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Stream temperatures and salmonid distributions: Proceedings of a workshop

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J. B. Dunham, Facilitator
Biological Resources Research Center, University of Nevada-Reno

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Introduction

J. B. Dunham

Interest in stream temperatures and salmonid distributions has grown rapidly over the past 5-10 years. Much of the interest has been motivated by 1) recent listing or proposed listing of many salmonid taxa under the Endangered Species Act; 2) listing of stream habitats as "water quality limited" by temperature under the Clean Water Act; and 3) improved access to temperature data through technological advances, including geographic information systems, digital temperature recorders, biochemical and physiological assays, radio telemetry and archival fish tags, and access to large temperature databases.

This new generation of interest in thermal ecology of salmonids has brought with it many new and important perspectives on issues related to conservation of salmonid fishes and the coldwater ecosystems upon which they depend. The challenge will be to integrate these diverse perspectives to provide a useful framework for understanding the importance of temperature to salmonids, and to apply that understanding to effective management, monitoring, and restoration.

With these issues in mind, we began the workshop with presentations and discussion of regulatory and policy issues. Following this, a series of presentations describing recent research directions were delivered. Research issues were "stratified" by spatial scale and/or level of biological organization. The research focus, in terms of taxonomic groups, was on inland cutthroat trout and bull trout, both species of critical concern within the region.

The primary goal of the workshop was to share information among various researchers and agencies working on similar issues within the region. A second goal was to provide an interactive forum for discussion of emerging issues related to stream temperature and salmonids. The third and by far most ambitious goal of developing an integrated framework was postponed for later development.

From our sharing of information and discussion of the many important issues, it became very clear that much work needs to be done. Most encouraging was the high caliber of all of the presentations and discussion over the course of the workshop. Included herein are summaries of presentations by the participants and a short synopsis of discussions that followed.

Key Issues in the Development of Water Quality Standards for Temperature: Oregon=s Temperature Standard

Cara Berman, Environmental Protection Agency

Background:

The purpose of this presentation is to discuss findings associated with EPAs review of Oregon=s temperature standard and to describe why this is more than a debate over a Afew degrees.@ In the process of discussing our findings, I will also identify areas for possible collaboration and briefly discuss concerns related to habitat based indices such as Oregon=s Healthy Stream Initiative. It is EPAs hope that we may work collaboratively with the universities and other research institutions to better understand Pacific Northwest aquatic ecosystems.

The current Oregon Temperature Standard:

1. Salmonid spawning, egg incubation, and fry emergence: 12.8^{0}C or 55^{0}F
2. Salmonid rearing: 17.8^{0}C or 64^{0}F
3. Bull Trout: spawning, rearing, or resident bull trout: 10^{0}C or 50^{0}F
4. Columbia River to river mile 309: 20^{0}C or 68^{0}F
5. Willamette River to river mile 50: 20^{0}C or 68^{0}F

* The temperature is measured as the 7 day average of the maximum temperature.

* Adult migration, adult holding prior to spawning, smoltification and juvenile emigration are not specifically addressed.

Historically, standards have focused on the effect of point source thermal discharges and associated lethal responses. Current discussions focus on nonpoint source generated alterations to the thermal environment. These alterations are often basin-wide and result in complex changes to the biotic community.

The BA provides:
(1) a review of the ecological context and critical processes affecting both the stream network and cold-water biota,
(2) a summary of baseline condition within Oregon,
(3) a review of lethal, sublethal, and intermittent elevated temperature effects on native salmonids,
(4) an analysis of the temperature measurement unit and implications for its use (i.e., 7 day moving average),
(5) a determination of the effect of Oregon=s temperature standard on endangered, threatened, and proposed native salmonids,
(6) a summary of findings, and

(7) a summary of species-specific temperature preferences, tolerances, and thresholds of effect from the technical literature.

Key Findings:

1. The temperature criterion for spawning, incubation, and emergence is not likely to adversely effect T & E species: timing issues

   A. 12.8^{0}C is at the upper limit for successful spawning, incubation, and emergence. Therefore, a daily maximum rather than a 7 day moving average should be considered.

   B. All appropriate habitat and periods of spawning, incubation, and emergence must be identified. If the designations are too narrowly applied or incorrectly applied, species persistence may be at risk.

   C. Increased monitoring for susceptibility to criterion. Very little existing data.

2. The temperature criterion for bull trout is likely to adversely affect this species.

   A. Migration corridors were not explicitly incorporated.

   B. Review spawning and incubation criterion of 10^{0}C - concern that early spawners will not be adequately protected.

3. The temperature criterion for rearing is likely to adversely affect T & E species.

   Remember that the criterion for rearing is 17.8^{0}C except in the mainstem Columbia and lower Willamette where it is 20^{0}C.

