INDEPENDENT MULTIDISCIPLINARY SCIENCE TEAM (IMST)

State of Oregon

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May 7, 2004

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Enclosed is Technical Report 2004-1, the Independent Multidisciplinary Science Team's (IMST) report entitled "Oregon's Water Temperature Standard and its Application: Causes, Consequences, and Controversies Associated with Stream Temperature".

This report was written to fulfill former Governor John Kithzaber's and the State Legislature's request to review the scientific basis of Oregon's water quality standards for temperature. To accomplish this goal, we discuss the answer to science questions that the Independent Multidisciplinary Science Team (IMST) deemed to be relevant to this charge and important to accomplishing the goals of the Oregon Plan for Salmon and Watersheds. While this request was initiated based on concerns surrounding the 1996 temperature standards, the discussions in this report are completely applicable to the recently adopted 2003 temperature standards. Our primary focus was "non-point" sources of elevated temperature in streams and cumulative sources from across Oregon's landscape.

The IMST reviewed scientific literature, and scientific reviews concerning temperature effects on salmonids, how land uses and changes to watersheds can affect stream temperatures, the use of temperature models in the TMDL process and the Heat Source model used by Oregon Department of Environmental Quality. As with all IMST reports, this report results from evaluation of the best available science. The report has been subjected to intense technical review by 19 scientists and agency representatives. The final report was adopted with full consensus of the Team at our March 10, 2004 meeting.

The IMST was concerned that the debate among the public, natural resource managers, agencies, politicians, and scientists in Oregon has obscured the areas of agreement and disagreement regarding elevated temperatures and this has created confusion within many of the groups. While preparing this report we developed a stand alone section called *Straightforward Answers to Straightforward Questions* to help Oregonians better understand the issues surrounding water temperature and how our collective actions can protect and restore the natural resources of the state.

In this report the IMST lists several conclusions based on the report and makes eight recommendations to the State and its agencies.
In general, the IMST finds:

- That the scientific basis for Oregon's temperature standards is credible and is consistent with the body of scientific literature on the thermal requirements of Oregon's native salmonids.
- The temperature model, Heat Source, used by the State of Oregon is scientifically sound.
- Oregon's TMDL process is conducted at the basin scale, which is consistent with a landscape approach.
- Human activities can affect stream temperature by modifying channel morphology, streamflow, surface/subsurface water interactions, and riparian vegetation.
- Riparian vegetation can reduce stream heating, can influence temperatures by blocking incoming solar radiation, and maintain channel morphology and functioning floodplains. Riparian vegetation has direct and indirect impacts on stream temperatures.

Because there is widespread confusion and controversy among the public, resource agencies, and scientists, the IMST recommends that the Oregon State University (OSU) Extension Service and relevant state agencies develop a coordinated education and information distribution system for citizens, watershed councils, and special interest groups on the topic of elevated stream temperatures.

Recommendations are directed at one or more State of Oregon agencies or entities that the IMST believes have the ability to implement, or to affect changes in management or regulation that are needed for implementation. Senate Bill 924 requires the designated agencies to respond to each IMST recommendation. Agencies are expected to respond to the Oregon Plan Manager and IMST within six months of the release of the report. IMST then evaluates the responses for scientific merit and forwards the evaluations to the responding agency and to Jim Myron, Governor's Natural Resource Office.

In making its recommendations, the IMST did not consider the *current* legal, regulatory, or funding situation under which the responding agencies operate; nor does the IMST imply any sort of "performance evaluation" associated with these agency assignments. The IMST's responsibility is to identify issues that we believe are critical to the health and recovery of salmonids, and to advise the State of Oregon. While agency response may, under some circumstances, be that there is no legal authority and/or funding to implement certain recommendations, the IMST believes that these recommendations should be incorporated into long-range planning and impediments to implementation removed.

We hope that this report will be helpful as work on the Oregon Plan for Salmon and Watersheds continues.

Sincerely,

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Co-Chair, IMST

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Oregon’s Water Temperature Standard and its Application: Causes, Consequences, and Controversies Associated with Stream Temperature

A report of the Independent Multidisciplinary Science Team, Oregon Plan for Salmon and Watersheds

Technical Report 2004-1

May 7, 2004

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Citation: Independent Multidisciplinary Science Team. 2004. Oregon’s Water Temperature Standard and its Application: Causes, Consequences, and Controversies Associated with Stream Temperature. Technical Report 2004-1 to the Oregon Plan for Salmon and Watersheds, Oregon Watershed Enhancement Board, Salem, Oregon.

ACKNOWLEGEMENTS

The IMST thanks Ellen Deehan, Leah Gorman, Kathy Maas-Hebner, Cathleen Rose, and Randy Wildman for their contributions to writing and producing this report. We are grateful to Glenda Serpa for her administrative support in the production of the report. Our draft report received technical review by Mack Barrington, Cara Berman, Mike Borman, George Brown, Bob Beschta, Jason Dunham, Sherri Johnson, Rick Kepler, Larry Larson, Jeff Lockwood, Bill Krueger, Hiram Li., Dale McCullough, Ron Miner, Debra Sturdevant, Ken Tate, and Mike Unsworth. Brian Kasper, Ken Rodnick, and Laura Van Riper also provided helpful comments on sections of the report. Matt Boyd provided detailed information on the Heat Source model.

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LIST OF ACRONYMS AND ABBREVIATIONS

7DADM – Seven day moving average of daily maximum temperature
AgWQM – Agricultural Water Quality Management
BLM – (United States) Bureau of Land Management
DEQ – Oregon Department of Environmental Quality
EPA – (United States) Environmental Protection Agency
FLIR – forward looking infrared radiometer
IMST – Independent Multidisciplinary Science Team
NOAA – National Oceanic and Atmospheric Administration
NMFS – National Marine Fisheries Service (NOAA Fisheries)
NRC – National Research Council
OAR – Oregon Administrative Rule
ODA – Oregon Department of Agriculture
ODF – Oregon Department of Forestry
ODFW – Oregon Department of Fish and Wildlife
OSU – Oregon State University
OWEB – Oregon Watershed Enhancement Board
PFC – Proper Functioning Condition
TMDL – Total Maximum Daily Load
USDA – United States Department of Agriculture
USFS – United States Forest Service
USFWS – United States Fish and Wildlife Service

EXECUTIVE SUMMARY

This report was written to fulfill former Governor John Kithzaber's and the State Legislature's request to review the scientific basis of Oregon's water quality standards for temperature. To accomplish this goal, we discuss the answer to science questions that the Independent Multidisciplinary Science Team (IMST) deemed to be relevant to this charge and important to accomplishing the goals of the Oregon Plan. While this request was initiated based on concerns surrounding the 1996 temperature standards, the discussions in this report are completely applicable to the recently adopted 2003 temperature standards. Our primary focus was "non-point" sources of elevated temperature in streams and cumulative sources from across Oregon's landscape.

Stream temperatures and their modifications from changes in environmental conditions, including the various land uses within Oregon, are complex issues, and we have attempted to highlight areas of apparent conflicting information within the state. Stream temperature is a product of complex interactions between geomorphology, soil, hydrology, vegetation, climate, elevation, and aspect of the watershed. The relative influence of these factors can vary spatially across the landscape and over time. Water temperature can vary along the length of a stream as a result of local topographical and geological factors. Thermal heterogeneity within streams and rivers and can be affected by local energy inputs and outputs.

Salmonids require relatively cold water during most of their life history stages. Stream temperature is closely linked with salmonids' requirement for dissolved oxygen. As water temperatures increase, the amount of dissolved oxygen is reduced. Habitat degradation associated with human land uses (urbanization, agriculture, forestry) often increase surface water temperatures. Where human activities have caused water temperature to increase, survival and productivity of migrating or rearing salmonids may be lowered.

Human land use activities typically affect stream temperature by altering one or more of the following factors: 1) channel morphology 2) streamflow and water quantity, 3) surface/subsurface water interactions, and 4) riparian vegetation. These four factors are highly interrelated. The overall influence that individual factors may have on stream temperature will depend on stream size. Specific stream and watershed conditions cause wide variations in the processes affecting the rate of heating and water temperature therefore stream reach-specific information is critical to understanding stream temperature responses to human activities. Additionally, human activities and management of stream and river systems can shift thermal profiles and lead to earlier or later warming of seasonal water temperatures.

Recent debate in Oregon has been intense regarding the relative importance that shade has on influencing stream temperatures. IMST has found that the vast majority of published studies document that riparian shade has a significant effect on stream temperature. The scientific literature reviewed by the IMST indicates that removal of vegetation along small- to medium-sized streams usually results in increased surface water temperature. In addition, most scientists agree that riparian vegetation provides many benefits to stream and terrestrial ecosystems, in addition to shading streams (IMST 2000). Therefore, despite the level of public controversy, the IMST does not find substantial scientific disagreement on the topic of the importance of riparian vegetation to maintaining stream temperatures.

The IMST was concerned that the debate among the public, natural resource managers, agencies, politicians, and scientists in Oregon has obscured the areas of agreement and disagreement. We developed a new report section called Straightforward Answers to Straightforward Questions (p. 14) to help Oregonians better understand the issues surrounding water temperature and our collective actions to protect and restore the natural resources of the state.

The main body of this report 1) describes the process that the State of Oregon uses to manage water quality under the Clean Water Act and its history, 2) answers five major science questions posed by the IMST that are critically important in accomplishing the mission of the Oregon Plan, 3) develops specific recommendations of the IMST to state agencies and other entities, and 4) discusses policy implications.

Science Questions and IMST Conclusions

Science Question 1. Are the Oregon temperature standards for salmonids technically sound?

1. IMST concludes that the scientific basis for Oregon's temperature standards is credible.
2. Cool temperatures are vital to salmonids, which evolved in cold-water, oxygen-rich systems. Warm streams (in combination with other human impacts) are likely to hinder recovery of salmonid stocks.
3. IMST concurs with EPA and DEQ that the seven day moving average of daily maximum temperatures (7DADM) has a sound scientific rationale, and is an appropriate unit of measurement for stream temperature criteria.
4. Redband trout and Lahontan cutthroat trout exhibit higher thermal tolerances than the salmonid species examined in the 1995 Issue Paper (DEQ 1995). IMST concludes that it is appropriate for the State of Oregon to consider recent data on the physiological performance of Lahontan cutthroat trout & redband trout when setting stream temperature criteria.

Science Question 2. How can salmonids occur in streams that are warmer than criteria in Oregon temperature standards? Does this indicate a weakness in the standards?

1. There are numerous reasons why salmonids may be present in waters that exceed the temperature criteria in Oregon's water quality standards:
    - Physiological or genetic adaptations allow some individuals or populations to survive exposures to high temperatures;
    - Fish observed could be transients, not members of healthy populations resident in a warm stream reach;
    - Performance could be impaired (e.g., earlier emergence, faster growth, changes in migration timing, increased susceptibility to disease, altered response to competition and predation), the effects of which could be cumulative and not apparent until later life stages;
    - Variation in stream temperature over the course of a day or week might allow fish to survive unexpectedly hot conditions;
    - Fish are utilizing coldwater refugia in these warm streams;
    - Range of temperatures that fish populations can tolerate may be wider than scientists realized when Oregon's temperature standards were written.

2. Salmonids have physiological and behavioral mechanisms that allow them to survive high temperatures, up to some maximum temperature and over a maximum duration. Therefore, duration and magnitude of temperature extremes are relevant to setting temperature standards.
3. There is no evidence indicating that salmonids thrive in waters that exceed criteria in Oregon's temperature standards for prolonged periods of time.
4. Presence of individual fish in a stream does not necessarily indicate a population of healthy, reproducing fish. There are relatively few data on the response of fish populations to waters of different temperature in Oregon.
5. Temperatures affect salmonids differently at different life stages; therefore, requirements and optimal temperature ranges vary with life history stage. Temperature regulation must satisfy the most sensitive of these life stages.
6. In the future revision and application of temperature standards, the State of Oregon should consider recent data on coldwater refugia. Oregon's standard for coldwater refugia is difficult to implement when these habitats are difficult to identify and their distributions are not documented.

Science Question 3. How do land use activities influence stream temperatures?

1. Stream temperatures are affected by many environmental factors including, but not limited to, direct and indirect solar radiation, watershed elevation, aspect and topography, regional and seasonal climate, local climate (air temperature, vapor pressure, humidity, wind, etc.), precipitation amounts and timing, channel dimension, streamflow (water quantity), groundwater inputs, and riparian vegetation.
2. Riparian vegetation can reduce stream heating, can regulate temperatures by blocking incoming solar radiation, and maintain channel morphology and functioning floodplains. Riparian vegetation has direct and indirect effects on stream temperatures.
3. Human activities can affect stream temperature by modifying channel morphology, streamflow, surface/subsurface water interactions, and riparian vegetation.

Science Question 4. Is the temperature model used by the State of Oregon based on sound scientific principles? How can temperature models be used effectively in water quality actions under the Clean Water Act?

1. Heat Source, the temperature model used by the State of Oregon, is scientifically sound. The direct and indirect influences of climate, topography, elevation, riparian vegetation, channel morphology, hydrology, and point sources are accounted for in Heat Source, which can predict patterns of stream temperature at river network scales.
2. Further sensitivity analyses should be conducted on the current version of Heat Source (7.0) to evaluate the performance of this version of the model. In addition, the model should be compared with the output from several major stream temperature models to assess the performance of Heat Source. Other approaches to evaluating the consistency of model output with observed stream temperatures should be conducted by DEQ.
3. Temperature models, such as Heat Source, should not be used to set basin-specific temperature standards, but can be used to develop basin-specific total maximum daily loads for heat.
4. Oregon's TMDL process (public process, analysis of sources of elevated stream temperature, and Water Quality Management Plans) is conducted at the basin scale, which is consistent with a landscape approach. Therefore, the IMST concludes that the

State's application of the TMDL process and Water Quality Management Plans is appropriate for implementation of the water temperature standards at a landscape scale.

Science Question 5. What are the benefits of alternative watershed and stream evaluation methods to 1) identify appropriate actions or 2) effectively involve the public?

1. When restoring aquatic and riparian conditions, including stream temperature regimes, each watershed and stream reach is unique (based on soil, climate, topography, etc.). Accounting for these site-specific differences can greatly benefit restoration programs.
2. Site-specific assessment techniques are a means to evaluate the unique characteristics of a site relevant to restoration.
3. Many site-specific assessment techniques are dependent on understanding the expected vegetation and hydrology at a site. To determine expected conditions, scientists and managers often turn to local reference sites with minimal human impacts. When these reference sites are not available, conditions can be defined by groups of regional experts.
4. We are currently limited to case studies to determine the effects of channel restoration on temperature regimes. However, based on the well-documented relationship between riparian and channel degradation and elevated stream temperature, IMST concludes that restoring stream and riparian characteristics will often improve stream temperature.
5. Where water temperature limit salmonid recovery, restoration activities or changes in land uses that lead to reestablishing natural flow regimes, erosion rates, and riparian plant communities should be promoted.
6. Oregon Plan monitoring presents the opportunity to examine the effects of channel restoration on temperature regimes. Individual restoration projects could provide replication in studies evaluating the effectiveness of restoration practices on restoring stream temperature regimes.
7. Given the long time frame and large spatial extent necessary for restoring stream temperature regimes, participation of landowners, community groups, and state & federal partners is essential to minimize the non-point sources of elevated stream temperature across the landscape.
8. IMST agrees with NRC (2002) that confidence in the application of Proper Functioning Condition would be strengthened if the approach was validated.

Recommendations

Based on the five Science Questions and conclusions, the IMST makes the following recommendations to the State of Oregon and its entities. The bases for these recommendations are elaborated on in the Recommendations section of this report.

Recommendation 1. IMST recommends the Oregon State University (OSU) Extension Service and relevant state agencies develop a coordinated education and information distribution system for citizens, watershed councils, and special interest groups on the topic of elevated stream temperature. We recommend that OSU Extension Service conduct workshops to summarize current relevant scientific information to be included in educational programs.

Recommendation 2. IMST recommends that Oregon Department of Environmental Quality (DEQ) continue systematic evaluation of the performance of the Heat Source Model that is used in total maximum daily load (TMDL) planning for stream temperature.

Recommendation 3. IMST recommends that Oregon Department of Fish & Wildlife (ODFW) and Oregon Department of Environmental Quality (DEQ) conduct or fund studies of temperature requirements and/or use of coldwater habitat by redband trout, Lahontan cutthroat trout, and other temperature-sensitive aquatic species occurring in more arid areas in the state.

Recommendation 4. IMST recommends that Oregon Watershed Enhancement Board (OWEB) develop consistent guidance on assessment of current conditions of stream and riparian areas relative to elevated stream temperature.

Recommendation 5. IMST recommends that Oregon Watershed Enhancement Board (OWEB) and Oregon Department of Environmental Quality (DEQ) should jointly monitor effectiveness of protection and restoration activities aimed at improving stream temperatures. OWEB and DEQ should coordinate with other state agencies involved with temperature issues including ODA, ODF, and ODFW.

Recommendation 6. IMST recommends that the Oregon Water Resources Department (OWRD) should continue to promote protection of instream water flows for fish and aquatic life.

Recommendation 7. IMST recommends that Division of State Lands (DSL) and Oregon Department of Agriculture (ODA) should emphasize and implement programs to restore wetlands for use as natural water storage systems.

Recommendation 8. IMST recommends that the Governor's Natural Resource Office and the Oregon Legislature complete and implement a statewide program of riparian protection and restoration. The Oregon Riparian Policy should be expanded and used as a framework for restoring the riparian resources of the State of Oregon.

Implications for Policy

IMST suggests that the following actions are consistent with our review of science:

- Honest scientific inquiry needs to continue.
- Riparian zone management should be implemented.
- Over-appropriation of water in Oregon streams is a problem that needs to be resolved.
- Equity issues should be addressed.
- The State should continue to involve Oregon citizens in stream restoration and the TMDL process. By adopting an approach that allows citizens to become vested in the process and the potential benefits of stream restoration, we have a hope of achieving water quality goals.
- Strong educational programs should be implemented. Different state entities charged with public education need to deliver consistent messages about stream temperature, and to clarify these complex issues, rather than complicate them.

In some cases, citizen groups have criticized Oregon's temperature standard, and suggested that the standard is "bogus" or not supported by science. Groups have also criticized efforts to restore riparian vegetation as unnecessary and ecologically unsound. IMST finds these criticisms to be incorrect, misguided, and damaging to Oregon's resources in the long-term. IMST encourages all citizens, agencies, and politicians to move beyond these arguments, and to move forward with the protection and restoration of streams and riparian areas for the numerous important ecological and social functions of these critical features of Oregon's landscape.

STRAIGHTFORWARD ANSWERS
TO STRAIGHTFORWARD QUESTIONS

Here, we give short answers to questions that are asked frequently about stream temperature and Oregon's temperature standards. For more detailed information, see the main body of this report.

1. What is the purpose of Oregon's water quality standards?

The purpose of water quality standards is to formally describe the level of water quality necessary to protect aquatic life and desired human uses of water bodies. The Clean Water Act is a federal law, but it delegates authority to states and tribes to set water quality standards appropriate to their areas. The standards include 1) descriptions of the aspects of water quality to be protected (beneficial uses) and 2) thresholds that indicate potential problems in water bodies (water quality criteria). In simple terms, the criteria serve as a signal to warn that aquatic health may be problematic. As we describe in more detail later, once a stream passes these thresholds, the state or tribes can begin to examine: 1) if there is a problem, 2) potential causes of the problem, and 3) what actions can be taken to protect aquatic life and human use of streams. The purpose of the water quality standards is not to punish individual landowners, but to indicate when a stream may no longer be able to support beneficial uses and where different management practices may be needed to improve water quality.

2. Are temperature standards the most critical part of Oregon's management of water quality related to temperature?

No. The most important part of Oregon's water quality management is what happens on the ground---the many actions of citizens that influence the environment and water temperature. Standards establish a framework to protect water quality, and assist in the evaluation of watershed conditions and appropriate management actions.

Management actions are generally determined by community or watershed planning processes and guided by regulation. Regulations have been effective for controlling discharges from pipes. However, community involvement and coordinated management are essential to minimize temperature increases from cumulative ("non-point") sources across Oregon's landscape. Developing an analysis of the sources of elevated temperature (a "TMDL") and a water quality management plan for a basin are the most critical steps in the process leading to actual land management.

3. What is the TMDL process?

The term total maximum daily load (TMDL) was derived from the idea that one could calculate the maximum amount of a pollutant that could be added to a lake or stream without causing harm to aquatic life and human uses. This total amount could then be divided up, or allocated, among all polluters. In the case of stream temperature, heat is considered the pollutant that is added to a stream through human activities and land use.

In order to allocate allowable levels of each pollutant, the State carries out a multiple step process. This "TMDL process" is based on community involvement, development of local information, and application of sound scientific tools. The TMDL process is designed to apply water quality standards to the landscape through three steps. DEQ:

- Compiles a list of stream segments with impaired water quality needing TMDLs,
- Prioritizes watersheds for TMDL development, and
- Works with stakeholders to develop a TMDL analysis and a water quality management plan for each watershed (EPA 2003b).

4. What are Oregon's temperature standards?
Oregon revised its temperature standards in December 2003. The standards are designed to protect salmonids and other aquatic life. Water bodies must not be warmer than:

- 16.0 ºC (60.8 ºF) for core cold water habitat use,
- 18 ºC (64.4 ºF) for salmon and trout rearing and migration,
- 20 ºC (68 ºF) for migration corridor use,
- 20 ºC (68 ºF) for redband trout (*Oncorhynchus mykiss* subspecies)and Lahontan cutthroat trout (*O. clarki henshawi*) use,
- 13 ºC (55.4 ºF) for salmonid spawning, egg incubation, and fry emergence,
- .12 ºC (53.6 ºF) for native Oregon bull trout (*Salvelinus confluentus*) spawning and rearing, and
- 16.0 ºC (60.8 ºF) for native Oregon bull trout migration, foraging and sub-adult rearing.

The numbers are based on the different temperature requirements of salmonids during different seasons and life stages. The State has specified both times and locations where the standards apply on maps and in tables.

For other waters, the standards also limit the increase in temperature allowed from human activity to 0.3 ºC (0.5 ºF). These rules apply to:

- Natural lakes,
- Oceans and bays,
- Waters that support cool water species, and
- Designated rivers and streams that are colder than the numeric standards above and are important to endangered and threatened species.

The standards also describe how the State will implement the standards and how to treat streams that are "naturally" warmer than the criteria (see more discussion in No. 17). There are exclusions from the standards in cases of extremely low streamflow or high air temperatures. The standards also allow a small increase (0.3 ºC; 0.5 ºF) in water temperature caused by human activities. The exact language of the standards can be found on the Department of Environmental Quality web site at http://www.deq.state.or.us/wq/standards/WQStdsTemp.htm.

5. Are Oregon's temperature standards (1996 and 2003) scientifically sound?
Yes. Oregon's 1996, and now the 2003, temperature standards are based on several technical reviews by regional and national scientists. Reviews since the development of the 1996 standards have only added additional support. Standards are reviewed and revised on a regular basis to incorporate more recent scientific information. The revision and adoption of new standards by the Oregon Environmental Quality Commission is an appropriate step to keep water quality standards up to date with the current state of knowledge. While there are many questions about how to best implement the standards, the standards are scientifically sound and provide a reasonable framework for developing watershed management plans. Oregon's TMDL process

and temperature standards are some of the most well-reasoned and well-developed approaches in the United States. We conclude that the standards were based on the best science available at the time.

6. How can trout and salmon live in streams that exceed the criteria in Oregon's water temperature standards?

Trout and salmon can exist in water ranging from just above freezing to 75°F (~24°C) depending on how long they are exposed. Some salmonids can even survive temperatures above 75°F for short periods of time. This means they can survive, but short-term survival is not the same as growing and reproducing effectively. For example, people can tolerate extreme heat in a hot tub or sauna for a short time period, perhaps up to a few hours. If a person had to stay in a hot sauna for days or weeks, their health would be threatened. Similarly, people could survive for days, perhaps longer, at air temperatures well over 100° F (~38°C), yet they could not perform life-sustaining work for any period of time. Similarly, salmonids can persist for extended periods of time in warm streams, but are extremely vulnerable to other threats.

Temperatures in the high 60s to mid-70s ºF [approximately 18–24 ºC] can harm salmon and trout. More food is required and growth can be decreased, ability to compete with warm water fish is reduced, and risk of predation is increased. In addition, fish are more susceptible to disease and stress at high temperatures. Salmonids also sometimes avoid the highest temperature water in the stream. Just as people will sit in the shade on a hot day, salmon and trout are often found in colder portions of the streams (deep pools, close to the bottom, near cooler seeps and tributaries). Oregon's temperature standards include provisions to protect these "coldwater refugia".

Some evidence suggests that fish can cope with high temperatures if the daily highs do not persist too long and/or the daily lows are sufficiently low; however, the ways fish adapt to or cope with fluctuating temperatures are not yet well understood.

7. Other than fish, why is stream temperature an important ecological issue?

Stream temperatures are often seen as primarily directed at fish -- but in reality are a surrogate to overall stream health. Temperature influences many processes in a stream, including nutrient cycling and productivity. Temperature is also important because it influences the metabolic rates and physiology of aquatic organisms, including fish. In addition, cold water is able to absorb more oxygen than is warmer water; therefore, the question of oxygen-richness of water is directly linked to water temperature. Likewise, many processes influence temperature. For example, elevated temperatures are often linked with other signs of stream degradation including loss of riparian vegetation and wider than expected stream channels.

8. What environmental factors affect stream temperature?

There are a number of physical and biological features that influence water temperature: shade, streamflow, elevation, subsurface water flows, wind, climate and weather (e.g., air temperature, humidity, cloud cover), time of year (day length and sun angles), watershed orientation, and streambank entrenchment.

9. Which of these factors are influenced by human actions?
People change stream temperatures either at single points (e.g., warm water from pipe discharges into streams) or by human activities that accumulate over larger areas such as watersheds. In this second category, people affect stream temperatures by 1) altering the shade and vegetation along a stream, 2) changing the width and depth of a channel, 3) changing the amount of flow in the stream, and 4) altering the exchange between the surface water in the stream and the water flowing through its streambed and banks.

10. Do land uses (urbanization, agriculture, forestry, livestock grazing) influence stream temperature?
Yes. All of these land uses, depending upon where and how practiced, typically affect the four factors listed in the previous question, and therefore influence stream temperature.

11. Does shade from riparian vegetation influence stream temperatures?
Yes. IMST looked for every possible "real-world" experimental study on the influence of removing riparian vegetation on stream temperature. Of the 48 studies we found, 45 showed that when you removed riparian vegetation, stream temperatures increased. In these 44 studies, the stream temperatures increased from as little as 1.09 ºC [2 ºF] to as much as 12.7 ºC [22.9 ºF] after vegetation was removed.

The relative influence of shade on stream temperature is greatest for small streams and decreases as streams increase in width, depth, and velocity. For example, one would not expect riparian vegetation along the Columbia River to significantly influence the temperature of the mainstem river. In fact, most of Oregon's stream miles are made up of small streams. Stream size is taken into account in the analysis of stream temperatures in Oregon's TMDL process.

12. Can shade cool a stream?
No, not directly. Shade cannot cool a stream by physically transferring heat energy from water to the surrounding environment. Water temperatures decrease when heat energy is transferred from the water to the surrounding environment via evaporation (liquid becoming a gas), convection (mass movement of heat within a liquid or gas), and conduction (heat transfer by substances coming in direct contact with each other). Temperature indicates the direction heat energy will move; heat will move from the warmest to the coolest substance. Temperatures will also decrease when heat in the water is diluted by cool water inputs from ground water or precipitation.

The major source of heat added to streams is from solar radiation (both direct and indirect). Shade blocks radiation from reaching the surface of the stream and decreases the amount of heat added to the water. With increasing amounts of heat blocked and not allowed to reach the water's surface, cooling via evaporation, convection, and conduction will be more effective. If shaded reaches are long enough, the amount of heat leaving the stream will be greater than the amount entering the stream, causing water temperatures to decrease. Therefore, shade from riparian vegetation or topography plays a key role in lowering stream temperatures.

