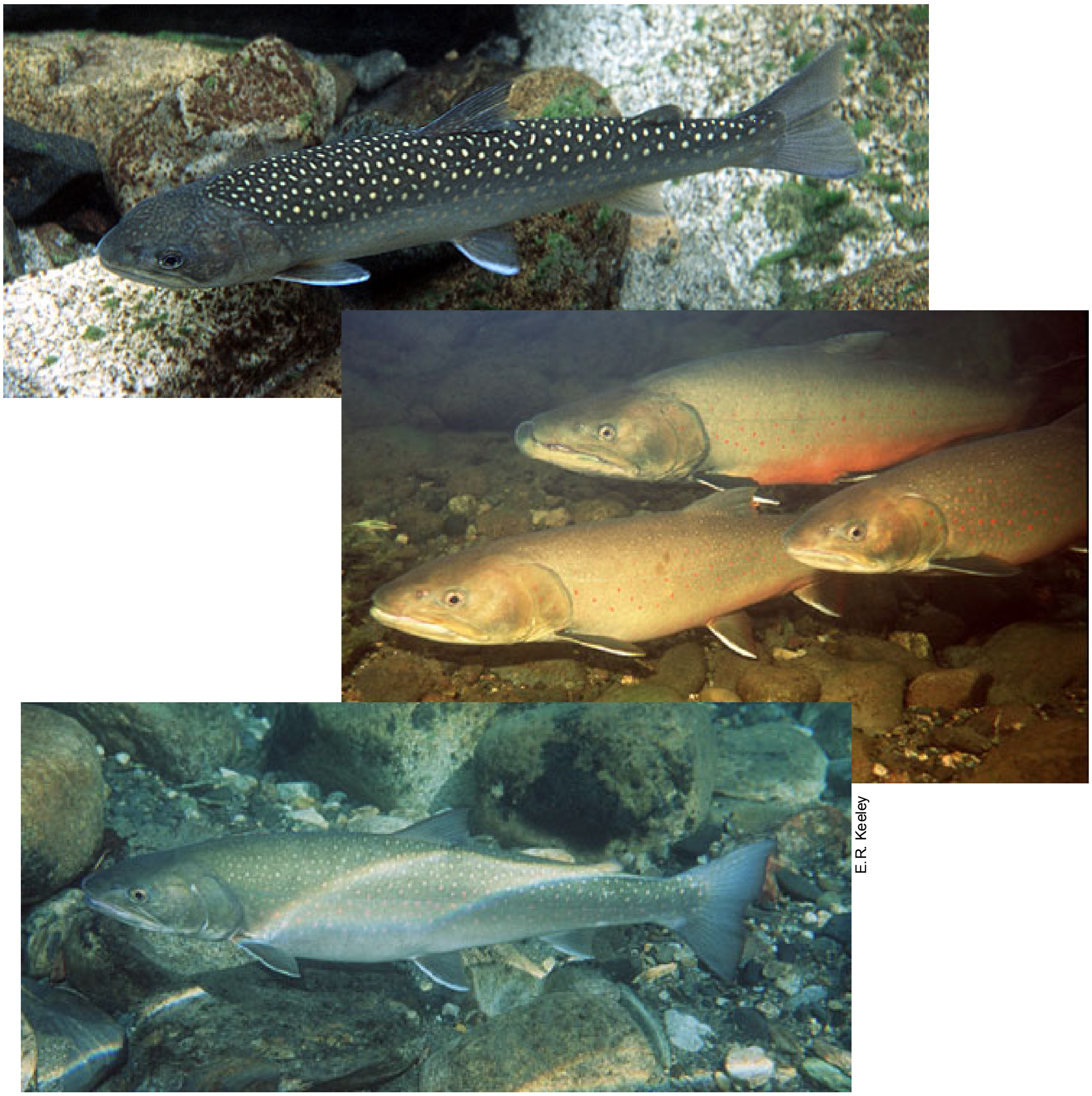
# Update of Bull Trout Temperature Requirements




*Idaho Department of Environmental Quality*

FINAL REPORT April 30, 2003

Bull trout photos used courtesy of Ernest R. Keeley, Idaho State University, Pocatello

# Update of Bull Trout Temperature Requirements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# INTRODUCTION

In 1998, the Idaho Division of Environmental Quality (IDEQ) responded to the U.S. Environmental Protection Agency (EPA) bull trout temperature rule. The IDEQ (Hillman and Essig 1998)[1] argued that the EPA was too conservative when they established a temperature standard of 10°C maximum weekly maximum temperature (MWMT)[2] for maintaining optimal juvenile growth and rearing. Hillman and Essig (1998) reviewed available field studies, presence-absence studies, laboratory studies, and the EPA criteria protocol (methods of Brungs and Jones 1977) and concluded that the optimal temperatures for juvenile bull trout growth and rearing ranged from 12° to 14°C, not 4° to 10°C as proposed by the EPA (Hillman and Essig 1998). This view now appears to more widely accepted, including by EPA in their proposal of a 12°C MWMT criterion for juvenile bull trout rearing in "Draft EPA Region 10 Guidance for Pacific Northwest State and Tribal Temperature Water Quality Standards" (EPA 2002).

In 1999, EPA retained three biologists (K. Pratt, S. Adams, and D. McCullough) to review the arguments and conclusions of Hillman and Essig (1998). These reviewers were asked to respond to eight specific questions regarding the IDEQ report, laboratory studies, and presence-absence studies. The purpose of this report is to use the information provided by reviewers, evaluate other new information, and to explain a revised recommended temperature criteria to protect juvenile bull trout during summer rearing.

It has been over four years since Hillman and Essig (1998) examined the temperature requirements of juvenile bull trout. Therefore, our purpose in this report is to revisit the temperature requirements of juvenile bull trout by examining "new" information (i.e., information made available since the IDEQ report) and evaluate the EPA review comments. It is not our purpose in this report to respond to each criticism offered by the reviewers. Rather, it is our intent to use the insights offered by the reviewers to more fully understand the temperature requirements of juvenile bull trout. We appreciate the fact that the reviewers spent considerable

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[1] When we refer to the IDEQ, we are referring specifically to Hillman and Essig (1998).

time critically thinking about the arguments and conclusions presented in Hillman and Essig (1998).

In this report we first review the relationships among metrics. We then review information on juvenile bull trout temperature requirements. Here we review laboratory studies, field studies, and presence-absence studies. Although we do not repeat information presented in Hillman and Essig (1998), we frequently refer to information in that report. We also draw upon the insights of the EPA reviewers. We conclude this report with what we believe is an appropriate temperature criteria for protecting juvenile bull trout rearing during June, July, and August in Idaho.

## RELATIONSHIPS AMONG TEMPERATURE METRICS

Stream temperatures are commonly characterized in the literature or in regulatory criteria using various summary metrics. The four most commonly used metrics are maximum daily maximum (MDMT), maximum weekly maximum (MWMT), maximum daily average (MDAT), and the maximum weekly average (MWAT); see Hillman and Essig (1998) for definitions of these and other metrics. Because of this, it is useful to describe relationships among these metrics. Information presented by Hillman and Essig (1998), this report, and others demonstrate that:

- The four common temperature metrics are strongly correlated;
- Correlation between different time periods was higher than correlation between maximum and average in the same time period;
- Correlating MDMT to MWAT gave the poorest result, but still explained 70-80% of the variability;
- Just as maximums are always greater than averages, daily values are always greater than weekly values, such that the four metrics at a given site typically order themselves MDMT > MWMT > MDAT > MWAT.

[2] Throughout this report we talk about various temperature metrics without defining them. We assume the reader understands the different temperature metrics. If not, we refer the reader to pages 6-7 in Hillman and Essig (1998).

The IDEQ (Hillman and Essig 1998) examined relationships among various temperature metrics by compiling 225 temperature records from several streams in Montana and Idaho. The temperature data were collected during the summers of 1994 to 1997. Using linear regression, they found that relationships among all combinations of temperature metrics were linear and highly significant. Simple linear regression models explained 80-99% of the variation between independent and dependent temperature metrics (see Table 4 in Hillman and Essig 1998). In addition, daily maximum temperatures were on average 1° to 5°C warmer and more variable than other temperature metrics. The mean difference between MDMT and MDAT and between MWMT and MWAT was about 3°C. On average, there was only about a 1°C difference between MDMT and MWMT, while there was less than a 1°C difference between MDAT and MWAT.

The relation between metrics means that metrics can be interchanged, but their values will be different for any given thermal regime and therefore must be translated to be compared. For example, a stream with a 12°C MDMT is colder than a stream with a MWMT of 12°C, but is about the same as a stream with a MWMT of 11°C.

Adams (1999) critically examined the steps used to summarize the temperature metric data and recalculated the correlation and regression statistics in Hillman and Essig (1998). She found no problems with the analyses or results. In addition, she compiled an independent temperature data set consisting of 65 sites within the Columbia River basin in Idaho and Montana. These sites fell within the range of bull trout. She used the methods of Hillman and Essig (1998) to assess relations among the temperature metrics. She found *"[m]ost regression equations from the two data sets were remarkably similar…, suggesting that the relationships among many of the metrics are fairly consistent in mountainous streams throughout Idaho and western Montana."*

McCullough (1999) criticized the temperature relations because they lacked temporal range and the data were not stratified according to watershed disturbance, stream size, and climatic conditions. Stratification was not the goal of Hillman and Essig (1998) when they analyzed the relations among metrics. Stratification would be useful if one were interested in the un-explained variability among temperature metrics in areas with specific disturbances and climatic conditions. However the residual or un-explained variability in the relations was relatively small, leaving little for stratification to explain. We do expect that the relations among temperature metrics in an undisturbed watershed would be different than in a disturbed watershed, all else being equal. However, it is not easy to stratify landscapes into various degrees of disturbance.

Likewise, we concur that stratification by stream size would likely improve correlations since small headwater streams and larger downstream waters would be expected to have different daily warming and cooling patterns. Stratification by climatic areas would likely reduce noise even more since waters in some climates have larger diurnal changes than others, e.g., high elevation mountain basins in Idaho versus coastal maritime areas. Streams in which logging, roading, fire, etc. removed streamside shade would also likely have greater temperature swings than streams with shade. Removing disturbed streams, especially those without their riparian canopy, would likely have tightened the relations as well. Nonetheless, even with no attempt at stratification, the relations were remarkably strong.

Hillman and Essig (1998) elected to pool all temperature data into one set of analyses. This decreased precision in the relations by including temperature data from different size streams, different ecoregions, and different degrees of disturbance. Even without stratification, the linear models explained 80-99% of the variability among metrics, which we believe is quite good. In general, we see this as a conservative approach if one predicts a warmer metric from a cooler one (e.g., MDMT from MWAT). This is because a less precise relation results in a wider confidence interval (CI) about the regression line. For example, using the information in Hillman and Essig (1998), 95% of the sites with an MWAT of 11°C would have an MWMT not exceeding 15°C (based on 95% prediction intervals calculated in Adams 1999). Thus, regardless of degree of watershed disturbance, one could assume that the MWMT would not exceed 15°C. If one were to stratify the temperature data for undisturbed conditions, one would likely find that the predicted MWMT would not exceed some lower temperature (e.g., 13°C).

We have since added additional temperature data from areas closer to the southern boundary of the bull trout distribution (e.g., Weiser, Boise, and Lost River basins; Figure 1). We used the methods described in Hillman and Essig (1998) to analyze these data. We analyzed the data separately (i.e., assessed relations among metrics for each separate database) and pooled. Unlike the original work by Hillman and Essig (1998), we looked only at relations among MWAT, MWMT, and MDMT, because reviewers focused on these metrics. We assume the data from the southern margin of the bull trout distribution represents warmer water temperatures and greater diurnal changes than those from more northern or coastal areas.

We summarized the results of the regression analyses in Table 1 and Figures 2-4. We found that the relations were quite similar among data sources. Generally, Hillman and Essig (1998) and Adams (1999) regressions were most similar. Regressions for the Little Lost River basin were most different. The intercepts for the Little Lost River basin regressions were 0.2-2.3°C higher than the other regressions (Table 1). This is likely because the Little Lost River basin has a warmer climate than the other sites. Not surprisingly, we found that when we pooled the data sets the “noise” in the relations increased. For example, an MWAT of 11°C could equate to an MWMT and MDMT of 17° and 18°C, respectively (Figures 2 and 3). On the other hand, the relations between MWMT and MDMT were tight (Figure 4). The maximum difference between these two metrics was generally about 2°C.

