the foundation of Ecology's proposal for protecting char.

Development of a Filter

Ecology studied the locations of known spawning areas documented in the "bullchar" database and found that their occurrence is largely restricted to a relatively narrow range of elevation and stream order. Ecology used this pattern of elevation and stream order to deduce which streams would reasonably be expected to be potential char habitat.

<u>Stream Order</u>

The stream order concept (Strahler, 1952) is a method of classifying streams. Headwater streams are assigned a stream order of 1. When two 1st order streams join, they form a 2nd order stream. When two 2nd order streams join, they form a 3rd order stream, and so on. When a lower order stream joins and higher order stream (for example, a 1st order stream joins a 3rd order stream), the stream order does not change.[1]



Ecology found that most known spawning areas were in 1st, 2nd, and 3rd order streams. Limited spawning occurred in 4th order streams. The following table shows the stream orders of the known spawning streams:

Stream Order	Known Spawning Streams:		
	East Side	West Side	Combined
1	18%	24%	21%
2	36%	36%	36%
3	35%	35%	35%
4	10%	5%	8%
5	1%	0%	0%

As the table shows, there is little difference between east side streams and west side streams. Approximately 92% of all known spawning occurs in 1st, 2nd, and 3rd order streams, so

[1] The original stream order system assigns the upper-most perennial streams to a stream order of 1. However, the WDFW bull trout data, and other commonly used data, are at a scale where not all perennial streams are identified. These data are from the Washington Hydrography Framework Layer, and are at the 1:100,000 scale. Given this limitation, the upper-most streams identified in the data is assigned a stream order of 1.

Ecology focused its efforts on those streams when developing the system for identifying char waters.

Elevation

An analysis of all the spawning data quickly shows that known spawning areas are concentrated in higher elevation streams. For each known spawning stream, the lowest elevation was calculated.[2] The following table provides summary information of known spawning streams and their elevations:

Elevations (in feet) of Known Spawning Streams	East Side	West Side
Number of Streams	77	67
Average Elevation	3136	1395
Maximum Elevation	4650	3320
Minimum Elevation	1419	420
Lower 95th Percentile	1889	676

This analysis found that 94% of the known spawning areas were above 2000 feet on the east side and above 700 feet on the west side. Thus this elevation filter captures most of the known spawning streams.

System for Identifying Char Waters

Using the information about the stream order and elevation of known spawning streams, Ecology developed the following proposed system for determining which water bodies should be protected for char. This system is used in all of the watersheds with known spawning areas or with suspected spawning populations identified by the USFW 1999 "Washington Distinct Population Segment – Bull Trout Subpopulation" map.

1. **All known char spawning streams will be protected**

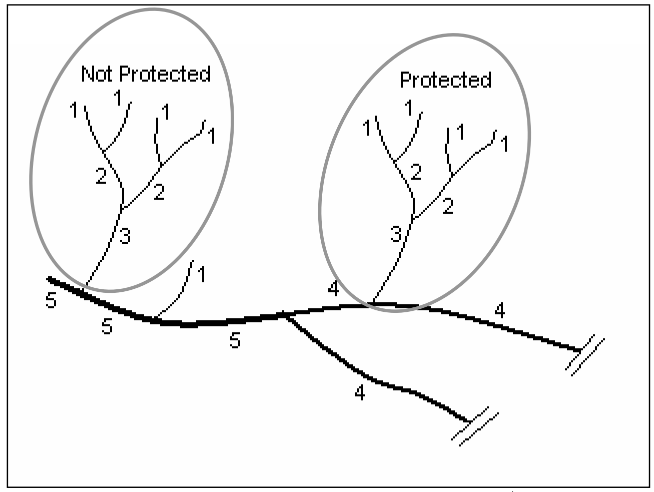
   The "known char spawning streams" are those streams identified by WDFW in either the "bullchar" database or in WDFW's 1998 Salmonid Stock Inventory (SaSI). If other streams are identified as known spawning streams during this rule-making process, they will also be included.

2. **All streams upstream of known char spawning streams will be protected**

   These are the streams upstream of those locations identified in (1) above.

[2] Throughout this analysis, the lowest elevation of the stream or stream segment was used. Both the known spawning streams and the application of the elevation filter used the lowest elevation to maintain consistency and reduce any bias.