13. Can the changes in temperature provided by shade really benefit salmonids?

Yes. The amount of influence shade exerts on salmonid health varies in relation to the combination of features at play on a given day and in a given location. Most studies indicate that removing shade increases stream temperatures by several degrees over the course of 24 hours, and causes wider variation in stream temperatures. These small changes in temperature can affect salmonids, especially if the water temperatures are near the critical point for invertebrate production and/or fish health.

14. In addition to providing shade, what else does riparian vegetation contribute to stream ecosystems?

Vegetation provides a myriad of features germane to stream form and function in addition to providing shade. These features include, but are not limited to:

- Roots that stabilize stream banks and protect the banks from erosion;
- Potential sources of large and small wood for pool formation;
- A source of detritus (decaying material) and terrestrial insects necessary for biological food chains;
- Creation of instream and riparian habitat for fish and other aquatic organisms;
- Encouragement of infiltration of precipitation into soil and groundwater;
- Allows soils to act as a sponge storing water and releasing it later in the season, and
- Encouragement of subsurface water flows and exchange of water in the stream with the area underneath the stream bed (called “hyporheic” exchange);
- Riparian plants that take up nutrients from soil solutions, which is important for maintaining water quality; and
- Creation of temperature and humidity microclimates that slow stream heating.

Riparian areas also provide many critical functions and habitat for wildlife communities and terrestrial ecosystems.

15. Are air temperature and elevation more important than direct solar radiation in determining stream temperature?

No. Solar radiation, both direct and indirect, is the principal energy source that causes stream heating. Air temperature and elevation are only two environmental factors affecting stream temperatures. Solar radiation directly affects air temperatures. Elevation influences the amount of solar radiation reaching the earth’s surface and therefore, air temperatures. Summer air temperatures are often correlated with stream temperatures giving rise to the commonly held belief that air temperatures have a major and direct effect on the warming of streams. However, heat transfer from air to water is a slow process, and yields minimal heat input into the water compared with direct solar radiation. Air temperature influences the exchange of heat between water and air; heat will go from the warmer medium to the cooler medium. Oregon accounts for the effect of elevation when it models and evaluates stream temperatures in the TMDL process.

16. Once a stream is placed on the 303(d) list, can it ever be removed?

Yes. The 303(d) list is composed of all water quality limited waters that do not have a TMDL. The Clean Water Act, a federal law, directs states to create these lists. According to EPA, the federal agency that oversees the Clean Water Act, water bodies can be removed from the 303(d) list for three reasons:

- A TMDL has been developed for those waters;

- New information concludes that the listing was inaccurate; or
- A formal analysis proves that a designated use in a particular water body is inappropriate. In this case, the designated use is then changed.

Generally, once EPA approves a TMDL document, streams in that watershed are no longer listed on the 303(d) list. However, streams and stream segments are considered to be water quality limited until they meet all criteria in the State's water quality standards (temperature being just one set of criteria). DEQ continues to track all water quality limited streams in its Integrated Report.

17. How does DEQ treat streams that are naturally warmer than the criteria in the water temperature standards?

When carrying out the Clean Water Act, a stream that was historically naturally warmer than the temperature criteria does not need to be restored to a temperature lower than the natural conditions.

DEQ estimates natural conditions – or the range of temperatures before human influence – from current data, historical data, and stream temperature modeling. DEQ uses modeling because historical temperature data are often very scarce. The agency uses a model called Heat Source, and conducts its analysis when creating a TMDL for each basin. If DEQ determines that a stream was naturally warmer than the temperature criteria, the agency no longer considers the stream to be in violation of the standards. The "natural thermal potential" determined by modeling becomes the goal for a water body found to be naturally warmer than the criteria.

18. Is the Heat Source model used in Oregon's TMDL process scientifically sound?

Yes. Heat Source, the model used in the TMDL process for developing watershed management plans for stream temperature, is a scientifically sound model and incorporates the major physical factors that determine stream temperature. Sensitivity analysis of the model has been conducted, and we have encouraged the State to continue to explore the sensitivity of the factors in the model. The process used by the state of Oregon to assess stream temperature and address the human activities that affect stream temperature is based on sound scientific principles and is comparable to the best models available.

19. Have private landowners in Oregon been forced to take actions on private lands as a result of temperature standards and the TMDL process?

IMST asked the Oregon Department of Agriculture (ODA) if the Heat Source model or TMDL process had been used to force any landowner to take an action on their land to protect or restore stream temperature. We were told that the agency knows of no circumstances when the State of Oregon required an agricultural landowner to take a mandatory action to protect or restore stream temperature.

As acknowledged in the Oregon Administrative Rules (OAR 603-095-0440), riparian vegetation is known to play several roles that ultimately reduce stream heating (control of erosion that widens streams, moderation of solar heating, and infiltration of water into the soil profile), and state law requires that agricultural activities allow development of riparian vegetation to control water pollution.

If agricultural landowners believe that the Heat Source model has not described the vegetation on their lands accurately (and therefore effective shade at site-potential is inaccurate), landowners may present their concerns to ODA. Personnel from ODA then investigate the site to determine site-specific differences and work with landowners for a voluntary solution. In the rules, ODA is directed to seek voluntary adoption of Best Management Practices; ODA is to pursue enforcement actions only after reasonable attempts at voluntary solutions have failed (OAR 603-095-0030).

Forest landowners have had to take actions on private land in order to meet water quality standards. However, Oregon relies on a different process to carry out TMDLs on forest lands; compliance with the Forest Practices Act is considered to be compliance with the water quality standards. Enforcement actions have also taken place with violations of point source pollution of nutrients (e.g., excess nutrients from Confined Animal Feeding Operations).

PREFACE

The Independent Multidisciplinary Science Team (IMST) was established by the 1997 Oregon Legislature via Senate Bill 924, signed by Governor John Kitzhaber on March 25, 1997. The Team is to advise the State on matters of science related to the Oregon Plan for Salmon and Watersheds. The Governor, the Senate President and the Speaker of the House jointly constituted the 7-member Team October 10, 1997. The establishment of the Team reflected the 1997 agreement between Oregon and the National Marine Fisheries Service concerning coho salmon (*Oncorhynchus kisutch*). This agreement has been terminated, but Executive Order 99-01, which expanded the scope of the Oregon Plan, specifies the continuing role of the Team in the recovery of wild salmonids in Oregon.

IMST Operational Framework

The operational framework of the IMST is summarized in the Team Charter (http://www.fsl.orst.edu/imst/). The primary means of communicating results of the Team's work is through written reports. In IMST reports, the Team assesses the best available science as it pertains to salmonid and watershed recovery and the management of natural resources. Based on the assessments, the IMST makes recommendations to Oregon state agencies or entities.

Recommendations are directed to one or more agencies or entities that have the ability to implement or to affect changes in management or regulation that are needed for implementation. It should be noted that the IMST looks beyond an agency's current ability to implement the recommendations because current legal, regulatory, or funding situations may need to change. It is the belief of the IMST that if an agency agrees that a recommendation is technically sound and would aid the recovery of salmonid stocks and watersheds, the agency would then determine what impediments might exist to prevent or delay implementation and work toward eliminating those impediments. The Team also assumes that each agency has the knowledge and expertise to determine how best to identify and eliminate impediments to implementation and to determine appropriate time frames and goals needed to meet the intent of the recommendation. In addition, the IMST recognizes that an agency may already have ongoing activities that address a recommendation. Our inclusion of such an "overlapping" recommendation should be seen as reinforcement for needed actions.

Senate Bill 924 specifies that agencies are to respond to the recommendations of the IMST, stating "(3) If the Independent Multidisciplinary Science Team submits suggestions to an agency responsible for implementing a portion of the Oregon Plan, the agency shall respond to the Team explaining how the agency intends to implement the suggestion or why the agency does not implement the suggestion." Once agency responses are received, the IMST reviews the scientific adequacy of each response and if further action or consideration by the agency is warranted. The IMST's review of responses is forwarded to the Governor and the State Legislature. State agencies are expected to respond to IMST recommendations within six months after a report is issued.

Conceptual Scientific Framework

The IMST developed the following conceptual scientific framework for the recovery of depressed stocks of wild salmonids in Oregon. It was developed originally as we evaluated Oregon's forest practices. Since then, it has been expanded to cover all land uses and fish management. Although not testable in a practical sense, we believe this conceptual framework is consistent with generally accepted knowledge and scientific theory.

The recovery of wild salmonids in Oregon depends on many factors, including the availability of quality freshwater and estuarine habitats, ocean conditions, the management of fish harvest, and the adequacy of natural and artificial propagation. Freshwater habitat extends across all the lands of the State, and includes urban areas and lands devoted to agriculture, forestry, and other uses. Estuaries provide a transition between fresh water and the ocean, and are a critical part of the habitat of wild anadromous salmonids. The ocean on which salmonids depend extends well beyond Oregon and is subject to fluctuations in productivity that markedly affect adult recruitment. Fish propagation and fish harvest are critical activities in which humans are directly involved with anadromous fish. The IMST is evaluating the science behind the management practices and policies that affect all of these freshwater and estuarine habitats and the management of fish and fisheries.

Concepts

IMST is conducting its analysis of land use practices and fish management within a framework made up of the following three fundamental concepts:

1. Wild salmonids are a natural part of the ecosystem of the Pacific Northwest, and they have co-evolved with it. The contemporary geological landscape of the Pacific Northwest was established with the formation of the major river/stream basins of the region, approximately two to five million years ago. The modern salmonids of the region largely developed from that time (Lichatowich 1999). The abundance of these species at the time of Euro-American migration to Oregon is a reflection of more than 10,000 years of adaptation to the post-glacial environment and 4,000 to 5,000 years of adaptation to contemporary climatic and forest patterns. There is some indirect evidence from anthropological studies that salmon in Oregon's coastal streams may not have reached the high levels of abundance that the first Euro-Americans saw until about 1,000 to 2,000 years ago (Matson and Coupland 1995). The point is that the salmonid stocks of today co-evolved with the environment over a relatively long period compared with the length of time since Euro-Americans entered this landscape.

2. High quality habitat for wild salmonids was the result of naturally occurring processes that operated across the landscape and over time. These same processes occur today, but humans have altered their extent, frequency, and to some degree, their nature. Humans will continue to exert a dominant force on the terrestrial, freshwater, and estuarine landscape of the Pacific Northwest, but current ecosystems need to better reflect the range of historical conditions (Benda 1994; Reeves et al. 1995).

3. The environment and habitat of these species is dynamic, not static. At any given location, there were periods of time when habitat conditions were better and times when habitat conditions were worse. At any given time, there were locations where habitat was better and locations where it was worse. Over time, the location of better habitat shifted, both in fresh water and the ocean.

Fresh water and estuarine salmonid habitat in the Pacific Northwest has been a continuously shifting mosaic of disturbed and undisturbed habitats. One of the legacies of salmonid evolution in a highly fluctuating environment is the ability to colonize and adapt to new or recovered habitat.

The ocean habitat also fluctuates and is dynamic, changing over several time scales. There are inter-decadal variations in climate called regimes (as well as shorter term variations) that affect the ocean productivity for salmonids. One regime that resulted in a shift from favorable to unfavorable ocean conditions, especially for coho salmon, occurred in 1977. Some believe that we are entering a more favorable regime that began with the 1998 La Niña. However, it is important to realize that full recovery of salmonid populations is a long-term process. A major assumption is that improved conditions of freshwater and estuarine habitat are buffers to poor ocean conditions. Without improvement of the condition of these habitats, the return to poor ocean conditions in the future will be more devastating to salmonids than what was experienced in the early 1990s (Lawson 1993).

These concepts apply regardless of the land use or fish management strategy and are the basis for the evaluations in this report.

<u>Operation of the Concepts in Salmonids</u>
Wild salmonid stocks historically accommodated changes in their environment through a combination of three strategies. Long-term adaptation produced the highly varied life history forms of these species, providing the genetic diversity needed to accommodate a wide range of changing conditions. High fish abundance distributed in multiple locations (stocks) increased the likelihood that metapopulations and their gene pools would survive. Occupation of refugia (higher quality habitat) provided the base for recolonization of poor habitat as conditions improved over time.

History
Since the mid 1850s, the rate and extent to which habitat conditions have changed has sometimes exceeded the ability of these species to adapt; therefore, abundance currently is greatly reduced. Although refugia exist (at a reduced level) today, population levels of wild salmonid stocks are seriously depressed because of other factors (ocean conditions, fisheries and hatchery management, land-use patterns and practices) that limit habitat productivity and the rate and extent to which recolonization can occur. In addition, some harvest and hatchery practices may have diminished the genetic diversity of salmonids (reviewed in Allendorf and Waples 1996; NRC 1996), potentially limiting their ability to cope with climate fluctuations. It is the combination of these factors and their cumulative effects since 1850 that have produced the depressed stocks of today.

The historical range of ecological conditions and the diversity of salmonid stocks in the Pacific Northwest are important because they provide a framework for developing policy and management plans for the future. The persistence and performance of salmonids under historical ecological conditions is evidence that these habitats were compatible with salmon reproduction and survival. Prior to European settlement of the western United States, artificial propagation was not practiced, yet the level of harvest by Native Americans may have reached the levels of peak harvests by Euro-Americans (Beiningen 1976; Schalk 1986).

Conclusions

Land uses and fish management strategies resulting in non-historical ecological conditions may support productive salmonid populations, but the evidence for recovery of wild salmonids under these circumstances is neither extensive nor compelling. Recovery of wild salmonids also requires fish management (artificial propagation and harvest) strategies that are consistent with the goals of recovery and are compatible with the condition of the terrestrial and ocean landscape within which they operate.

Therefore, we conclude that:

The goal of land use management and policy should be to emulate (not duplicate) natural processes within their historical range.

The goal of fish management and policy should be to produce and take fish in a manner that is consistent with the condition of the environment and how it changes with time.

The recovery of wild salmonid stocks is an iterative and a long-term process. Just as policy and management have changed in the past they will continue to change in the future, guided by what we learn from science and from experience.

INTRODUCTION

Oregon water temperature standards were described by former Governor John Kitzhaber's Office as "an important component of the water quality element of the Oregon Plan". In 1998, Governor Kitzhaber's Office[1] and the Oregon Legislature asked the IMST to examine and review the scientific basis of Oregon's water quality standards for temperature. This report was prepared to address this specific request and to address some of the major concerns about stream temperature that have arisen in Oregon.

This IMST report is divided into four major sections:

> **Introduction.** The introduction provides the history, context, and scope of the report. We describe the process that the State of Oregon uses to manage water quality under the Clean Water Act. We also provide more detailed information on the history of Oregon's water quality standards for temperature.
>
> **Science Questions.** This section presents and answers five questions posed by the IMST. Major conclusions based on the answers to the science questions are presented at the end of each question.
>
> **Recommendations.** These are the specific recommendations of the IMST to state agencies and entities.
>
> **Implications for Policy**. This section is at the interface between science and policy. This discussion is intended to help those addressing policy to do so in ways that are consistent with scientific information.

Scope of this Report

This report was written to fulfill former Governor Kitzhaber's and the Legislature's requests to review the scientific basis of Oregon water quality standards for temperature. To accomplish this goal, we discuss the answer to science questions that the IMST deemed to be relevant to this charge and important to accomplishing the goals of the Oregon Plan for Salmon and Watersheds (Oregon Plan). Our primary focus was "non-point" sources of elevated temperature in streams and cumulative sources from across Oregon's landscape. While this request was initiated based on concerns surrounding the 1996 temperature standards, the discussions in this report are completely applicable to the recently adopted 2003 temperature standards.

This report does not represent primary research, but rather a scientific review of work done by other researchers. In preparing this report, we reviewed analyses presented in primary scientific literature and in other scientific literature reviews. We drew information from peer-reviewed journals, graduate theses and dissertations, and other technical documents, including state and federal agency reports[2].

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[1] January 14, 1998 letter to Logan Norris (IMST Chair) from Paula Burgess (Governor's Office), Senator Ted Ferrioli and Representative Ken Messerle (Co-Chairs of the Joint Committee on Salmon and Stream Enhancement).

[2] Graduate theses, Masters theses and Ph.D. dissertations, undergo peer-review by a committee of university faculty or other scientists. The level of review for government documents varies widely. Reports are sometimes subjected to extensive external and internal technical review, but this is not a universal practice.

Management of Water Quality in Oregon

To evaluate Oregon's water quality standards for temperature, it is important to understand them in the context of Oregon's approach to managing overall water quality. The federal Clean Water Act directs many of Oregon's water quality programs. The Clean Water Act[3] was enacted by the United States Congress to protect and restore the quality of surface waters in the country. Under the Clean Water Act (Section 303), each state is required to:

- Adopt water quality standards for state waters (see Box A), and.
- Establish a Total Maximum Daily Load (TMDL)

Box A. Terms commonly associated with the Clean Water Act.

Water quality standards. Water quality standards formally describe the level of water quality necessary to protect aquatic life and human uses of surface waters (lakes, rivers, and streams). In Oregon, water quality standards are state administrative rules, regulations adopted by Oregon's Environmental Quality Commission.

Water quality standards consist of two main parts: a "beneficial use" and one or more accompanying "criteria" that have been developed to protect that use. The set of standards for each pollutant are often identified as a group; for example, the set of standards identified to prevent harm from temperature are known as "temperature standards" or "the temperature standard".

Beneficial use. A description of resources protected by the Clean Water Act. Examples of beneficial uses in Oregon are: aesthetics, aquatic life, drinking water, fishing, livestock watering, resident fish, salmonid spawning and rearing, shellfish, water contact recreation, and water supply. The Clean Water Act uses the term "designated uses" (EPA 2003a), while Oregon water quality standards refer to "beneficial uses" and "designated beneficial uses."

Criteria. Numeric or narrative descriptions of conditions that protect beneficial uses.

Narrative criteria. A qualitative description of conditions that protect a specific aquatic resource.

Numeric criteria. A numeric threshold designed to protect a specific aquatic resource. Numeric criteria are developed for measurable aspects of water quality: such as stream temperatures, concentrations of pollutants, dissolved oxygen, or chlorophyll.

The Oregon Department of Environmental Quality (DEQ) is responsible for protecting water quality in the state by administering the Clean Water Act. As we will describe in the following sections, DEQ establishes water quality standards as state administrative rules, conducts a TMDL process for each river basin with impaired water quality, and collaborates with other agencies on stream restoration activities. A summary of the Oregon procedure to manage water pollutants under the Clean Water Act is outlined in Figure 1 and described in detail in the following sections.

[3] The "Clean Water Act" commonly refers to the Federal Water Pollution Control Act Amendments of 1972, as supplemented by the Clean Water Act of 1977 and the Water Quality Act of 1987 (NRC 2001).

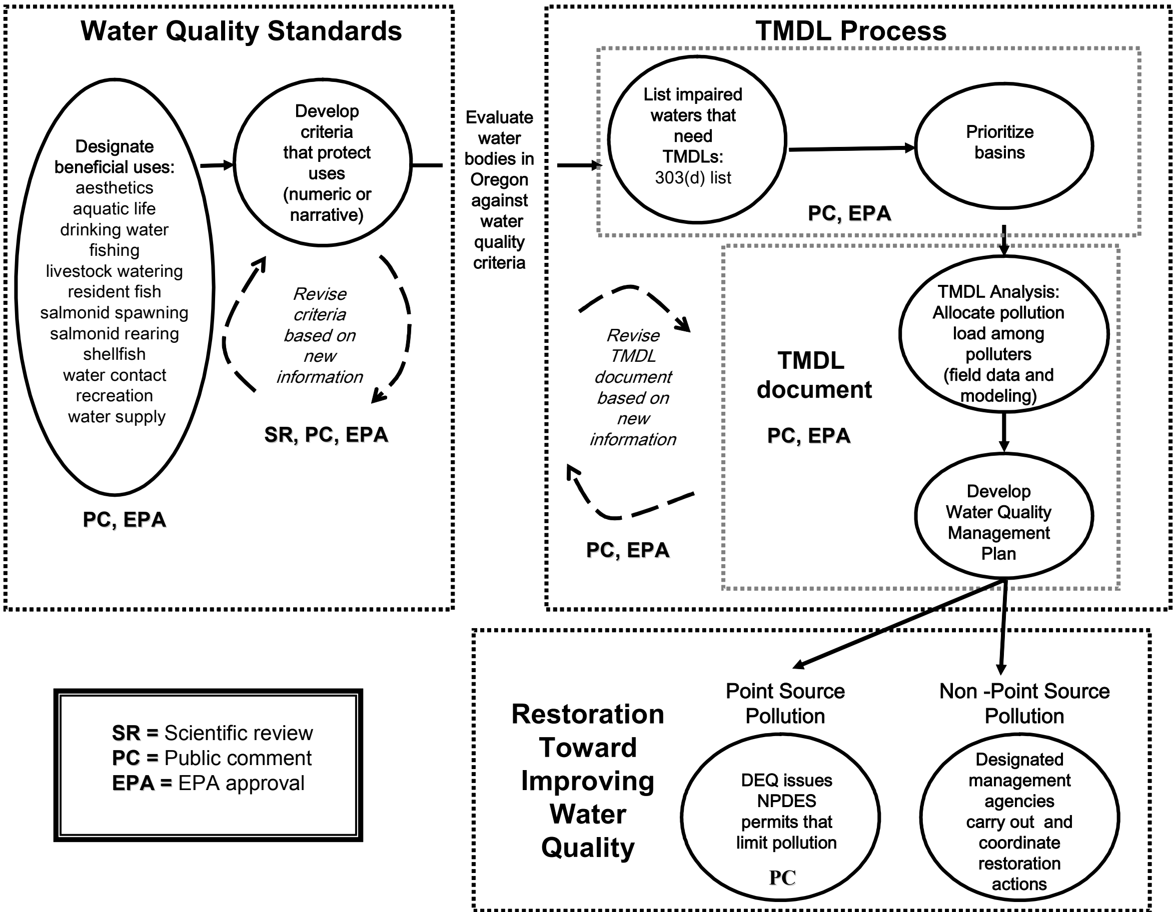

Figure 1. Oregon's approach to managing water quality under the Clean Water Act.

Water Quality Standards

The purpose of water quality standards is to formally describe the level of water quality necessary to protect aquatic life and human uses of surface waters (lakes, rivers, and streams). The Clean Water Act is a federal law, but it delegates authority to set specific water quality standards to states and tribes. EPA sets standards for states and tribes only in rare cases when state/tribal standards do not meet EPA approval after multiple opportunities; EPA has never set standards for Oregon (M. Charles, pers. comm[4].) The first step Oregon takes to set water quality standards is to determine what needs to be protected, or a list of beneficial uses (Box A). DEQ does not prioritize among the beneficial uses, but develops programs to ensure that all are protected.

DEQ then sets water quality criteria that must be attained in order to protect the designated beneficial uses. The criteria are essentially thresholds designed to indicate problems in surface waters. The criteria can be either qualitative (narrative) or quantitative (numeric; Box A). Criteria are developed to protect the most sensitive of the beneficial uses. For example,

[4] Charles, Mark. Personal Communication. 2003. DEQ, Portland, OR

temperature criteria are developed to protect salmonid spawning and rearing, and bacteria criteria are developed to protect water contact recreation.

Each state is required to review water quality standards every three years in order to incorporate new information and reflect evolving social priorities. As part of this process, DEQ solicits advice from panels of outside technical experts (including fish biologists, stream ecologists, hydrologists, and environmental engineers). DEQ then proposes revisions to standards, solicits public comment, and brings revised rules to the Environmental Quality Commission (DEQ's policy and rule-making board) for approval/adoption. Water quality standards proposed by a state must then be reviewed and approved by EPA. EPA must consult with and obtain approval from USFWS and NOAA Fisheries when threatened or endangered species are affected by the standards.

When a water body does not meet the criteria described in standards, it is considered *water quality limited*. As we describe in more detail later, once a lake, river, or stream passes the threshold, the state or tribes can begin to examine: 1) if there is a problem, 2) potential causes of the problem, and 3) what actions can be taken to protect aquatic life and human uses of the water body.

<u>TMDL Process</u>
The term "total maximum daily load" (or TMDL) was derived from the idea that one could calculate the maximum amount of a pollutant that could be added to a lake, river, or stream without causing harm to aquatic life and human uses. This total amount could then be divided up, or allocated, among all of the polluters. In the case of stream temperature, heat is the pollutant added to surface waters through human activities and land use. In order to allocate allowable levels of each pollutant, DEQ carries out a multiple step process, described below.

The TMDL process is designed to apply water quality criteria to the landscape through three steps (EPA 2003b). EPA describes the TMDL process as:

- Compile a list of streams and lakes with impaired water quality [303(d) list],
- Prioritize watersheds for TMDL development, and
- Develop TMDL documents for each watershed (EPA 2003b).

In the first step of the TMDL process, DEQ assesses all Oregon lakes, rivers, streams, and stream segments to determine compliance with the water quality criteria, including water temperature criteria. After determining that a lake, river, or stream reach does not meet the water quality criteria, DEQ is required to document the criteria not met and the basis for the determination, and to provide this information for public comment and review. The 303(d) list[5] is composed of all water quality limited waters in Oregon that do not have an approved TMDL document. Most water quality limited Oregon streams and rivers are listed as water quality limited because, at some point each year, they become too warm to meet temperature criteria (DEQ 2000c).

In the second step of the TMDL process, DEQ prioritizes river basins based on the severity of their water quality problems. Section 303(d) of the Clean Water Act states that each state shall

[5] The 303(d) list must be approved by EPA.

rank waters, dealing with the most serious water quality problems and the most valuable and threatened resources first.

In the third step of the TMDL process, DEQ develops a document for each river basin (or subbasin) in the prioritized order. The TMDL document 1) establishes TMDL allocations for all pollutants that impair water quality in that watershed and 2) describes a Water Quality Management Plan intended to restore water quality in that watershed (e.g., DEQ 2002a).

TMDL Analysis and Allocations for Heat

In each watershed basin with water bodies listed as being impaired by temperature, a TMDL analysis of heat is conducted. The analysis is based on: data review, monitoring of heat source contributions, and temperature models (e.g., the Oregon Heat Source Model). For each basin, a TMDL analysis determines:

1. Heat sources (point, non-point, and natural background sources) and assesses how heat sources are warming the water body.
2. Natural background heat and estimates the "heat loading capacity": the capacity of waters to absorb heat from other sources while still meeting the temperature standards for salmonids.
3. Allowable heat loads for all point and non-point sources of heat in a watershed to provide the reduction necessary for a stream to comply with the water temperature standards. A "total maximum daily load" for heat is the sum of all heat load allocations (including natural background heat) and cannot exceed the heat loading capacity for that basin (EPA 2003b). The State of Oregon has developed a computer model called Heat Source (see Science Question 4), which has been used to establish TMDL allocations for water temperature in some Oregon basins.

Water Quality Management Plan

In each river basin, a Water Quality Management Plan describes implementation measures, or actions, that are intended to move a water body toward meeting all water quality criteria. For each basin, 1) DEQ recommends reductions of each point source and non-point source pollutant (via load and wasteload allocations[6], and National Pollution Discharge Elimination System permits), and 2) DEQ names land management agencies that will identify and carry out restoration projects and land management practices (including best management practices) in the basin (e.g., DEQ 2002a; EPA 2003b).

In Oregon, the following designated management agencies (and their programs) may be named in a Water Quality Management Plan:

- Oregon Department of Agriculture (ODA; Confined Animal Feeding Operation program and Agricultural Water Quality Management Plans as stipulated by Oregon Senate Bill 1010),
- Oregon Department of Forestry (ODF; Oregon Forest Practices Act),
- Federal agencies (watershed management plans), and
- Urban and rural areas (management plans).

As of March 2004, Oregon has completed sixteen TMDLs for temperature (including Water Quality Management Plans).

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[6] Wasteload allocations are allocations for point sources of pollution, while load allocations are for non-point sources or natural background sources of pollution.

Restoration of Water Quality

To help streams eventually meet criteria in Oregon's water quality standards, designated management agencies and local collaborators carry out restoration projects and land management practices based on the DEQ Water Quality Management Plan[7]. Designated management agencies then continue adaptive management through: monitoring water quality (including temperature), evaluating results, and modifying management practices in response to those results. Some restoration and land management actions that are specifically designed to reduce temperatures may also improve other aspects of water quality in Oregon's water bodies (see Question 5). Over time, restoration and land management actions should improve water quality to meet all criteria in Oregon's water quality standards.