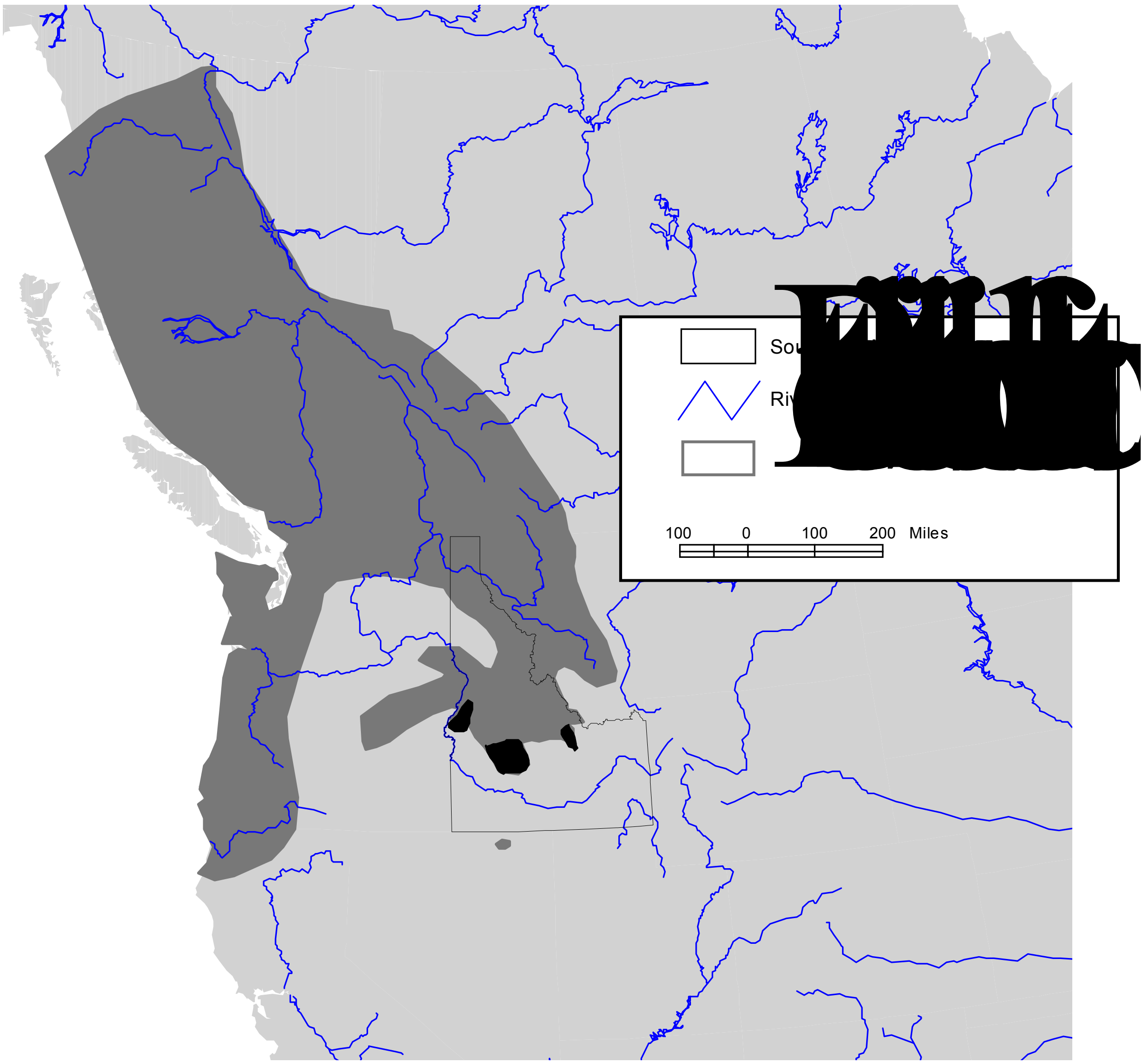



Figure 1. The bull trout streams used in the temperature regressions were from watersheds located near the southern margin of the distribution of bull trout in North America. We are assuming that stream temperatures from warmer areas would be more variable than in the more northerly habitats. Approximate bull trout distributions were drawn from Cavender (1978) and Lee et al. (1997, Figure 4-10).

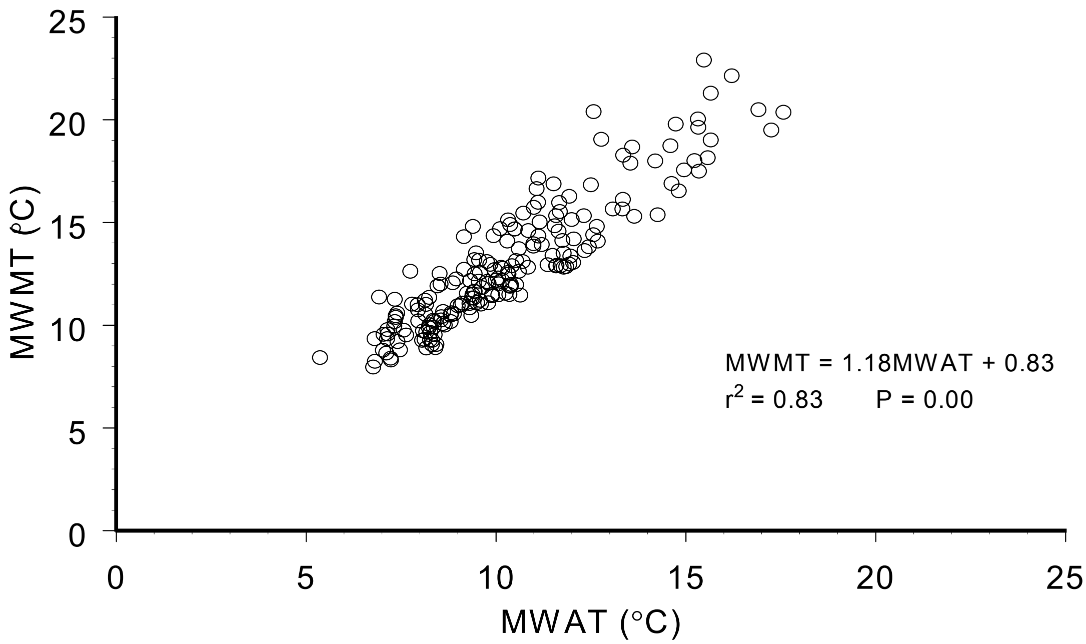



Figure 2. Relationship between MWAT and MWMT using pooled data in Table 1. Simple linear regression results are shown.

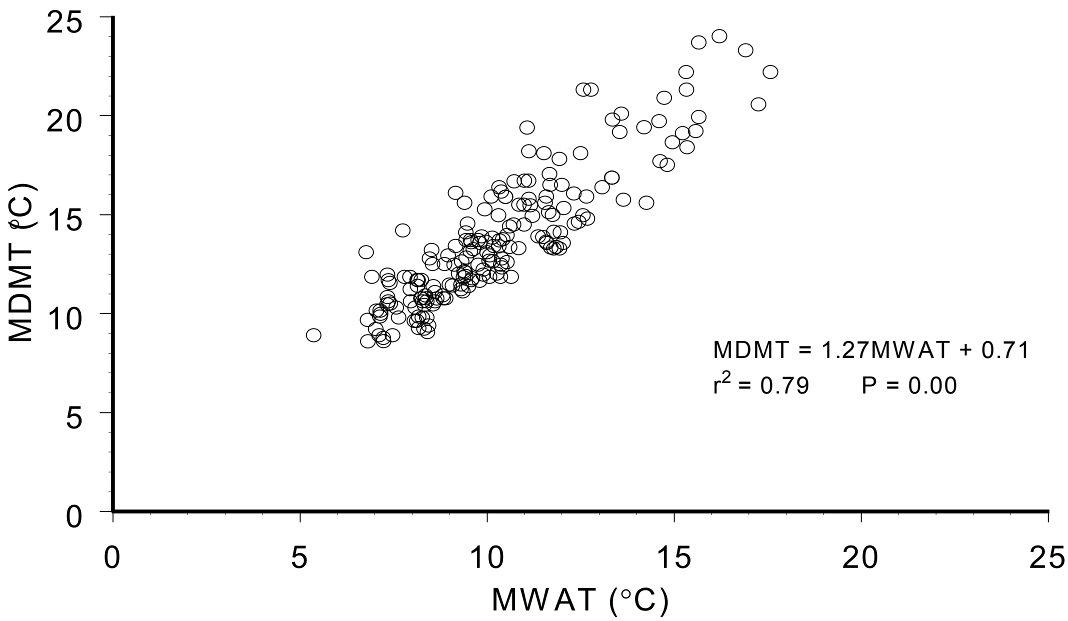



Figure 3. Relationship between MWAT and MDMT using pooled data in Table 1. Simple linear regression results are shown.

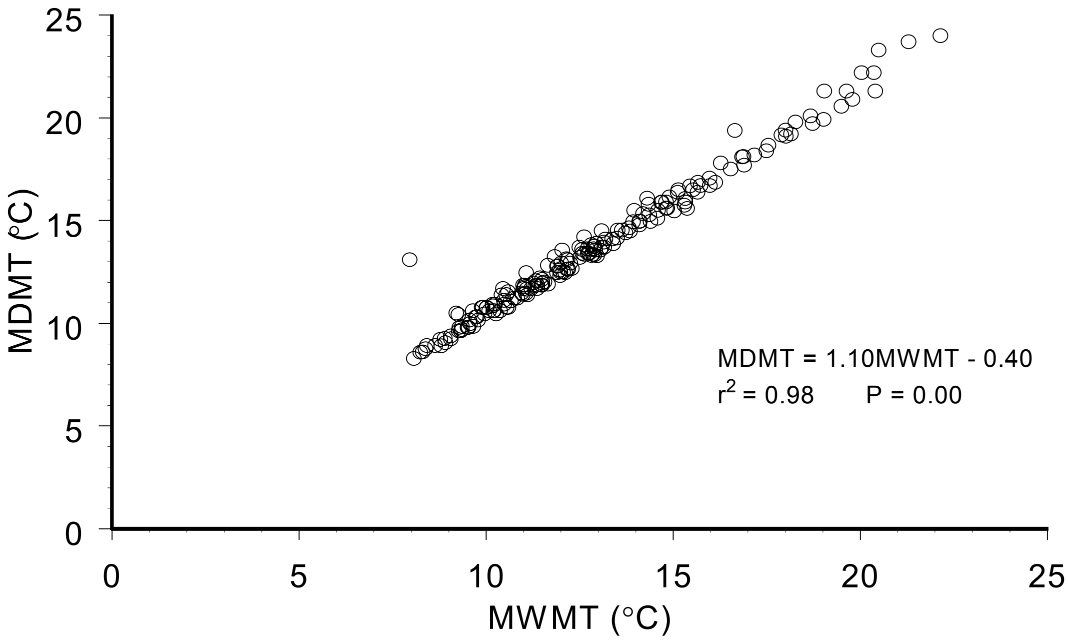



Figure 4. Relationship between MWMT and MDMT using pooled data in Table 1. Simple linear regression results are shown.