   A. 17.8^{0}C and 20^{0}C thresholds expose these organisms to temperatures resulting in mortality via sublethal and lethal mechanisms (e.g., reduced disease resistance; reduced ability to compete and to avoid predators, altered run timing, decreased reproductive success). Whether lethal or sublethal mechanisms the result is mortality. Preferred temperatures are 10^{0}C to 15^{0}C.

      Cross-over temperature (warm water - cold water ecotone) of 17^{0}C. Additionally, maximum rather than average temperatures appear to be better predictor of species distribution.

      Furthermore, this criterion in not protective of these species during adult migration, adult holding prior to spawning, and smoltification and juvenile emigration. These are critical and sensitive LH stages. Preferred temperatures occur at approximately 15^0C. Issue of hidden mortalities.

4. The concept of diel fluctuation is important in establishing temperature criteria. Usually standards acknowledge fluctuating or intermittently elevated temperatures. To address this phenomenon, the criteria are typically measured as an average such as Oregon=s A7 day moving average of the max.@

   However, there are two important points to consider:

   1 - although diel temperature fluctuation is a natural phenomenon, disturbed systems may show a pronounced diel cycle (a 100% increase).

   2 - organisms exposed to exaggerated diel fluctuation respond negatively with physiological and behavioral changes.

   3 - a temperature criterion set at a sublethal and/or lethal level in combo with a measurement unit that allows averaging will expose organisms to even higher temperatures, potentially large diel swings, and does not account for cumulative thermal history.

5. Studies have shown that salmonids respond to max diel fluctuation (distance between daily max and min temperatures), max daily temperatures, mean daily temperatures, mean monthly temperatures, and cumulative thermal history through physiological and behavioral changes.

   Given these findings, numeric temperature criteria should be established below demonstrated sublethal temperature ranges.

   Temperature units (7day moving average) that mask or allow excursions above sublethal effects thresholds or that do not adequately consider cumulative exposure history should not be used.

6. Shifts in the timing of temperature change within a river (i.e., phase shift) may generate a cascade of changes affecting the successful completion of LH stages. This phase shift of riverine temperatures should be evaluated in conjunction with single maxima.

7. The standard rests on DEQs ability to accurately locate spawning, incubation, and rearing locations for salmonids as well as to define the timing associated with spawning and incubation.

   Of concern is the representativeness, completeness, and accuracy of the stream and salmonid data. Use of data to make designations, incomplete surveys of locations and timing, incomplete data collection for water quality standards.

8. A. The maintenance and restoration of spatially diverse, high quality habitats that minimize the risk of extinction is key to beneficial use support of cold water species. As temperature defines species distribution, restoration of thermal regimes over large geographic areas is important to species recovery/persistence.

Therefore, areas of historical species distribution should be identified and restored. Additionally, cold water systems and remnant patches and refugia should be protected (antidegradation policy) .

B. Refugia and the role of habitat in mediating adverse thermal conditions.

This is a very complex issue. We know that land use activities through increases in ambient water temperature can increase the importance of cold-water refugia. However, we believe that in certain systems and for certain species that cold water refugia have always played a role and have increased or decreased in importance depending on annual climate.

There are several points to keep in mind:

A. Refugia may occur at various scales and may expand or contract depending on controlling variables for ex. annual variation in climate.

Micro habitat features such as deep pools or area of upwelling as well as macro-habitat such as reaches, tributaries, watersheds, subbasins, as well as basins.

B. Refugia may only be accessed during unfavorable conditions - therefore presence/absence of certain species may not be appropriate.

Land use actions may affect refugia distribution, abundance, and accessability. Land use patterns may actually appear to generate Arefugia@ or they may eliminate them. Land use certainly increases the importance of these systems in all landscapes. Therefore, short-term restoration actions should identify and maintain these areas.

Although refugia may be critical habitat elements, they do not rid us of the need to address water quality standards for temperature.

Why:
1. Importance of annual thermal regimes e.g., phase shifts

2. The reduction of overall distribution is not due solely to the loss of micro-habitat e.g., pools. It has to do with the matrix of high quality, connected segments of the system.

Refugia may actually represent remnant contiguous cold water habitat and therefore regulation would only protect remaining habitat - no restoration.

3. With an overall decrease in accessible, suitable habitat, remaining areas may become increasingly crowded, this may in turn lead to an increase incidence in disease.

Also, a limited number of available refugia may decrease the time spent at lower temperatures for any one organism thereby increasing the time spent at or above sublethal thresholds.

4. Refugia are maintained by processes affected by land use. Therefore, it is likely that they too are negatively affected by land use. Additional research is needed.

Refugia must still be accessible, thermal blocks.

5. Historical importance may vary by species and ecoregion.

6. In an unmanaged system, refugia may not be stable elements of the landscape - role of natural disturbance. Therefore, one cannot regulate solely for an unstable element.

We need more information on these issues, but the most expedient tack to take includes:

1. Short-term protection of remaining remnant habitat and refugia including landscape elements that contribute to subsurface flows e.g., wetlands, unstable slopes, alluvial fans and other alluvial features such as islands and off-channel habitats.