3. **All 3rd order streams and their tributaries will be protected <u>if</u> they join a 4th order stream**



As discussed earlier, bull trout spawning areas are concentrated in 1st-3rd order streams. This part of the system includes certain 3rd order streams and their tributaries (i.e. the 1st and 2nd order streams). It does not include the lower elevation 3rd order streams that join a 5th or higher order river. The known spawning areas generally did not include these lower elevation 3rd order streams, so they were not included in the filter.

Some 1st and 2nd order streams are not protected by this filter. These include 1st and 2nd order streams that directly flow into a 4th or higher order streams, except at outlined below in (4). The known spawning areas generally did not include these 1st and 2nd order streams that flow into 4th or higher order streams, so they were not included in the filter.

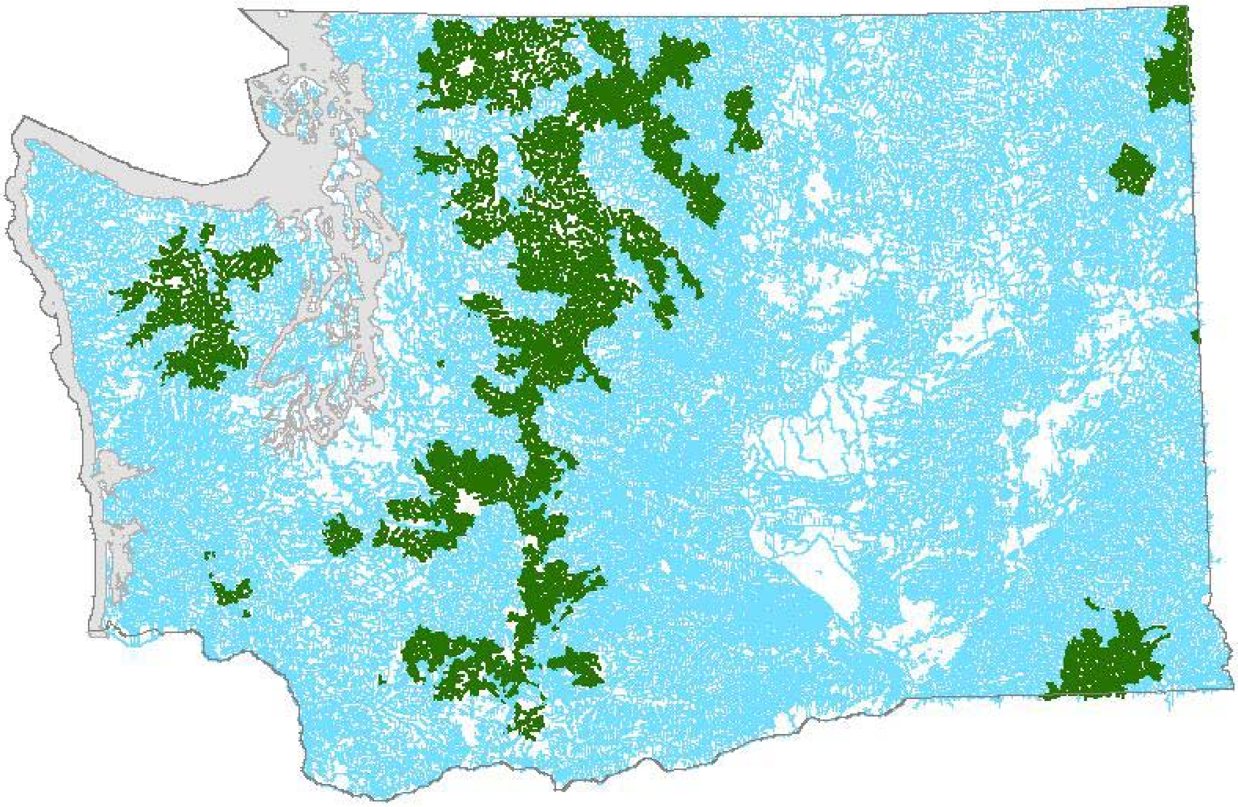
4. **All 2nd order streams and their tributaries will be protected <u>if</u> they join a 4th order stream <u>and</u> they are above a stream protected by sections (1), (2), or (3).** This part of the filter captures the higher elevation 2nd and 1st order streams that are used for char spawning.