Table 1. Comparison of regression equations from Hillman and Essig (1998), Adams (1999), Boise National Forest, and the Little Lost River basin.

| Data source | Regression equation | $r^2$ |
|---|---|---|
| Hillman and Essig (1998) | MWMT = 1.15 MWAT + 0.41 | 0.90 |
| Adams (1999) | MWMT = 1.18 MWAT + 0.55 | 0.90 |
| Boise NF | MWMT = 1.12 MWAT + 1.52 | 0.88 |
| Little Lost River basin | MWMT = 1.09 MWAT + 2.74 | 0.90 |
| All sites pooled | MWMT = 1.18 MWAT + 0.83 | 0.83 |
| | | |
| Hillman and Essig (1998) | MDMT = 1.17 MWAT + 0.95 | 0.84 |
| Adams (1999) | MDMT = 1.18 MWAT + 1.32 | 0.84 |
| Boise NF | MDMT = 1.16 MWAT + 1.85 | 0.84 |
| Little Lost River basin | MDMT = 1.24 MWAT + 2.10 | 0.89 |
| All sites pooled | MDMT = 1.27 MWAT + 0.71 | 0.79 |
| | | |
| Hillman and Essig (1998) | MDMT = 1.04 MWMT + 0.15 | 0.99 |
| Adams (1999) | MDMT = 1.04 MWMT + 0.11 | 0.99 |
| Boise NF | MDMT = 1.06 MWMT - 0.04 | 0.99 |
| Little Lost River basin | MDMT = 1.15 MWMT - 1.12 | 0.99 |
| All sites pooled | MDMT = 1.10 MWMT - 0.40 | 0.98 |

McCullough (1999) criticized the data in Hillman and Essig (1998) as lacking temporal range. His criticism is correct. As noted by Hillman and Essig (1998), temperature data were collected during the summers of 1994 to 1997. If one were to fully understand the effects of climatic variations on water temperatures within a given site, several years, perhaps decades, would be needed. Recent work by Essig (in press) examined the long-term inter-annual variation in water temperature, due to climatic and hydrologic variations. He found inter-annual differences on the order of 3-5°C were quite common (see Figure 5). In the context of regulatory criteria and species thermal preferences this would be quite significant. But what is more germane to the correlation among metrics is Essig's observation that the four common metrics for the most part change in concert from year to year.  That is, they all respond similarly to the inter-annual variations in climatic factors. Thus, while one year may be much warmer than the next, the relations between metrics remain relatively unchanged.

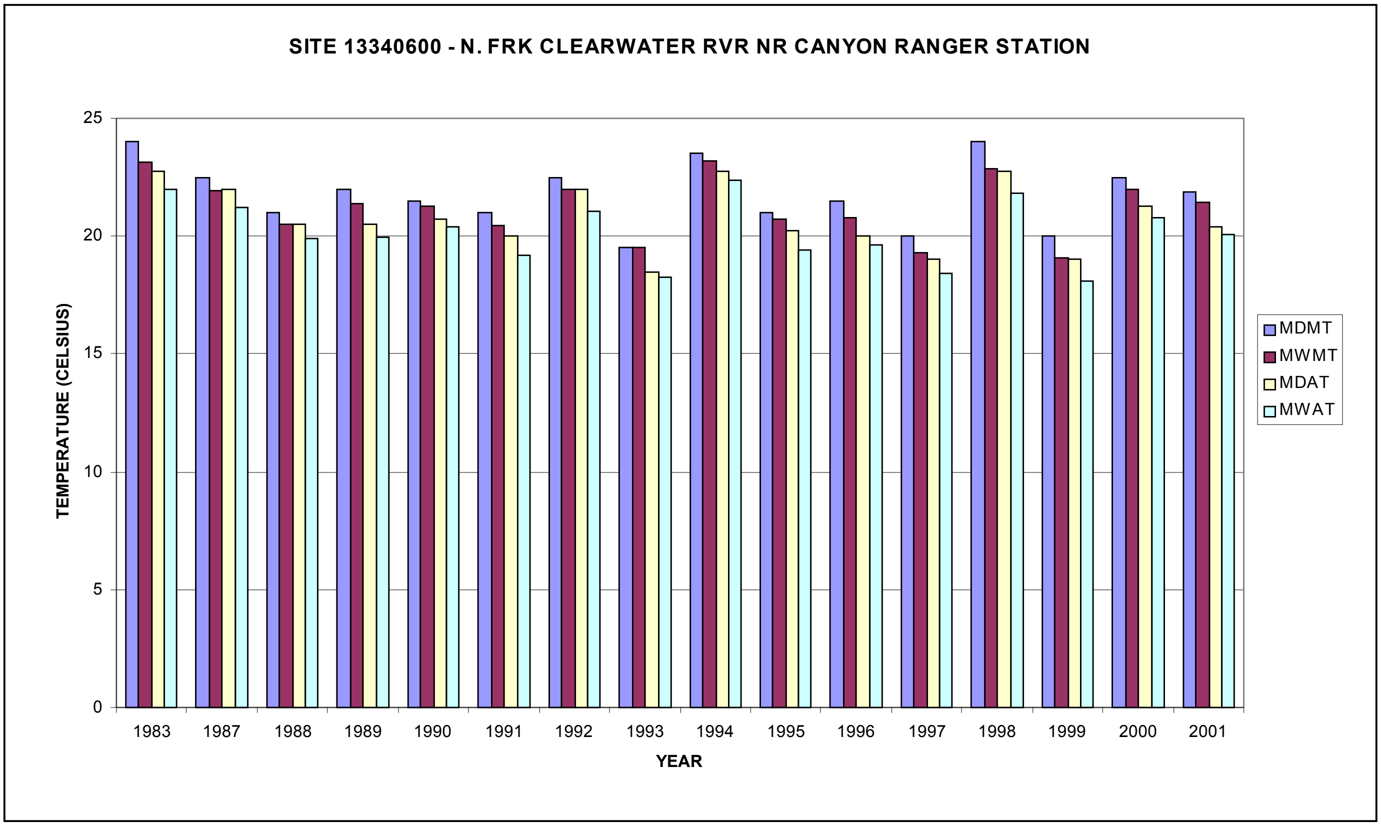



Figure 5.  Example of year-to-year variation in four common temperature metrics at a USGS long term temperature monitoring site on an unregulated river.  Annually metrics often vary by 3-5ºC, but the metrics vary together and in a predictable order.

## TEMPERATURE REQUIREMENTS

In this section we examine the temperature requirements of juvenile bull trout for rearing and growth. We review the results of laboratory studies, field studies, and presence-absence studies. As pointed out by Hillman and Essig (1998) and the EPA reviewers, all studies have weaknesses. In general this is because the researchers designed the studies for purposes other than for describing the temperature requirements of juvenile bull trout, save the laboratory studies. In addition, as a general rule, laboratory studies suffer from challenges to external validity (i.e., it is difficult to generalize laboratory studies to natural environments), and field studies suffer from challenges to internal validity (i.e., rival hypotheses often confound cause-and-effect field studies). Therefore, both laboratory and field studies are needed to better understand the temperature requirements of bull trout (Hillman and Essig 1998; Adams 1999; McCullough 1999; Pratt 1999). And even though one can criticize any given study, the results of the collective studies should converge on a temperature range that best describe the temperature requirements of juvenile bull trout. Our purpose here is to find that range without relying too much on any one study. This is similar to the multiple lines of evidence approach used by Hicks (WDOE 2002) in deriving Washington State's proposed juvenile bull trout criterion of 13° MWMT, and to the expert consensus "Delphi" technique or the weight-of-evidence approaches.

It is important to note that maximizing growth is not by itself the goal of criteria. Growth studies can be informative because we assume that growth is related to fitness, competitiveness, ability to avoid predation, and reproductive success (Weatherley 1972). Survival during cold winters has been directly related to the size achieved before winter in a number of salmonids and nonsalmonids. Growth can be limited by food availability, cohort density, habitat complexity, and stream geomorphology. Even when food is abundant during their first winter, young-of-year fish may be unable to assimilate it. A size-dependent overwinter survival relationship appears especially strong for populations at the northernmost or most upstream portions of their ranges (Connolly and Petersen 2003). Shuter and Post (1990) argued that in cold, temperate climates, equilibrium population abundance is dependent on winter survival of young-of-year fish. Whether young-of-year fish survive their first winter is closely related to their growth during their first summer. Stream dwelling trout often suffer a metabolic deficit in early winter where their feeding and digestion cannot keep up with their metabolism, resulting in starvation. Because basal metabolism decreases as size increases, smaller fish tend to be less resistant to starvation and use their energy stores sooner than larger fish (Cunjak and Power 1987; Shuter and Post 1990). It is not the purpose of criteria to produce maximal growth in fish. Rather, criteria should protect a balanced and indigenous fauna and not jeopardize the continued existence of any threatened or endangered species, or impede their recovery.

## Laboratory Studies

After Hillman and Essig (1998) drafted their report, a series of three laboratory studies examined the growth and survival temperatures for juvenile bull trout (McMahon et al. 1998, 1999, 2001). The EPA reviewers provided critical comments on the first report (McMahon et al. 1998; later published as Selong et al. 2001). Below we briefly summarize the results of these laboratory studies.

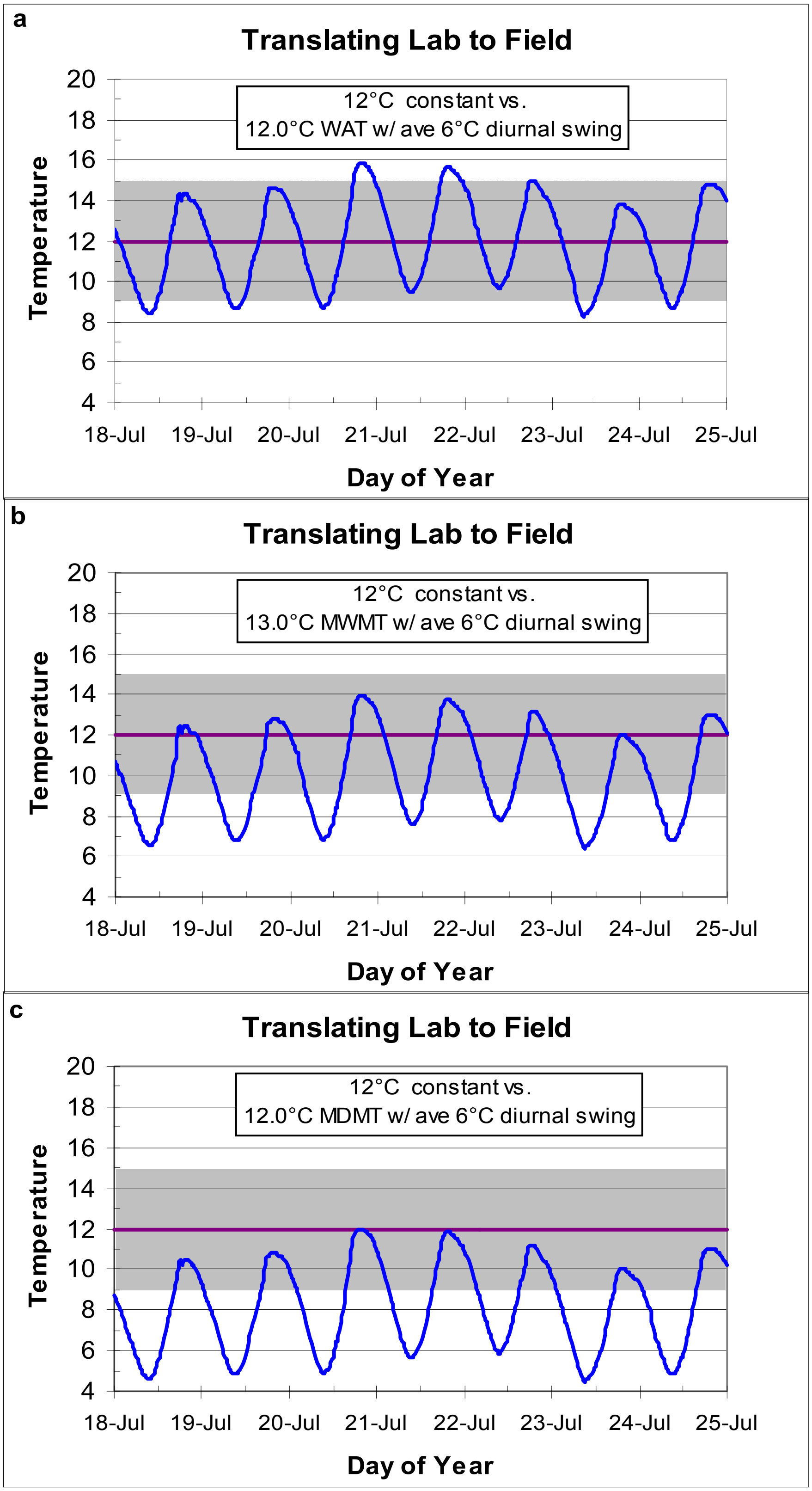
McMahon et al. (2001) summarize the results of the first two years of their studies as follows:

> *In the first year of our study (1998) we conducted two long-term experiments to define upper thermal limits and optimum growth temperatures for bull trout. These results indicated that the optimum growth of bull trout is 13.2°C (10.9-15.4°C 95% CI), and the ultimate upper incipient lethal temperature (UILT) and critical thermal maxima (CTM) are 20.9°C and 26.4-28.9°C, respectively (McMahon et al. 1998). Our first year studies were conducted at constant temperatures and satiation feeding. These test conditions are commonly employed in thermal tolerance studies of fishes and used in setting water quality standards, but do not encompass the full range of important variables that could influence fish response to temperature.*
>
> *To more closely mimic conditions that bull trout are subjected to in nature, our studies in year two (1999) focused primarily on how bull trout growth and survival responds to varying food levels and the presence of a nonnative competitor, brook trout. This past*

*year (2000) our primary focus was to add fluctuating temperature as an additional variable potentially affecting bull trout response to temperature.*

The primary criticisms of the initial 1998 study, as offered by the EPA reviewers, were that the researchers used constant temperatures and satiation feeding. With constant laboratory temperatures all metrics are equal, MDMT = MWMT = MDAT = MWAT = mean temperature. The reviewers noted that this would not allow one to generalize the results to natural environments, because natural environments have predators, competitors, fluctuating temperatures and flows, and limited food. In their opinions, these factors could result in optimal temperatures for growth less than 12-16°C.