2. Develop a temperature standard that reflects the biological needs of these species and our current understanding of thermal variability in the environment

3. Restore processes creating and maintaining aquatic habitat including those affecting temperature.

4. Increase our understanding of refugia and their role in various landscapes, the effect of land use on refugia creation, maintenance, and loss, and the movement and habitat use of native fishes in response to thermal changes.

5. Monitor/research - We would like assistance from universities and research institutions!

6. Revise the standard based on additional information.

In the near-term we will be focusing on the following areas:

a) physiological and behavioral responses to thermal regimes,

b) species distribution, pattern, and movement in relation to annual or seasonal thermal regimes

c) the role of landscape context, complexity and connectivity in mediating thermal exposure

d) potential site-specific situations and requirements including data needs.

e) appropriate monitoring and measurement approaches as well as diagnostic indicators for degradation.

f) appropriate approaches to thermal restoration of riverine systems.

Habitat Based Indices: Oregon=s Healthy Streams Initiative:

The State of Oregon will introduce a healthy streams initiative to define characteristics of functioning riverine systems supporting native biota. There is some discussion that these characteristics or criteria will replace a temperature standard.

Although temperature is a component of Oregon=s initiative, EPAs effort will focus on the thermal requirements of native salmonids and the landscape elements and processes important to maintaining an intact thermal environment. It is our understanding that Oregon will focus on current landscape condition, instream indicators, and constraints to thermal recovery.

Based on current research, the state=s approach and intended products raise red flags. It appears that the state will likely develop an index of good, moderate, and poor habitat based on instream parameters and pre-determined values or targets. Where a stream (i.e., reach) is Agood@ or Amoderate@ based on a habitat index, stream temperatures above the state standard would be interpreted as Anatural.@ Studies such as conducted in the Salmon River Basin illustrate the difficulties in developing numeric objectives for habitat parameters without appropriate landscape and stream network stratification as well as calibration based on empirical data.

There are other issues that must be addressed as well:

(1) Complexity may be described at different scales including habitat complexity.

Often we talk about the complexity of a stream reach including the number of deep pools, large woody debris, and stream width to depth ratio. All of these parameters may be described at some perceived optimum and we can conclude that the reach is performing functions that fully support native salmonids. However, we must also look at larger scale units such as watersheds or basins.

It is critical that we take this view in order to credibly evaluate salmonid persistence. At larger spatial scales, we are looking at more than the accumulated number of pools or wood in a system. Instead we=re looking at the availability and accessability of suitable resource conditions as they vary across the basin and over time.

So, when we describe the thermal environment in riverine systems, we are ultimately looking at the pattern, distribution, and connectivity of this environment as well as the processes and key landscape elements that shape and maintain this environment.

Therefore, a description of number of pools, LWD frequency, and W:D may not adequately reflect the spatial and temporal needs of aquatic species including their thermal requirements.

(2) We are looking at the annual thermal regime rather than a single point - again an issue of scale, but we need to address annual thermal requirements and issues surrounding the effects of phase shifts.

(3) Temperature reflects the functioning of processes operating at different scales as such temperature is an integrator of the landscape - temperature reflects conditions at a site but is also a product of cumulative actions in the system. Water temperature changes relatively slowly resulting in a long travel distance before temperature stabilizes. Temperature increase may originate several miles upstream from a given sample site. As physical habitat is restored within a reach, a time lag for temperature recovery may occur.

(4) A riverine system is a palette containing a variety of temperatures and habitat types shaped by natural disturbance regimes - salmonids are capable of maximizing time spent at or near optimal conditions including temperature (behavioral thermoregulation - 0.05^0C).

In the long-term, connectivity and re-establishment of annual thermal regimes should be restored. In the short-term, fragmented remains of contiguous cold-water habitat as well as thermal refugia must be secured from further degradation. It is important however that we do not rely on the remaining fragments of cold water to preserve these species. Natural disturbances will continue to occur, and the full range of these species provides a hedge against the loss of any single population. Restoration priorities and the sequencing of actions should be based on an understanding of basin-scale complexity, diversity, and connectivity as well as refugia.

(5) Finally, I would make a case for the use of biological date (both threshold data as well as life history data) to point to those temperatures necessary for species survival. There is a high degree of consistency among the Pacific salmon and thermal requirements. The

range of greatest preference by all species of Pacific salmon is 12^0C to 14^0C for acclimation temperatures ranging from 5^0C to 24^0C. Additionally, there is a general avoidance of water over 15^0C. For bull trout, we are finding that somewhat cooler temperatures are required. However, as with other salmonids preferences may vary by life history stage. For the non- anadromous westslope cutthroat and redband trout further information is required. As human alteration to the environment is pervasive, as there may be a time lag between various stages of physical habitat restoration and thermal restoration, and as our ability to accurately model stream temperature is low, biological information is critical in standards development.