Once EPA approves the TMDL document developed for a basin, streams in the basin are no longer part of the 303(d) list, but are tracked by DEQ in its Integrated Report. They are still considered to be water quality limited until they meet all criteria in the water quality standards, not only temperature criteria.

History of Oregon's Temperature Standards

Water temperature standards are designed to protect the ecological health of water bodies in Oregon. Stream biota may experience ecological harm when a stream is warmer than water temperature criteria in the standards.

Oregon first instituted water quality standards for temperature in 1967. Since then, Oregon's standards for temperature have been periodically revised based on available scientific information and guidance. As we will describe, the State has taken a variety of approaches to protect aquatic life from elevated temperature.

Standards instituted in 1979 limited allowable increases in stream temperature. Both maximum stream temperatures allowed and the allowable increases in temperature varied among Oregon's river basins. These standards were not changed between 1979 and the early 1990's (DEQ 1995).

In 1992, DEQ initiated a comprehensive review of Oregon water quality standards, including temperature. A technical advisory committee ("1995 Temperature Subcommittee") analyzed the existing temperature standards,[8] and a Policy Advisory Committee conducted a policy analysis. In 1995, these committees prepared a final issue paper (DEQ 1995) that made recommendations to DEQ and Environmental Quality Commission concerning the water temperature standards. The Commission adopted changes to Oregon's water quality standards, including temperature, as administrative rules on January 11, 1996 (Box B).

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[7] Designated management agencies describe how they plan to carry out implementation measures in their agency Implementation Plans, which they submit to DEQ for approval (OAR 340-042).

[8] IMST Team Members Dr. Stan Gregory and Dr. Carl Schreck served on the 1995 Temperature Subcommittee.

Box B. Numeric Criteria Identified in Oregon's 1996 Temperature Standards.
This is a short summary of the 1996 standards. For details, please refer to the 1996 Oregon administrative rules.

Numeric criteria in the 1996 Oregon water temperature standards are based on the temperature requirements of salmonids, which vary by salmonid life stage and corresponding season:

- 64 ºF [17.8 ºC] for juvenile salmonid rearing (summer maximum).
- 55 ºF [12.8 ºC] for salmonid spawning, egg incubation, and fry emergence (fall, winter, spring).
- 50 ºF [10 ºC] for native Oregon bull trout, *Salvelinus confluentus* (summer maximum).
- 68 ºF [20 ºC] for the Columbia River below mile 309 and for the Willamette River below mile 50.

In addition to numeric criteria, the 1996 Oregon water temperature standards include narrative criteria that limit the increase in temperature allowed from human activity, even when streams are colder than the numeric criteria:

- No measurable increase from anthropogenic activities in ecologically significant coldwater refugia*
- No measurable increase from anthropogenic activities in stream segments containing federally listed Threatened or Endangered species if the increase would impair the biological integrity of the population.
- No measurable increase from anthropogenic activities when dissolved oxygen levels are within 0.5 mg/L or 10 percent saturation for the water column or intergravel dissolved oxygen criterion for a given stream reach or sub-basin.
- No measurable increase from anthropogenic activities in natural lakes.

DEQ granted exclusions to numeric temperature criteria in cases of the highest air temperatures (top 10%).

* "Ecologically Significant Cold-Water Refuges exists when all or a portion of a waterbody supports stenotypic cold-water species (flora or fauna) not otherwise widely supported within the subbasin, and either:(a) Maintains cold-water temperatures throughout the year relative to other segments in the subbasin, providing summertime cold-water holding or rearing habitat that is limited in supply, or, (b) Supplies cold water to a receiving stream or downstream reach that supports cold-water biota.." (OAR 340-41-006, 1996)

EPA, National Marine Fisheries Service (NMFS; now NOAA Fisheries) and US Fish and Wildlife Service (USFWS) reviewed the standards proposed by DEQ and found several areas where they felt salmonids and other beneficial uses would not be adequately protected (NMFS 1999; USFWS 1999)[9]. EPA then initiated an interagency regional review of temperature standards appropriate to protect salmonids in the Pacific Northwest. In early 2003, EPA issued non-binding guidance to Pacific Northwest states based on their regional review (EPA 2003a). In the fall of 2003, DEQ proposed revisions to the state's temperature standards in response to EPA's (2003a) guidance on stream temperature standards. As in 1992–1994, DEQ consulted a technical advisory committee of outside reviewers about the scientific basis for revising standards (DEQ 2003). Revised standards were adopted by the Environmental Quality Commission on December 4, 2003 and approved by EPA on March 2, 2004 (see Box C).

[9] In this report, IMST conducts an independent review of Oregon's standards, and does not discuss in detail specific criticisms raised by the federal regulatory agencies in their biological opinions (USFWS 1999; NMFS 1999).

Box C. Summary of Oregon's 2003 Temperature Criteria.
This is a short summary of the standards described in OAR 340-041-0028. Criteria for point sources of heat are not included here. For details, see DEQ web site (http://www.deq.state.or.us/wq/standards/WQStdsTemp.htm).

Numeric criteria in the 2003 Oregon water temperature standards are based on the temperature requirements of salmonids by salmonid life stage and corresponding season. Times and locations of these categories are specified in maps and tables accompanying the standards. Unidentified tributaries have the same criteria as the nearest downstream water body depicted on the relevant map. The standards allow a 0.3 ºC/0.5 ºF increase in temperature above the criteria for human use.

- 64.4 ºF (18 ºC) for salmon and trout rearing and migration*;
- 60.8 ºF (16.0 ºC) for core cold water habitat use**
- 55.4 ºF (13 ºC) for salmonid spawning, egg incubation, and fry emergence;
- 68 ºF (20 ºC) for migration corridor*** use;
- 60.8 ºF (16.0 ºC) for native Oregon bull trout (*Salvelinus confluentus*) migration, foraging and sub-adult rearing.
- 53.6 ºF (12 ºC) for native Oregon bull trout spawning and rearing;
- 68 ºF (20 ºC) for redband trout (*Oncorhynchus mykiss* ssp) and Lahontan cutthroat trout (*O. clarki henshawi*) use.

The 2003 Oregon water temperature standards also include narrative criteria that limit the increase in temperature allowed from human activity to 0.3 ºC (0.5 ºF), even when streams are colder than the numeric criteria. These rules apply to:

- Natural lakes,
- Oceans and bays,
- Waters that support cool water species, and
- Designated rivers and streams that are colder than the numeric standards above and are important to endangered and threatened species.

In addition,

- State waters in the Malheur Lake Basin supporting the borax lake chub (*Gila alvordensis*) may not be cooled more than 0.3ºC (0.5 ºF) below the ambient condition.
- Water bodies having salmonid migration corridor use must have coldwater refugia sufficiently distributed so as to allow salmon and steelhead (*O. mykiss*) migration without significant adverse effects.
- Where DEQ determines that the natural thermal potential of all or a portion of a water body is warmer than the criteria above, the natural thermal potential becomes the criteria.
- DEQ may make site-specific criteria for cases where the department determines that a different criterion is appropriate and will protect the aquatic ecosystem. Some considerations that DEQ may use to set site-specific criteria include: streamflow; riparian vegetation potential; channel morphology; cold water tributaries and groundwater; and natural physical features.
- DEQ grants exclusions to numeric temperature criteria in cases of the highest air temperatures (top 10%) and lowest flows (less than the 7Q10 low flow conditions).

**Core cold water habitat* use is defined as "waters that are expected to maintain temperatures within the range generally considered optimal for salmon [chinook, chum, coho, sockeye and pink salmon] and steelhead rearing, or that are suitable for bull trout migration, foraging and subadult rearing that occurs during the summer."
***Salmon and trout rearing and migration* is defined as "thermally suitable rearing habitat for salmon and steelhead, rainbow, and cutthroat trout."
****Migration corridors* are defined as "waters that are predominantly used for salmon and steelhead migration during the summer, and where there is little or no anadromous salmonid rearing occurring in the months of July and August."

SCIENCE QUESTIONS

Many science questions were considered during the development of this report. From these, we selected five questions that the IMST considered to be most important in accomplishing the goals of the Oregon Plan. Specifically:

> Science Question 1. Are the Oregon temperature standards for salmonids technically sound?
>
> Science Question 2. How can salmonids occur in streams that are warmer than the Oregon temperature standards? Does this indicate a weakness in the standards?
>
> Science Question 3. How do human activities influence stream temperature?
>
> Science Question 4. Is the temperature model used by the State of Oregon based on sound scientific principles? How can temperature models be used effectively in water quality actions under the Clean Water Act?
>
> Science Question 5. What are the benefits of alternative watershed and stream evaluation methods to 1) identify appropriate actions or 2) effectively involve the public?

Science Question 1. Are the Oregon temperature standards for salmonids technically sound?

Oregon's water quality standards for temperature are based on research on the physical and biological responses of organisms, particularly salmonid fishes, to stream temperatures. In the answer to this question, we briefly review the importance of stream temperature to salmonids. We then evaluate whether the technical basis for Oregon's standards is consistent with the scientific literature on salmonid temperature requirements, including scientific information that has become available since the adoption of the 1996 standards. We also discuss some of the technical challenges faced by agencies when using scientific information as the basis for standards.

Importance of Stream Temperature to Salmonid Recovery

Salmonids require relatively cold water during most of their life history stages as compared with other aquatic organisms (Brett 1952; Fagerlund et al. 1995). Pacific salmonids are generally classified as "cold-water stenotherms", or organisms that require relatively constant cold-water environments. Habitat degradation associated with human land uses (urbanization, grazing, agriculture, forestry) often increases surface water temperatures (see Science Question 3). Where human activities have caused water temperatures to increase, survival and productivity of migrating or rearing salmonids may be lowered (see Science Question 2). Since 1991, several evolutionarily significant units of salmonids have been listed by NOAA Fisheries as threatened under the US Endangered Species Act. Based on these listings and on the conclusion that healthy native anadromous salmonid stocks now constitute a small fraction of the historical resource (Huntington et al. 1996), we conclude that the status of many anadromous and resident salmonids in Oregon is poor. Therefore warming of surface waters over large geographic areas, in combination with other factors[10], has the potential to greatly limit the recovery of declining stocks (see also Oregon Plan 1997; Independent Science Group 2000; IMST 2000; IMST 2002).

In addition to direct effects high temperatures may have on salmonids, stream temperature is closely linked with salmonids' requirement for dissolved oxygen. Water temperature and dissolved oxygen concentrations are inversely related; as water temperatures become higher, the amount of dissolved oxygen is reduced. This situation stresses cold-water fishes (Brett 1964; Matthews and Berg 1997).

The scientific literature on the effects of temperature on the physiology and ecology of salmon has grown substantially over the last 50 years. The pioneering research of Dr. J.R. Brett established lethal tolerance ranges for most species of Pacific salmon (Brett 1952), documented effects of temperature on physiological performance (Brett et al. 1958; Brett 1964, 1967; Brett et al. 1969; Brett and Higgs 1970), and conducted field experiments (Brett et al. 1982). Numerous other researchers contributed to the substantial body of information on effects of temperature in the laboratory and field. We do not attempt to provide an exhaustive review of all of the thermal effects literature for Pacific salmonids, but several existing reviews can assist interested readers (Warren 1971; Reynolds and Casterlin 1979; EPA 1986; Boles 1988; Armour 1991; Materna 2001; McCullough et al. 2001; Sauter et al. 2001; see Appendices A and B). While many

[10] Other factors include siltation, loss of rearing habitat, over-harvest, migration barriers, hatchery practices, predation, and ocean conditions.

knowledge gaps regarding thermal requirements and limits for our native salmonids remain (e.g., Table 1), the IMST concludes that a great deal is known about the physiological and behavioral effects of temperature on salmonids, and this body of knowledge is adequate for developing sound temperature standards for the State of Oregon.

Table 1. Examples of uncertainties and certainties associated with determining water temperature criteria that protect salmonid populations in the Pacific Northwest. These certainties and uncertainties are conclusions reached by the technical working group of EPA Region 10 water temperature criteria guidance project (Poole et al. 2001). These conclusions are consistent with IMST's review of water quality standards for temperature.

	Uncertainty	Certainty
How Cold	Relationships between lab-derived temperature thresholds and requisite temperatures in the field	Salmonids can experience physiological stresses where water temperatures are not optimal
	Maximum allowable temperatures that will support viable populations	General ranges of water temperatures necessary for survival and reproduction
	Precise thresholds of harmful temperatures	Both lethal and sub-lethal effects affect salmonid survival
	Effects of multiple stressors	Thermal tolerance in salmonids is affected by other stresses and vice versa
How Much, When and Where?	Mechanisms and dynamics of cumulative effects on stream temperature dynamics	Cumulative effects occur and can result in synergistic temperature changes within streams subject to multiple disturbances
	Patterns of environmental variability required to support populations	Complex physical habitat structure creates spatially and temporally diverse coldwater habitats that salmonids have evolved to exploit
	Historical thermal regimes in streams	Salmonid survival requires a variety of cold water temperatures that are well-distributed over space and time
	Measures of historical fish distribution and trends in fish populations	Salmonid populations have declined precipitously and their distributions have been reduced throughout the region.
Human Influence	Data on the alteration of thermal regimes	Thermal regimes have been altered substantially over time; where altered, streams are generally warmer in the summer and more spatially homogeneous
	Exactly what management actions are necessary to protect salmonids	The types of activities affecting stream temperature
	Maximum levels of degradation that will allow salmon to persist	Salmonid populations require a safety buffer in the face of a variable environment

Scientific Basis of the 1996 and 2003 Temperature Standards

As we described in the introduction to this report, the State of Oregon adopts water quality standards on the basis of both science and policy considerations. In the answer to this question, we evaluate only the scientific basis for temperature standards. This report was initially written in response to a request to review the 1996 temperature standards. Therefore, this discussion emphasizes the scientific basis for the 1996 temperature criteria. However, we highlight areas where 1996 and recently adopted 2003 standards have a similar basis.

Foundation for Temperature Standards

When the 1996 standards were developed, a Temperature Subcommittee assembled by DEQ reviewed more than 500 scientific publications on the effects of temperature on aquatic organisms, and evaluated whether the existing standards were consistent with the scientific literature (DEQ 1995). This (1995) Temperature Subcommittee reached a number of general conclusions about stream temperature and salmonid health that provided a technical context for setting temperature standards (Box D).

Box D. Findings and Conclusions of 1995 Temperature Subcommittee
Findings and conclusions are reproduced verbatim from DEQ (1995), p. 2-25 to 2-26.

The native aquatic species in Oregon most sensitive to warm temperatures are chinook salmon, bull trout, and first-year tadpoles of tailed frogs. If the temperature standard protects these species, the committee expects the standard will also protect other native aquatic biota.

Nearly all the native Oregon fish species are classified as cold- or cool-water species. The only known warm-water native in Oregon is the borax chub, found near hot springs.

The temperature requirements of chinook and coho salmon and bull trout are presented graphically in Section 2.4 of this issue paper. For Northwest salmon species, incidence of disease increases significantly when temperatures exceed 60–62 ºF (15.5–16.7 ºC). Bull trout, a native resident trout species are found at temperatures less than 54 ºF (~12 ºC) for most life stages and less than 44 ºF (6.6 ºC) for egg incubation.

In order to maintain viable, sustainable fish populations, the standard must be based on temperatures that allow individuals to remain healthy and reproduce. Therefore the standard will not be based simply on avoiding lethal temperature limits, nor on a sole objective of maximum growth rates. The standard should be based on temperatures that prevent dominance by nuisance or non-native species, and provide for successful growth and reproduction.

Indirect effects of warming occur along a continuum with the incidence or severity of the effect increasing as temperature increases. Any specific temperature included in a standard is a point along that continuum.

Not only absolute temperatures, but also the temperature regime (the timing of temperature changes through the year) is important to the development of fish and aquatic invertebrates. Maximizing an organism's growth rate is not the sole objective. The timing of development of organisms from one life stage to another is also critical to their survival and reproductive success.

Various species, runs, and stocks have developed on an evolutionary time scale, and the ability to utilize the variety of temperature regimes found in different rivers and reaches, and within the same river at different times. This has produced a diversity of life histories that utilize these opportunities for growth and survival. It is not desirable to homogenize the temperature regimes by allowing them to increase to a threshold temperature value.

Insufficient information is available to distinguish different temperature requirements for different stocks or races of cold-water fish species. Other aquatic organisms may also have stock differences, but there is even less information available for non-fish species.

Oregon is toward the southern end of the geographic range in which many cold water fish species occur. Consequently, there is little opportunity to increase summertime stream temperatures and still maintain viable coldwater communities and fish populations.

Summertime stream temperatures recorded over approximately the last 30 years are generally warmer than is optimal for cold-water fish species. Land use activity, point sources and natural factors have contributed to this condition.

Stream temperatures vary naturally in the environment through time – daily, seasonally, following natural disturbances (e.g., floods), and with long-term climatic changes. Stream temperatures also exhibit natural variability, i.e. headwaters versus lower reaches – a result of elevation, time of exposure to air temperatures, amount of groundwater inflow, and shade.

The 1995 Temperature Subcommittee (DEQ 1995) also found that:

- The temperature standards in effect at the time needed to be defined explicitly and revised to provide for more effective application.

- There is very limited information on the temperature history of Oregon's waters. Proposing a single standard for all of Oregon's waters that is scientifically defensible in a site-specific manner is a daunting task. Similarly, there is little scientific basis for proposing unique or specific standards to each body of water.
- Though temperature models are useful for interpreting and understanding stream temperature at the scale of reaches, at the time of the review they were not adequate for accurately predicting temperature through the river network of an entire basin. As a result, they were not adequate for setting basin-specific standards at that time. The sub committee felt that there was great potential for application of basin models in the future[11].
- Bull trout (*Salvelinus confluentus*) required lower water temperature than other species of salmonids. Specific standards to protect this species were needed within the species known historical distribution.

Biologically-based numeric criteria

After reviewing temperature requirements of salmonids at various life history stages throughout the year, the 1995 Temperature Subcommittee evaluated which life history stages were likely to be most vulnerable to elevated stream temperatures (Figure 2, see also Table 2). Species considered included chinook salmon (*Oncorhynchus tshawytscha)*, steelhead trout (*O. mykiss)*, sockeye salmon (*O. nerka)*, coho salmon (*O. kisutch),* and bull trout. "Biologically-based" numeric temperature criteria were adopted with the aim of protecting life stages of fish that were vulnerable to elevated stream temperature. Temperatures specified in the criteria (Table 3) were based on field and/or laboratory research studies on the impacts of temperature on salmonids (such as studies listed in Appendices A and B).

For example, Boyd and Sturdevant (1997) describe the process used to develop the 64 ºF [17.8 ºC] criterion adopted to protect salmon and trout use in warm summer months,

> "The 64 ºF [17.8 ºC] criterion was established by: 1) identifying the widespread native species in the State that are sensitive to temperature, 2) identifying what life stages occur during the summer months, and 3) reviewing the available scientific literature on the temperature needs of those species during the summer months...."
> (Boyd and Sturdevant 1997, p.2)

Compared with the 1979 standards, 64 ºF [17.8 ºC] was an increase from the 58 ºF [14.4 ºC] applied to many basins west of the Cascades, but it was lower than the 68 ºF [20 ºC] criteria for many streams in eastern Oregon.

[11] See Science Question 4 for a discussion of currently appropriate applications of models.

After Oregon adopted temperature standards in 1996, several comprehensive reviews identified a larger and growing body of empirical evidence about the effects of temperature on aquatic organisms (Berman 1998; Coutant 1999; McCullough 1999; Poole and Berman 2001). For the most part, the IMST finds that these additional reviews reinforced the conclusions of the 1995 Temperature Subcommittee.

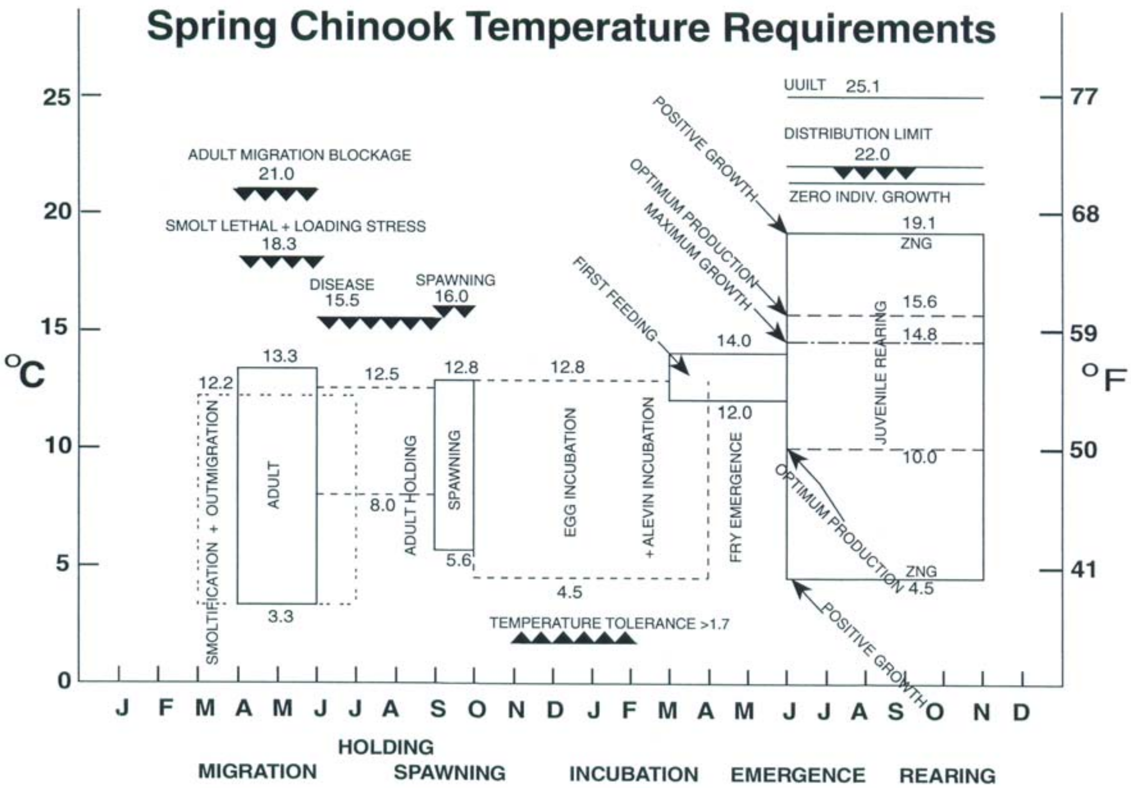

Figure 2. Spring chinook temperature requirements at each life stage – from upstream migration of adults to downstream migration of next-generation smolts (McCullough 1999). This figure summarizes scientific information compiled in Appendix D of the 1995 Issue Paper (DEQ 1995), and is supplemented with additional information reviewed in McCullough (1999). Multiple methods were used to derive temperatures reported in this figure.

Temperature standards adopted in 2003 are based on an approach similar to that used for the 1996 standards (Table 3). However, 2003 criteria are more specific about geographic locations. The new rules use maps and table to specify locations where criteria apply. The locations in the rules are based on mapping of salmonid habitat use at different life stages conducted by Oregon Department of Fish and Wildlife (ODFW), DEQ, EPA, USFWS, and NOAA Fisheries. In the new rules, criteria for redband trout (*Oncorhynchus mykiss* ssp.) and Lahontan cutthroat trout (*O. clarki henshawi*) were added based on recent studies (see following section). The 2003 standards also include a "human use allowance", limiting the cumulative amount that temperature can be increased by human activities; the standards limit the cumulative increase above the biologically-based criteria resulting from human use to 0.3 ºC/0.5 ºF. Waters colder than temperature criteria are also limited to a 0.3 ºC/0.5 ºF increase if the waters contain endangered species, constitute critical habitat, or help to keep temperatures below criteria downstream.

Table 2. Effects of human-caused elevated stream temperatures on salmonids in the Pacific Northwest. Effects were identified by EPA (2003a). -- = Location not specified**;** * Downstream fry migrations can also be affected.

Stock	Life stage	Vulnerable Time of Year	Location	Notes on effects of elevated temperature
Spring chinook	Spawning	Late summer-early fall	Mid-upper reaches	Can 'shrink' available habitat for adult spawning/holding, limiting spawning to habitat higher in the watershed
	Juvenile	Throughout summer	Mid-upper reaches	Can 'shrink' available habitat for rearing, limiting rearing to habitat higher in the watershed
Fall chinook	Adult	Summer	Lower river reaches	Can adversely affect fall chinook in lower river reaches during the summer months when the adults are migrating upstream and holding to spawn.
	Spawning	Early fall	Lower river reaches	Can delay spawning
	Juvenile	Summer	Lower river reaches	Historically, juvenile fall chinook out-migrated throughout the summer months, but today human-caused elevated temperatures have made this impossible in some rivers (e.g., Yakima River).
Coho salmon	Juvenile	Summer	--	Can render water unsuitable for rearing, thereby 'shrinking' the amount of available habitat*
	Adult	Early fall	--	Can adversely affect adults as they start migrating upstream
Sockeye salmon	Adult	Mid- to late summer	Between ocean and upstream lakes	Can adversely affect adults as they migrate upstream
Chum salmon	Adult	Late summer	Low reaches and side channels of major rivers just upstream from tidewater areas	Can adversely affect adults as they migrate upstream
Pink salmon	Adult	Late summer	Lower reaches of large rivers	Can adversely affect adults as they migrate upstream
Winter steelhead	Juvenile	Summer	Mid-upper reaches	Can 'shrink' available habitat for rearing, limiting juveniles to habitat higher in the watershed
Summer steelhead	Adult	Summer	--	Can adversely affect adults as they migrate upstream
	Emerging fry	Mid-summer	--	Can adversely affect fry that incubate into July in some watersheds
	Juvenile	Summer	Mid-upper reaches	Can 'shrink' available habitat for rearing, limiting juveniles to habitat higher in the watershed
Bull trout	Juvenile	Summer	Upper reaches	Adults migrating upstream to spawn in summer can be adversely affected by loss of coldwater refugia.
	Adult	Summer	Between lower reaches or lakes and upper reaches	Can adversely affect adults as they migrate upstream, loss of cold water refugia can be a problem for migratory adults

Table 3. Basis for biologically-based numeric criteria in temperature standards adopted by Oregon in 1996 and 2003. OAR = Oregon Administrative Rule. *Times and locations identified in maps and tables in administrative rules. † Times and locations identified through consultation with ODFW. Continued on next page.