In our experience, in order to compensate for these uncertainties, the tendency is to translate constant laboratory temperatures to limits on maximum temperatures in the field. We believe this is an unjustifiable and overly conservative approach. We know that a 12°C constant temperature in the laboratory exposes a fish to much more heat than a fish in a real stream that only reached 12°C as a MDMT. A couple examples illustrate this fundamental point that is often overlooked. The first (Figure 6) is a hypothetical example that shows the vast difference in thermal regime and exposure between a 12°C MWAT and a 12°C MDMT. The second (Figure 7) presents actual temperature data from Vanity Creek in Idaho, showing the duration of exposure over 12°C for a stream that reached an annual maximum of 14°C. This stream also had a MWMT very close to Idaho's bull trout criterion of 13°C. In our view, a constant laboratory temperature is most comparable to a summer average, monthly average, or even maximum weekly average in the field depending upon the length of the study. Uncertainties related to predation, competition, or limited food availability might justify applying a constant lab temperature at one time period as a limit on averages in a shorter time period (e.g., a 60 day laboratory result as a maximum monthly average). In our judgement, it is not reasonable to apply constant laboratory studies to field maximum temperatures without adjustments based on metric correlations.




Applying McMahon et al. growth optimum as a MWAT

**MWAT = 12.0°C**

MDAT = 13.3°C
MWMT = 14.7°C
MDMT = 15.8°C

Time in optimum range: 85%
Optimum = 12±3°C

Hours > 12°C = 85 (51% of week)
Hours > 13°C = 64 (38% of week)

Applying Idaho's BT criterion

MWAT = 10.3°C, sub-optimal for growth

MDAT = 11.6°C
MWMT = 13.0°C

MDMT = 14.1°C

Time in optimum range: 64%

Hours > 12°C = 36 (22% of week)
Hours > 13°C = 15 (9% of week)

Applying McMahon's growth optimum T as a MDMT

MWAT = 8.2°C, stream spends most of the time at T sub-optimal for BT growth

MDAT = 9.4°C
MWMT = 10.9°C
MDMT = 12.0°C

Time in optimum range: 40%

Hours > 12°C = 0 (0% of time)

Figure 6. Examples of translation of laboratory physiological thresholds to the field. Shaded area of the graphs represent range of maximum growth observed in fluctuating temperatures (12±3°C, McMahon et al 2001). Data are based on measured temperature in Silver Creek Idaho, chosen because the actual record for the warmest week of the year exhibited the same diurnal range as targeted by McMahon et al. (2001). Actual data recorded were shifted downward in temperature so that temperature record would just meet the bolded temperature metric.

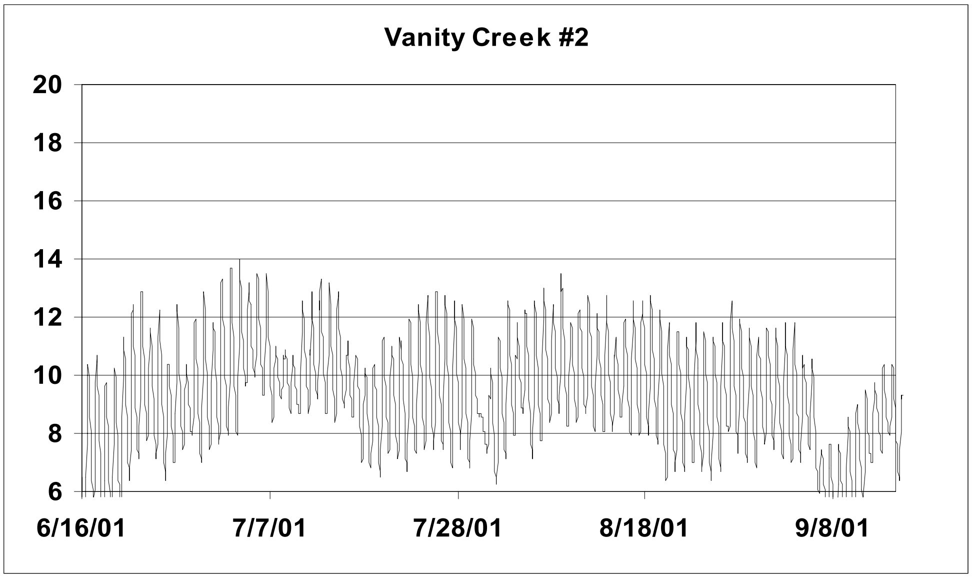
## Vanity Creek, Idaho

Annual max. T = 14.0°C MWMT = 13.3°C for week ending July 7th July/Aug ave. T = 9.7°C
Diurnal range at summer peak ~ 6°C

Time > 12°C (within 2°C of max)

| | Greatest duration | Week centered on 7-4 | Total 6/16 to 9/15 |
|---|---|---|---|
| Hours (days) | 7 hours | 30 hours | 155 hours (~ 6 days) |
| Date or % of time | 7-6-01 | 17.9% of week | 3.9% of summer |

(a) Temperatures over the entire summer




(b) Temperatures during the warmest week.

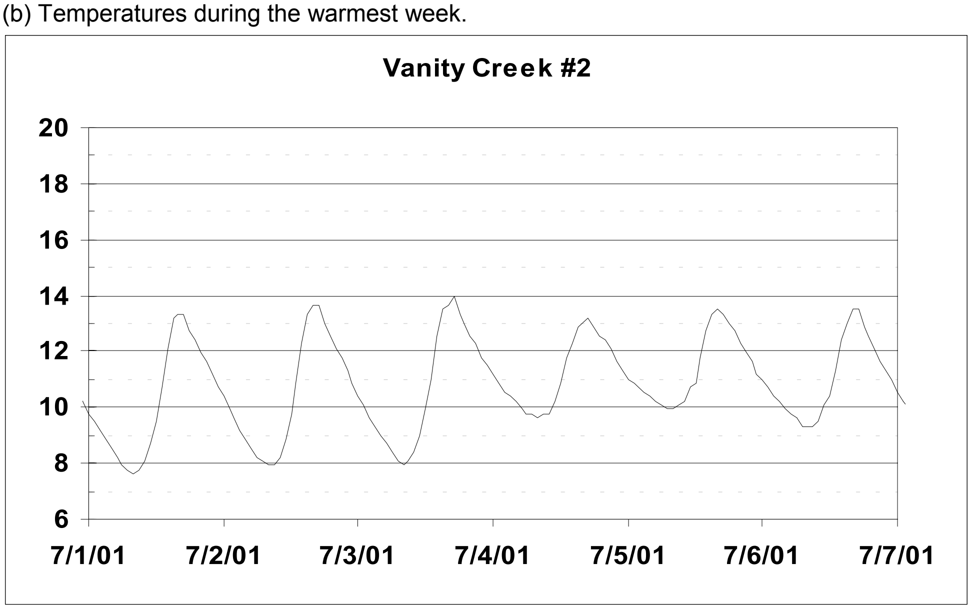



Figure 7. Duration of exposure to high temperatures is limited in real streams by diurnal and seasonal fluctuations.

Our judgement on relating laboratory exposures to field conditions is supported by recently published work comparing constant to cycling thermal regimes with Bonneville cutthroat trout. Johnstone and Rahel (2003) found that no fish died in a 7-day exposure to a 16-26°C cycle, even though this cycle included regular daily exposure to temperatures above those demonstrated to be lethal at constant exposure (7-day $LT_{50}$ 24.2°C). This concords with earlier work by Fry (1946) that showed duration of exposure to lethal heat is not accumulative when spread cross intervening cooler periods. In Fry's work, brook trout survived exposures of 3 hours and then 5 hours to 27°C on consecutive days with 21 hours of 20°C in between, while 8 hours of uninterrupted exposure to 27°C was fatal. This ability of fish to withstand intermittent exposure to stresses that would be lethal over longer periods of exposure is attributed to an ability to repair damage between exposures, evidenced by development of heat shock proteins. Johnstone and Rahel (2003) caution that the ability to repair damage has limits, as evidence by mortality after only 1-2 days at a cycle of 18-28°C, and note that the fish held at 16-26°C did experience reduced activity and feeding during the warm part of the cycle as compared to a 10-20°C cycle. They did not address the population level meaning of these sub-lethal effects. They did conclude that thermal tolerance based on constant "… exposures may not be representative of thermal conditions in nature and therefore could provide misleading results."

In follow-up work, Schrank et al. (2003) observed two populations of Bonneville cutthroat trout in the field. The two streams studied exposed fish to 2 and 5 weeks of daily exposure to temperatures above their laboratory derived LT50 of 24.2°C, with peak temperatures of 26.0 and 27.1°C respectively. Despite these high exposures, they observed no evidence of mortality, emigration, or use of cooler refugia, but issue caution about sub-lethal effects that may have occurred. This work clearly illustrates that constant exposures are not equivalent to cyclic exposures, and that thermal criteria based on constant lab studies will be conservative (underestimate maximum temperature tolerance) when applied to fluctuating field environments. We expect lab estimates of optimal temperatures are similarly misleading.

The 1999 and 2000 studies by McMahon et al. provide results that are directly relevant to those concerns. We have summarized significant findings from those studies, which were not available to the EPA reviewers at the time, in the following discussion.

### *Temperature and energy conversions for bull trout and brook trout:*

McMahon et al. (2001) conducted several studies to address questions raised by their 1998 study. One of the studies, proximate analysis, assessed how temperature influenced conversion of food to body constituents (i.e., tissue moisture, lipid, protein, and ash) with different ration sizes, temperatures, and with or without brook trout being present. These studies are significant because they relate to growth and lipid content, which in turn are related to overwinter survival. The combination of reduced growth and reduced lipid conversion efficiency at high temperatures or reduced rations would likely have a significant adverse effect on overwinter survival of juvenile bull trout (McMahon et al. 2001). Proximate analysis indicated no consistent temperature effects on tissue moisture, lipid, protein, or ash among groups of similar-size fish. In the 1999 tests using full satiation rations, protein and lipid efficiencies were similar from 7.5-18°C, but declined at 20°C. The researchers noted that satiation feeding may have allowed the bull trout to maintain similar protein and lipid efficiencies over a wide range of temperatures. In the 2000 tests at restricted rations (33% of satiation), lipid conversions efficiencies were significantly higher at lower temperatures (8 and 12°C) than higher temperatures (16 and 18°C), whereas the differences were much less pronounced at higher rations. The 1999 results showed that brook trout suppress the growth of bull trout particularly at temperatures greater than 12°C. In 2000 they tested differences in body composition to provide another measure to assess relative competitive ability of bull trout with temperature. Brook trout has higher lipid conversion efficiencies than bull trout at all temperatures tested (8 - 20°C). Taken together, the ration studies demonstrated that sustained temperatures greater than 16°C are generally unsuitable for long-term survival of bull trout.

In their first temperature trial, McMahon et al. (1998) observed a higher incidence of ventral lesions in bull trout held at constant temperatures ≥16°C than those held at lower temperatures.

However, after three years of study, they reported there was no consistent pattern in incidence of lesions with temperature (McMahon et al 2001).