(Models -OSU experience - landscape-scale, hyporheic networks including wetland systems, hydraulic complexity in unmanaged systems is related to temperature profile).

That does not mean that we do not need further investigation of habitat use by salmonids (i.e., species movement and habitat use relative to temperature), characterization of diverse thermal regimes to understand spatial and temporal variability of thermal environments, or increased understanding of the processes affecting stream temperature or the translation of that understanding into the development of models.

There is much to be gained from this type of forum. I look forward to working with all of you in the future.

Empirical evaluation of temperature and bull trout distribution across the Columbia River Basin.

Bruce Rieman, USDA Forest Service Rocky Mountain Research Station

A collaborative approach involving biologists throughout the bull trout range was successful in generating a large data set on temperature and bull trout distribution. Verification of observations and methods is in progress, but preliminary results show that the current data provide a broad representation of the species' potential distribution that should also encompass a broad range of environmental and ecological conditions. We believe the completed data set will provide a new and generalizable picture of the temperature regimes characteristic of suitable bull trout habitats. Preliminary 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 8 -10 C or with summer maximums less than about 14 C . These values are similar to existing observations associated with rearing and habitat preference. Although the larger data set should help refine estimates of critical temperatures for bull trout it should also provide an important context of the spatial and temporal variation in temperature associated with bull trout habitats. Models of occurrence across a broad range of environments might be particularly useful in describing the expected suitability of different temperatures given the uncertainty in other ecological conditions.

Rock Creek Bull Trout Telemetry Study: First Season Report

Gary Carnefix, and **Chris Frissell**, University of Montana

A radio telemetry study of bull trout (*Salvelinus confluentus*) in the Rock Creek drainage (tributary to Clark Fork near Clinton, MT) was begun in March, 1998 in conjunction with water temperature profiling, instream and riparian habitat characterization via aerial photos, and compilation of information on biophysical parameters. The goal of the study is to examine possible correlations between the telemetry data on movement and microhabitat use, and the temperature, habitat characterization, and biophysical data. These results will provide important baseline information on the current status of bull trout in the Rock Creek drainage, as well as a basis for decisions on future research, habitat conservation/restoration activities, and management, including bull trout recovery efforts.

First season tagging efforts were much more successful in the upper 3 sections than in the lower 2 sections of Rock Creek, resulting in a quite uneven distribution of the sample. Second season efforts are nearly complete and were much more successful in the lower reaches than the first season's efforts. Of the tagged fish that either expelled transmitters, died, or were lost to contact; we found evidence suggesting predation in 6 cases. There was an apparent "pulse" in mortalities in the period following spawning activity. 3 tagged bull trout migrated past suspected barriers to areas where spawning had been considered doubtful or of limited importance. As a result, Forest Service personnel were able to adjust redd survey efforts and verify some previously undocumented spawning areas. Movements of tagged fish into tributaries seemed to occur in 2 phases: earlier, during high runoff and not apparently related to spawning; and later, seemingly related to spawning. We hope second season data and in-depth analysis of first season data will provide further insight into this first phase of movements. Some evidence of a pattern of lower-middle reach fish migrating to lower-middle reach tributaries, and middle-upper reach fish migrating to middle-upper tributaries is apparent in the first season movement data, but should be viewed with caution due to the very uneven distribution of sampling success in the first season. A second season of data from a much better-distributed sample should allow us to evaluate whether this apparent pattern is real and, if so, how strong it is. If this pattern holds, analysis of temperature data may allow us to test the hypothesis that mid-summer thermal barriers might limit connection of mainstem adult habitat with distant spawning habitat. Finally, tagging of several apparent bull trout x brook trout (*Salvelinus fontinalis*) hybrids has the potential to lead us to unknown hybridization "hot spots".

Preliminary Investigations of Air and Water Temperature Relationships in the Upper Missouri River Basin, Montana

Matt Sloat, Montana State University; **Brad Shepard**, Montana Fish, Wildlife and Parks and Montana State University; **Daniel Goodman**, Montana State University

Interest in the role of temperature in limiting salmonid distributions has increased because of the relegation of native salmonids to headwater streams and because of concerns of global warming. Stream temperature is assumed to be highly correlated with air temperature. We investigated the ability of a model developed by Keleher and Rahel (*Trans. AFS*, 1996) to accurately predict ambient air temperature in the Upper Missouri River Basin, as well as the correlation between predicted air temperatures and observed stream temperatures. The Keleher and Rahel (KR) model is a regression relation between latitude, elevation and mean July air temperature in the Rocky Mountain region. Correlation between predicted mean July air temperatures and observed mean July air temperatures collected from 65 climate sites in southwestern Montana was moderate and significant ($r^2 = 0.498$; $P < 0.001$). Correlation between predicted mean July water temperature and observed mean July stream temperature collected from 33 sites was weaker, but remained significant ($r^2 = 0.377$; $P < 0.001$).