Category	Target Species	1996 Criteria	2003 Criteria	Basis of Criteria
1. General salmonid use	All salmonids:	**64 ºF [17.8 ºC]**	see no. 1b – 1e below	<u>1996 criteria:</u> "To protect general salmon and trout use during the warm summer months... (Boyd and Sturdevant 1997, p.2) "The standard is based not on... directly lethal temperatures (usually above 70 º [21.1 °C]), but on **sub-lethal effects**, of which there are many....Sub-lethal effects of temperature on salmonids occur gradually as stream temperatures increase. **Some of these effects begin when stream temperatures are below 64 ºF [17.8 ºC], such as increased incidence of disease and a reduction in juvenile growth rates for chinook. Optimal juvenile growth rates for chinook and coho occur at temperatures below 58 to 60 ºF [14.4 to 15.6 °C]. At 64 ºF [17.8 °C], temperatures are less than optimal, but not yet at levels where growth ceases or direct mortality occurs.** In selecting the criteria, this information was balanced with the fact that the unit is a maximum temperature and that if the criteria is met, the fish will be exposed to temperatures above 60ºF [15.6 °C] for only part of the day during a few of the warmest weeks of the summer. The intent is that while this criterion does not eliminate all risk to the fish whatsoever, it keeps the risk to a minimum level." (Boyd and Sturdevant 1997, p. 3)
1b. Core cold water habitat use	Chinook, chum, coho, sockeye, and pink salmon; steelhead; bull trout	see no. 1	**16.0 ºC (60.8 ºF)***	<u>2003 criteria:</u> Expected to maintain temperatures within the range generally considered optimal for salmon and steelhead rearing. (OAR 340-04I-0002) Expected to maintain temperatures suitable for bull trout migration, foraging and sub-adult rearing that occurs during the summer (OAR 340-04I-0002, see no. 3 below).
1c. Salmon and trout rearing and migration	Chinook, chum, coho, sockeye, and pink salmon; steelhead; rainbow trout; cutthroat trout	see no. 1	**18 ºC (64.4 ºF)***	<u>2003 criteria:</u> Expected to maintain thermally suitable rearing habitat for salmon and steelhead, rainbow and cutthroat trout. (OAR 340-04I-0002)
1d. Migration corridor use	Chinook, chum, coho, sockeye, and pink salmon; steelhead	see no. 1	**20 ºC (68 ºF)*** [12]	<u>2003 criteria:</u> Expected to maintain temperatures suitable for salmon and steelhead migration during the summer where there is little or no anadromous salmonid rearing occurring in the months of July and August. (OAR 340-04I-0002) "There may not be much migration during the warmest weeks of the year, but neither is 20 ºC [68 °F] an optimal thermal condition for migration. The idea is that when the bulk of migration occurs, temperatures will not be at their peak and migration will be protected. It is also important in these reaches to protect the natural thermal heterogeneity, such as cold water refugia, colder tributary inputs, and natural diurnal fluctuations that provide cooler temperatures during a portion of each day." (DEQ 2003, p. 9)

[12] In addition, these water bodies must have coldwater refugia sufficiently distributed so as to allow salmon and steelhead migration without significant adverse effects from higher water temperatures elsewhere in the water body. Finally, the seasonal thermal pattern in Columbia and Snake Rivers must reflect the natural seasonal thermal pattern.

Table 3 (cont.). Basis for biologically-based numeric criteria in temperature standards adopted by Oregon in 1996 and 2003.

Category	Target Species	1996 Criteria	2003 Criteria	Basis of Criteria
1e. Lahontan cutthroat trout and redband trout	Lahontan cutthroat trout; redband trout	see no. 1	**20 ºC (68 ºF)***	**2003 criteria:** "Redband trout, like Lahontan cutthroat trout have the ability to function unimpaired at somewhat higher temperatures than other salmonids. Therefore, there is a scientific basis for a somewhat higher criterion for these species during maximum summer conditions." (Appendix A in DEQ 2003, p.18)
2. Salmonid spawning, egg incubation, and fry emergence	all salmonids chinook, chum, coho, sockeye, and pink salmon; steelhead	**55 ºF† [12.8 ºC]** --	-- **13 ºC (55.4 ºF)***	**1996 and 2003 criteria:** "These salmonid life stages require colder water temperatures, but occur at specific times of the year. This criterion applies to those times and locations when these life stages occur (Boyd and Sturdevant 1997, p.4)
3. Native Oregon bull trout	bull trout	**50ºF [10ºC]**	spawning and juvenile rearing: **12 ºC (53.6 ºF)*[13]** migration, foraging and subadult rearing: **16.0 ºC (60.8 ºF)*** see core cold water habitat above	**1996 criteria and 2003 spawning and rearing criteria:** "Bull trout have colder temperature requirements than other salmonids and their distribution is not as broad. Therefore, this specific criterion was established to only apply to bull trout habitat. While less information was available for bull trout than other species, there was enough to identify colder temperature requirements. One of the primary concerns for bull trout is competition with other species. Optimal juvenile growth occurs at 39 to 50 ºF [3.9 to 10 ºC]" (Boyd and Sturdevant 1997, p.4) "The assumption is that if 12 ºC [53.6 ºF] is met as a MWMT (7 day average maximum for the warmest week of the year) that temperatures of 9 or 10 [48.2 or 50 ºF] should be available at the appropriate times. Because this assumption would not necessarily hold true for spawning areas below reservoirs, a narrative has been added to the rule that prohibits more than a de minimis warming from above to below the reservoir...during spawning and egg incubation times." (DEQ 2003, p.12) **2003 migration, foraging and subadult rearing:** "Data from the Wenaha River in Northeast Oregon, a river that is relatively unimpacted by human activity in upper reaches, showed that the highest relative abundance of sub-adult and adult bull trout were found where 7-day average maximum temperature was greater than 16 [60.8 ºF]" (DEQ 2003, p.11)
4. Columbia River below mile 309 and for the Willamette River below mile 50	N/A	**68 ºF [20 ºC]**	--	**1996 criteria:** "For these lower mainstem rivers, the criteria is somewhat higher for the following reasons: 1) it is less likely that adult holding and juvenile rearing uses occur in these river segments during the warmest months of the year (July and August), and 2) in these deep lower mainstem rivers, temperature varies by depth so that the fish may find acceptable temperatures at depth" (Boyd and Sturdevant 1997, p.3–4)

[13] From August 15 though May 15, in bull trout spawning waters below Clear Creek and Mehlhorn reservoirs on Upper Clear Creek (Pine subbasin), below Laurance Lake on the Middle Fork Hood River, and below Carmen reservoir on the Upper McKenzie River, there may be no more than a 0.3 ºC (0.5 ºF) increase between the water temperature immediately upstream of the reservoir and the water temperature immediately downstream of the spillway when the ambient seven day average maximum stream temperature is 9.0 ºC (48 ºF) or greater, and no more than a 1.0 ºC (1.8 ºF) increase when the seven-day-average stream temperature is less than 9 ºC.

In implementation of 1996 and 2003 standards, stream temperatures are measured with recording sensors. For each temperature monitoring location, DEQ examines the warmest consecutive seven-day period during the year. If the average of the daily maximum temperatures during this week is warmer than the number specified in the criteria, the stream is warmer than the standard (or "exceeds" the standard). Certain criteria (such as salmonid spawning, egg incubation, and fry emergence) apply to the time of year that those activities occur and not to the summer maximum (see Boxes B and C, p. 31 and 32).

Redband trout and Lahontan cutthroat trout

One area of growing literature is the performance of resident and anadromous salmonids in eastern Oregon. Some forms (subspecies or evolutionary significant units) of endemic trout that have evolved in arid basins may be able to tolerate temperatures above those commonly accepted for the species. In general, there is a paucity of information on the temperature tolerances of such fishes.

The limited literature on redband trout, a subspecies of rainbow trout found in many basins east of the Cascade Mountains in Oregon (Behnke 2002; Dambacher and Jones, *in press*), suggests that redband trout may have upper thermal tolerance limits above those of coastal rainbow trout or other salmonids. Surveys for these fish in the Owyhee Mountains, Idaho during drought conditions revealed that they could tolerate maximum daily temperatures of 25.5–29.0 ºC [77–84.2 ºF], with a daily fluctuation in temperature of 9.5–11 ºC [17.1–19.8 ºF] (Zoellick 1999). The reports on the tolerances of redband trout were based on distribution and did not ascertain whether the reproductive fitness of the fish was impaired at those temperatures. Since dissolved oxygen concentration varies inversely with temperature, it is difficult to discern which of these variables, or both, is the most important in affecting redband distribution. Data in Vinson and Levesque (1994) suggest that hypoxia (low dissolved oxygen concentration) was limiting to redband trout in a southwestern Idaho stream.

Rodnick et al. (2004) found that the critical thermal maximum[14] of three distinct redband trout populations in southeastern Oregon averaged 29.4 ºC [84.9 ºF]. Larger redband trout were more thermally sensitive than smaller individuals at water temperatures between 24 and 28 ºC [75.2 and 82.4 ºF]. The body mass of the larger fish ranged between 400–1400 g [663 ±75 g (standard error)] whereas smaller fish were just 40–140 g, and averaged about 60 g. Rodnick (pers. comm.[15]) indicated that redband have more available metabolic energy at 24 ºC [75.2 ºF] than rainbow trout do at the same temperature. He suggested that enhanced aerobic fitness may be an important factor, which allows the fish to persist near or above 24 ºC [75.2 ºF] for several hours during the day. Preferred temperatures for redband were found to be significantly lower, just below 13 ºC [55.4 ºF]; although metabolic power[16] was observed to be comparable at 24 ºC [75.2 ºF] and 12 ºC [53.6 ºF] (Gamperl et al. 2002; Gamperl and Rodnick 2003).

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[14] Fish were held overnight in tanks supplied with water from the streams where redband were captured. Starting between 7 and 9 AM, water temperatures were raised from 14 ºC at an ecologically relevant rate of 2 ºC per hour until fish lost equilibrium. These tests were performed during the hottest period of the summer.

[15] Personal Communication. 2003. Letter from K. Rodnick, Idaho State University to C.B. Schreck, August 19, 2003.

[16] Metabolic power was defined as maximum oxygen consumption minus routine oxygen consumption.

Gamperl and Rodnick (2003) recommend that the temperature criterion for redband trout be 22 ºC [71.6 ºF] average weekly maximum temperature[17]. Based on their study of metabolic and thermal physiology of redband trout, they observed that sublethal stress in redband trout occurs above 24 ºC [75.2 ºF]. Based on temperature of heat shock protein expression in other salmonids, they inferred that sublethal stress is likely to intensify at 26 ºC [78.8 ºF]. Gamperl and Rodnick then examined probability of maximum water temperatures reaching 24 and 26 ºC [75.2 and 78.8 ºF]. The probabilities were derived from an analysis of stream temperature regimes from Willow Creek in southeastern Oregon (Dunham 1999). They concluded that the 22 ºC [71.6 ºF] average weekly maximum temperature "would not completely eliminate the potential for sub-lethal stress, but short-term (1–2 hrs) exposure to 24 ºC [75.2 ºF] on one or two days during the summer is unlikely to have any significant negative effects on redband trout" (Gamperl and Rodnick 2003, p. 10). They also noted that multiple metrics might be more biologically relevant, but their recommendation is based in part on the policy consideration that a single metric is easier to interpret (see p. 48 in this report for further discussion of this subject).

Lahontan cutthroat trout are endemic to the Great Basin (Coffin and Cowan 1995) and are found in southeastern Oregon (Hanson et al. 1993; Jones et al. 1998). These fish may also have temperature tolerances above those considered "normal" for salmonids. Dunham (1999) recommends that "to minimize risk of mortality and sublethal thermal stress for Lahontan cutthroat trout, water temperatures should not exceed a daily maximum of 22 ºC [71.6 ºF]". While Dunham (1999) considered this recommendation conservative, we do not necessarily share this view. There is no information in Dunham's report that suggests that this or somewhat lower temperatures could not have negative consequences to reproductive fitness (the ability to produce offspring). Dunham (1999) also concludes that the maximum daily temperature (maximum temperature observed on any single day of the year) is a more appropriate criterion for this group of fish than is the 7 day average maximum temperature (7DADM) as used in Oregon's standard (see discussion of 7DADM, p. 47).

Given that there are no data to the contrary, there appears to be a scientifically defensible reason to believe that Oregon's temperature standard for waters containing redband and Lahontan cutthroat trout could be somewhat higher than for waters containing other salmonids or rainbow trout. Confidence in Gamperl and Rodnick's (2003) recommended criterion for redband trout would be enhanced by analysis of temperature regimes across the range of redband trout and by studies of heat shock protein expression in redband. The suggestions for the upper thermal limit for Lahontan cutthroat trout (Dunham 1999) and redband trout (Gamperl and Rodnick 2003) ignored potential sublethal effects of elevated temperature on reproductive fitness. Overall, we caution that the available scientific knowledge isn't sufficiently accurate and exhaustive to justify recommending temperature standards within fractions of a degree, or in some cases within a few degrees. Regardless, maintaining temperatures at the margins of thermal tolerance for salmonids is not likely to be an effective recovery strategy (see Table 1).

[17] Average weekly maximum temperature (AWMT) is equal to the 7DADM temperature.

Some Challenges in Applying Scientific Information to Set Temperature Criteria

Applying Field and Laboratory Studies to Setting Numeric Criteria

Both field and laboratory studies provide useful information on thermal requirements of fishes, but each study approach has different strengths and weaknesses (Table 4). No single approach can comprehensively address the question of thermal habitat requirements for a species. Accordingly, the specific questions that each research approach can best address are often considerably different.

Data obtained from field studies generally answer the question: what do fish actually do under a set of specific environmental circumstances? The power of field studies rests with the fact that they are conducted in the appropriate environmental context. However, when trying to discern the effects of a variable of interest, such as temperature, they are frequently hampered by an inability to determine specifically which of a number of variables caused the response observed. This is further confounded by the fact that having true experimental controls in field studies is often difficult. It is also difficult to have replication of field studies. For example, no two streams or even reaches within a stream are the same in all respects. In addition, while temperature may be the variable of interest, temperature tends to co-vary, usually in a non-linear way, with other environmental conditions such as oxygen concentration, water flow, depth, food availability and quality, accessibility to predators, and the species and virulence of pathogenic organisms present. In addition, field studies typically ignore the fact that fish may be selecting microhabitats that may be considerably different than the general area they appear to be occupying. It is also possible that certain members of a population may be more temperature resistant than other members of that same population, and it is also likely that this difference has some genetic basis. Therefore, while elevated temperatures may not eliminate a population from an area, it could readily decrease the genetic variation found in that population, a fact that would be missed by presence-absence or proportionate abundance data that are typically collected for field studies.

On the other hand, laboratory research can establish potential fish responses. In other words, such studies would address the question: what can animals do? The power of laboratory studies stems from the fact that they can isolate variables and rigorously control and reproduce the tests, allowing more robust statistical analyses. Unfortunately, there can be difficulty in extrapolating findings from laboratory studies to applications in the field. This is because it is impossible to simulate in the laboratory the exact conditions of all environmental variables beyond the one, or perhaps at most a few, of prime interest. For example, laboratory tests to determine temperature tolerances of fish, while rigorously controlling test temperatures, are conducted in a relatively unnatural habitat and largely ignore most other relevant environmental conditions such as water flow, intra- and inter- specific social crowding, nutritional status of the test fish, food availability or quality, cover, predators, or pathogens. In addition, the temperature to which the fish are acclimated to at the start of an experiment and the rate of temperature change to which the fish are exposed during the test can affect the final thermal tolerance determined for the fish. Such laboratory experiments are improved through use of laboratory or experimental streams that provide a wide variety of habitat types, natural levels or naturally occurring food organisms, natural background water temperatures and seasonal fluctuations, competitors, and predators (Warren and Davis 1967). However, even these cannot include the physical and ecological complexity of a natural stream.

Table 4. Potential difficulties with and differences between field and laboratory determination of temperature tolerances in fishes, as concluded from the representative literature. (Continued on next page).

	Field Studies	Laboratory Studies
Experimental Design		
Controls	Difficult to have true controls because of spatial and temporal variability.	Researchers can know and control environmental variables other than temperature. Difficult to establish which test treatment should be considered the "control".
Replication	Replication possible but very difficult. Not true replicates if repeated through time.	True replication possible.
Fish studied (study population)	Study population heterogeneous (e.g., genetically variable; various ages, life history stages).	Study population homogenous (e.g., genetically similar, usually hatchery or laboratory stock; identical age; similar life history stage). Often only juveniles.
	Study population may change during study period. Fish may move depending on thermal conditions (e.g., behavioral thermoregulation, exploration, home range not static.	Study population usually constant.
	Unit of measurement may be stream or stream reach, not individual fish. Hence, replication necessary but difficult to achieve.	Unit of measurement may be tanks, not individual fish. Much replication necessary.
Feasibility of experimentation	May be observational study or experimental manipulation. Confounding variables may be difficult to control in experimental manipulations.	Readily lends itself to experimental manipulations.
Test Conditions		
Acclimation	Fish acclimated to a fluctuating thermal regime which is often unknown to researchers.	Fish typically acclimated to a constant temperature set by researchers. Acclimation temperature employed likely ecologically unrealistic. Length of acclimation period can affect results of experiment. Previous thermal history experienced by fish usually not accounted for in research design.
Food rations	Food availability may be limiting factor at elevated temperatures, not temperature per se; the energetic cost of foraging and digesting can outweigh the energy content of the food. In addition, temperature could also affect the prey base more than the fish.	Rations usually not limiting as it may be in the field; hence may not be ecologically realistic. Food consumption, however, could be a good indicator of when temperature affects appetite. Food could be rationed if desired, but determining an ecologically realistic food ration could be problematic.
Disease	Disease organisms may be more infective and pathogenic in warmer waters and the immediate cause of mortality. Pathogens not readily identified and impossible to control.	Pathogens often not present, can be controlled, or can be identified as source of mortality. In the field, pathogens are likely a direct source of mortality at elevated temperatures; something that would be missed in most laboratory studies.

Table 4 (cont.) Potential difficulties with and differences between field and laboratory determination of temperature tolerances in fishes, as concluded from the representative literature.

	Field Studies	**Laboratory Studies**
Test Conditions (cont.)		
Similarity to natural conditions	Can be ecologically realistic.	May not be ecologically appropriate. Thermal conditions often not realistic, rates of change typically unrealistic. Tests are sometimes conducted at wrong time of year or employing wrong developmental state of the fish.
Duration of tests	Variable. Can be ecologically relevant.	Usually not ecologically relevant.
Physiological condition of fish	Difficult to assess.	Can be readily determined.
Data Analysis		
Inference	Results at population level are correlative. Results generally do not allow conclusions of cause and effect.	For randomized experiments, results may be indicative of cause and effect. Results often relate to individual fish and have little information content regarding population-level effects. Results difficult to relate to production.
Variability	Spatial and temporal heterogeneity must be accounted for in analysis. Variability is often high, with many confounding and often interacting factors. This limits between study comparisons.	Low variability in test conditions makes data analysis more straightforward.
Metrics	Choice of how stream temperature data should be summarized (e.g., degree days, 7-day running maximum, etc.). Determining which method is most biologically relevant may not be straightforward.	Choice of which model of fish response to temperature should be used (e.g., CTM, UILT, preferred temperature, physiological condition, etc.).
Production	Typically, results are number of fish or biomass, not production.	Consequences of results relative to recruitment are almost impossible to define.
Genetic interpretation	Population-level genetic consequences of elevated temperature are difficult to determine.	Consequences of results relative to genetic variation are almost impossible to determine.
Other confounding variables	Direct source of mortality ultimately consequent to elevated temperature but proximately due to some other variable (e.g., predators, competitors, and pathogens)	Between-fish interactions can markedly affect results (e.g., social interactions stressful; in mortality studies, surviving fish benefit from absence of respiration of dead fish).

Appropriate Methods to Analyze Stream Temperature Data

Because stream temperatures vary across time and space (see Question 2), measuring stream temperature is not as simple as placing a thermometer in a stream (see Poole et al. 2001). Important considerations include where stream temperature is measured, when it is measured (time of day and season), how often, and how the data are analyzed.

DEQ has set minimum quality control procedures that must be followed for collecting stream temperature data. In brief, standard field protocols must be followed and accuracy checks on instruments must be conducted. These procedures are listed on DEQ's web page (http://www.deq.state.or.us/wq/303dlist/303dpage.htm). The agency recommends that stream temperatures be monitored according to the rigorous protocol described in the Oregon Plan Water Quality Monitoring Technical Guide Book (Oregon Plan 1999).

When analyzing stream temperature data for applying temperature standards, DEQ examines the warmest consecutive seven-day period during the year. If the average of the daily maximum temperatures during this week is warmer than the number specified in the applicable criterion, the stream is warmer than the criterion (or "exceeds" the criterion). This unit of measurement is called the seven day moving average of daily maximum temperatures (7DADM).

The 7DADM is one of many units of measurement that could have been chosen for use in temperature standards. Other possible metrics include (DEQ 1995):

Daily maximum temperature – maximum temperature recorded within a day;
Daily mean temperature – mean temperature recorded within a day;
Seven day moving average of daily mean temperatures – the average of average temperatures over any seven day period throughout the year.

Analysis of continuous temperature datasets for Pacific Northwest streams has estimated that the 7DADM is most often in the range of 3 ºC [5.4 ºF] above the mean weekly stream temperature (Dunham et al. 2001; Chapman 2002). However, this difference is highly dependent on the amount of diel variation in stream temperature (EPA 2003a). For example, Dunham et al. (2001) observed that the difference between mean weekly temperature and 7DADM among streams ranged from 1–9 ºC [1.8–16.2 ºF].

Recent guidance from EPA on setting temperature standards endorses the use of 7DADM (EPA 2003a). The IMST agrees with several of EPA's conclusions about this unit of measurement for temperature criteria (EPA 2003a, p. 18–19):

- The emphasis on daily maximum temperatures is appropriate for protecting salmonids against acute effects (lethality, migration blockages),
- The average of maximum temperatures over a week reduces bias that could be caused by a single exceptionally hot day,[18]
- Supplementing this criterion with more protective temperatures for sensitive species and life stages is appropriate,
- Careful consideration needs to be taken in selecting 7DADM values to protect for sub-lethal and chronic effects (growth, disease, smoltification, competition).

[18] However, a single hot day can cause adverse effects on organisms and communities.

From a technical perspective, any unit of measurement for stream temperatures has advantages and disadvantages. One disadvantage of 7DADM (as a unit of measurement) is that it does not give information about duration of exposure of aquatic life to maximum temperatures. In other words, it gives no information on variation in water temperatures. For example, the length of time a stream stays at a maximum temperature during a day could have important physiological consequences for fish. The number of times a stream reaches the maximum temperature over weeks or months could also be important (EPA 2003a). In addition, timing of maximum temperatures in the annual cycle in relation to fish development can have consequences for fish populations. The 7DADM also does not provide information about minimum temperatures, which may be important in determining starting temperatures for warming during a day.

Some authors have suggested that using multiple metrics as temperature criteria might better capture the range of lethal and sublethal effects of elevated temperature on fish (Dunham 1999; Gamperl and Rodnick 2003). Dunham et al. (2001) point out that as stream temperature become more variable, the difference between average and maximum temperatures grows; therefore, correlations (or redundancies) among metrics become smaller. Gamperl and Rodnick (2003) give an example of how multiple metrics might be combined in temperature criteria. They suggest that redband trout might be more comprehensively protected by a standard that incorporated two different units of measurement. They proposed that a maximum daily temperature (24 ºC, 75.2 ºF) that protected against short-term effects could be combined with an average weekly temperature (18.5 ºC, 65.3 ºF) to ensure that stressful temperatures were not persistent. While multiple units of measurement can provide more information to managers, policy makers must also consider that they may be difficult to apply and to explain to the public.

To determine whether a metric (or combination of several metrics) is appropriate to use in temperature criteria, its strengths and weaknesses must be weighed. Overall, IMST concurs with EPA and DEQ that the seven day moving average of daily maximum temperatures has a sound scientific rationale and is an appropriate unit of measurement for numeric stream temperature criteria.

Question 1 Conclusions

Conclusion 1-1. IMST concludes that the scientific basis for Oregon's temperature standards is credible.

The scientific basis for Oregon's temperature standards is credible and consistent with the body of scientific literature on the thermal requirements of salmonids (see Science Question 2; Appendices A and B). The temperature standards for Oregon are a scientifically valid measure of the potential impacts of water temperature on coldwater fishes and represent a reasonable balance of the array of information on the effects of temperature on different ecological processes and salmonid life history stages.

The IMST recognizes the many knowledge gaps regarding thermal requirements and limits for our native salmonids. However, we conclude that Oregon's temperature standards are based on the best science available. Oregon's approach to setting stream temperature standards is an iterative process, which allows for revision of the standards in the face of new scientific information. Later in this report (Science Question 4), we evaluate whether application of Heat Source (a model that has been developed since the development of the 1996 temperature standards) by DEQ is technically sound.

Temperature standards are a starting point: the “natural” exact temperature may be slightly lower or higher. Oregon must implement policies and programs that establish landscape-level reductions in stream temperature where temperature is a limiting factor for salmonid recovery.

Conclusion 1-2. Cool temperatures are vital to salmonids, which evolved in cold-water, oxygen-rich systems. Warm streams (in combination with other human impacts) are likely to hinder recovery of salmonid stocks.

Salmonids require relatively cold water throughout their life history stages compared with many other aquatic organisms. Overly warm, oxygen-poor waters are detrimental to salmonids and their ecosystems. Habitat degradation is associated with salmonid decline in the Pacific Northwest. Increased temperature of streams and rivers is one major consequence of habitat degradation. As we discuss in more detail in the answer to Science Question 3, loss of historical riparian vegetation, reduced flows, and other human impacts have directly or indirectly caused an increase in the temperature and habitat degradation for many streams and rivers.

Conclusion 1-3. IMST concurs with EPA and DEQ that the seven day moving average of daily maximum temperatures (7DADM) has a sound scientific rationale and is an appropriate unit of measurement for stream temperature criteria.

The 7DADM used by the Oregon in the 1996 temperature standards is a credible representation of ecologically relevant temperatures. Temperature measurements that reflect cumulative exposure and the effects of diel temperature fluctuations are appropriate in certain types of studies, but the existing metric used in the temperature standards is scientifically valid.

Conclusion 1-4. Redband trout and Lahontan cutthroat trout exhibit higher thermal tolerances than the salmonid species examined in the 1995 Issue Paper (DEQ 1995). IMST concludes that it is appropriate for the State of Oregon to consider recent data on the physiological performance of Lahontan cutthroat trout & redband trout when setting stream temperature criteria.

We note that DEQ has taken these recent data into account in current (2003) revisions to the temperature standards.

Science Question 2. How can salmonids occur in streams that are warmer than criteria in Oregon temperature standards? Does this indicate a weakness in the standards?

Salmonids have been reported in streams that exceed criteria in Oregon's temperature standards. Some of these reports have been documented as part of published or unpublished scientific studies (e.g., Torgersen et al. 1999; Price 1998), while members of the public have made other reports. If these salmonids are indeed members of healthy populations, and exposure is for prolonged periods of time, then the adequacy of the temperature standards comes into question. In this section, we discuss why fish may be observed in streams that are warmer than the criteria in the temperature standards.

When explaining the presence of salmonids in streams warmer than the temperature criteria, the first step is to evaluate the adequacy of the documentation. There are several reasons why there could be inadequacies in information documenting fish in streams with temperatures exceeding the criteria (IMST 2000):

1. Seasonal observations may not indicate use of the habitat during times of maximum temperatures.
2. Observations may be anecdotal, rather than documented observations, or may be incorrect. In some cases, the credibility of observations of salmonids in streams with temperatures exceeding the criteria may be questioned. For example, species may have been misidentified. In other cases, there might be errors in the measurement of stream temperature.

In cases where salmonid populations are accurately observed in streams warmer than the temperature criteria, there are several reasons why fish could be able to survive:

1. With physiological or genetic adaptations to survive brief exposures to high temperatures;
2. As transient fish, not members of healthy populations resident in warm stream reach;
3. With impaired performance (e.g., earlier emergence, faster growth, changes in migration timing, increased susceptibility to disease, altered response to competition and predation) the effects of which could be cumulative or obviated at some later life stage;
4. Because they are utilizing coldwater refugia in these warm streams;
5. Because variations in stream temperatures over the course of a day or week might allow fish to survive unexpectedly hot conditions.
6. The upper extreme of temperatures that fish populations can tolerate may be higher than we realized when Oregon's temperature standards were written, warranting revision of the standards.

These six reasons are described in more detail in the following sections. We caution that some of these mechanisms are speculative, and substantial experimental research is necessary to determine their influences on fish in different stream systems (IMST 2000).

Physiological adaptations to high temperatures
Salmonids acclimate to warm temperatures within the physiological or genetic limits of a population, stock, and species. Acclimation also depends on the amount and rate of temperature change (reviewed in McCullough et al. 2001).

Genetic variation might allow some individual fish to tolerate higher temperatures than other fish. Physiological performance of individuals in a population varies (Gamperl et al. 2002); some individuals may be able to tolerate temperatures above thresholds specified in the temperature criteria. However, extreme temperatures may not allow optimum survival rates for the majority of salmonids in a population (see following section).

Salmonid stocks have diverse life histories, with variable growth rates and migration timing (reviewed in Groot and Margolis 1991). These variable life history patterns, along with salmonids' wide geographic range, expose populations to different temperature and stream flow regimes. Researchers have hypothesized that populations might experience different selective pressure from these varying environments, and could have adapted to local temperature regimes (e.g., Taylor 1991; Konecki et al. 1995).