In their 1999 studies, McMahon et al. assessed the effects of 33%, 66%, and 100% satiation rations on bull trout growth at four different temperatures (8°, 12°, 16°, and 18°C). In 2000 they analyzed an even lower ration (11% satiation) at three temperatures (8°, 12°, and 16°C). Not surprisingly, the highest growth at all temperatures occurred at satiation feeding. The temperature of maximum growth declined as ration declined. Growth rate at satiation peaked at 13.2°C, while at 33% and 11% satiation growth was highest at 12°C. McMahon et al. concluded that when energy availability is low, such as in might be expected at some times in most natural environments, maximal growth occurs at constant temperatures ≈12°C. Based on these results and using an MWAT to MWMT translation, we would expect maximum growth in the field for streams with an MWMT of about 15°C. We will see later that this comports well with various field studies.

### *Temperature mediated interactions of bull trout, brook trout, and temperature:*

McMahon et al. (1999) assessed the effects of temperature and brook trout, a potential competitor, on the survival and growth of juvenile bull trout. The researchers examined three treatments (bull trout alone, brook trout alone, and bull and brook trout together) at four temperatures (8°, 12°, 16°, and 20°C). Survival was high for both species at all four temperatures. Results indicate that when alone, bull and brook trout growth was similar at lower temperatures (8° and 12°C), but brook grew significantly faster than bull at higher temperatures (16° and 20°C). The highest growth for bull trout occurred at 12°C, while the highest for brook trout occurred at 12-16°C. Brook trout had a significant negative effect on bull trout growth at all temperatures (bull trout together with brook trout averaged about 25% lower growth than when alone). The researchers opined that bull trout may be disadvantaged in competition with brook trout at all temperatures, but especially so at constant temperatures above 12°C.

In their 2000 studies, brook trout both maintained higher lipid content than bull trout and exhibited dominance over bull trout over the entire temperature range of 8 - 20°C. Differences were more pronounced at higher temperatures (≥ 16°C). Temperature, species differences, and presence of a competitor influenced levels of aggression of bull trout and brook trout. In allopatry, aggression in both species decreased at higher temperatures, but more so for bull trout. Brook trout were much more aggressive than bull trout, even at low temperatures, especially in sympatry.

While tests of interactions of bull trout with a competitor are not by themselves grounds for setting regulatory temperature criteria, they do provide some insight into possible factors controlling field distributions of bull trout and other salmonids.

### *Growth at fluctuating vs. constant temperatures:*

To better mimic natural temperature regimes, McMahon et al. (2001) compared bull trout growth after 60-d exposures to four constant (10, 12, 14, and 16°) and four 6°C daily fluctuating temperature treatments that were centered around the four constant exposures (7-13, 9-15, 11-17, and 13-19°C). All of the treatments used the same feeding ration (0.66). Growth of bull trout at constant and fluctuating temperatures was both highest and most similar at a mean temperature of 12°C (range of 9-15°C). The researchers attributed the results to the fact that the fish exposed to a daily range of 9-15°C were within their optimal growth temperatures for more hours of the day than were fish exposed to colder or warmer daily temperature ranges (7-13 or 11-17). They concluded that the duration of exposure outside the optimal thermal envelope for bull trout growth likely affected the differences in growth responses between constant and fluctuating temperatures. Peak growth rates at 0.66 rations were similar in both the constant and fluctuating temperatures (12.4 and 12.2°C, respectively), although growth was higher at constant rather than fluctuating temperatures.

Examples of how commonly reported field metrics of stream temperatures could be related to these findings are illustrated in Figure 6. For a stream with a diurnal range comparable to McMahon et al.'s fluctuating experimental temperatures (6ºC), the amount of time fish would experience temperatures that are in the optimal range for growth are plotted within the shaded range versus temperatures above or below the range which are too warm or too cold for maximium growth. During the warmest week of the year (i.e., the week that maximum stream temperature metrics occur) temperatures from a stream with an MWAT of 12ºC would fluctuate through the optimal growth range (12±3°C) so that 85% of the time, temperatures were in the range for high growth (Figure 6a). In that case, temperatures were warmer than optimal for a few hours on each 20 and 21 July, and cooler than optimal for brief periods most days of the week. Making the same comparison with a stream with an MWMT of 13ºC (Figure 6b), no temperatures are warmer than the optimal range for growth, but temperatures are cooler than optimal for a part of each day. Overall a stream with a 13ºC MWMT would be in the temperature range for optimal growth about 65% of the time during the warmest week of the summer. In a colder stream with an MDMT of only 12ºC (Figure 6c), temperatures would be in the range for optimal growth only about 40% of the time during the warmest week of the summer. Obviously, during other weeks of the year, temperatures would be cooler than these illustrations, which come from the warmest week of the year.

These examples illustrate the complexity of comparing controlled experiments to field conditions. As we noted earlier, maximizing growth is not the primary measure of suitability of a criterion. We focus on it here because growth is a predictor of overall fitness, competitiveness, overwinter survival of young-of-year fish, and reproductive success. We are aware of few similar studies of the growth of salmonids under controlled, fluctuating temperatures. The results of McMahon et al. (2001) are mostly consistent with a study of rainbow trout under constant and fluctuating temperatures. Hokanson et al. (1977) studied the growth of juvenile rainbow trout reared in water fluctuating daily over a range of ~ 8°C about mean temperatures from 12° to 22°C. Hokanson et al. also found that with fluctuating temperatures, peak growth occurred when fish were within their optimal growth ranges for most hours of the day (for rainbow trout, centered on 15.5 to 17.3°C, ± an amplitude of 3.8°C). Unlike the tests with bull trout, Hokanson et al. found that the maximum growth of trout reared in fluctuating temperatures was about 1.5°C cooler than trout reared at constant temperatures, which was fairly consistent across the 12-22°C range of temperatures tested. This may in part be due to the high (~8°C) diurnal fluctuations in this study, but such high diurnal ranges are not uncommon in Idaho streams in high mountain valleys.

### *Upper incipient lethal temperature for juvenile bull trout:*

McMahon et al. (1998, 1999) attempted to determine the upper incipient lethal temperature for juvenile bull trout. They examined juvenile bull trout survival after 60-day exposure to four treatment temperatures of 20°, 21°, 22°, and 23°C. The researchers placed 50 trout (mean weight 21 g/fish) into each of three replicate tanks (a total of 12 tanks). The researchers used the same protocol developed in the first laboratory study. They found that the time of 50% mortality decreased at temperatures >21°C. Sixty-day survival was 46% at 21°C and 53% at 20°C. Regression analysis revealed that the upper incipient lethal temperature for juvenile bull trout was 20.8°C for a 60-day exposure, and between 22-23°C for a 7-day exposure.

### *Summary:*

In summary, the laboratory studies indicate that juvenile bull trout under benign conditions and satiation feeding grow fastest at constant temperatures between 12° and 16°C. Under more realistic conditions of daily fluctuation, maximal growth occurs at lower average temperatures. For example, the temperature at maximum growth decreases as ration declines. At the lowest ration tested (33% satiation), perhaps similar to natural environments, maximal growth occurred at constant or average temperatures ≈12°C. In the presence of a potential competitor, bull trout growth rate decreased at all temperatures tested. In contrast, growth rate of the competitor increased in the presence of bull trout. The effects appeared to be greatest at temperatures above 12°C. Our take on these studies is that under various laboratory conditions, juvenile bull trout survival is high at temperatures ≤18°C and growth appears to be highest at temperatures centered around ≈12°C. For a stream with a 6°C diurnal swing, the average observed in Idaho, these temperatures would translate to MWMTs of about 20°C and 14°, respectively.

## Field Studies

Both Hillman and Essig (1998) and Adams (1999) reviewed the validity of field studies that suggest associations between temperatures and bull trout densities and growth. We will not repeat those reviews in this section. Rather, we will summarize the most salient points from those studies and mention some newer studies. Because the researchers designed these field studies with other purposes in mind, it is important to remember that potential relationships may be confounded by other factors (see e.g., McCullough's 1999 review). However, if similar relationships are observed among several independent studies, including presence-absence studies and laboratory studies, then the relationships may be less suspect.

Relationships between bull trout density and temperature should help identify temperature requirements of bull trout; although, it is important to recall that densities can be related to other confounding variables (see McCullough 1999). Pratt (1999) considered juvenile bull trout densities of 10 fish/100 $m^2$ as high and unlikely to be found in most places, and 5 fish/100 $m^2$ as reasonable to expect. That said, we looked for temperatures that were associated with these densities.

Bull trout, stream temperatures, and other environmental variables have been intensively studied from 1992-2000 in the Little Lost River subbasin, Idaho, located at the southeastern margin of the bull trout distribution (Figure 1). The Little Lost River subbasin has likely been isolated from other streams since about 8,000 years BP in the late Pleistocene (Gamett 1999). Bull trout, brook trout, rainbow trout, and cutthroat trout occur in the subbasin. Bull trout have a wide but fragmented distribution in the subbasin; environmental conditions vary greatly from forested streams above 2400 m in elevation to the terminus of overland flows in the Snake River desert at less than 1500 m. For these reasons, the Little Lost River subbasin provides an excellent setting for studying relationships between bull trout populations and environmental factors.

Gamett (2002) examined the relationships between temperature metrics and three measures of bull trout populations – presence/absence, composition (% of all salmonids that were bull trout), and density. He estimated fish densities using multi-pass electrofishing with block nets and monitored stream temperatures at about 80 sites in the subbasin. Site selection was restricted to those that all salmonid species had access to; streams with fish passage blockages were excluded. Only non-young-of-the-year salmonids (>70 mm length) were counted to avoid possible biases due to know difficulty in capturing young-of-the-year.

Relations between bull trout occurrence and temperature metrics differed among the three population measures. Of 18 temperature metrics examined, summer (Jul-Sep) mean temperature was the only metric that was highly correlated with all three measures. Below 7ºC mean summer (July 1-Sep 30) temperature, bull trout were the only salmonid present in streams in the Little Lost River subbasin. Above 12ºC mean summer temperatures, bull trout were never present. Optimum summer mean temperatures for bull trout were probably 7-8ºC. The highest densities of bull trout occurred in sites with maximum stream temperatures ranging from 10-14ºC. Bull trout were present at all sites with maximum temperatures below 17ºC; they were not present where maximums were above 21ºC. The site with the highest density of bull trout (40/100 $m^2$) had a maximum temperature of 14.7ºC and an overall summer mean temperature of 7.7ºC. While temperature appeared to control the range of bull trout within the Little Lost River basin, other factors appeared to control their abundances (Gamett 2002).

It is important to note that a given temperature (e.g., 12°C) has little meaning without mention of the metric. This is because widely different numbers can result from the same temperature record depending on choice of metric. Gamett's work provides insight into this lack of direct comparability between various temperature metrics. The summer (July-Sept.) mean temperatures he observed were several degrees lower than the MDMT temperatures at the same site, as should be expected in a climate with strong seasonality. Consequently, his relation of water temperature to bull trout population measures changes greatly with the temperature metric used. For example, looking at bull trout distribution, Gamett found that the temperature at which bull trout were no longer present changed from 12.0° to 20.0°C, when switching from summer mean to summer maximum. Similarly the temperature associated with maximum density changed 7°C, from 7.7° to 14.7°C, if expressed as a summer maximum rather than a mean. While a 7-8°C difference in these metrics for the same thermal regime is among the highest we have seen, it illustrates the fundamental importance of specifying the metric when speaking of temperature. It also highlights the need to pay attention to metrics, and translate the numbers where possible, especially when comparing studies.

Data in Saffel and Scarnecchia (1995) indicate that juvenile bull trout densities increase with temperature up to a MDMT of 14°C, and decrease with MDMT from 18-23.3°C. There were no density data between 14° and 18°C. There was virtually no difference in bull trout density between a site with a MDMT of 7.8°C and one with a MDMT of 20.0°C. The highest densities (>10 trout /100 $m^2$) occurred within sites with MDMT between 11° and 14°C. These observations comport with data described in Hillman and Essig (1998) from 42 sites in several different streams in northern Idaho and western Montana. The highest densities (>10 bull trout/100 $m^2$) occurred within sites with MWMT between 9° and 14°C. The highest density (30 fish/100 $m^2$) occurred at a MWMT of 12.2°C (recall MWMT is roughly 1°C lower than MDMT). In the Little Lost River basin, age-0 bull trout occurred in sites with MWMTs that ranged from 12.1° to 15.5°C (Gamett 2002). The largest number of age classes occurred in sites with MWMTs of 12.1-15.1°C. Gamett (2002) found the highest densities (19.5-30.3 bull trout/100 $m^2$) in streams with MWMTs of 12-15°C.