The KR model may be correlated with actual air and stream temperatures but the accuracy of the model needs to be enhanced to the level of biological meaningfulness. Correlation with observed temperatures may improve with the addition of more sites, as well as replication across years. However, the KR regression relation between latitude, elevation and air temperature may cover too large a climatic gradient. Local air and stream temperature relationships may differ fundamentally within the Rocky Mountain region. Additional variables such as stream size, aspect, groundwater influence and riparian vegetation types are important factors affecting stream temperatures. Mean July air temperature also may not be the most meaningful measure of the thermal characteristics species encounter. Seasonal and diurnal variation, as well as time of exposure to critical temperatures may be equally important.

We propose to model stream temperatures in the Upper Missouri River Basin as a function of air temperature, stream size, and groundwater influence, by adopting the strategy of Jourdonnais et al. (*Rivers*,1992). This approach models the rate of change of temperature in a "parcel" of water as an approach-to-equilibrium process and is conceptually represented by the equation: $dT(t) / dt = k[T(eq)-T(t)]$
where t is time, T(t) is the temperature of a "parcel" of stream, T(eq) is the equilibrium temperature for the parcel in that environment, and k is a rate coefficient determining the rate of approach of temperature to equilibrium. Coefficient T(eq) will vary with air temperature, while coefficient k will vary with stream size, groundwater influence. We will build our model with extensive sampling of longitudinal temperature profiles in the Madison River drainage and calibrate it with additional sampling of stream temperatures throughout the Upper Missouri River Basin.

Developing an Integrated Framework for Defining the Influence of Stream Temperature on Lahontan Cutthroat Trout

Jason Dunham, **Robert Schroeter**, **Lee Weber**, **Mike Meeuwig**, University of Nevada-Reno; **Bruce Rieman**, USDA Forest Service Rocky Mountain Research Station

Lahontan cutthroat trout is a threatened subspecies endemic to the Lahontan basin of northeast California, southeast Oregon, and northern Nevada. It is estimated that Lahontan cutthroat trout presently occupy about 10.7% and 0.4% of historically occupied stream and lacustrine habitats, respectively (Coffin and Cowan 1995, *USFWS Recovery Plan*). This dramatic reduction in the range of Lahontan cutthroat trout has led to extensive habitat fragmentation, which has been quantitatively identified as a major threat to the viability of stream-living populations (Dunham et al. 1997, *NAJFM*).

Fragmentation of stream habitats has been linked to the influences of several factors, including habitat destruction, non-native salmonids, and water diversions and dams (Coffin and Cowan 1995). Recent analyses of distribution limits of Lahontan cutthroat trout in streams of the eastern Lahontan basin (where most extant populations are found) have suggested strong influences of both climate and non-native salmonids on the amount, distribution, and fragmentation of suitable habitat (Dunham et al. 1999, *TAFS*). Distribution limits were found to closely parallel regional clines in mean July air temperatures (Keleher and Rahel 1996, *TAFS*), suggesting that climate and stream temperature may be important (Dunham et al. 1999).

Further evidence supporting the importance of temperature is provided by laboratory studies. Recent study of thermal tolerance of Lahontan cutthroat trout suggests an upper incipient lethal temperature that lies between 23-26^{o}C. Major growth inhibition was found to occur at 23-24^{o}C (Dickerson and Vinyard 1999, *TAFS*), which corresponds exactly with the temperature at which Lahontan cutthroat trout begin to synthesize heat shock proteins (Weber, unpublished data). Heat shock proteins are a major indicator of physiological stress in vertebrates. Because water temperatures in potentially occupied habitats frequently exceed 23^{o}C, restoration of cool water habitats is one of the major challenges facing recovery of Lahontan cutthroat trout.

Results of this landscape and laboratory research motivated an analysis of the effects of temperature on the distribution of Lahontan cutthroat trout within streams. The stream temperature monitoring project utilizes inexpensive digital temperature dataloggers to continuously monitor stream and air temperatures in habitats occupied by Lahontan cutthroat trout. Over 150 dataloggers were deployed in over 13 Lahontan cutthroat trout streams in 1998 using a standardized protocol. The locations of these streams encompassed the majority of the geographic range of Lahontan cutthroat trout in the eastern Lahontan basin.

The primary goal of the stream temperature monitoring project is to characterize temperature (air and water) regimes in habitats occupied or not occupied by Lahontan cutthroat trout to develop probabilistic models of fish occurrence. Several different temperature metrics are being considered. We have summarized daily and weekly mean, variance, maximum, and minimum air and water temperatures in occupied and unoccupied habitat. Temperature data also are summarized to provide information on cumulative daily and weekly exposure of Lahontan cutthroat trout to warm water temperatures. Preliminary analysis of the data suggests significant differences in the ability of these different temperature metrics to discriminate occupied and unoccupied habitats.