Little information is available on differences in the temperature tolerances of stocks or populations of salmonids and other coldwater species. Laboratory studies have demonstrated little variation (a few degrees) in lethal temperatures among salmonid species, leading McCullough et al. (2001) to conclude that even less variation would be expected within species. In reviewing the scientific literature, McCullough et al. (2001) found some evidence for differences in lethal thermal tolerance among subspecies of trout, but little evidence for differences among stocks (Hart 1952; McCauley 1958; Sonski 1984). There could be more variation among populations in responses to sub-lethal temperatures, but research has not documented that these differences represent local adaptations. Unfortunately, local adaptation is a difficult hypothesis to prove, particularly in long-lived species like salmonids (Taylor 1997).

Transient fish /warm streams may not support healthy populations
Fish observed in a warm stream reach could be "transient" fish. They may have strayed from another stream system, or could be moving through the reach to another habitat. These fish are not long-term residents of the warm reach, and do not carry out their entire life cycle within the warm stream reach.

Participants in an IMST workshop on stream temperature agreed that observations of fish in streams that exceeded temperature criteria could be individual fish that are not a part of a healthy population. A healthy population was defined by scientific workshop participants as having (IMST 2000):

1. The capacity to persist or grow through time and across its range[19];
2. Components that can occupy all available and suitable habitats and maintain its distribution in time and space;

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[19] Note: There are often individuals at the extreme of a species range with marginal growth and productivity.

3. An adequate number of individuals to maintain itself through perturbations and environmental stresses;
4. Adequate variation in life histories and genotypes;
5. The presence of all life history stages at some time and some place within its overall distribution;
6. The ability to perform in all life history functions and have the ability to continue life history functions through time and space, and to persist through disturbance events and environmental stresses;
7. Enough fish to perform ecological functions (e.g., nutrient supply, food base for predators); and
8. The ability to deal with multiple sources of mortality (e.g., disease, predation, fishing).

Point observations do not indicate healthy populations. The occurrence of fish at any point may not reflect the status of populations within the stream reach or stream network. Individual sightings of fish in warm water do not indicate population fitness or individual fish health. In other words, fish can occur in a wide range of thermal conditions, but it is a matter of probability. Managers might ask, "What is the probability of observing a species, given the observed temperature in a stream?" In the case of bull trout, Dunham et al. (2003) described probability of occurrence as a repeatable probabilistic function. Meaning, that while salmonids have been noted to occur at sites with warm temperatures, the probability of such sites supporting healthy fish populations is extremely low relative to colder temperatures.

In summary, fish may be present in temperatures that are not suitable for long- or short-term health. Often fish may be present under tolerable temperature conditions that are not optimal for growth and long-term survival (Bjornn and Reiser 1991).

Effects of Temperature on Salmonid Performance

Presence of fish in a stream does not indicate that those temperatures are physiologically suitable (reviewed in McCullough 1999; McCullough et al. 2001). Even when temperatures are not high enough to be immediately lethal to salmonids, elevated stream temperatures may have "sub-lethal" effects on behavior and long-term survival (Table 5). As we will describe, fish may be able to tolerate short periods of elevated temperatures but the consequences of this stress may occur later (Table 5). In this section, we discuss these "sub-lethal" effects on salmonid performance.

Table 5. Modes of thermally induced coldwater fish mortality. Modified from DEQ (2000a).

Modes of Thermally Induced Fish Mortality	Description	Time to Death
Instantaneous Lethal Temperature	Denaturing of bodily enzyme systems	Instantaneous
Incipient Lethal Temperature	Breakdown of physiological regulation of vital bodily processes, namely respiration and circulation	Hours to Days
Sub-Lethal Temperatures	Conditions that cause decreased or lack of metabolic energy for feeding, growth, or reproductive behavior, encourage increased exposure to pathogens, decreased food supply, increased susceptibility to predation, and increased competition from warm water tolerant species	Weeks to Months

Adult migration and spawning

Typically, spawning can occur over a wider range of temperatures than eggs can survive, so it is not usually the limiting life history stage. However, high temperatures can result in direct adult mortality (reviewed in McCullough et al. 2001), delays in migration and spawning (Bjornn and Reiser 1991; McCullough et al. 2001), depletion of energy stores (McCullough et al. 2001), accelerated or retarded maturation (Bjornn and Reiser 1991), deformation of eggs and reduced gamete (egg and sperm) viability (reviewed in McCullough et al. 2001), or increased incidence of disease (Bjornn and Reiser 1991; McCullough et al. 2001).

Several studies indicate that high temperatures, even if not lethal, can affect the timing of spawning. Temperatures above 13–15.5 ºC [55.4–59 ºF] can lead to increased "pre-spawning" mortality in female chinook salmon (reviewed in DEQ 1995). Inhibition of spawning has been observed at 15.5 ºC [59 ºF] (reviewed in DEQ 1995). Temporal patterns in spawning times of Fraser River sockeye salmon are directly related to the temperature regime of the streams with spawning times occurring earlier in cooler streams (Brannon 1987). McCullough (1999) concluded that temperatures above 12.8 ºC [53.6 ºF] inhibited spawning in chinook salmon, and that spawning will not occur at temperatures above 16 ºC [60.8 ºF]. Warmer temperatures (21–22 ºC [69.8–71.6 ºF]) create migration barriers to adult salmon; although fish may be able to survive in areas with cooler temperatures, they run the risk of not reaching spawning grounds in time to spawn (McCullough 1999). Delayed spawning could lead to increased egg mortality. A recent review of the physiological temperature requirements of salmonids conducted by EPA summarized studies on temperature blockages to adult migration (Table B-3 in Appendix B, McCullough et al. 2001).

Incubation success and egg maturation

Mortality and development rates of salmonid embryos during incubation are greatly influenced by water temperature (Tang et al. 1987). Beacham and Murray (1990) found that temperature influenced embryo and alevin survival in five species of salmon [coho, chum (*Oncorhynchus keta*), chinook, pink (*O. gorbuscha*), and sockeye], with each species exhibiting a temperature range in which optimum survival occurred.

Temperature also affects emergence timing because water temperatures affect the rate of development. Incubation times tend to be shorter in warmer temperatures. In general, warmer temperatures (up to a maximum) shorten development time, leading to earlier emergence (Bjornn and Reiser 1991; McCullough 1999). Despite the fact that incubation can occur at higher temperatures, survival is likely greatest at temperatures below criteria in Oregon's temperature standards. Earlier emergence could be detrimental if fish are exposed to conditions, such as freshets, not normally encountered after emergence (Bjornn and Reiser 1991).

Holtby (1988) also recorded earlier emergence of coho salmon in British Columbia with increased stream temperature after logging. These fish were larger as yearlings and, therefore, migrated earlier than smolts did prior to logging. Based on modeling, Holtby (1988) concluded that this would likely have a negative impact on adult recruitment from this cohort. Early emergence of salmonids because of elevated temperatures could increase the risk of exposure to high flow events, and early ocean entry may not be advantageous (Holtby and Scrivener 1989; Pearcy 1992).

To illustrate the importance of synchronization of spawning and incubation timing with the historical temperature regime, consider this example: In the Fraser River, British Columbia, the timing of emergence of juvenile sockeye salmon is synchronized to coincide with the food availability in the nursery lakes. Because colder water temperatures result in slower development, streams with cold winter water temperatures would require longer incubation time. The 45 stocks of sockeye salmon in the Fraser River have evolved spawning timed with the river's temperature regime to ensure that juveniles emerge from the gravel close to the time food is available in the nursery lakes. Timing of spawning among the 45 stocks of sockeye salmon in the Fraser River is spread over a five-month period; however, the emergence of juveniles from the gravel occurs within a span of a few weeks (Miller and Brannon 1982).

Growth

Elevated water temperature can impair growth by increasing a fish's metabolic rate enough so that energy intake (from food) is no longer adequate to power physiological processes involved in growth (Fry 1947; Warren 1971). If temperatures are extremely warm, all energy is used in standard metabolism (the energy needed just to maintain physiological processes), and fish have inadequate energy remaining for feeding. Therefore, fish slow or stop eating when water temperatures are too high (Bjornn and Reiser 1991). In other words, fish reach a point where the energetic cost of processing food outweighs the cost of obtaining food.

Recently, EPA summarized studies on optimum growth temperatures for salmonids feeding on full rations (Table B-1 in Appendix B; McCullough et al. 2001). In general, temperatures above a species optimum result in a decline in growth rates:

> "Optimum growth depends on food availability. As food availability declines, the temperature producing optimum growth also is lowered. The growth optimum is also found near the temperature for maximum metabolic scope (Brett 1952). The greater the scope, the greater the ability of fish to divert energy to either somatic growth or gamete production." (McCullough et al. 2001, p.6)

Thus, scientists have concluded that salmonids need more food to maintain growth rates at elevated temperatures (Warren 1971). In addition, consequences of elevated temperature on growth may be greater for smaller, younger fish than larger, older fish. This is because the smaller life stages tend to have greater energetic demand and higher growth rates as a function of their body weight (Warren 1971).

Food will often be limited in natural systems, resulting in salmonids feeding to less than satiation. Therefore, consequences of elevated temperatures on growth are assumed to be greater in natural systems than the consequences observed in laboratory studies on full rations (reviewed in McCullough et al. 2001). However, limited anecdotal evidence supports the hypothesis that abundant food supply could buffer some effects of elevated temperature in natural systems. Bisson et al. (1999) investigated productivity of salmonids stocked in streams around Mount St. Helens in the years following the volcanic eruption. They observed that fish persisted in streams with daytime maximum temperatures that exceeded 26 ºC [78.8 ºF]. They speculated that persistence of fish under elevated temperatures could be partially due to the observed abundance of prey in streams.

Prey availability and abundance may dramatically change as the result of altered temperature regimes, having implications for salmonid growth (reviewed in Materna 2001). Unshaded, warm streams with high primary productivity have been shown to have high invertebrate production (e.g., Newbold et al. 1980). Therefore, elevated temperature has the potential to accelerate growth, with consequences for migration timing (see following section). However, Tait et al. (1994) studied changes in invertebrate assemblages in small third order tributaries in eastern Oregon with increasing solar exposure. They found that as solar exposure increased (presumably stream temperatures increased as well) invertebrates shifted from small soft-bodied invertebrates to large, less desirable caddisflies (order: Trichoptera) . The study showed that 55–96% of invertebrates at sites exposed to solar radiation were these caddisflies, which were rarely consumed by the redband trout in the stream (H. Li, pers. comm[20]). More research is needed to understand the complex changes in salmonid prey assemblages with altered stream temperature regimes.

Elevated temperatures are of particular concern for species -- such as coho salmon -- that have juvenile rearing during the warmest months of the year (DEQ 1995; EPA 2003a). For example, Everson (1973) concluded that an incremental increase in stream temperature with a limited food supply would result in reduction of juvenile coho salmon growth.

For fall-run chinook, the most productive and stable rearing areas can be mainstem rivers. However, habitat modification, wetland draining, and water diversions have dewatered many lower reaches and/or elevated stream temperatures (reviewed in IMST 2002). Fall chinook reared under sublethal rearing temperatures (69.8–75.2 °F [21–24 °C]) had lower growth rates than chinook reared at 55.4–60.8 °F (13–16 °C) (Marine and Cech 2004). Since many mainstem rivers often have high temperatures in recent decades, chinook salmon are now confined to cool tributaries, with a loss of both connectivity among habitats and fish productivity (Lichatowich and Mobrand 1995). Nicholas and Hankin (1988) believe that migration and rearing of sub-yearling juvenile chinook salmon in Oregon's coastal rivers during the summer is related to

[20] Li, Hiram. Personal Communication. 2003. USGS Fish and Wildlife Cooperative Unit, Corvallis, OR

water temperature, with "cooler" rivers supporting juveniles for a longer period of time before migration into estuaries. Therefore, life history types that rear in the mainstem rivers, such as populations of subyearling chinook in the Columbia River estuary, may not be expressed if rivers are too warm or degraded (Bottom et al. 2001).

Juvenile Migration and Smolt Transformation

Water temperature controls growth rates, and therefore, influences size at smolting (reviewed in Clarke and Hirano 1995). A minimum body size appears to be necessary before smolting begins (reviewed in McCormick et al. 1997). If growth is accelerated by warm conditions, smolting may occur earlier. A study in the South Fork, Umpqua River basin demonstrated a relationship between the timing of emigration of chinook salmon smolts and stream temperature. Emigration occurred earlier in the spring when water temperatures were higher (Roper and Scarnecchia 1999). As we discussed above, earlier migration could result in decreased smolt-to-adult survival (Holtby 1988).

Laboratory experiments indicate that species or stocks appear to have optimum temperatures (or range of temperatures) for smolting, with less smolting activity in warmer and cooler conditions. Reversal of smolting or "desmoltification" has also been observed at elevated temperatures in salmonids (reviewed in McCullough 1999). McCormick et al. (1997, p.284) summarize experimental evidence regarding temperature, growth, and smolting (Figure 3):

> "An optimal temperature for growth exists, but is greater than the optimal temperature for smolting. At temperatures that favor smolt development, an increase in temperature will accelerate the parr-smolt transformation…At temperatures where smolt development is impaired, peak gill Na+, K+ - ATPase activity levels [physiological signs of smolting] and saltwater tolerance are reduced or only occur transiently."

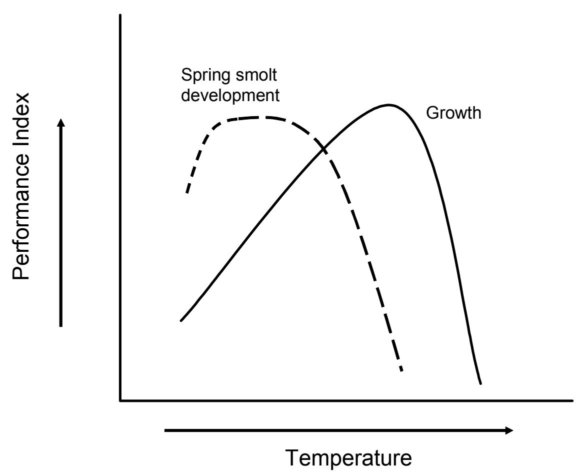

Figure 3. Theoretical relationship between water temperature, smolt development, and growth presented in McCormick et al. (1997).

McCormick et al. (1997) also point out that photoperiod, rather than temperature, appears to be the primary factor driving transformation of parrs to smolts. They conclude that temperature has a relatively limited ability to accelerate smolting.

High temperatures could also cause direct mortality, block migration, or increase stress in migrating juvenile salmonids (reviewed in McCullough et al. 2001). Recently, EPA summarized studies on impairment of smolting, ability of smolts to migrate, and survival rates (Table B-2 in Appendix B, McCullough et al. 2001).

Ecological Interactions

Exposure to elevated temperatures may change the interaction of salmonids with other organisms. This may occur at any life history stage. Three major ecological interactions that may change along with elevated stream temperature are 1) resistance to parasites and disease, 2) competition, and 3) predation.

Resistance to Parasites and Disease

Stream temperature can influence the immune response of salmonids and influence which pathogens are present in the system. In general, the virulence of salmonid pathogens tends to increase with stream temperature (reviewed in Materna 2001). Stream temperature directly affects the infection rate of many pathogens and the mortality rate in infected fish. Materna (2001) points out that the severity of disease for salmonids in warm water varies depending on: temperature regime, fish condition, genetic susceptibility to disease, virulence of diseases organisms, and other stressors.

Fryer and Pilcher (1974) documented an increase in the infection rate of *Flavobacterium columnaris* with increasing temperature. While the infection rate in juvenile spring chinook was negligible below 54 º F [12.2 ºC], the rate increased to 27% to 80% of the population at 59 º F [15 ºC]. Fryer and Pilcher (1974) also studied the infection rates of *Ceratomyxa shasta*, a protozoan parasite on salmonids. They found an increase in mortality at higher water temperatures in both rainbow trout and coho salmon. *Flavobacterium columnaris* and *Ceratomyxa shasta* have both been documented in the Columbia River and tributaries (Hoffmaster et al. 1988; Materna 2001).

The die-off of salmon and steelhead in the lower Klamath River in September 2002 is another example of how warm river temperatures can enhance disease transmission with catastrophic consequences. California Department of Fish and Game (2003) concluded that this fish kill appeared to be caused by a combination of 1) high densities of fish in the lower river due to low streamflows and restricted passage, 2) warm temperatures (20.5 ºC [68.9 ºF] is typical at this time of year) that were stressful for salmonids, and 3) favorable conditions for transmission and outbreak of salmonid diseases.

Competition and Predation

Scientists have hypothesized that high temperatures may make salmonids more susceptible to predators and both inter- and intraspecific competition (Magnuson et al. 1979; Materna 2001). There is little literature available on the effects of temperature on intraspecific competition. However, Reeves et al. (1987) documented the effect of stream temperature on interspecific interactions. Temperature influenced competitive interactions between juvenile steelhead trout and redside shiner (*Richardsonius balteaus*). While steelhead production was the same regardless of shiner presence at cool temperatures (12–15 ºC [53.6–59 ºF]), it decreased by 54% when shiners were present in warm water (19–22 ºC [66.2– 71.6 ºF]) compared to when they were not. Also, steelhead distribution was affected by the presence of shiners in warm water, but not in cool water. In study of coho salmon and steelhead trout conducted in a model stream, Hughes and Davis (1986) concluded that presence of coho might reduce stream productivity for steelhead more than elevated temperature.

A recent EPA review of regional information on ecological consequences of stream temperature noted several studies that demonstrate the influence of temperature on interspecific competition:

> " Hillman (1991) found that water temperature influenced the interactions between redside shiner and juvenile chinook salmon. Shiners affected the distribution of juvenile chinook salmon in the laboratory when temperatures were warmer (66.2 °F–69.8 °F [18–21°C]) but not at cold temperatures (53.6 °F–59 °F [12–15 °C]). Taniguchi et al. (1998) similarly studied competition between trout (brook trout [*Salvelinus fontinalis*] and brown trout, *Salmo trutta*) and creek chub (Cyprinidae: *Semotilus atromaculatus*) and found the latter to be competitively dominant at higher (>68 °F [20 °C]) water temperatures. This pattern extended to longitudinal zonation of fish within streams." (Sauter et al. 2001, p. 23)

Temperatures can influence the seasonality and intensity of both competition and predation in salmonids (reviewed in McCullough 1999). Warmer temperatures may give the advantage to non-native warmwater species that compete with or prey on native salmonids. A number of predators are warm or cool water fish: walleye (*Stizotedion vitreum*), largemouth bass (*Micropterus salmoides*), and smallmouth bass (*M. dolomieu*). Stream temperature could potentially introduce predation, as well as competition, with warm water exotics. Matthews and Berg (1997) speculated that trout they observed associating near seeps were out in the open and more susceptible to predation. Juvenile chinook exposed to warmer temperatures (17–24 ºC [62.6–75.2 ºF]) experienced higher predation than those exposed to cooler temperatures (13–16 ºC [55.4–60.8 ºF]; Marine and Cech 2004). More research is needed to clarify the relationship between predation and behavioral thermoregulation.

<u>Cumulative Effects</u>

Multiple or cumulative effects occur at any life stage (McCullough abstract in IMST 2000). Cumulative effects on the growth and survival of salmonids can occur both by:

- Exposure to other stressors in conjunction with high temperatures.
- Exposure to elevated temperatures multiple times.

Often the effects of temperature are difficult to separate from other stressors and may be compounded by the secondary stressors. These secondary stressors include ecological interactions such as disease, competition, and predation. In addition, temperature effects can be accentuated by physical factors such as pH, toxicity, fine sediment concentrations, and dissolved oxygen concentrations (reviewed in McCullough 1999). For example, tolerance of coho salmon to suspended sediment at 18 ºC [64.4 ºF] was only 33% of the tolerance at 7 ºC ([44.6 ºF];

Servizi and Martens1991). Exposure to nickel caused juvenile rainbow trout to lose equilibrium and die at lower temperatures than control fish not exposed to nickel (Becker and Wolford 1980).

The effect of warm stream temperatures may be cumulative, even if lethal temperature maxima are not reached (e.g., DeHart 1974). If temperatures reach stressful levels for a portion of a day over a number of days, heat stress may be cumulative as growth, survival, reproductive success, migration success, feeding territoriality, aggressiveness, swimming, other metabolic functions, and disease resistance are affected (reviewed in McCullough 1999). Salmonids may exhibit delayed effects of exposure to warm stream temperatures, which would be difficult to document in the field.

Implications for Setting Temperature Standards

DEQ notes that:

> "The temperature standard must be based on temperatures that allow individuals to remain healthy and successfully reproduce. Therefore, the standard will not be based simply on avoiding direct lethal temperature limits nor on a sole objective of maximum growth rates. The standard should be based on temperatures that prevent disease, prevent dominance by nuisance or non-native species, and provide for successful growth and reproduction." (DEQ 1995, p.2–25)

The IMST agrees that temperatures should be managed to optimize population production, population health, and life history diversity (McCullough 1999). Fish may perform better in cooler temperatures, but still be abundant in warmer temperatures. Temperature standards should consider biological optima for salmonid species. Standards should not be judged by the level of protection provided to a single reach (McCullough abstract in IMST 2000). As described above, temperatures affect salmonids differently at different life stages; therefore, requirements and optimum temperature ranges vary with life history stage and likely with genetic variability. McCullough (1999) recommends that temperature regulation and temperature standards should satisfy the most sensitive of these requirements. IMST agrees that this is a reasonable approach to protect salmonids.

Spatial Variability in Stream Temperature and Coldwater Refugia

Even if most of a river is too warm for salmonids, the river may contain pockets of cool water, often called "coldwater refugia" or "thermal refugia". Streams and rivers are naturally composed of a mosaic of temperatures. Stream temperatures vary upstream to downstream, laterally across channels, and vertically with depth. Many studies have documented situations where salmonids are able to survive in warmer streams than expected by moving into areas of cooler water to lower body temperature. This phenomenon is also sometimes called *behavioral thermoregulation*. For example:

- Berman and Quinn (1991) documented behavioral thermoregulation in chinook salmon, which were able to maintain an internal temperature well below the ambient stream temperature by residing within coldwater refugia.

- Nielsen et al. (1994) found that thermally stratified pools provided refuges for young-of-the-year, yearling, and adult steelhead in northern California when stream temperatures reached upper incipient lethal levels. However, use of these habitats varied with stream and with life history stage.

- Matthews and Berg (1997) noted that rainbow trout vacated pools that exceeded lethal temperatures in summer or died. They observed trout aggregating along suspected seeps in other pools during the warm parts of the day.

- Torgersen et al. (1999) examined the distribution of spring chinook salmon in the Middle and North Fork John Day Rivers, Oregon in relation to habitat characteristics and temperature. They found significant positive associations of salmon density with pool density and with pool volume in both rivers.

- Baigun et al. (2000) documented summer steelhead use of coldwater pools in a stream in the Umpqua Basin, Oregon. Occupied pools were, on average, 3 ºC [5.4 ºF] cooler than empty pools. The authors concluded that temperature drove pool occupancy, but other factors affected pool selection as well.

- In warm stream reaches (highs of >22 ºC [71.6 ºF]) of the Lower Grande Ronde River and Pine Basin Oregon, Ebersole et al. (2001) observed 10–40% of rainbow trout used thermal refugia during mid-day maximum temperature periods. In an analysis of data from the Grand Ronde Basin, Ebersole et al. (2003) estimated that doubling cold water patch frequency was associated with a 31% increase in rainbow trout abundance and a 59% increase in chinook salmon abundance.

- Baird and Krueger (2003) found that brook trout (*Salvelinus fontinalis*) remained 4 ºC [7.2 ºF] cooler than river temperatures when river temperatures were above 20 ºC [68 ºF]. The trout occupied groundwater discharge areas and tributary confluences, leading Baird and Krueger to conclude the fish were exhibiting behavioral thermoregulation.

In addition to behavioral thermoregulation, salmonids use cold water pockets for spawning and redd construction. Many studies have documented that trout and salmon select high groundwater exchange areas that provide relatively stable temperatures for redd site construction (Hansen 1975; Webster and Eiriksdottir 1976; Fraser 1985; Geist and Dauble 1998; Baxter and Hauer 2000). Benson (1953) showed that trout population size and density of redds varied directly with the amount of groundwater discharge. In fact, the size of many trout populations is strongly dependent on the amount of near-optimal thermal habitat available during critical warm summer months. Bowlby and Roff (1986) demonstrated that groundwater discharge accounted for the greatest variability in brook trout biomass in streams of southern Ontario.

The majority of examples provided thus far emphasize coldwater refugia found within stream reaches. At this scale, thermal refuges include thermally stratified pools, as well as input from springs or tributaries that have not mixed with surface streamflow (IMST 2000). Coldwater refugia have also been linked to hyporheic exchange (subsurface flow); however, studies of hyporheic zones, their distribution, and ecological effects are still relatively scarce (IMST 2000).

Research is needed in this important, emerging field. Local variation in stream temperature is also associated with shading and variability in channel form (Ebersole et al. 2003; reviewed in Poole and Berman 2001).

Spatial variation in stream temperature at coarser scales can also be important to salmonids (Table 6). Stream temperatures vary from headwaters to mainstems, among watersheds, and across geographic regions (reviewed in Poole et al. 2001). For example, Torgersen et al. (1999) demonstrated how salmonid distribution among reaches within a watershed can be related to temperature. They observed significant positive associations between chinook salmon density and cool-water reaches of the Middle Fork John Day River.

Table 6. Examples of temperature regimes at different spatial scales and implications for salmonids. From review in Poole et al. (2001).

Scale	Description	Implications for Salmonids
Reach-scale regime	Variation in stream temperature due to geomorphic variation at fine scales such as pools, riffle, backwaters, etc.	Temperature variation at this scale provides pockets of cool water ("micro-refugia") used by fish to avoid thermal stress.
Segment-scale regime	Variation in mean stream temperature between stream reaches. May be driven by changes in stream valley geomorphology and channel pattern along the stream profile.	Cool reaches provide staging areas for migrating salmonids. Loss of variability at this scale may result in "warm at the bottom/cool at the top" streams.
Catchment-scale regime	Variation in temperature between stream basins. Includes the concepts of "mountain streams" and "desert streams." Driven by differences in climate, geography, topography, and vegetation between basins.	Relative temperature of a basin can be altered by catastrophic disturbances (fires, volcanic eruptions, industrial land use, river regulation). Salmonids' extensive distributions historically allowed species to persist in face of these disturbances.

Furthermore, processes that create coldwater refugia may be best understood by examining the distribution of refugia at several spatial scales. Baxter and Hauer (2000) studied bull trout in the Swan River of Montana. They found bull trout were more likely present in valley segments with geomorphic characteristics that caused hyporheic exchange and upwelling. At a finer scale (within stream reaches), bull trout selected sites with downwelling water to construct redds. More research is needed to understand the geologic and hydrologic processes that create coldwater refugia at various spatial scales in Oregon's river basins. Given differences in underlying geology, processes that create coldwater refugia may vary significantly across the state.

Berman and Quinn (1991) caution that although salmon may be able to mitigate sub-lethal temperature effects by residing in coldwater refugia, these areas must be abundant and easily accessible to benefit the fish throughout all life history stages. Furthermore, size and distribution of refugia likely vary over time. Therefore, IMST supports management strategies that emphasize the *processes* that create and maintain natural variability in stream temperature.

Thermal patchiness in streams could provide habitat for species that exist on the margins of their temperature tolerances (Torgersen et al. 1999). Sauter et al. (2001) concluded that coldwater refugia could be particularly important in salmonid populations that occur at the southern end of their ranges. On an evolutionary time scale, refugia may ensure the long-term persistence of some salmonid populations.

Managers should consider that some colder water areas observed today may be remnant high quality habitat. Salmonids may be concentrated in these areas because of degradation elsewhere. Excessive temperature can temporarily crowd fish into habitats that are incapable of supporting fish over the long-term, potentially increasing competition among fish and enhancing disease transmission (reviewed in IMST 2000, 2003). Although coldwater refugia can play an important role in salmonid survival in warm streams, coldwater refugia do not replace the need to lower temperatures in streams that have been warmed excessively by human activity.