Elevation Exception: The default system described in (3) and (4) above is not applied to streams below 2000 feet on the east side of the Cascades or below 700 feet on the west side of the Cascades.

Known spawning locations and all streams upstream of known spawning locations will be protected regardless of their elevation. (In other words, elevation can prevent a stream from being covered under (3) and (4), but not under (1) or (2)). This part of the system reflects the fact that about 94% of known spawning streams are above 2000 feet on the east side and 700 feet on the west side.

Protected Streams

Ecology's proposal to apply the proposed system to designate char waters results in the protection of the dark green streams in the following map.



For more detailed maps, please visit Ecology's website at www.ecy.wa.gov/programs/wq/swqs/bull_trout. Copies of the GIS map files that are viewable for users with ArcView are available upon request from Ecology.

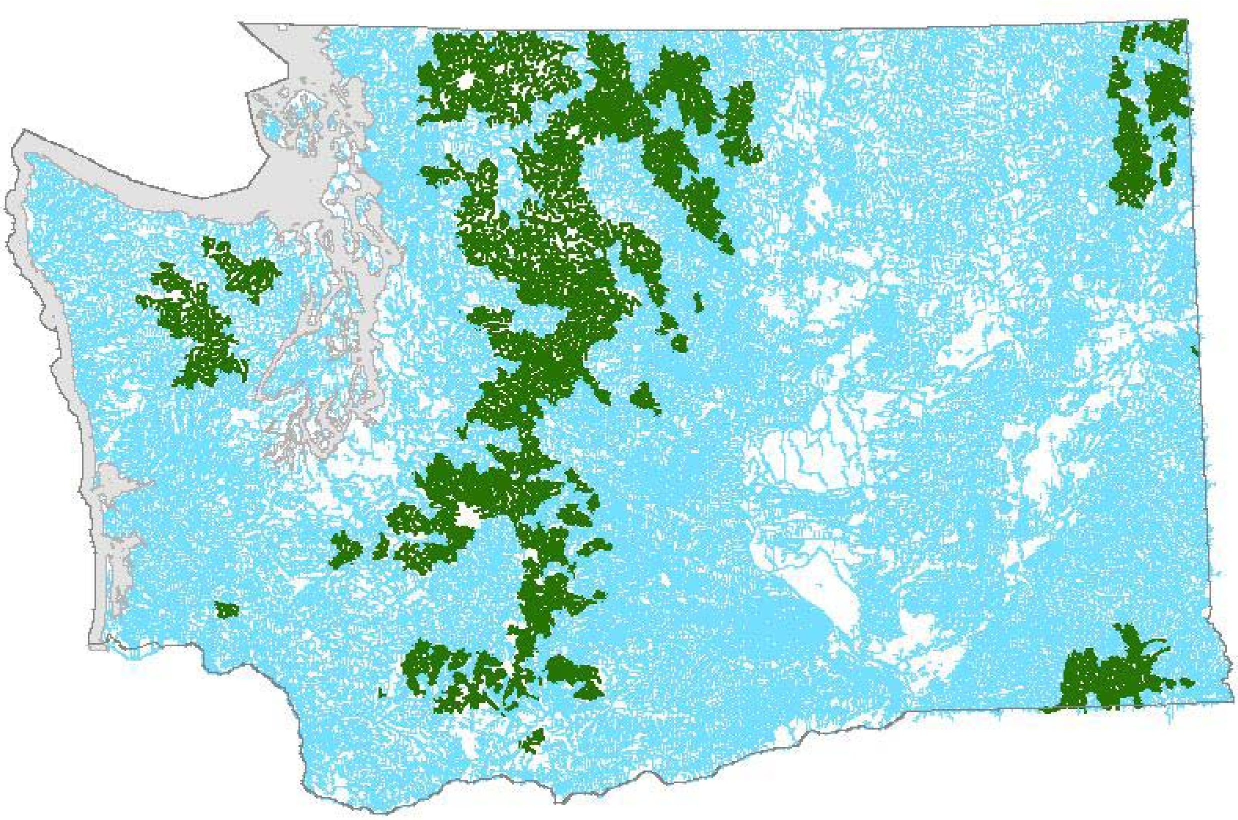
Alternative Proposal for Protecting Char