Preliminary data from 1998 confirmed the strong effect of stream temperature on occurrence of Lahontan cutthroat trout. Results of this work agree closely with laboratory studies of thermal tolerance and heat shock protein induction experiments. In all except one stream surveyed, Lahontan cutthroat trout occurrence appeared to be tied strongly to maximum summer water temperatures of less than 26^{o}C. Continued monitoring of stream temperatures will be conducted in 1999 to confirm this result.

The single exception to this result occurred in a translocated population of Lahontan cutthroat trout found in Edwards Creek, Nevada. In this stream, Lahontan cutthroat trout distribution appeared to be constrained by maximum summer water temperatures of less than 19^{o}C. This pattern appeared in the upstream reaches of Edwards Creek, where increasing temperatures at lower elevation sites correspond with a downstream distribution limit, and again downstream where a large spring discharge produces a transient cooling in stream temperature. Fish occupied habitat within the plume of cool water discharged by this spring, but downstream temperatures rapidly increase and warmer habitats were once again unoccupied.

The difference in thermal response between Lahontan cutthroat trout found in Edwards Creek and other stream-living populations may be explained by the influence of other factors, such as food supply, that may affect selection of thermal habitat by fish. A more detailed description of environmental conditions in this stream will be needed to eliminate alternatives.

A second possibility is that Lahontan cutthroat trout in Edwards Creek are genetically distinct from other populations studied in the stream temperature monitoring project. It is suspected that Lahontan cutthroat trout in Edwards Creek were established by transplants of fish from Pyramid Lake before the original native stock of cutthroat trout was extirpated in the 1940s (M. Sevon, Nevada Division of Wildlife, personal communication).

Pyramid Lake is a deep (>100 m) terminal lake located at the mouth of the Truckee River in northwest Nevada. Presumably in summer, cutthroat trout in Pyramid lake had access to cooler hypolimnetic habitats and were able to avoid stress from exposure to warmer surface temperatures. It is possible therefore that cutthroat trout in Pyramid and other deep lakes may have evolved in a thermal environment that differed dramatically from many stream or shallow lake habitats, particularly those in the warmer deserts of the eastern Lahontan basin.

The diversity of habitats and thermal environments currently or historically occupied by Lahontan cutthroat trout include small desert streams, larger rivers draining the eastern Sierra-Nevada range, high-elevation oligotrophic lakes, and lower-elevation eutrophic lakes. Therefore, it seems reasonable to assume different populations may have experienced a variety of different selective pressures. This diverse ecological context may have provided a selective arena favoring local adaptation of some populations.

This work forms part of a larger effort to more define critical limiting factors for imperiled inland salmonids (including our work on bull trout *Salvelinus confluentus*, and westslope cutthroat trout, *O. c. lewisi*), and implications for these species at individual, population, metapopulation, and regional levels of organization. Our understanding of the influence of temperature on fishes at these different spatial and temporal scales will provide the basis for developing an integrated framework for defining the influence of stream temperature on imperiled inland salmonids.

Temperature Requirements for Threatened Bull Trout from the Pacific Northwest

Jason Selong, **Thomas E. McMahon**, Montana State University; **Frederic T. Barrows**, U.S. Fish and Wildlife Service, Bozeman Fish Technology Center; **Alexander V. Zale**, Montana State University

Although widely regarded as having among the most stringent requirements for cold temperatures among salmonids, specific thermal requirements for survival and growth of threatened bull trout are unknown. Such data are critical to develop and evaluate thermal criteria for land management and reintroduction programs. We conducted long-term (60 d) experiments of survival and growth of juvenile bull trout at 12 constant temperatures ranging from 7.5 – 26 C. Survival of test fish was ≥98% at temperatures of 7.5-18 C. However, no fish survived test temperatures of 22, 24, and 26 C. Time to 100% mortality was 24 hr at 26 C, 10 days at 24 C, and 38 days at 22 C. Seventy-nine percent of test fish survived for 60 d at 20 C, suggesting that the upper incipient lethal temperature for juvenile bull trout is between 20 and 22 C. Maximum growth occurred at 12 C, and declined sharply at temperatures ≤10 and ≥ 18 C. Fish held at temperatures ≥ 16 C displayed elevated incidence of jaw and ventral sores indicative of reduced osmoregulatory function. Bull trout optimal growth and upper lethal temperatures are lower than co-ocurring brook trout, rainbow trout, and brown trout, suggesting a possible mechanism for replacement of bull trout by these nonnative salmonids, and for the high degree of isolation of remaining populations.

Summary of Discussion Topics

J. B. Dunham

Six major topics were identified for discussion during the second day of the workshop. These included:

1) Sampling issues with temperature dataloggers
2) Selection and definition of temperature metrics or numeric criteria
3) Fish occurrence at unusual temperatures and probability
4) Larger-scale issues
5) Collaborative opportunities
6) Regional databases

I attempted to summarize (with some embellishment) the discussions on Topics 1-4. Little time was available to do proper justice to Topics 5 and 6, so they are not discussed herein. It is clear, however, that the issues covered here are complex and multifaceted, and can only be addressed rigorously in a collaborative context.