Finally, although the importance and use of coldwater refugia are well documented, their distribution and abundance are not well known (IMST 2000). Oregon currently has standards to protect coldwater refugia (p. 31-32). However, implementing these is challenging when these habitats are difficult to identify and their distribution is not well documented.

Temporal Variability in Stream Temperature

A fifth hypothesis of why salmonids may be found in waters warmer than the criteria, is that variation in stream temperature over the course of a day or week might allow fish to survive unexpectedly hot conditions. Stream temperatures vary naturally with climate, seasonally, and daily. For salmonids, consequences of exposure to high temperature may depend on length of exposure or cumulative exposures (see earlier section on cumulative effects). Minimum stream temperature can vary among streams with any given maximum temperature. In some cases, diel (24 hour) variation in stream temperature could moderate effects of high maximum temperatures on salmonids. For example, Bonneville cutthroat trout (*Oncorhynchus clarki utah*) in Montana survived multiple days with maximum temperatures exceeding the lethal temperature (LT_{50}) derived in a laboratory study (24.2 ºC [75.6 ºF]; Schrank et al. 2003). Schrank et al. (2003) hypothesized that the 10–13 ºC [18–23.4 ºF] daily variation in stream temperature allowed fish to persist despite high maximum temperatures. This hypothesis was corroborated by a laboratory experiment; all cutthroat trout exposed to fluctuating daily temperatures of 16–26 ºC [60.8–78.8 ºF] over 7 days survived.

Conversely, fish performance and survival has been shown to decrease when increasing variation in stream temperature results in *higher* average or maximum temperatures. In a laboratory study, Hokanson et al. (1977) documented slower growth in steelhead when fluctuating water temperatures were above optimum temperatures. After the eruption of Mount St. Helens, juvenile coho salmon mortality was highly correlated with increased diel fluctuation in stream temperature, as well as increases in maximum monthly mean temperatures (Martin et al. 1986). Overall, our understanding of the effects of diel fluctuations on fish survival in natural systems is limited, as temperature is difficult to separate from other stressors in field studies. Nonetheless, the issue is important because diel fluctuations in stream temperature can be often be enhanced in disturbed stream systems (e.g., Moring 1975; Feller 1981; Johnson and Jones 2000).

Temperature Tolerances of Salmonids Could Be Wider than was Known When Standards Were Developed

In some cases, the range of temperatures that fish populations can tolerate may be wider than we realize. Much research has been conducted on the physiological and behavioral response of salmonids to elevated temperature (reviewed in McCullough et al. 2001 and Sauter et al. 2001). However, scientists continue to investigate these issues. For example, we now understand the temperature requirements of redband trout better than we did when 1996 temperature standards were adopted (see Science Question 1). New information can be incorporated into temperature standard revisions.

Science Question 2 Conclusions

Conclusion 2-1. There are numerous reasons why salmonids may be present in waters that exceed the temperature criteria in Oregon's water quality standards:

- **Physiological or genetic adaptations allow some individuals or populations to survive exposures to high temperatures;**
- **Fish observed could be transients, not members of healthy populations resident in a warm stream reach;**
- **Performance could be impaired (e.g., earlier emergence, faster growth, changes in migration timing, increased susceptibility to disease, altered response to competition and predation), the effects of which could be cumulative and not apparent until later life stages;**
- **Variation in stream temperature over the course of a day or week might allow fish to survive unexpectedly hot conditions;**
- **Fish are utilizing coldwater refugia in these warm streams;**
- **Range of temperatures that fish populations can tolerate may be wider than scientists realized when Oregon's temperature standards were written.**

  Fish may be present under tolerable temperature conditions that are not optimal for growth and long-term survival; therefore, presence of fish in a stream does not necessarily indicate that those temperatures are physiologically suitable. Length of exposure, degree of exposure, strain or race of fish species, and presence of cold-water micro-sites all influence how well an individual fish copes with elevated river and stream temperatures.

Conclusion 2-2. Salmonids have physiological and behavioral mechanisms that allow them to survive high temperatures, up to some maximum temperature and over a maximum duration. Therefore, duration and magnitude of temperature extremes are relevant to setting temperature standards.

Conclusion 2-3. There is no evidence indicating that salmonids thrive in waters that exceed criteria in Oregon's temperature standards for prolonged periods of time.

IMST finds a great deal of evidence that warm temperatures impair salmonid performance. Oregon's temperature standards reflect that body of evidence. Redband trout may persist in streams warmer than temperature criteria, but evidence of redband population status is scarce and inconclusive. We find no evidence that redband or any other salmonids thrive for any prolonged period of time above these temperatures.

Conclusion 2-4. Presence of individual fish in a stream does not necessarily indicate a population of healthy, reproducing fish. There are relatively few data on the response of fish populations to waters of different temperature in Oregon.

A fish may be present in temperatures that are not suitable for long or short-term health. Watershed temperatures should be managed to allow for population production, health, and life history diversity.

Conclusion 2-5. Temperatures affect salmonids differently at different life stages; therefore, requirements and optimal temperature ranges vary with life history stage. Temperature regulation must satisfy the most sensitive of these life stages.

Temperature criteria should not be based simply on avoiding lethal temperature limits. They should consider tolerance thresholds where physiological and behavioral functions are significantly impaired for each salmonid species, stock, and life history stage.

Conclusion 2-6. In the future revision and application of temperature standards, the State of Oregon should consider recent data on coldwater refugia. Oregon's standard for coldwater refugia is difficult to implement when these habitats are difficult to identify and their distributions are not documented.

DEQ's 2003 revisions to the temperature standards (see p. 32) change the criteria to protect coldwater refugia. Methods for identifying coldwater refugia are still lacking. Simple protection of existing coldwater refugia will not provide for restoration of historical coldwater refugia that have been lost because of past alterations of streams and their watersheds. Coldwater protection is a critical issue in any stream that does not meet the temperature standard and tributaries that flow into streams that do not meet the standard. Coldwater refugia may be restored through storage of alluvial gravels, restoration of springs and subsurface flow, and retention of water in riparian corridors and floodplains.

Science Question 3. How do human activities influence stream temperature?

In the answer to this question, we will briefly describe how human activities change stream temperature by affecting four factors: channel morphology, streamflow, surface/subsurface water interactions, and riparian vegetation. First, we provide a background discussion on how heat is transferred into and out of the stream environment and how water temperatures are affected. We then discuss each of the four factors, listed above, that influence stream temperature, highlighting how they interact and influence one another. We then review how human actions affect these factors, thereby affecting stream temperatures. Detailed discussions of watershed hydrology and other watershed processes can be found in more comprehensive texts such as Naiman and Bilby (1998), Jones and Mulholland (2000) and Brooks et al. (2003).

Background Information

This section discusses how human activities can influence stream temperatures. It is important to note the difference between temperature and heat and how heat is transferred between water and its surrounding environment. *Temperature* is a numerical characterization of the mean random motion of molecules within an object, organism, gas, or liquid. Energy added to or removed from the substance affects the rate the molecules move, therefore changing the temperature of the substance. *Heat* is energy and the direction heat is transferred between substances is dependent on the temperature of the two substances in contact. Heat will flow from the warmest substance to the coolest substance.

Heat is transferred by several mechanisms. For streams, these mechanisms include:

- *Radiation* – Radiation is energy emitted from the sun and absorbed (reflected) by water and other substances. Radiation is either short-wave (direct) or long-wave (indirect). *Short-wave* radiation is emitted from the sun and absorbed by a substance. *Long-wave* radiation is radiation that has either been scattered by the atmosphere before reaching earth, re-emitted from objects that have absorbed radiation, or reflected off the surface of objects or liquids. Long-wave radiation can add or remove heat from a stream, short-wave adds heat to a stream. The amount of radiation reaching a stream's surface is affected by solar angle (varies by time of day and season), cloud cover, elevation, and interception by vegetation and topographical features. Water turbidity[21] affects surface reflectivity and penetration of radiation into the water column.
- *Conduction* is the transfer of heat between two substances in direct contact with each other. Substances have different abilities to conduct heat. Air is a poor conductor of heat (Ahrens 2001).
- *Convection* is the mass movement within a liquid or gas resulting in transport and mixing of heat within that substance. Within a column of water, colder water will move downward as warmer water moves upward. The movement will cause mixing until equilibrium is reached. Heat is transferred across the thin air-water interface by convection and is often referred to as *sensible heat exchange*.
- *Evaporation* is the process by which a liquid becomes a gas and will remove heat from a stream. Evaporation can be a primary cooling process (Boyd 1996; Benner 1999). The

[21] Turbidity is an indicator of the property of water that absorbs or scatters light (Brooks et al. 2003). Turbidity is caused by suspended clays and silts, organic matter, plankton, and other suspended and dissolved organic and inorganic particles (both from natural and human origins).

rate of evaporation is dependent on air temperature, vapor pressure, humidity, and air velocity. In contrast, *condensation* (gas becomes a liquid) can add heat to the system.

- *Advection* is the mixing of precipitation, groundwater, or tributary water into the water of a stream. Cold water inputs will dissipate heat (not remove it) already in the stream and temperatures may decrease. Hot or warm water inputs from geothermal or industrial point-sources will add heat and may raise stream temperatures.
- *Friction* adds heat to a stream as sediments and bed load material are dragged across the stream bottom and as water flows across the stream bed (sometimes referred to as *fluid friction*). More heat will be added with turbulent flows and along steep gradients.

Heat can also be added to a stream when it is released through biological processes such as decomposition of organic material. In contrast to the mechanisms listed above, biological processes are considered to transfer little heat into or out of water. Each mechanism listed above has a different level of effectiveness for transferring heat into or out of stream water, and the rates can be influenced by other environmental factors. When a system is at equilibrium, the amount of heat added to the system is equal to the amount of heat removed from the system.

Heat budgets are used to determine the relationship between fluxes of heat into and out of a system at a given time. These budgets can be used to determine the relative influence environmental factors may have on stream temperatures. Few heat budgets have been done for rivers or streams based solely on field data because the process can be cost prohibitive. One study did develop a heat budget for reaches in the Exe Basin, Devon (United Kingdom). Webb and Zhang (1997) reported that non-advective heat exchange into streams was due to net radiation (56.0%), fluid friction (22.2%), sensible heat transfer (air-water transfer, 13.2%), condensation (5.8%), and bed conduction (2.8%). The authors noted that inter-reach variability in individual budgets did exist and could be attributed to the influence of channel morphology, valley topography, riparian vegetation, bed substrate, and hydrological conditions (especially river-regulation by dams).

Stream temperature is a product of complex interactions between geomorphology, soil, hydrology, vegetation, climate, elevation, and aspect of the watershed (Sullivan and Adams 1991; IMST 2000; Poole and Berman 2001). The relative influence of these factors can vary spatially across the landscape and over time. Water temperature can vary along the length of a stream as a result of local topographical and geological factors (Smith and Lavis 1975). Thermal heterogeneity within streams and rivers and can be affected by local energy inputs and outputs.

Although many variables influence stream temperatures, stream temperature drivers are external to the stream system and control the rate of heat and water delivery that enable changes in water temperatures (Poole and Berman 2001). The use of the term “driver” appears to be used differently by researchers (W. Krueger, pers. comm[22]). In contrast to Poole and Berman’s description above, others may consider that there is only a single driving factor affecting temperature, the single factor being the dominant factor. The authors of this report agree with the use of multiple drivers as used by Poole and Berman (2001); however, to avoid confusion, this report uses “influencing factors” instead of drivers.

[22] Krueger, William. Personal Communication. 2003. Department of Rangeland Resources, OSU, Corvallis, OR.

Relationship between air temperatures and stream temperatures

The relative influence that environmental factors have on stream heating, particularly vegetative shade are being debated in Oregon (e.g., Larson and Larson 1996; Beschta 1997). Air temperature is often cited as strongly influencing stream temperatures (e.g., Edinger et al. 1968; Smith and Lavis 1975; Larson and Larson 1996; Sullivan and Adams 1991). Johnson (2003) points out that the relationship between air and stream temperatures can be misleading because air temperatures are strongly correlated with stream temperatures. Correlations have been reported by several researchers (e.g., Pilgrim et al 1998; Mohseni and Stephan 1999) with very good results obtained at monthly and weekly timescales (Mohseni et al. 1998). Correlations statistically describe linear relationships between variables and can be used to create prediction equations based on the relationships. Strong correlations do not indicate a cause and effect relationship, that can only be determined under completely randomized experimentation, not with observational or case studies (Ramsey and Schafer 1997; pp. 21 & 189). Since solar radiation strongly influences both air and stream temperatures, the correlations are understandable.

Since summer air and water temperatures are highly correlated, summer air temperatures can be used to predict summer water temperatures. For management and modeling, such predictions are useful because air temperatures can be measured more easily (and less expensively) than stream temperatures and at off channel stations. Erickson and Stefan (2000) reported that the relationship between air and stream temperatures is affected by impoundments, reservoirs, artificial heat inputs, groundwater inputs, stream shading, and wind sheltering. When researchers have looked at extreme air temperatures or at temperatures over long time periods, the air-water temperature relationship varied. Winter air temperatures below 0 ºC [32 ºF] did not show a linear relationship with water temperatures (Crisp and Howson 1982; Webb and Nobilis 1997). Linear relationships are also not seen at high temperatures (Erickson and Stefan 2000). As air temperatures increase, the moisture holding capacity of the air also increases, and consequently the rate of evaporative cooling along a streams surface also increases. As the water looses more heat through evaporation, stream temperature no longer increases linearly with air temperature (Mohseni et al. 1998; Mohseni and Stefan 1999).

Notably, Webb and Nobilis (1997) examined air and stream water temperature data from a 90 year period for a small river basin in Austria. Based on the variation in relationships, they concluded: "... that the air-water temperature relationship is not stable throughout the year and suggest that the link between air and river temperatures is not one of true cause and effect." (Webb and Nobilis 1997; p. 145)

Heat transfer between air and water occurs along the thin layer where air meets the water's surface. As long as a temperature gradient exists between the two media, heat will be transferred from the warmer media to the cooler media. The transfer of heat from air to water via convection is the slowest of all the heat transfer pathways (Bowen 1926; Beschta and Weatherred 1984; Boyd 1996; Chen 1996). The rate of heat transfer is proportional to the temperature gradient (McCutcheon 1989). If, however, humidity is low and vapor pressure is high, evaporation will occur and heat will be transferred from the water to the air.

In summary, correlations have been documented between summer air temperatures and summer water temperatures. However, these correlations do not indicate a cause-and-effect relationship. Long-term and multi-seasonal studies show that air-water temperature relationships vary and that other environmental factors influence the relationship.

Human land use activities typically affect stream temperature by altering one or more of the following factors:

- Channel morphology,
- Streamflow and water quantity,
- Surface/subsurface water interactions, and
- Riparian vegetation.

These four factors are highly interrelated (Figure 4). The overall influence that individual factors may have on stream temperature will depend on stream size. Specific stream and watershed conditions cause wide variations in the processes affecting the rate of heating and water temperature therefore stream reach-specific information is critical to understanding stream temperature responses to human activities. Additionally, human activities and management of stream and river systems can shift thermal profiles and lead to earlier or later warming of seasonal water temperatures.

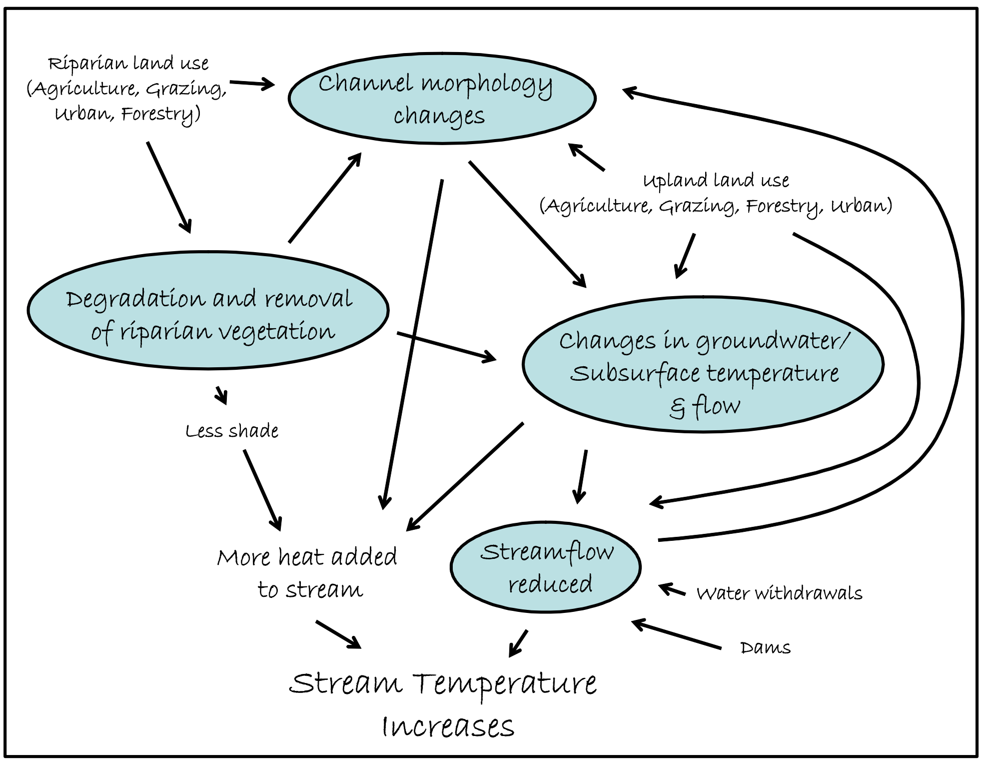

Figure 4. Relationships among four ways that human activities influence stream temperature. See text and Figures 5, 7, and 8 for more detail about the relationships among the factors.

Channel Morphology Influences on Stream Temperatures

The size and shape of a stream or river channel reflects its prevailing flow and sediment load (Kondolf 1994). Channel characteristics and morphology, particularly the width and depth of the channel, influence the amount of heat gained or lost from a stream. As streams widen, the more stream surface area increases, providing more surface area for heat energy exchange (short and long-wave radiation processes) with the atmosphere (Boyd 1996).

Water depth is another important stream characteristic in terms of rates of heating and cooling. For pure water, 55% of the incident solar radiation penetrates to a depth of 10 cm and 18% penetrates to a depth of 10 m (Sellers 1965; p. 38). Light penetration in pure water is dependent on wavelength, the shortest wavelengths (0.2–0.6 microns) penetrating the deepest; practically all radiation at wavelengths greater than 1.2 microns is absorbed in the first centimeter of water (Sellers 1965; p. 38). Penetration of light into water in the natural environment is considerably less than pure water and in general, the more turbid the water, the less radiation can penetrate to a given depth and the higher the albedo (reflectivity) of the water's surface (Sellers 1965; p. 39). The bed of shallow streams (< 20 cm) can be heated by solar radiation (Brown 1969). The amount of bed area exposed and substrate composition are also important variables. Large amounts of cobble, boulders, and bedrock exposed to direct solar radiation in the streambed can store and conduct heat to the stream as long as the bed is warmer than the stream.

Channel dimensions can be expressed as width-to-depth ratios. High width-to-depth ratios usually imply wide, shallow channels. Low width-to-depth ratios suggest that the channel is deep and narrow. One can then expect that, narrow, deep channels with a low width-to-depth ratio will have less surface area exposed to solar radiation. McSwain (1987) found that tributaries to the Elk River (coastal Oregon) with relatively large width-to-depth ratios (≥ 14) generally had large diurnal fluctuations in temperature indicating that the wide, shallow streams heated more easily.

Channel width and depth also affect stream temperatures in the winter. Wide, shallow streams are more likely to become super-cooled than deep, narrow streams (Chisholm et al. 1987; Swanston 1991). Underwater ice (frazil and anchor ice) forms when water temperatures fall below 32 ºF [0 ºC] (Needham and Jones 1959). Anchor ice forms when frazil ice crystals form in the water column, accumulate, and attach to streambed substrates or objects. Anchor ice can form dams in streams, backing up water; as temperatures warm, the ice can release from streambed and move downstream, scouring the channel. Chisholm et al. (1987) also reported that snow bridging (snow cover spanning the stream channel and water surface) was more likely to occur on deep, narrow streams and would prevent surface and anchor ice from forming by insulating the stream.

Human Activity Influences on Channel Morphology

Channel morphology can be directly affected by erosion and sedimentation. Surface erosion of soils within a watershed (from agriculture, grazing, timber harvest, fires, roads, and urbanization) and events such as landslides can add sediment to channels. Erosion within channels also occurs during high flows, as stream flows carry sediments that abrade banks and channel beds. Severe erosion of streambanks can cause channels to widen, while erosion of the bed can cause channels to incise, disconnecting the floodplain from the stream system. Sedimentation, or sediment deposition, occurs when streamflows no longer have sufficient velocities to transport suspended sediments or bedload materials. Friction from transported sediments, riparian vegetation, large wood, or boulders can decrease water velocities, causing deposition of sediments. Sediments that enter a stream can be deposited 1) directly into the streambed, 2) along the streambank, 3) along gravel bars, or 4) on the floodplain during flooding. Sediments may also remain suspended in the water column and be transported downstream. Excessive deposition in the stream channel can contribute to a decrease in stream channel depth.

Human activities can directly affect channel morphology through livestock grazing, channelization, diking, dredging, instream gravel mining, placer mining, road construction and indirectly by changing erosion and sedimentation rates in the stream channel. Many rivers and streams flowing through urban and agricultural areas have been channelized to facilitate rapid storm runoff and reduce local flooding. Removal of riparian vegetation by human activities can lead to increased bank erosion during high flow periods (Beeson and Doyle 1985). Erosion and sedimentation rates can be altered by changing stream velocity and increasing erosion in upland areas as a result of gravel roads, agriculture, grazing, timber harvesting, and fires. Some specific land use examples follow:

Urbanization

Stream channel morphology changes with increased urbanization. Paul and Meyer (2001) reported that during the construction phase of urbanization, hillslope erosion increases sediment supply leading to bed aggradation and overbank deposition. After construction ceases hillslope sediment supply is reduced, but bankfull flows are increased owing to increased imperviousness. This leads to increased channel erosion as channel incision and widening occur to accommodate increased bankfull discharge. Hammer (1972) studied 78 small watersheds near Philadelphia, PA, and found channel enlargement ratios (the channel cross sectional area of each stream as a proportion of the expected channel area in the absence of urbanization) of 2.2 for impervious area associated with residential area houses and up to 6.8 for other impervious areas (commercial buildings, apartment houses, factories, airport runways, shopping centers, row houses, and parking lots) with paved ground and a higher building density. Interestingly, residential areas with streets and houses not connected to a storm sewer system had little effect on channel morphology, suggesting there may be ways to mitigate for this effect. Channel slope, slope to channel and impervious slope area were found to have a large effect on channel enlargement, whereas distance of the development from the channel had little effect.

Livestock grazing

Overuse of riparian zones by livestock results in the loss of riparian vegetation, streambank trampling, bank erosion, soil compaction, and increased sedimentation (Platts et al. 1977). In Utah, the US Bureau of Land Management constructed a ¼ mile long exclosure along Big Creek to exclude livestock (Duff 1977). Over a six-year period, the exclosure area was compared to two areas of Big Creek still being grazed by cattle and sheep from mid-May through mid-October. During the six-year period, mean channel width increased by 1.4 ft and 0.7 ft (0.43 and 0.21 m, respectively) in the two sections still being grazed while channel width decreased by 2.5 ft 90.76 m) within the exclosure (Duff 1977). Similarly, mean water width increased and water depths decreased in the grazed sections as the channels widened and within the exclosure the water widths decreased and depths increased (Duff 1977).

In eastern Oregon, Kauffman et al. (1983) reported that streambank losses, bank erosion and disturbance was significantly greater along Catherine Creek grazed by cattle (late season grazing; August-September) than in exclosures with no grazing (sections were grazed prior to exclosures). Grazed areas also had fewer undercuts than ungrazed areas. In Idaho, Platts (1981) reported that a stream section with intensive sheep grazing had a channel 5 times wider and 1/5 as deep as an adjoining section receiving light or no grazing. Within the heavily grazed area, undercut banks were eliminated and streambanks were outsloped (Platts 1981). In Montana, Gunderson (1968) reported that an ungrazed section of a creek had more undercut banks [indicating low erosion of banks and stability provided by vegetation] than grazed sections.

Dams

Dams (including hydroelectric, flood control, and storage types) can influence channel morphology by altering discharge events (e.g., delay and decrease flood peaks) and bedload transport (decrease available bed load). The majority of the bedload in a river is transported during high flows, particularly floods. Multiple factors can slow water velocity in streams and rivers, including decreasing gradient, widening of the channel, and friction of transporting bedload along the streambed. In cases where bedload is trapped behind dams, water velocity does not decrease as quickly as a stream carrying more bedload (since it is not transporting as much bedload material). As a result the water picks up sediment and new bedloads by eroding banks and removing gravel from other deposits including downstream gravel bars and salmonid spawning beds (Kondolf 1997; Nilsson and Berggren 2000). The erosion can lead to channel simplification, reduced geomorphological activity in the river bed, incision, disconnected channels, head cuts, and lost riparian vegetation.

Streamflow and Water Quantity Influences on Stream Temperatures

Streamflow results from precipitation on a watershed, with water entering the stream channel by precipitation falling into the channel, surface runoff of rain or snowmelt, or sub-surface flow[23]. The sum of these is often called stormflow or runoff. Additionally groundwater[24] and any long-term sub-surface drainage from uplands sustain streamflows year around in perennial streams, particularly between periods of snowmelt and rainfall. Often called baseflow[25], such flows are common in the summer months when high stream temperatures typically occur.

Watershed features can influence the magnitude and timing of storm discharge. The physical properties of watersheds influence storm flow and are not greatly influenced by human activity or weather patterns. Large watersheds exhibit large flows and higher peakflows than small watersheds. Watersheds with steeper channels or higher densities of channel route water to the channel faster. Natural wetlands and lakes retain water and dampen the storm hydrographs. Climatic variation can influence the magnitude and duration of floods within a basin, thus flood hydrographs are highly variable. Human activities also influence the magnitude and timing of peakflows. Reduction of vegetative cover, alteration of plant types, compaction of soil surfaces, road building, drainage ditches, channel simplification, removal of riparian vegetation, channelization, levees and dykes, and impervious surfaces and buildings route water more quickly, increase peakflows, and cause them to occur more quickly. Man-made reservoirs can detain water and dampen peakflows.

[23] Shallow lateral flow below the soil surface but above an impermeable or slowly permeable layer above the groundwater table. Sub-surface flows occur early during storms and contributes to stormflow.

[24] Groundwater (in both phreatic and vadose zones; saturated vs unsaturated) is water that moves down into the soil and underlying geological strata. Groundwater is recharged by infiltration and enters streams through seepage and springs. It is stored in aquifers. The boundary layers between aquifers and overlying unsaturated soils is the watertable.

[25] Baseflow is the typical flow rate for a given stream at a particular time of year and is sustained by groundwater inputs.

Stream flow is a significant parameter leading to temperature changes, and low flow streams are very sensitive to temperature changes (Boyd 1996). Stream temperature is proportional to the amount of heat energy divided by water volume (Poole and Berman 2001). Streamflow or discharge represents the volume of water, per unit time, passing a given cross-section. Stream temperature is inversely proportional to volume of water at any given level of solar radiation or heat (Brown and Krygier 1970). Therefore any process that affects the heat load to the channel or stream discharge will affect stream temperature (Poole and Berman 2001). Stream temperatures may be greatly influenced by the thermal characteristics of the dominant water source (e.g., snow melt, rain fall, groundwater; Smith and Lavis 1975).

McSwain (1987) found that summer stream temperatures in tributaries of the Coquille River (southwestern Oregon) increased when flows decreased. In a northern England basin, Smith and Lavis (1975) reported that a sudden increase in streamflow usually resulted in a drop in stream temperature. During summer, precipitation from storms decreased stream temperature if the volume of discharge increased at a faster rate than it could be heated in the stream channel (Smith and Lavis 1975). In one storm event, water temperatures decreased quickly by about 1 ºC [1.8 ºF] but rose again once the storm pulse ended.