Work by Adams and Bjornn (1997) in three streams in the Weiser River basin indicated moderate bull trout densities (about 5-6 trout/100 $m^2$) at MDMT of 15°C and lower densities (3.0 trout/100 $m^2$) at MDMT of 9.9°C (densities included both juvenile and adult bull trout). The latter density included sampling only in pool habitat, while the former included sampling in all habitat types. We assume that the density at the MDMT of 9.9°C would be even lower if other habitat types were included. Thurow and Schill (1996) found that roughly 1.9 to 11.6 bull trout/100 $m^2$ (assuming a mean area per site of 714 $m^2$) lived in Profile Creek at temperatures of 9° to 13.5°C (densities included age-0 and 1+ bull trout). They noted, however, that except for one site, there was no relationship between counts of bull trout and water temperatures. Martin et al. (1992) reported that daily maximum temperatures in Mill Creek reached 13°C and age-0 and juvenile bull trout numbered 6.0 and 7.4 fish/100 $m^2$, respectively. In sum, these data suggest that the highest densities of bull trout occur in sites with MDMT of 11-14°C or MWMT of 9-14°C.

Ott and Maret (2003) evaluated environmental variables, with a focus on stream temperature, and corresponding aquatic biota from 34 least-disturbed streams in the Salmon River Basin, Idaho, during July – September 2001. Purposes of their study were to document the thermal regime of least-disturbed streams; characterize the distribution of aquatic biota at streams that represent a gradient of temperature; and to describe relations between temperature, other environmental variables, fish assemblages, and invertebrate assemblages. Sampling sites were selected to represent minimally disturbed conditions with an emphasis on selection of sites with little or no prior logging or mining activity in the watershed and no physical barriers that would prevent fish movements between study streams. In their analysis of relations between stream temperature and fish variables, only bull trout had a strong negative correlation with increasing stream temperature. In contrast, rainbow/steelhead trout and chinook salmon had positive correlations with most stream temperature metrics. The strong negative correlation between stream temperature and bull trout densities in these least-disturbed streams is shown in Figure 8. Two sites had much higher bull trout percentages and densities than the other 34 sites. MWMT values were 11.5°C and 13.2°C at the sites with the highest densities.

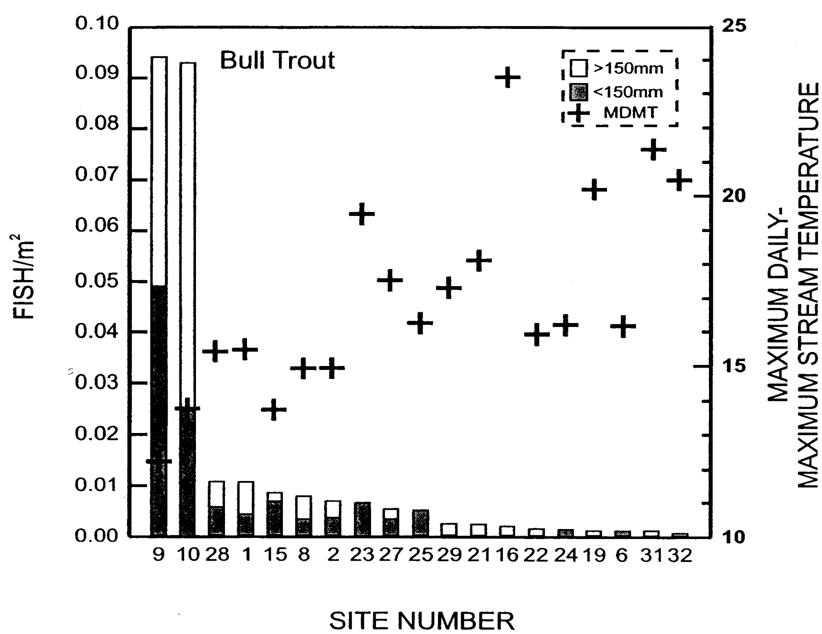



Figure 8. Bull trout densities in relation to maximum-daily maximum stream temperature at selected least-disturbed reference sites in the Salmon River Basin, Idaho, 2001 (from Ott and Maret 2003, their Figure 5).

Relations between bull trout growth and temperature may also help identify temperature requirements. Again, it is important to remember that growth in the field can be confounded by other factors. Hillman and Essig (1998) referred to data in Mullan et al. (1992) that indicated that average bull trout length and weight increased as temperatures increased (see Figures 11-15 in Hillman and Essig 1998). For all age groups sampled, average size (growth) was greatest at MWAT greater than 10°C (MWMT of about 12°C). Mullan et al. (1992) noted that not only did bull trout grow slower in the coldest water sampled, but that bull trout in the coldest water also matured at a late age. Data in Spangler (1997) also suggest an increase in growth rate of age-0 bull trout as temperatures increase. In 1993, summer stream temperatures averaged 6-7°C and age-0 trout averaged 45 mm in length on 1 September. In 1994, summer temperatures averaged 10-13°C and age-0 trout averaged 55 mm in length on 1 September. Although field data are scarce, information available suggests that juvenile growth is highest at MWMT temperatures between 12° and 14°C.

### *Field evidence of temperature-mediated interspecific competition:*

Gamett (2002) believed that temperature-mediated competition affected the distribution of bull trout and brook trout in streams where both species had access to all study sites. He compared the distribution of brook trout in two adjacent watersheds (Big Lost River and Little Lost River basins, Idaho) where similar temperature and habitats were available. He noted:

> *The Big Lost River basin does not contain bull trout, but brook trout have been established throughout the drainage. Distribution patterns in this basin suggest that brook trout can occupy the coldest streams available, including streams where the maximum summer temperatures are likely well below 15°C. However, in the Little Lost River basin, where brook trout were introduced by at least 1915 and are believed to have had access to all of our study sites, we did not find brook trout in any of the eight sites where MAX* [MDMT] *temperature was less than 11.0°C and they were present in only one of the 16 sites where MAX temperature was less than 15.0°C. However, brook trout were present in 39% of the 23 sites where MAX temperature was greater than 15.0°C.* (Gamett 2002)

G. Haas (unpublished data) studied temperature mediated interactions between bull trout and native rainbow trout in 26 sites in southwest British Columbia that were minimally disturbed by human activities. The highest densities and catch per unit effort of bull trout occurred at a site with a MWMT of about 12.5ºC and were lower at cooler and warmer sites. At the four sites where both rainbow and bull trout occurred (sympatry), bull trout were dominant at sites with maximum temperatures below 13°C. Of the 11 sites with bull trout present, the average MWMT was 11.6°C (G. Haas, British Columbia Fisheries, personal communication with C. Mebane, 9/1/2000). A limitation to the general applicability of this study is that stream reaches were chosen to maximize differences in temperature and species composition due to barriers such as waterfalls or other factors (see also Adams 1999).

## Presence-Absence Studies

Since Hillman and Essig's (1998) review, several studies have been completed that analyzed temperature patterns associated with observations of presence or absence of bull trout. Each has shown that at higher maximum stream temperatures, temperature becomes increasingly important as a limiting factor in bull trout occurrence. Some of these studies are summarized below.

Rieman and Chandler (1999) empirically evaluated temperature effects on bull trout distribution in the Northwest. The purpose of their report was to summarize progress on efforts to develop empirical descriptions and models of the temperature regimes associated with the presence of juvenile bull trout. They assumed that a large number of temperature observations broadly distributed across the species range provide a description of the temperatures that act to limit the species distribution. We agree with Rieman and Chandler (1999) that although the distribution of temperatures associated with juvenile bull trout occurrence provides an approximate range of suitable temperatures, it is difficult to infer preferred or optimal temperatures. However, evaluating these results in light of other field studies and laboratory studies should help us to better understand the temperature requirements of juvenile bull trout.

Rieman and Chandler (1999) compiled a database of consistent, reliable temperatures associated with the presence of juvenile bull trout (<150 mm). That is, they required records of at least one-month duration, uniform sampling interval with not less than four instantaneous observations per day, and status of bull trout within 500 m of the temperature site. The researchers also considered the accuracy and quality of the data, although verification was incomplete at the time the report was released. In all, a total of 581 sites and 908 records (site/year observations) spanning four years were included in the report. The observations contain a broad range of sites in the southern portion of the bull trout's range, although extensive data from the Little Lost River basin were not included.

Rieman and Chandler (1999) found that although the maximum temperatures associated with the presence of juvenile bull trout ranged widely, 95% of the observations were <18°C and 65% were ≤14°C (their Figure 7, reproduced as Figure 9 in this report). Approximately 55% of the observations occurred between 12° and 15°C; the highest frequency of occurrence was at 14°C.

Rieman and Chandler (1999) believed that these data encompass a wide range of environmental and ecological conditions and thus provide a broad representation of bull trout potential distribution. They stated, "[p]*reliminary summaries suggest for example that juvenile/resident bull trout occur across a wide range of 'summer' temperatures and at temperatures considerably higher than commonly indicated in the available literature. The distribution of observations, however, also indicates that the occurrence of bull trout at higher temperatures is not particularly common. For example, bull trout were observed more frequently and appear more likely to occur at summer means of about 6-9°C or with summer maximums less than about 13-14°C.*"