The issue of regional databases (Topic 6) was briefly touched upon, but it was agreed (in part) that a more comprehensive protocol for quality assurance and control (see Topics 1 & 3) was needed, as well as a quantitative statement of the goals and/or objectives of such an effort. Definition of these goals may depend in part on developments in the first four Topics.

Topics #1 and 3. Sampling issues with temperature dataloggers

The group identified several sources of sampling error that may occur with use of digital temperature dataloggers:

1) <u>Instrument error:</u> Precision of temperature measurements usually reported by manufacturers is within $\pm 0.5^{o}$C, and different models have varying levels of precision, depending on cost. Bias in temperature measurements can be corrected by ice bath calibration or by use of standardized thermometers (e.g. National Institute of Standards and Testing, NIST). Calibration may be performed prior to deployment or immediately after retrieval of instruments from the field. A combination of both pre- and post-calibration may be preferable if instrument readings tend to drift over the time period. Regular battery changes also may help reduce instrument error.

2) <u>Casings:</u> Protective instrument casings may affect temperature readings. Color may be important. Clear casings may act as miniature greenhouses and produce erroneously high readings. More reflective casings (e.g. white or metallic) should be preferred. Conductivity of the casing material (including the insulating air layer within the casing) may affect temperature readings and time lags between measured temperature and actual temperature.

3) Sampling within sites: Dataloggers should be placed out of direct sunlight whenever possible. Vertical or lateral thermal stratification or heterogeneity should be carefully investigated with a hand-held thermometer before installing dataloggers, unless this is the objective of the survey. Water depth may affect the degree of heating by dataloggers (A. Herlihy, EPA-Corvallis, personal communication). Microsites with good mixing (e.g. turbulent flow) and relatively deep water should be preferred (unless study objectives are to quantify small-scale variation). Dataloggers should not be in contact with stream substrate to avoid heat conduction.

4) Sampling within reaches or streams: If many dataloggers are to be arrayed to describe thermal patterns within whole streams or reaches, careful site selection (see above) and stratification of sampling may needed. Information from remote sensing, such as Forward-Looking Infrared Videography may be useful for designing temperature surveys. Otherwise careful manual surveys with hand-held probes is recommended.

5) Sampling interval: Programming of dataloggers can be employed to measure temperatures at widely varying intervals. Recent work compared temperature metrics calculated from measurements taken at 15 minute intervals (96 readings per day) to random subsamples taken from 4 evenly spaced measurements (6 hour intervals). The absolute error for metrics ranged from 0.0 to 0.03 ^{o}C, and was greatest for summer maximum temperatures (B. Rieman, personal communication). Sampling error resulting from longer sampling intervals will likely increase as diurnal variation in temperatures increases, so site-specific calibration may be required.

6) Error detection: Several filters have been used to check the quality of data from digital dataloggers. The Rocky Mountain Research Station (B. Rieman, personal communication) used numeric filters to identify observations that were potentially incorrect. These included temperatures > 30 ^{o}C or < -1.0^{o}C (water temperatures deemed unlikely to be exceeded in the study area); or series of observations with rates of change greater than 3 ^{o}C per hour, which was the maximum rate of change observed with previously verified data in the study area. Observations within the upper or lower 5% of the total distribution of temperatures also were flagged as potential errors or outliers. Verification of these records involved inspection of temperature time series and contacts with field personnel responsible for datalogger deployment. At the University of Nevada (J. Dunham and R. Schroeter, unpublished data), visual inspections of temperature time series and comparison with matched air temperature records were employed to validate observations. Replicate dataloggers also may provide useful information on error rates. This may be feasible given the low cost of dataloggers relative to travel and personnel costs associated with stream temperature sampling. Field checks with NIST calibrated thermometers also may be useful, if travel to sampling sites is not too expensive. Standardized procedures for quality control are needed.

7) <u>Correspondence between fish and temperatures:</u> When assessing correspondence between fish habitat use and temperature, it is critical to ensure that temperature and fish data correspond as closely as possible in space and/or time. It also is important to think about the relative condition of fish exposed to thermal regimes, and to the relative *probability* of fish using habitats with differing thermal regimes. For example, point observations of fish in unusually warm temperatures must be interpreted cautiously. Occurrence of fish in "unusual" thermal conditions may indicate something unusual about the fish themselves.

Topic #2. Selection and definition of temperature metrics or numeric criteria.

The group briefly considered this topic and outlined several considerations in selection of numeric temperature criteria or temperature metrics.

1) Sensitivity to measurement error. The selected metric should be robust to the types of errors described above (Topics # 1 & 3).

2) Biological relevance. The metric must incorporate important information on biological responses of interest (e.g. time to death, growth rate, migration timing, emergence, etc.).