An alternative proposal for protecting char is also being considered. Using the same information about the stream order and elevation of known spawning streams, the alternative proposal would protect char according to the following system:

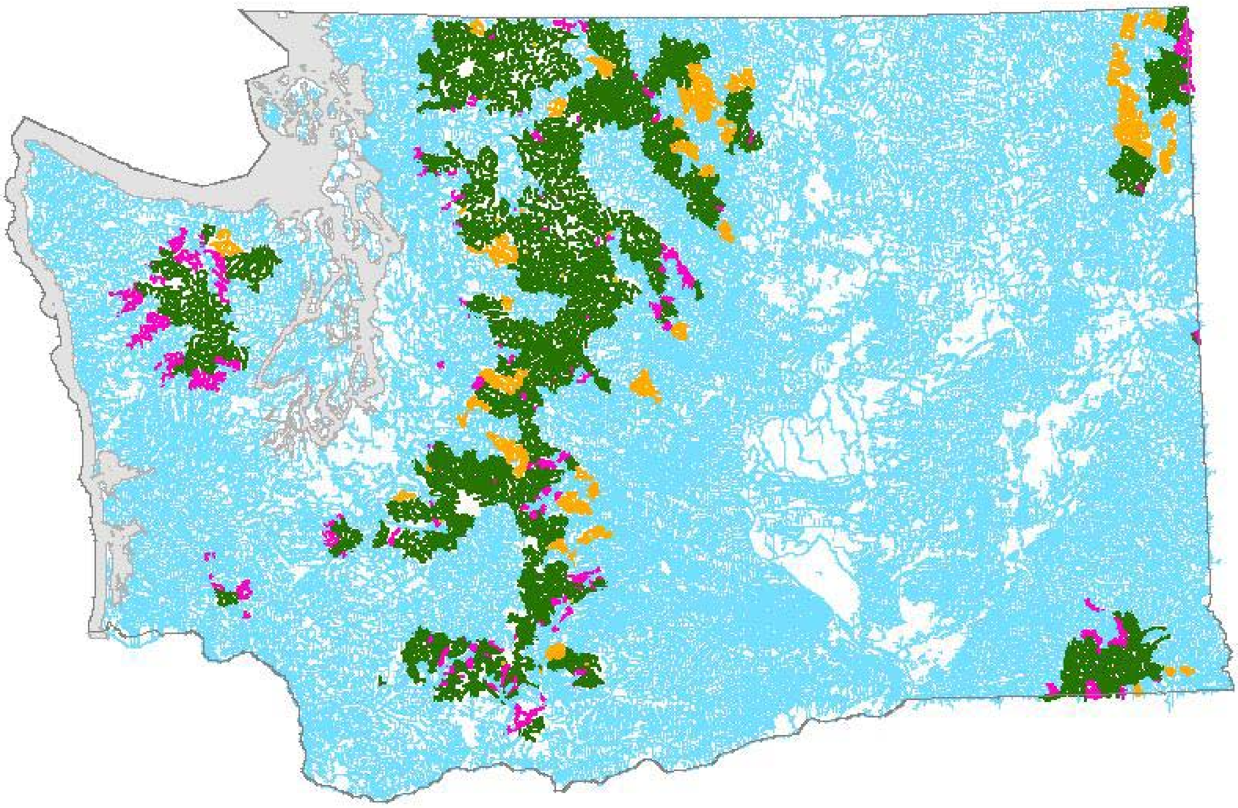
1. All known char spawning streams will be protected
2. All streams upstream of known char spawning streams will be protected
3. All 3rd order streams and their tributaries will be protected IF the 3rd order stream is above 700 feet elevation (west side of the Cascades) or 2000 feet elevation (east side of the cascades). If only part of the 3rd order stream is above the specified elevation, only that part of the stream (and all its tributaries) will be protected.

This system, while similar to Ecology's proposal detailed above, results in more streams being protected for char.

The following map shows the streams that would be protected by this alternative. The protected streams are in dark green.



The following map compares the water bodies protected by Ecology's primary proposal and the water bodies protected by the alternative proposal. The streams that would be protected by both proposals are in dark green, the streams protect only by Ecology's primary proposal are in pink, and the streams protected only by the alternative proposal are in gold.



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