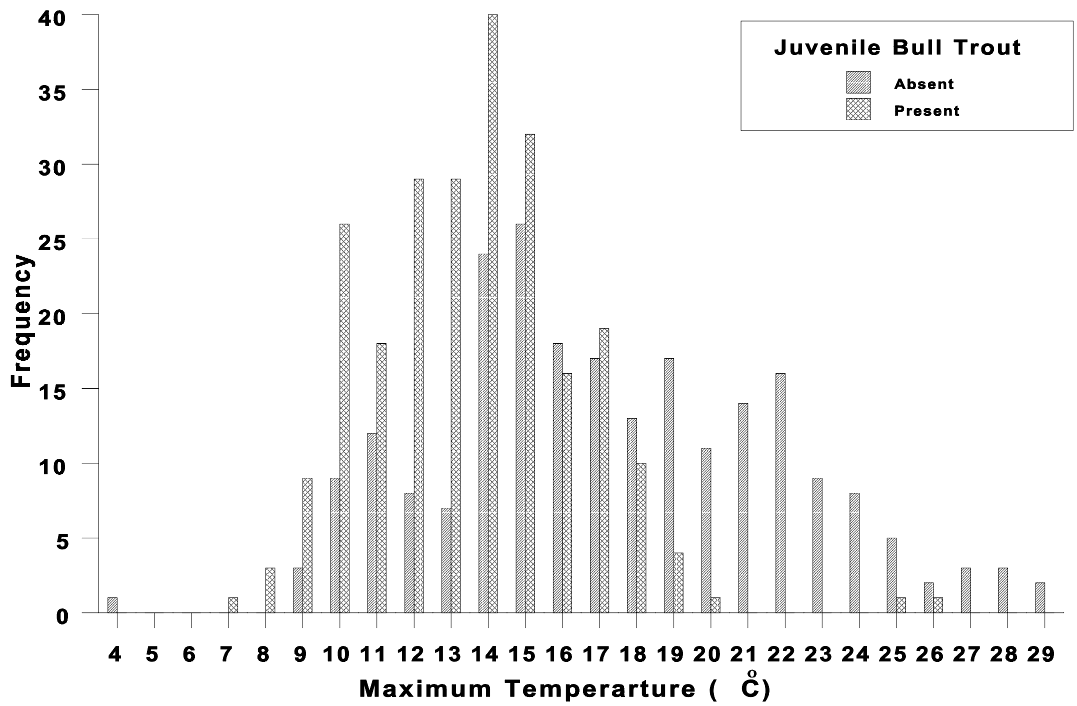


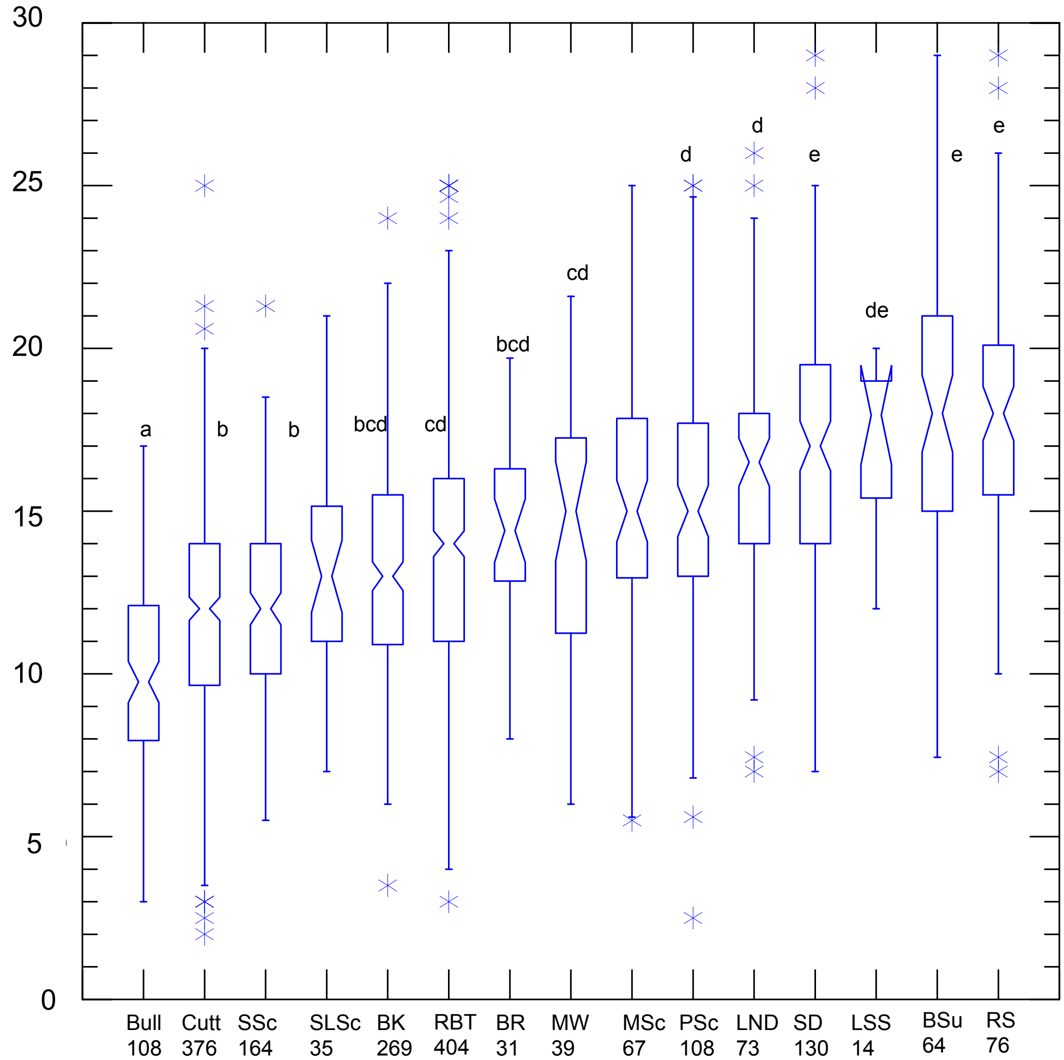

Figure 9. Frequency distribution of the summer maximum temperature at sites with and without juvenile or small bull trout (from Rieman and Chandler 1999, their Figure 7).

Through the IDEQ beneficial use reconnaissance program (BURP), Mebane (2002) compiled instantaneous temperature records and summertime fish species occurrence at several hundred stream sites across Idaho. Bull trout were observed at 108 sites with *ad hoc*[3] temperatures ranging from 5-17°C; 50% of the observations occurred between 8° and 13° (Figure 10). The median temperature at which bull trout were observed was 10°C, 75% of observations were <13°C, and 95% of observations were ≤16°C. Overall, the mean temperatures at which bull trout were observed were significantly colder than any other fish species encountered (Tukey's test; P<0.05). These instantaneous temperature observations cannot be compared directly to any of the annual maximum temperature metrics discussed in this report. However, this comparison has the advantage of the temperature measurements being matched in space and time with the fish collections. In contrast, annual maximum metrics are usually matched in space, but they

[3] *ad hoc* means that the temperatures were point measurements taken at various times of the day, not necessarily representative of maximums or averages. Their strength is that they were measured at the same time and place as fish were observed.

may not be matched in time (i.e., it is unlikely they coincide with the time that the fish surveys were conducted).

In a similar way, Ott and Maret (2003) presented their data from least-disturbed Salmon River Basin streams (Figure 11). Although these data are from a much smaller set of streams than displayed in Figure 7, strengths of Ott and Maret's data include the collection of continuous temperature measurements at the sites prior to fish sampling. Ott and Maret analyzed their occurrence data with the maximum weekly-maximum temperature for the date of sample (MWMTS). This metric is similar to a MWMT, except it included the day of sample and the 6-days prior. This metric was designed to account for the disconnect in time that usually occurs when the maximum summer-long temperature metrics at a site do not occur at the same time as fish sampling. In their study, bull trout occurred at sites where the MWMTS values ranged from 11.3ºC to 20.0ºC and corresponding MWMT values ranged from 11.5ºC to 22.1ºC (Figure 11). The patterns of fish species occurrence over a range of temperatures observed by Ott and Maret (2003) were similar to those reported by Mebane (2002), as shown in Figure 10.




| Code | Common Name | Scientific Name | Code | Common Name | Scientific Name |
|---|---|---|---|---|---|
| Bull | Bull trout | *Salvelinus confluentus* | MW | Mountain whitefish | *Prosopium williamsoni* |
| SSc | Shorthead sculpin | *Cottus confusus* | MSC | Mottled sculpin | *Cottus bairdi* |
| Cutt | Cutthroat trout | *Oncorhynchus clarki* | PSC | Paiute sculpin | *Cottus beldingi* |
| SLSC | Slimy sculpin | *Cottus cognatus* | LND | Longnose dace | *Rhinichthys cataractae* |
| BK | Brook trout | *Salvelinus fontinalis* | SD | Speckled dace | *Rhinichthys osculus* |
| RBT | Rainbow trout | *Oncorhynchus mykiss* | LSS | Largescale sucker | *Catostomus macrocheilus* |
| BR | Brown trout | *Salmo trutta* | BSU | Bridgelip sucker | *Catostomus columbianus* |
| | | | RS | Redside shiner | *Richardsonius balteatus* |

Figure 10. Ranges of temperatures at which selected fish species were captured in Idaho, 1995-1999. The boxes indicate the median and upper and lower quartiles (the central 50% of the values), the whiskers extend up to 1.5X the interquartile value, and asterisks show outlying values. Notches in the boxes indicate 95% confidence intervals of the median. Plots marked with the same letter indicates that their means are not significantly different at $P < 0.05$ using Tukey's multiple comparison procedure (from Mebane 2002, his Figure 4-2)

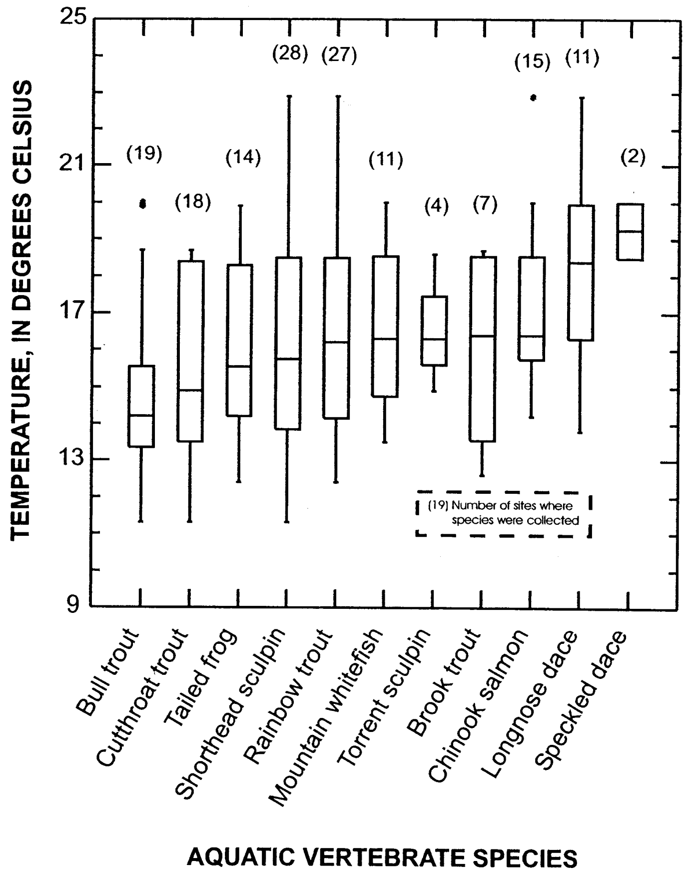



Figure 11. Range of maximum weekly maximum stream temperautres (MWMTS, based on date of sample collection and six days prior) at which species occurred in selected least-disturbed streams in the Salmon River Basin (from Ott and Maret 2003, their Figure 4).

## Predictive Models of bull trout occurrence

Several recent studies have used logistic regression models to predict summertime temperatures that likely limit the occurrence of bull trout or other coldwater fishes (e.g., Dunham et al. 2001; Gamett 2002; Maret and Ott 2003; Picard et al. 2003). Using stream temperature data collected near sites of fish surveys, these researchers used logistic regression to predict the probabilities of occurrence of bull trout or other species with increasing temperatures. Probabilities of bull trout occurrence at different maximum summer temperatures from a regional Pacific Northwest model, and two basins near the southern margin of the bull trout range in central Idaho are shown in Table 2 and Figures 12 and 13. Models predicted that bull trout were likely to occur (>50% probability) in streams with maximum temperatures less than 16.5 to 18.6°C. In streams that would not exceed 14ºC MDMT (≈ 13ºC MWMT) probabilities of bull trout occurrence were 68-98%.

Table 2. Predicted occurrences of juvenile bull trout at different maximum stream temperatures.

| Area | Bull Trout likely to occur (>50% probability of occurrence, MDMTºC) | Probability of occurrence at 14ºC MDMT (similar to Idaho criterion of 13ºC MWMT) | Reference |
|---|---|---|---|
| Little Lost River Basin, Idaho | <18.6ºC | 98% | Gamett 2002 |
| Salmon River Basin, Idaho | <16.75ºC | 88% | Ott and Maret 2003 |
| Pacific Northwest | <16.5ºC | 68% | Dunham et al. 2001 |

For comparison with these model predictions, within the range of present bull trout occurrence (Figure 1), measured median and upper quartile ($75^{th}$ percentile) maximum stream temperatures for streams where bull trout were either present or not observed were calculated in Table 3. Data were remarkably consistent across studies; the medians of the summer maximum temperatures at sites where bull trout were observed only ranged from 14.1 – 15.6ºC. Using the upper quartile ($75^{th}$ percentile) to define the upper range of summer maximum temperatures where bull trout occur also resulted in a narrow range across studies, ranging only from 14.8 – 16.5ºC. Temperatures were cooler in the Washington State dataset than in the Idaho or regional Pacific Northwest datasets (Table 3).

Table 3. Medians and upper ranges (75th percentiles) of summer maximum stream temperatures from streams where bull trout were present or apparently absent (MDMT ºC).

| Area | Statistic | All sites | Sites with bull trout present | Sites where bull trout were not observed | Data source |
|---|---|---|---|---|---|
| Little Lost River basin, Idaho (n=39) | | | | | Gamett 2002 |
| | Median | 16.3 | 14.7 | 19.4 | |
| | 75th %tile | 19.1 | 16.5 | 22.1 | |
| Salmon River basin, Idaho (n=34) | | | | | Ott and Maret 2003 |
| | Median | 18.2 | 15.6 | 20.1 | |
| | 75th %tile | 20.5 | 16.3 | 21.6 | |
| Washington (n=109) | | | | | Dunham and Chandler 2001 |
| | Median | 14.9 | 14.1 | 16.6 | |
| | 75th %tile | 17.5 | 14.8 | 19.8 | |
| Pacific Northwest (n=643) | | | | | Dunham et al 2001 |
| | Median | 15.1 | 14.1 | 17.5 | |
| | 75th %tile | 17.9 | 15.8 | 21.2 | |

The logistic regression model approach is a powerful tool for predicting high temperatures that limit bull trout occurrence. However, the approach is not well suited for predicting the upper range of preferred or optimal temperatures for bull trout occurrence. Results of logistic regression models produce a curve that looks similar to the right half a bell-shaped normal distribution curve (Figures 12 and 13). The logistic regression models cannot predict the peaks in occurrence, such as the hump at the top of a bell curve. Thus, although these models effectively predict upper temperatures that limit bull trout occurrence, they cannot predict the maximum likelihood of bull trout occurrence. Taken as a simple model output, the maximum predicted probability of occurrence of bull trout would be at 0ºC, which is a artifact of the logistic regression equation and is obviously impossible. Probabilities of bull trout occurrence also decrease at temperatures below those where they most frequently occur (e.g., maximum summer stream temperatures of 14ºC had the highest frequencies of bull trout occurrence in Figure 9; cooler and warmer streams had lower frequencies of occurrence). Similarly, highest bull trout densities are observed at moderately-cold sites in streams, not at the lowest temperatures.