Human Influences on Streamflow and Water Quantity

The quantity of water flowing in a stream, or the stream's discharge, can have a strong influence on the rates of heating and cooling in the stream and are directly controlled by human activities in many stream systems. Figure 5 depicts some of the major pathways by which impoundments and water withdrawals effect changes in streamflow, and therefore stream temperature (further reviewed in Poole and Berman 2001).

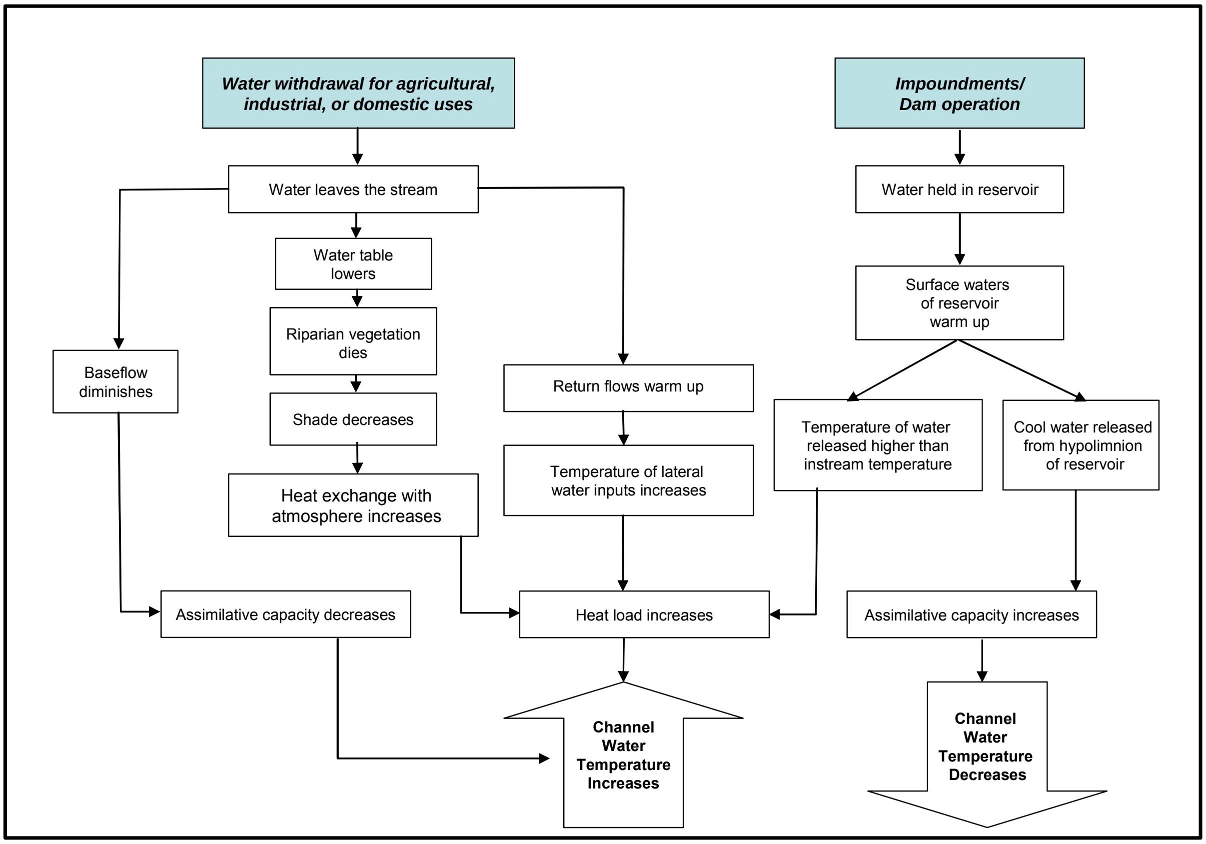

Figure 5. General pathways by which water withdrawals and impoundments influence streamflow, and therefore stream temperature. Modified from Poole and Berman (2001).

Dams and Reservoirs

Most dams in the Pacific Northwest are operated to store water in surface reservoirs during periods of high stream flows and release this water during periods of lower flows for irrigation, electrical generation, and augmentation of flows for pollution dilution. Some rivers in Oregon (such as the Walla Walla River) have very large withdrawals, with flows completely eliminated during certain times of year.

The effects of reservoirs on stream temperatures below dams vary from stream to stream and dam to dam (Collings 1973). The effect an impoundment can have on downstream temperatures depends on several factors, including size and shape of the reservoir, elevation of the water being released, length of time water is held, velocities of currents within the impounded water (as it relates to mixing of water), altitude of the water's surface, and volume of water released (Collings 1973). When water in a reservoir behind a dam is deep enough, the reservoir may become thermally stratified. The temperature of water released from dams depends upon whether withdrawals are made from the lower layer of cold water (hypolimnion) or from the upper layer of warm water (epilimnion). Some dams release cold water from the hypolimnion in the summer, thus cooling downstream reaches. As the summer continues, surface waters of reservoirs are warmed by direct solar radiation and water levels decrease due to withdrawals or releases.

Discharges from most dams in the fall are typically warmer than natural flows. This can have profound effects on the development of the biotic community, including salmonids downstream. For example, ODFW (2000) found that the warmer water released from the Lost Creek Dam on the Rogue River negatively affected spring chinook salmon by accelerating embryonic development and emergence, as well as increasing pre-spawning mortality.

Irrigation

Irrigation accounts for roughly 50% of water withdrawals in western Oregon and over 90% of water withdrawals in eastern Oregon (Boggess and Woods 2000) with maximum quantities of instream water withdrawals typically occurring in late summer and early fall. This decrease in available instream flow coincides with the highest natural maximum stream temperatures, exacerbating the problem. Irrigation methods can influence stream discharge. For example, in Wyoming, Sando (1985) showed stream flows increased by 58.7% when farmers in an agricultural watershed switched from surface [flood] irrigation systems to sprinklers.

Water withdrawals from streams whose bedform is designed for large flows simply makes the remaining flow more susceptible to warming, because the width to depth ratio has increased. Reduced summertime flows from instream water withdrawals for agricultural and domestic use can have profound physical and biological effects on stream systems. As discharge decreases the stream temperature tends to increase if other energy processes remain the same (Boyd 1996).

Surface/Subsurface Water Interactions and Influences on Stream Temperatures

Phreatic[26] and hyporheic[27] groundwaters interact with surface waters and can substantially affect stream water temperatures (Figure 6). The types of interactions between surface streamflow, stream temperature, and groundwater depends on whether the stream is losing (water goes from channel to subsurface areas) or gaining (water enters channel from subsurface sources) water at any given reach (Constanz 1998). Depending on localized subsurface flow dynamics, the amount of phreatic and hyporheic groundwater entering a stream will vary (Poole and Berman 2001), with some stream systems and reaches having little or no hyporheic flow. Groundwater discharges into stream channels do not occur equally along a channel so some reaches will have more groundwater inputs than others.

Groundwater flows are slower and move through deeper soil layers than subsurface flows (which drain fairly quickly through surface soil layers). This slower and deeper movement by groundwater results in temperatures lower than surface waters and water flowing through surface soils as storm runoff. In the United Kingdom, Evans et al. (1995) reported that during periods from March–April and September–October, water temperatures in the hyporheic were lower (4.6–7.7 ºC [40–45.9 ºF], respectively) than surface waters (10–10.9 ºC [50–51.6 ºF], respectively).

Groundwater is insulated from daily and seasonal warming and cooling, so groundwater temperatures fluctuate very little. Therefore, groundwater inflow to a stream usually has a

[26] Phreatic groundwater derived from the watershed's catchment aquifer.

[27] Hyporheic water is water from a stream or river channel that enters an alluvial aquifer (i.e., sediments beneath and beside the active stream channel or within the riparian zone) and subsequently flows back into the stream at a later time.

cooling effect on warm summer water temperatures and a warming affect on colder winter water temperatures. DEQ (2000b) determined that reductions in groundwater would have a warming affect on the upper Grande Ronde River. In a northern England drainage basin, Smith and Lavis (1975) reported that during summer low flows, groundwater seepages reduced local water temperatures by 4–5 ºC [7.2–9 ºF].

Streams that have well-connected terraces and large amounts of deep gravel will typically have cooler water temperatures. Alluvial gravel in both large and small floodplains store cold water from periods of high runoff and releases the water gradually during periods of low runoff (Coutant 1999). Adequate recharge of alluvial gravels depends on high spring peaks in river elevation (Coutant 1999). Stream reaches with sloughs and side-channels can also supply large amounts of subsurface flow to the main channel.

Streams with constrained reaches with underlying bedrock allow for poor hyporheic and groundwater exchange and may have warmer water temperatures (Johnson, *in press*). Johnson (*in press*) reported that a stream on the west slope of the Oregon Cascade Range had higher maximum water temperatures in an upstream bedrock reach than a downstream alluvial reach. Within each reach, temperatures also changed over short periods of time.

The layers of sediment (type and porosity) on the stream bottom can strongly influence the rate and volume of flow of and exchange of hyporheic water into stream systems. In one example from an Oregon river, Landers et al. (2002) reported that during low-flow periods a substantial amount of water in the Willamette River (reach flowing north from the McKenzie River to Corvallis) will enter the hyporheic zone. However, in the Middle Fork of the John Day River, Hopson (1997) found that hyporheic flows into the channel were uncommon and therefore not a major factor contributing to the thermal patches Torgersen (1997) documented using remote sensing imagery.

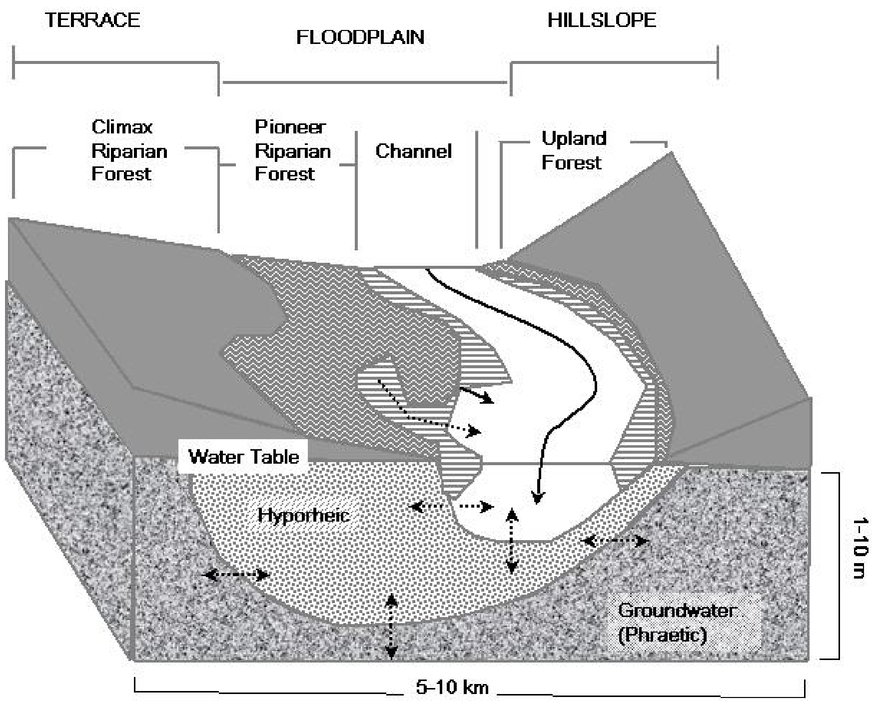

Figure 6. Movement of water between groundwater, hyporheic zone, and stream channel. (Adapted from Stanford et al. 1996). Arrows indicate direction of water movement.

The ability of the ground to conduct heat to streams is much higher than air since ground surfaces have higher conductivity. Conductivities of soils are higher than that of water and air. Ground surfaces can conduct heat to the water much more efficiently than through transfers with the air. When groundwater is warmer than the stream, heat will be transferred to the stream. In the winter, there can be warming of the streamflow by groundwater inputs. Needham and Jones (1959) reported that anchor ice did not form in a section of a high altitude stream receiving groundwater inputs, but anchor ice formed readily in a section with no groundwater inputs.

Human Influences on Surface/Subsurface Water Interactions

Groundwater, subsurface flows, and hyporheic flow can be affected by human activities. Activities can change upland vegetation and soil properties, create impervious surfaces in floodplains and uplands, decrease water table depth, lose water storage in floodplains and wetlands, and alter hydrographs by impounding water and withdrawing water for irrigation (Figure 7).

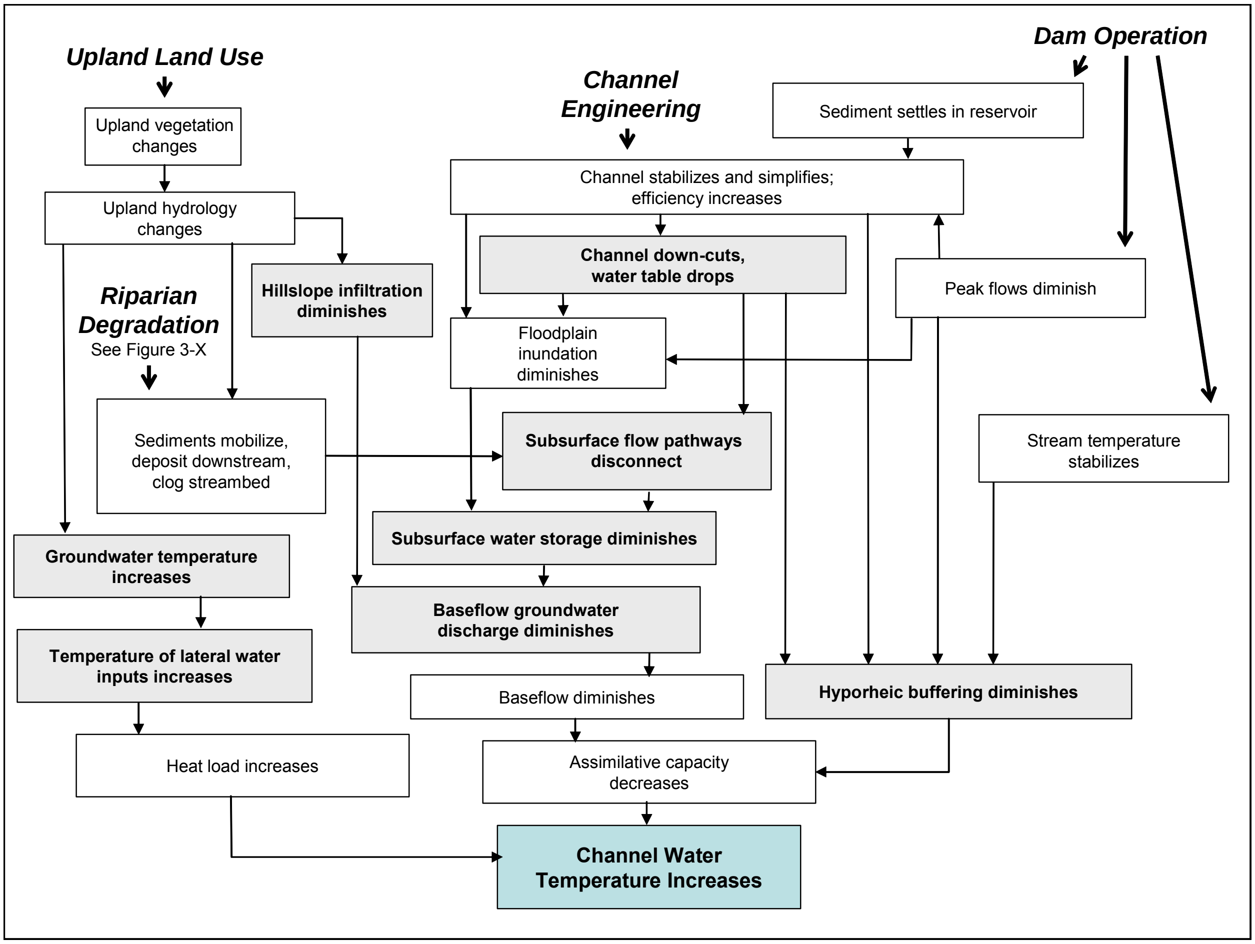

Figure 7. General pathways by which human activities influence groundwater and hyporheic flow into streams, and therefore stream temperature. Modified from Poole and Berman (2001). Note: Dam releases can directly affect stream temperatures by releasing cooler or warmer waters. This relationship is shown in Figure 5 on factors influencing streamflow and water quantity.

Riparian areas can be degraded by timber harvest, fires, agriculture, urbanization, grazing/trampling by livestock, roads, and utility right-of-way maintenance. Disturbances such as road building can impair the connectivity between the floodplain and stream (DEQ 2000b). Road crossings can also fragment stream reaches. Human land use and disturbance mentioned above can also decrease the storage capacity of riparian soils. The ability of riparian soils to capture, store, and slowly release groundwater is a function of the relative depth and composition of the soil and the level of riparian disturbance. Disruption of the riparian soil surface and loss of organic litter on the riparian floor will increase the overland runoff of precipitation and decrease the infiltration of water into the ground (Coutant 1999).

<u>Forest Harvesting</u>

In temperate, rain-dominated forests of the Pacific Northwest, groundwater temperatures may increase after riparian and upland vegetation is removed within a basin. Brosofske et al. (1997) looked at small streams before and after clearcutting in western Washington. Results showed that after clearcutting upland forests, the streams became warmer even with riparian buffers.

Brosofske et al. (1997) also found a relationship between stream temperatures and soil temperatures and suggested that subsurface water was warmed as it moved through the heated soils of the clearcut watershed. In the southeastern US, Hewlett and Fortson (1982) found that inadequate buffer strips led to solar exposures of the lower slopes just outside the buffer strip, which caused an increase in the temperature of groundwater as it migrated toward the stream. They concluded that groundwater temperatures could be increased with timber harvest, which in turn would affect stream temperatures. The extent of subsurface exchange and the degree to which ground water is affected could vary substantially from site to site and seasonally (Wondzell and Swanson 1996).

Urbanization

Human development and urbanization result in greater surface flow to streams and less infiltration into the ground. Water spends more of its time in contact with solar radiated surfaces such as pavement, roofs, and other developed areas and gains heat energy (Paul and Meyer 2001). Urban areas also have increased surface runoff of rain and snowmelt waters which reduces groundwater recharge, resulting in decreased baseflows in urban stream (Paul and Meyer 2001).

Reservoir Management

Reservoir management also changes the normal magnitude and timing of stream flows and can reduce peak storm flows thereby changing flooding patterns. Reduced flows below dams (due to impoundment and withdrawals) alter downstream hydrology and reduce groundwater recharge in riparian areas resulting in a lowering of the water table (reviewed by Nilsson and Berggren 2000). The alterations in flood regimes and drop in water tables below dams will also affect the composition of riparian vegetation communities (Nilsson and Berggren 2000) and may allow riparian communities to be replaced by upland communities. The change in plant communities may have further negative impacts on groundwater hydrology.

Livestock Grazing

In a study in Oregon's John Day basin, Li et al. (1994) found that damage from severe cattle grazing (amount and type of grazing was not specified) along Alder Creek caused the creek to become intermittent. Impacts from cattle can cause streams to become intermittent by causing channel incision, lowering the water table and decreasing interaction between the stream channel with riparian vegetation, decreasing riparian soil permeability by foot fall compaction, and dewatering the stream (Li et al. 1994; Belsky et al. 1999).

Irrigation

Irrigation water returning to stream channels (either as runoff or as subsurface flows) may have profound effects on surface water temperatures. Whitney and White (1984 as cited in Northwest Power Planning Council 1986) identified temperature increases as one problem associated with irrigation return flows. Sylvester and Seabloom (1962 as cited by Stober et al. 1979) reported that return irrigation surface flow in the Yakima Basin of Washington were substantially warmer after passing through irrigation canals and laterals.

Alluvial gravels are normally recharged by cool floodwaters. When floodplains are converted to agricultural fields, the alluvial gravels may be recharged with warmer irrigation return flows (reviewed by Coutant 1999). Agricultural fields stripped of vegetation will heat quickly from direct solar radiation and when irrigation water is applied to the agricultural fields in the summer the water is warmed by the soil and then, in turn, flows into the subsurface (reviewed by Coutant 1999).

In a meeting abstract, Todd and Buckhouse (1998) reported that water temperatures of return flows to tributaries of the Sprague River in Upper Klamath Basin were not significantly higher than main channel temperatures (which exceeded DEQ's temperature standards). In contrast, results from case studies conducted in eastern Oregon (Stringham et al. 1998; Taylor et al. 2003) suggest that under some situations, irrigation water may cool as it returns, subsurface, to a stream channel and may lower stream temperatures. Stringham et al. (1998) reported that a stream reach flowing through an irrigated meadow was 1.0 to 3.0 ºC [1.8 to 5.4 ºF] cooler than a reach immediately upstream flowing in a non-irrigated meadow. More research is needed to determine: 1) under what site conditions cooler flood/subterranean irrigation return flows may occur, 2) how much they may contribute to cooling a warm stream, and 3) what the trade-offs are between managing for return flows versus the amount of surface water withdrawn from the stream system in order to maintain saturated soil conditions that allow for return flows.

Draining Wetlands

Wetlands have been drained in order to facilitate conversion of land for urban, industrial, and agricultural uses. Natural riparian and floodplain wetlands collect and distribute flood flows, recharge groundwater aquifers, and store water for slower releases. Wetlands play an important role in storing water from winter floods, making water available for recharging groundwater aquifers, and later providing water to surface streams during summer low flows (SOER Science Panel 2000). Hydrologic alterations, such as dams, diversions, drainage-tile installation, and channelization have re-routed surface flows so that wetlands are no longer part of the hydrologic system in many basins. Drainage tile installation in wetlands may have altered hydrology by accelerating the draining of water in winter. Normally, wetland soils store water from winter rains, and slowly release the water over longer periods of time. Loss of wetlands has reduced the potential recharge of groundwater aquifers and reduced their ability to provide flow during dry summer and fall months (IMST 2002).

Upland Management

Management of upland vegetation and soils can affect the volume of subsurface flows by altering both infiltration and percolation of water from rainfall and snowmelt. Soil compaction from ground-based logging, livestock grazing, or recreational vehicles can reduce infiltration. Removal or reduction of vegetation and soil organic matter can reduce both infiltration and percolation rates. Living vegetation and dead vegetative material is effective at protecting soils from raindrop impact and thus allowing a soil to maintain soil structure and macropores (spaces between soil particles large enough to allow the movement of air and water through the soil). The maintenance of macropores, in turn, allow rainfall and snowmelt water to infiltrate at the soil surface. Soil organic matter and plant roots can increase soil porosity and aid percolation and absorption of water. High temperature fires can cause some soils to become water repellent and prevent infiltration (DeBano 2000).

In addition to affecting infiltration and percolation rates, plant community composition can also affect overland and subsurface water flow, evapotranspiration, and precipitation interception thereby affecting the hydrological cycle (Miller and Wigand 1994). Evapotranspiration is a significant hydrological process that can be altered by management of plant cover within watersheds (Brooks et al. 2003). The type, density, and cover of plants within a watershed affect transpiration rates and loss of water to the atmosphere over time (Brooks et al. 2003). Woody plants are considered to have a greater influence (as compared to crops and other herbaceous vegetation) on the amount of water removed from the soil and lost through evaporation due to their size, extent of cover, and length of growing seasons (Brooks et al. 2003).

In eastern Oregon, fire suppression and overgrazing has replaced native bunchgrass (*Agropyron* spp., *Festuca* spp., *Stipa* spp., and *Sitanion hystrix*) communities with western juniper/sagebrush (*Juniperus occidentalis*/*Artemisia* spp.) communities. This shift to juniper/sagebrush communities on large areas of basins can increase storm runoff and soil erosion, and decrease subsurface flows (Miller and Wigand 1994). Evans (1988) estimated that juniper woodlands with 40% canopy cover intercepted 15 to 20 % of precipitation. This interception and resulting evaporation of intercepted moisture could increase the amount of precipitation lost from the hydrological cycle through evaporation. Juniper woodlands also influence soil moisture depletion patterns through transpiration and can affect watershed value and site productivity (Angell and Miller 1994).

Riparian Vegetation Influences on Stream Temperatures

Riparian vegetation affects channel morphology, streamflow (riparian soils absorb waters during floods and release water during low flows), surface/subsurface water interactions, and thermal regulation of streams through shading and microclimate modification (Figure 8). Riparian vegetation can indirectly influence stream temperature by affecting channel morphology, streamflow, connection to hyporheic groundwater, infiltration and percolation rates, wind speed, humidity, soil temperature, water use, and local air temperatures. Riparian vegetation can directly affect stream temperature by shading the stream, thereby reducing solar inputs and water heating. The influence riparian vegetation has in regulating water temperature through any of these factors will vary based on stream size, position in landscape (headwater vs. river mouth), vegetation community type (herbaceous vs. woody), season, and regional climate (coastal vs. high desert). Riparian areas often support trees and/or shrubs but in arid and high-altitude streams, grasses, sedges, and rushes may be more prevalent than woody species (National Research Council [NRC] 2002).

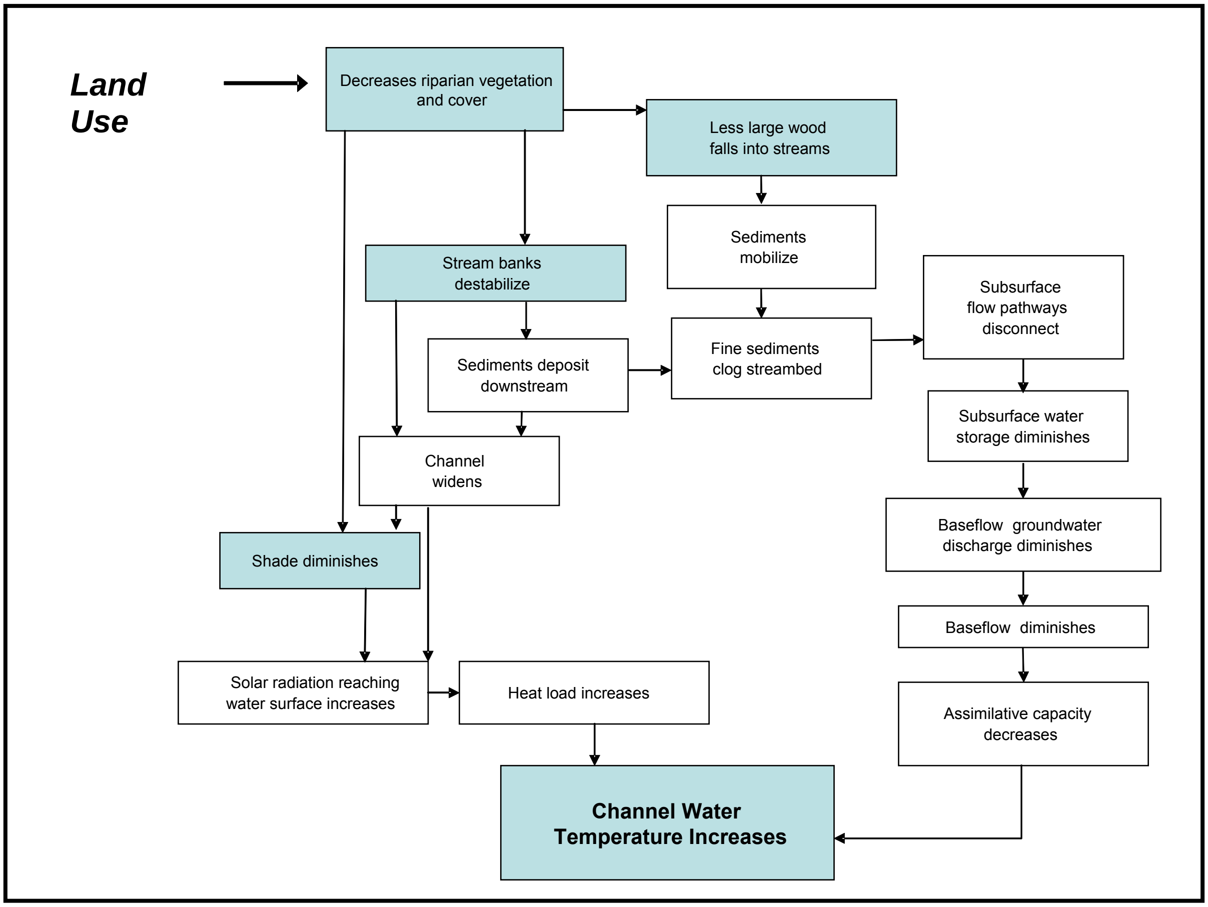

Figure 8. General pathways by which decreases in riparian vegetation could influence stream temperature. Note: Riparian vegetation can influence stream flow, but it is not represented in this figure but is discussed in earlier text. Modified from Poole and Berman (2001).