3) Sensitivity to varying conditions. Of particular concern was the practice of extrapolating laboratory results to field situations. A good temperature metric would incorporate information from both.

4) Covariation among metrics. How closely do different temperature metrics covary? E.g. Maximum, minimum, average, variance, range, cumulative exposures, summarized at daily, weekly, monthly, seasonal, and annual time scales? Can one metric be substituted for another? How comparable are they?

5) Life history stage. How do different temperature metrics perform for different life history stages or requirements? How much overlap is there?

Quantitative studies to address these questions are lacking, and would provide important insights for improvement of numeric criteria and selection of appropriate temperature metrics.

Topic #4. Larger scale issues.

The group identified a need for understanding thermal characteristics of stream habitats at a larger spatial scale. Numerous site-specific models have been used to simulate thermal characteristics of streams and to predict the effects of land use changes or habitat manipulation. These models are useful at small scales, but limited in scope because they are data and labor intensive. Furthermore, this approach is logistically impossible to apply to all stream habitats of concern.

A broader perspective on stream temperatures and thermal potential that incorporates information on large-scale controls may provide a useful context for understanding local thermal regimes. Classification of stream habitats based on information from these large-scale controls may help to prioritize smaller-scale assessments of stream temperature. Information on available stream temperature data on large-scale controls, such as topographic shading, geomorphology, groundwater sources, geographic location, basin size, elevation, climatic patterns, etc., may provide a basis for defining stream basins with common thermal characteristics. These groups may be defined geographically or purely from individual landscape characteristics.

Information from larger-scale controls should be linked quantitatively to fish distributions and site-specific temperature criteria. In essence, the issue of stream temperature and salmonids should take the form of both a coarse and fine-filter approach. Until recently, the focus has been almost exclusively on a fine-filter approach. An approach that is capable of integrating information on multiple spatial and temporal scales is needed.

List of Participants

Berman, Cara	Environmental Protection Agency	1200 6th Ave, ECO-086, Seattle, WA 98101	berman.cara@epa.gov
Carnefix, Gary	University of Montana	115 Turner ct. #3, Missoula, MT 59802	carnefix@selway.umt.edu
Danehy, Bob	Boise Cascade	P.O. Box 50, Boise, ID	bdanehy@bc.com
Dunham, Jason	University of Nevada	UNR - 1052 SW Western Boulevard, Corvallis, OR 97333	jdunham@proaxis.com
Frissell, Chris	Univeristy of Montana	Flathead Lake Biological Station, University of Montana, 311 Bio Station Lane, Polson, MT 59860	frissell@selway.umt.edu
Gamett, Bart	Idaho State University	34 USU Aggie Village, Apt. E., Logan, UT 84341	slggl@cc.usu.edu
Goodman, Daniel	Montana State University	Biology Department, Montana State University, Bozeman, MT 59717	goodman@rivers.oscs.montana
High, Brett	Ricks College	Dorm II, Ricks College, Rexburg, ID 83604	highbret@isu.edu
Jensen, Mark	USDA Forest Service	USFS, Regional Office, Missoula, MT 59807	mjensen/r1@fs.fed.us
Martin, Don	Environmental Protection Agency	EPA - 1435 N. Orchard Ave, Boise, ID 83706	martin.don@epa.gov
McMahon, Tom	Montana State University	Montana Cooperative Fisheries Research Unit, Montana State University, Bozeman, MT 59717	ubitm@montana.edu
Meeuwig, Mike	University of Nevada	Department of Biology/314 University of Nevada, Reno, 89557	mhmeeuwi@scs.unr.edu
Rieman, Bruce	USDA Forest Service	Rocky Mountain Research Station, 316 E. Myrtle, Boise, ID 83702	brieman/rmrs_boise@fs.fed.us
Schroeter, Robert	University of Nevada	2851 Seine Avenue, Davis, CA 95616	RSCH5146@aol.com
Selong, Jason	Montana State University	Montana Cooperative Fisheries Research Unit, Montana State University, Bozeman, MT 59717	jselong@yahoo.com
Shepard, Brad	Montana State University	Biology Department, Montana State University, Bozeman, MT 59717	fwpbs@montana.edu

Sloat, Matt	Montana State University	Biology Department, Montana State University, Bozeman, MT 59717	msloat@montana.edu
Stowell, Rick	USDA Forest Service	P.O. Box 7669, Missoula, MT 59807	rstowell/rl@fs.fed.us
Ulmer, Linda	USDA Forest Service	P.O. Box 7699, Missoula, MT 59807	lulmer/r1@fs.fed.us
Weber, Lee	University of Nevada	Department of Biology/314 University of Nevada, Reno, 89557	weber@med.unr.edu
Zale, Al	Montana State University	Montana Cooperative Fisheries Research Unit, Montana State University, Bozeman, MT 59717	zale@montana.edu