Figure 13 illustrates the differences between the “ski-jump” shaped logistic regression curves that have no peaks and a “bell curve” distribution with a hump at the peak of the modeled distribution. Using the logistic regression approach to predict brook trout occurrence in northern Ontario streams, Picard et al. (2003) found that logistic regression presence/absence models predict absence better than presence of brook trout. They noted that “[b]*ecause of the lethality of these higher temperatures, trout absence is nearly certain, thus producing more accurate prediction rates. Conversely, at lower temperatures, trout presence and absence are less clearly discriminated, because cooler stream temperatures do not themselves ensure brook trout presence. Rather, temperature is only one prerequisite of many for brook trout survival and persistence. Other factors, such as the lack of adequate spawning and rearing habitat, the influence of other species, stochastic climatic catastrophes (e.g., drought), and migration barriers may prevent brook trout from colonizing and persisting in some thermally suitable streams.*”

Reiman and Chandler also cautioned that the presence/absence approach is essentially correlative and the apparent patterns could be spurious, resulting from relationships with other confounding variables (see also criticisms in McCullough 1999). For example, the presence of juvenile bull trout in certain locations may be the result of species interactions or habitat degradation. Therefore, because presence-absence data cannot separate thermal effects from other rival hypotheses, one cannot clearly identify optimal temperatures for juvenile bull trout survival and growth. Since most human-caused disturbances likely raise, rather than lower stream temperatures, from an environmental management perspective this may not be a significant limitation when these models are used for the purpose of predicting potential bull trout habitats to protect or restore. As we noted earlier, evaluation of these results in concert with other field and laboratory studies does aid in identifying temperature requirements for juvenile bull trout.

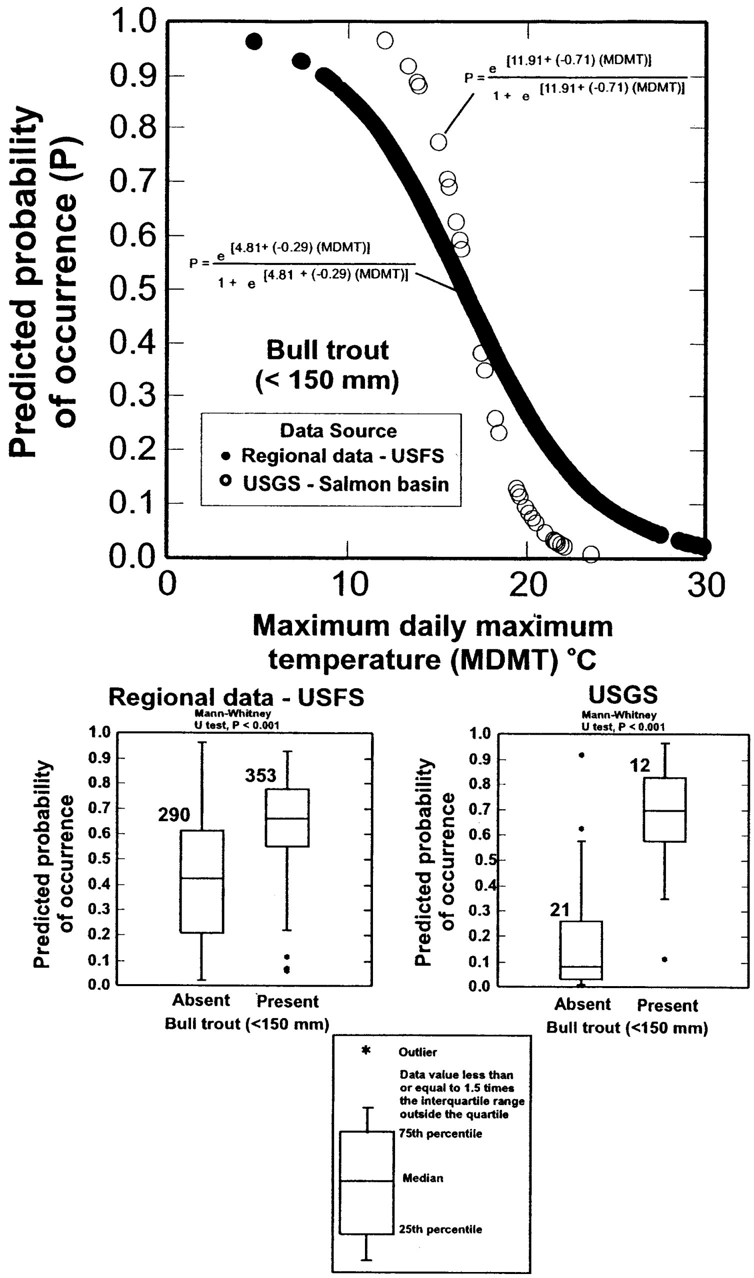



Figure 12. Logistic regression model predictions of juvenile bull trout presence or absence in relation to maximum daily-maximum stream temperature (MDMT) for the regional Pacific Northwest dataset ("USFS", Dunham et al. 2001) and least-disturbed sites in the Salmon River basin ("USGS", Ott and Maret 2003). Box plots show the ranges of predicted occurrence probabilities for sites where juvenile bull trout were actually present or were apparently absent (from Ott and Maret 2003, their Figure 6).

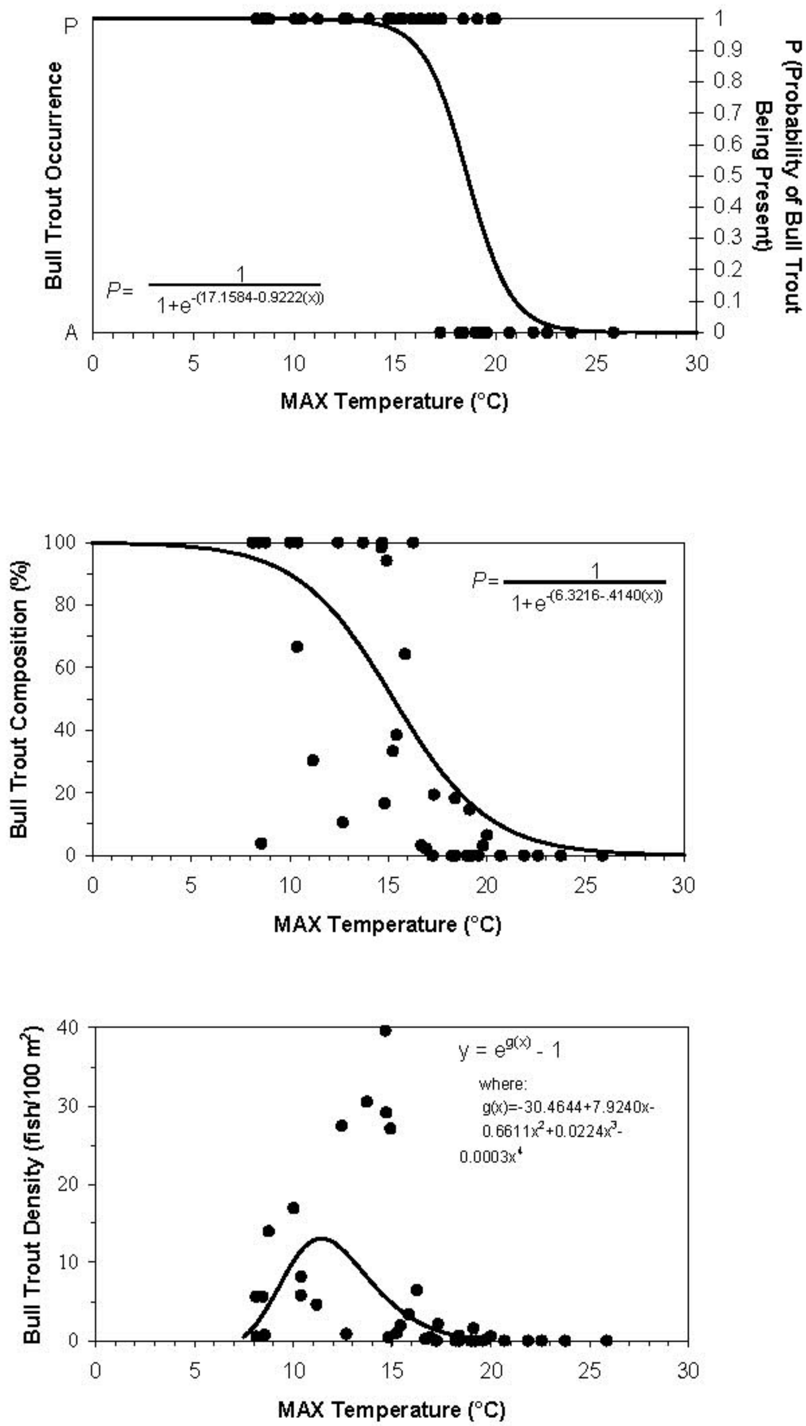



Figure 13. The relationship between maximum temperatures (MDMT) and bull trout occurrence, bull trout density, and the percentage of salmonids that were bull trout. The logistic regression models generated the ski jump-shaped curves on the occurrence and composition graphs whereas the bell-shaped curve on the density graph was generated with a polynomial regression model (from Gamett 2002; his Figure 2-4).

# CONCLUSIONS

We believe that no single study can be used to establish temperature criteria for juvenile bull trout. Laboratory data, although important in identifying relationships between thermal regimes and growth and survival rates, often cannot be easily generalized to natural settings and must be appropriately translated to be applied in the field. Field studies, on the other hand, are usually correlative (observational studies) and as such are vulnerable to the effects of uncontrolled variables, but they more closely represent natural conditions. We believe that both approaches are necessary and complimentary, but without knowledge of the temperature metric, it is inappropriate to compare results among studies. Therefore, we use the results from the various approaches, paying careful attention to the metric used to summarize temperature, to find what we think is the most appropriate temperature criterion for juvenile bull trout rearing.

Based on our review of laboratory studies, field studies, and presence-absence studies, it appears that optimal temperatures for juvenile bull trout rearing occur between 11° and 14°C MWMT. In laboratory studies under reduced rations (11-33% satiation) and in the presence of a competitor, growth of juvenile bull trout was highest at a constant temperature of about 12°C. Highest densities of juvenile bull trout in streams were usually associated with MDMTs of about 11-15°C and MWMTs of about 10-14°C. Four separate presence-absence studies around the Pacific Northwest found the median (i.e., half the observations were higher and lower) maximum temperatures of streams where juvenile bull trout were present ranged from 14.1-15.6ºC MDMT. Although each the studies reviewed have various strengths and weaknesses, the fact that they complement each other increases our confidence that juvenile bull trout do best at temperatures between 9° and 14°C, depending on which metric is examined.

Based on this review, we conclude that a temperature standard of 13°C MWMT would be fully protective of juvenile bull trout rearing during June, July, and August. Under typical cases this standard is similar to a standard of 11°C MWAT, 12°C MDAT, and mean July-August stream temperatures of about 8.5-8.7°C, based on the relationships described here and in Hillman and Essig (1998). This also should provide MDMTs below 14°C most of the time, rarely reaching as high as 15°C (Figure 4). Adams (1999) and Pratt (1999) reached similar conclusions. Adams

(1999) indicated that her best estimate of an appropriate maximum temperature criteria was a MWMT of 12°C, while Pratt (1999) reported that 13°C was high enough for a MWMT. We acknowledge that laboratory tests designed to mimic natural conditions (daily fluctuations in temperature and limited food availability) indicate that streams with a 13°C MWMT will have summertime temperatures that are somewhat cooler than optimal for juvenile bull trout growth (McMahon et al. 2001; Figure 6). We chose this lower temperature to provide a safety margin, postulating that poorly defined factors such as limited food availability and interspecific competition could be important in some circumstances.

The weight of the evidence indicates that when summer stream temperatures do not exceed an MWMT of 13°C, thermal conditions will be fully protective of and should not jeopardize the continued existence of or impede recovery of bull trout.

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