Influence of Riparian Vegetation on Channel Morphology

Riparian vegetation aids in maintaining stream channel dimensions and bank stability, and affects where erosion and sedimentation of channels and floodplains occurs. Healthy riparian vegetation contributes to good root growth and root strength in stream banks. Riparian vegetation communities are critical in maintaining channel stability during high flow to allow maintenance of stream dimension, pattern, and profile (Kleinfelder et al. 1992; Cornwall 1998; Lyons et al. 2000; Toledo and Kauffman 2001; Liquori and Jackson 2001; Micheli and Kirchner 2002). Millar (2000) reported that vegetation communities had significant influence in determining whether systems would become braided or single thread systems in gravel bed rivers. Millar and Quick (1993) analyzed the same data used by Millar (2000) using an analytical model and demonstrated that for well-developed bank vegetation, the channel widths, depths, and slopes were 0.6, 1.4, and 0.9 times narrower than their respective dimensions for weakly vegetated channel dimensions. Bank vegetation also exerts an important control on lateral instability and planform channel patterns. Beeson and Doyle (1995) reported that vegetated bends experienced significantly less erosion during high flow periods than channel bends without riparian vegetation.

Another mechanism by which riparian vegetation maintains the dimensions of a stream channel is by increasing the roughness of the banks and floodplain, thereby decreasing erosion and increasing sedimentation. If the rooting strength of riparian vegetation and the surface roughness is sufficient, sediments will be deposited, not eroded. Reduction in root mass through removal of riparian vegetation can lead to increased bank erosion and sedimentation rates. During high discharge events, water naturally overtops stream banks and inundates stream floodplains. In healthy riparian communities, high floodplain roughness traps sediments on stream banks and floodplain surfaces during these floodplain inundations. Riparian communities in poor condition lose this ability to trap material, and sediments are actually eroded from the floodplain surface during high discharge events.

Riparian communities with a tree or shrub component also maintain channel dimensions and improve stream health of lower order streams by supplying large wood (relative to channel size) and root wads to the stream channel and banks. Presence of large wood in stream channels will increase the pool frequency and have a large influence on channel shape (Keller and Swanson 1979; Montgomery and Buffington 1998).

Riparian Vegetation Influences on Streamflow and Surface/Subsurface Water Interactions

In alluvial rivers, the hyporheic zones are one of the dominant links between riparian vegetation and the stream channel (Edwards 1998). Natural river floodplains can store cold water during high spring discharge events and will release this cooler water gradually to surface flow in the summer when discharge is reduced (Figure 9). During floods, riparian areas will temporarily store excess water which delays and attenuates the flood peak in downstream areas (NRC 2002). Bank storage occurs when surface waters move laterally from the channel into the subsurface areas when river stages are high and the water is released when the river stages go down. Bank storage in riparian areas can affect water storage, surface water temperatures, and riparian vegetation communities (NRC 2002)

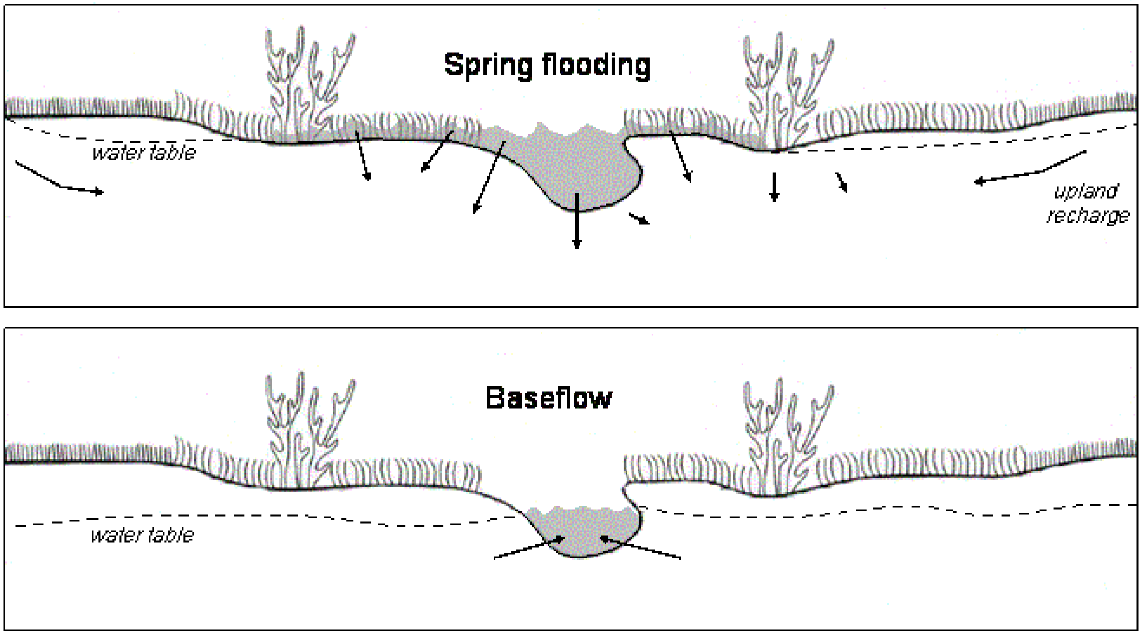

Figure 9. Process of cool water storage from spring flooding over floodplain. Cool water is released into channel during summer low flows. Arrows indicate direction of water movement.

Riparian Vegetation Influences on Thermal Environments Through Shading

Riparian vegetation can directly influence streams through shading (the interception of solar radiation lowers the amount of heat reaching the stream channel) as well as indirectly by influencing the local thermal environment (local wind patterns, local air temperatures, humidity, conductive and convective heat transfer, outgoing or long-wave radiation) (NRC 2002). The local microclimate in riparian areas is more thermally moderate (less fluctuation in temperatures and cooler) than the microclimate in adjacent upland areas (NRC 2002). The amount of influence riparian vegetation may have on stream temperature is dependent upon the size of the stream, water depth, riparian vegetation community (e.g., forest vs. meadow), length of stream channel shaded, slope, aspect, and region.

In an experimental shading study on a 2nd order stream in the west slope of the Oregon Cascade Range, Johnson (*in press*) reported that maximum water temperatures declined significantly in the shaded reach, but minimum and mean temperatures did not change. Heat budgets calculated prior to adding artificial shade indicated that solar energy was the dominant factor influencing temperatures in the stream. During shading the other energy fluxes showed little change, although their relative importance increased. Johnson (*in press*) also reported that under the artificial shade the largest energy fluxes were evaporation and net long-wave radiation.

There are disagreements among some Oregon researchers about the role shade has on stream temperatures. In a discussion paper, Larson and Larson (1996, p. 152) concluded that "...shade does not control stream temperature". From preliminary results on shaded streams in eastern Oregon, Krueger et al. (2003) concluded that, "Our study does not provide evidence that shade is a driving force in temperature change on these streams" (p. 34). Two of the streams were in the

Snake River Ecological Province (described in Anderson et al. 1998) and one stream was in the Blue Mountain Ecological Province (described in Anderson et al. 1998). The streams were described as having high-cover (81–85 %), mid-cover (35–68 %), or low-cover (12–57 %). The high-cover stream showed the greatest longitudinal change in temperature over the twenty hottest days in 2001. However, the stream with the highest shading was the coldest at the start of the study segment (48.9 ºF [9.4 ºC]) and warmed to a maximum of 72.1 ºF [22.3 ºC]. The streams with mid- and low levels of shade were already warm at the start of the study segments (64.2 ºF and 64.6 ºF [17.9 ºC and 18.1 ºC], respectively) and warmed to maximum temperatures of 70.2 ºF and 72.9 ºF [21.2 ºC and 22.7 ºC]. The IMST finds that this difference in starting temperatures makes comparisons of heating difficult.

In a second component of the study, Krueger et al. (2003) examined two sections of the mid-cover stream. On the hottest day in 2001 from 14:00 to 15:20 hrs (a single 80-minute period) they took measurements to determine the relationship of shade to maximum daily water temperature. Temperatures in the upper reach with 65% shade increased more than the lower reaches with shade ranging from 19 to 43% shade, although the authors noted that there were inconsistencies between reaches. They concluded that there was no apparent relationship between the level of shade and change in temperature for either a common time period or a common base temperature (they did a single 80-minute monitoring period when the stream sections hit 64 ºF [17.8 ºC]). The IMST finds that the majority of studies (many are described in the following discussion) conducted in Oregon and in other regions do not support the conclusions by Larson and Larson (1996) and Krueger et al. (2003).

Small streams that are wide and shallow with low discharge rates are at the highest risk of temperature problems but are the easiest streams to shade (Welch et al. 1998). Low order, narrow stream channels are more likely to be well shaded in comparison to wide stream channels that can be expected to have lower levels of shade simply due to their geometric relationship between vegetation height and channel width. On large streams and rivers, riparian shade may be present only along bank edges or secondary channels; nevertheless, these areas serve as important refuges for aquatic life and are benefited by shade (Welch et al. 1998). Ebersole et al. (2003) found that experimental shading of cold water patches lowered daily maximum temperatures of the surface waters by 2 to 4 ºC [3.6 to 7.2 ºF]. They concluded that this indicated that riparian vegetation had a strong influence of the expression of cold water patches exposed to solar radiation. Shading will lower the rate of heating of side channels and back water areas where water movement is slower than the center of the channel.

Winter stream temperatures have not been studied to the extent summer temperatures have been, but like summer temperatures, winter temperatures are also affected by riparian vegetation. Riparian vegetation and canopies provide thermal regulation to stream areas during the winter and can insulate the stream and riparian area from freezing air temperatures and wide diurnal air temperature fluctuations. Greene (1950) reported that during February in North Carolina, a stream in a hardwood forested watershed was 7 ºF [3.9 ºC] warmer than a stream flowing through an agriculturally dominated basin with no riparian canopy cover. Graynoth (1979) reported that a New Zealand stream flowing through a clear cut basin was 2.5 ºC [4.5 ºF] colder in the winter than a forested stream. A few authors (Anderson et al. 1976; Swanston 1991) have suggested that riparian canopies may also prevent the formation of frazil ice and anchor ice in northern latitude and high altitude streams that may be subject to supercooling during the winter.

<u>Cooling of warm waters in shaded reaches</u>
Water warmed in streams with no riparian canopy may decrease in temperature after entering fully shaded sections. Greene (1950) showed a stream temperature decrease from 80 to 68 ºF [26.7 to 20 ºC] after a stream, flowing through an agriculturally dominated watershed, traveled only 400 feet through a forested reach. Caldwell et al. (1991) observed the cooling of a stream running through a forested reach from 67.6 to 65.8 ºF [19.8 to 18.8 ºC] after passing through 450 feet of intact riparian canopy. In eastern Oregon, Bohle (1994) reported that maximum temperatures increased at a rate of 0.45 ºC/km [0.81 ºF/km] as the Upper Grande Ronde River flowed through an unconstrained reach with little stream cover, and very wide shallow channel in Vey Meadow. Immediately below Vey Meadow, the river flowed through a very narrow, steep-sided valley providing topographic and vegetative shade. Maximum temperatures decreased through this reach as much as 0.11 ºC/km [0.2 ºF/km].

The cooling reported by authors, including those listed above, is not necessarily a direct result of shading. Heat in a stream is lost through convection, conduction, and evaporation. Evaporation can be a major cooling agent for streams when temperature gradients, vapor pressure gradients, and winds are high enough and humidity is low enough to transfer heat from the water to the air. The riparian canopies will intercept direct solar radiation and slow down the rate of heating. The riparian canopy can lower local air temperatures over the stream channel and change the rate of evaporation. Heat energy is lost to the air, stream channel and bank in shaded reaches until equilibrium occurs.

Cold groundwater or tributary inputs will also contribute to water temperature cooling in shaded sections. Brown et al. (1971) studied a small stream in western Oregon (Zinc Creek) that warmed 8 ºF [4.4 ºC] to a temperature of 65 ºF [18.3 ºC] while flowing through a clear-cut with no riparian buffer but some shade. After the stream traveled through a forested reach, the temperature dropped to 60 ºF [15.6 ºC]. The large reduction in stream temperature was a result of cold groundwater entering the stream. Brown et al. (1971) reported that groundwater temperatures averaged between 45 and 59 ºF [7.2 and 15 ºC].

Story et al. (2003) reported that streamflows in a British Columbia basin that were warmed in clearcut reaches cooled as much as 4 ºC [7.2 ºF] after entering shaded sections. Radiative and convective heat exchange in the heavily shaded sites did not account for the cooling. One stream had the greatest cooling when the streamflow dropped below 5 L/s and temperatures were controlled by local inflow of groundwater, because the warmer upstream flow was lost by infiltration. In the second stream, water temperature patterns remained fairly stable, and energy balance estimates suggested that groundwater inflow caused about 40% of ~ 3 ºC [5.4 ºF] gross cooling effect in the daily maximum temperature. Bed heat conduction and hyporheic exchange accounted for the other 60% of the decrease.

In other situations, no detectable change in temperature may be seen once a stream enters a shaded stretch. In a small western Oregon tributary (Cedar Creek) Brown et al. (1971) reported stream temperatures approaching 80 ºF [26.7 ºC] downstream from a large clearcut. No significant reduction in temperature was seen after the stream entered a 600 ft (183 m) reach with a forested canopy. The authors found that there were insufficient wind speeds, temperature gradients, and vapor pressure gradients to cause either evaporative or convective cooling of water once the stream entered a shaded reach.

Human Activities Influencing Riparian Vegetation and Stream Shading

Canopies of riparian vegetation are very effective at intercepting large amounts of solar radiation. Solar radiation is the primary source of energy responsible for the warming of water in streams and the air in riparian areas. When a stream is exposed to summer solar radiation, large quantities of heat will be delivered to the water (Brown 1969; Beschta et al. 1987). Riparian canopies can depress both the water temperature in streams and the local air temperatures in riparian areas. If riparian canopies are removed, the largest increases in stream temperature will occur in small headwater streams. Stream temperature responses to riparian canopy removal have been shown to occur at various temporal and spatial scales. Increases in the mean maximum temperature, increased daily fluctuations, and a shift of the maximum temperature to earlier in the summer have all been documented. The mean water temperature of a particular stream reach will be a function of all effects from upstream reaches. The daily water temperature of a particular stream reach will be a function of all upstream reaches that contribute to the system, not just the function of local conditions.

In a review of the scientific literature, the IMST found 48 published, empirical studies that measured changes in summer stream temperatures as a result of canopy removal or modification due to either land use practices or experimental manipulation of riparian vegetation (Table 7). Most of these studies were conducted on small streams in forested basins, though the examples from outside western North America included studies in pastures or rangeland. At first glance it may appear that several notable studies conducted in eastern Oregon are missing are from Table 7 (e.g., Borman and Larson 2003, see p. 89; Krueger et al. 2003 see p. 83–84). These studies, as well as others from western Oregon, were not included because they did not compare temperatures of streams with canopy cover to streams without canopy cover or they did not examine stream temperatures before and after canopy removal. Table 7 also does not include studies on artifical shading.

Maximum summer stream temperatures increased in 45 of the 48 studies (Table 7). In two studies (James 1957; Fowler et al. 1987), small decreases in temperature of 0.6 ºC and 2.0 ºC, respectively, were observed following vegetation removal. James did not offer an explanation for the decrease. Fowler et al. (1987) speculated that the decrease in stream temperature was a result of increased nocturnal cooling after canopy removal, increased snow accumulation in the clearcut, and, possibly, a delayed melt affecting stream volume and timing. In one study (Mosley 1983), no change in temperature was observed, which was attributed to substantial subsurface exchange in a braided river with deep alluvial deposits.

Table 7. Empirical studies that measured changes in summer stream temperatures as a result of decreased riparian vegetation and canopy removal due to either land use practices or experimental manipulation. This table represents studies that 1) compared temperatures of streams with canopy cover to streams without canopy cover or 2) examined stream temperatures before and after canopy removal. Artificial shading studies are not included. Direction of change in stream temperature: ↑= increase, ↓ = decrease, — = no change. (Table continued on next page).

	Location	Maximum Change (ºC)	Maximum Change (ºF)	Direction of Change	Citation
	Oregon				
1	Blue Mountains	7.2	13	↑	Helvey and Fowler (1996)
2	Blue Mountains	-2	-3.6	↓	Fowler et al. (1987)
3	Blue Mountains	11	19.8	↑	Li et al. (1994)
4	Cascades, west slope	7.7	14	↑	Levno and Rothacher (1969)
5	Cascade & Coast Ranges	8.9	16	↑	Brown and Krygier (1967)
6	Coast Range	7.7	14	↑	Brown and Krygier (1970)
7	Cascades, west slope	7.7	14	↑	Brown et al (1971)
8	Cascades, west slope	8	14.4	↑	Adams and Stack (1989)
9	Coast Range	1.4	2.5	↑	Dent and Walsh (1997)
10	Cascades, west slope	6	10.8	↑	Beschta and Taylor (1988)
11	Cascades, west slope	7	12.6	↑	Johnson and Jones (2000)
12	Cascade & Coast Ranges	1.09	2	↑	Zwieniecki and Newton (1999)
13	Coast Range	3.8	6.9	↑	Robison et al. (1999)
14	Coast Range	12.7	22.9	↑	Moring (1975)
	Pacific Northwest – OTHER				
15	Alaska	5	9	↑	Hetrick et al. (1998)
16	Alaska	-0.5	-1	↓	James (1957)
17	Alaska	5	9	↑	Meehan et al. (1969)
18	Alaska	2.08	3.7	↑	Meehan (1970)
19	British Columbia	3.2	5.8	↑	Holtby and Newcombe (1982)
20	British Columbia	4.8	8.6	↑	Feller (1981)
21	British Columbia	6.0	10.8	↑	Macdonald et al. (2003)
22	California	11.1	20	↑	Burns (1972)
23	Washington	6.0	10.8	↑	Sullivan et al. (1990)
	USA outside Pacific Northwest				
24	Connecticut	5.6	10	↑	Titcomb (1926)
25	Georgia	6.7	12.1	↑	Hewlett and Fortson (1982)
26	Maine	1.5	2.7	↑	Garman and Moring (1991)
27	Maryland	3.2	5.8	↑	Corbett and Spencer (1975)
28	New Hampshire	6.1	11	↑	Hornbeck and Federer (1975)
29	New Hampshire	5	9	↑	Burton and Likens (1973)
30	New Jersey	3.3	5.9	↑	Corbett and Heilman (1975)
31	North Carolina	7.2	13	↑	Greene (1950)
32	North Carolina	11.7	21	↑	Swift and Messer (1971)
33	North Carolina	3.3	5.9	↑	Swift (1982)
34	North Carolina	5.6	10	↑	Swift and Baker (1973)
35	Pennsylvania	9	16.2	↑	Lynch et al. (1984)
36	Virginia	3.5	6.3	↑	Pluhowski (1972)
37	West Virginia	3.9	7	↑	Patric (1969)

Table 7 (continued). Empirical studies that measured changes in summer stream temperature as a result of decreased riparian vegetation and canopy removal due to either land use practices or experimental manipulation. Direction of change in stream temperature: ↑ = increase, ↓ = decrease, – = no change.

	Location	Maximum Change (ºC)	Maximum Change (ºF)	Direction of Change	Citation
	USA outside Pacific Northwest cont'd				
38	West Virginia	4.4	8	↑	Eschner and Larmoyeaux (1963)
39	West Virginia	4.4	7.9	↑	Kochenderfer and Aubertin (1975)
40	West Virginia	9.0	16.2	↑	Lee and Samuel (1976)
	World				
41	Japan	4	7.2	↑	Sugimoto et al. (1976)
42	New Zealand	6.5	11.7	↑	Graynoth (1979)
43	New Zealand	0	0	—	Mosley (1983)
44	New Zealand	10.2	18.4	↑	Quinn et al. (1992)
45	New Zealand	6	12.6	↑	Rutherford et al. (1999)
46	New Zealand	4	7.2	↑	Hopkins (1971)
47	United Kingdom	3.6	6.5	↑	Gray and Edington (1969)
48	United Kingdom	1.5	2.8	↑	Weatherley and Ormerod (1990)

Most studies examining the effects of riparian vegetation and canopy removal on stream temperatures have been concerned with timber harvest practices on small streams. Several of the logging-related studies were conducted on previously unmanaged forests and included pretreatment data and unlogged basins for comparison (e.g., Levno and Rothacher 1969; Brown and Krygier 1967, 1970; Moring 1975; Johnson and Jones 2000). Since these forested streams were previously unmanaged, they were hydrologically intact and had functioning riparian areas when the studies began. However, this is not the case for many agricultural and grazing studies, which do not include unmanaged streams for comparison. Stream segments with "ungrazed treatments" had a history of grazing prior to the studies being conducted (e.g., Gunderson 1968; Platts 1981; Kauffman et al. 1983; Maloney et al. 1999).

The following discussion first summarizes the studies involving land use impacts on riparian vegetation and canopies on agricultural and rangelands, and then summarizes forestry related studies conducted in the Pacific Northwest and Intermountain West. Fewer forest studies have been conducted east of the Cascade Mountain Range; most have been conducted in lower elevation mesic forests west of the Cascade crest.

Agricultural and grazing related studies

Claire and Storch (1977) studied an exclosure area designed to limit livestock grazing along a stream in Oregon's Blue Mountains. At the time the study began, the streamside was reported to be devoid of a shrub canopy and streambanks were exposed. No grazing occurred in the exclosure (size not specified) from 1964–1967 and controlled grazing was allowed after August 1 from 1968–1974. Within the exclosure, alder and willow shrub canopy developed and provided up to 75% shade to the stream. Outside the exclosure, the area was grazed yearly between June 1 and October 15, and conditions remained unchanged. Ten years after construction, maximum water temperatures inside the exclosure averaged 12 ºF [6.7 ºC] lower than temperatures outside and downstream of the exclosure. Daily fluctuations in water temperature averaged 13 degrees (ºF scale) inside the exclosure and 27 degrees (ºF scale) outside the exclosure.

Gunderson (1968) reported grazed (for 11 months each year) stream sections in Idaho had less shrub cover overhanging the stream channel and less stream cover provided by overhanging banks than a section that was ungrazed. Also in Idaho, Platts (1981) reported that heavily grazed (by sheep) banks had similar amounts of overhanging vegetation. However, within the grazed section much less of the water's surface area was covered than in an adjoining ungrazed section.

In the John Day River basin, Li et al. (1994) compared reaches in two creeks, Alder and Service Creeks. At an elevation of 580 m, Alder Creek, exposed to solar radiation due to the lack of vegetative shade, was 11 ºC [19.8 ºF] warmer than shaded Service Creek. At 550 m, cold spring water lowered water temperatures in Alder Creek to temperatures identical to the "focal reach" (the lower margin of shaded and unshaded "patches" of Alder Creek).

On the Middle Fork John Day River in eastern Oregon, Kauffman et al. (2002) reported that there were significant differences in riparian plant cover, species composition, and vegetation structure between grazed areas and ungrazed exclosures. Exclosure ages ranged from 3 to >30 years and grazing treatments ranged from light cattle grazing one out of three years to heavily season-long grazing. Exclosed areas had more forb, shrub, and sedge cover and less exposed bare ground than grazed areas. The study indicated that the plant communities shifted away from plants adapted to grazing and drier environments to more mesic wetland riparian vegetation once grazing was halted in the exclosures.

Different agricultural land uses may have similar effects on water temperature. Borman and Larson (2003) conducted a case study in the Burnt River basin in northeastern Oregon; they examined stream temperatures for two summers in a river segment flowing through pasture and another segment flowing through irrigated hay. Riparian shading over the channel was minimal, 1 to 5 %. They reported that stream temperatures were not significantly different between the existing land uses. No unmanaged, reference streams with intact riparian vegetation were included in the study to determine the overall effect the land uses may have had on stream temperatures.

<u>Forestry related studies</u>

Most studies of forest harvest effects on stream temperatures have been limited to a few post-harvest years (Beschta et al. 1987). A few studies have analyzed the long-term effect of timber harvest in the Oregon Cascades (e.g., Adams and Stack 1989; Johnson and Jones 2000) and the Coast Range (e.g., Brown and Krygier 1967 and 1970; Moring 1975). Forest harvest in riparian zones has been shown to increase stream temperatures and the amount of this change can vary among sites and regions (Swift and Messer 1971; Anderson 1973; Beschta et al. 1987).

Hetrick et al. (1998) conducted a controlled experiment in southeast Alaska where all riparian vegetation was removed from the banks of several streams. Results indicated the summer stream temperatures increased when riparian vegetation was absent. Meehan (1970) measured stream temperatures at 20 yard intervals in southeast Alaskan small streams. He found that the streams warmed in sunlight and cooled under shaded canopies.

Holaday (1992) examined data from 1969 through 1990 for the Steamboat Creek basin (Umpqua River, southwestern Oregon) to determine long-terms trends in summer stream temperature. Logging has occurred in the basin since 1955. Holaday found decreasing summer stream temperatures during the 1969–1990 period, with the largest decreases (3.9 to 6.1 ºC; 7 to 11 ºF) occurring in small streams with summer base flows less than 0.17 m^3/sec and had the highest proportion of stream length adjacent to units logged prior to riparian buffer requirement in 1974. The smallest decreases (0 to 1.7 ºC; 0 to 3 ºF) were seen in streams with little or no history of timber harvest in riparian areas. Holaday did not find similar changes in either air temperature or stream flow during the 1969–1990 period and concluded that the decrease in temperatures was a result of riparian vegetation regrowing after being removed by harvest, flood damage, or debris torrents, thereby intercepting more solar radiation and shading the stream. Similar results were also found by Hostetler (1991) when stream temperature data from 1969 to 1989 in other tributaries in the Steamboat Creek basin were examined.

Adams and Stack (1989) studied the long-term changes in a stream in the southern Oregon Cascade Mountains and documented the effects of regrowth on stream temperatures. One year after timber harvest, maximum annual stream temperature was 14 ºF [7.8 ºC] above pre-harvest temperatures. Four years after timber harvest, some riparian vegetation had recovered, and maximum annual stream temperature was only 6 ºF [3.3 ºC] above pre-harvest temperatures.

In the Bull Run watershed in the western Oregon Cascades, Harr and Fredricksen (1988) reported that annual maximum stream temperatures increased 2–3 ºC [3.6–5.4 ºF] after patches were clearcut on southern slopes in two watersheds compared to an uncut watershed. Within three years, the stream temperatures in the patch cut watersheds were only 1 ºC [1.8 ºF] higher than the uncut watershed. The authors attributed the change to regrowth of streamside vegetation.

The Alsea Watershed Study, a long-term study in the Coast Range of Oregon, began in 1958 and was the first detailed long-term study to document the effects of timber harvest on temperature patterns in small streams. Brown and Krygier (1967, 1970) studied the effects of clear-cut logging and slash burning with no riparian buffers in small watersheds within the Alsea Basin. After logging, the clear-cut watershed (Needle Branch) had higher stream temperatures than before logging, and higher temperatures than the unlogged watershed (Flynn Creek). No temperature changes were seen after logging in a third watershed (Deer Creek) that was patch-cut with a buffer left along the stream. Brown and Krygier (1967) reported that the main change occurring in Needle Branch was the amount of shade over the streams and the amount of radiation reaching the stream's surface. Shading over the streams in the other two watersheds was not altered in the study. Moring (1975) reported that during the 15-year period after clear-cutting the forest in the Needle Branch watershed, elevated stream temperatures recovered once logging and slash burning decreased and stream side vegetation recovered.

Streams in the H.J. Andrews Experimental Forest in the Cascade Range of Oregon have been studied for 50 years (Johnson and Jones 2000). As part of a study in Oregon, Brown and Krygier (1967) investigated stream temperature response to clearcut logging without riparian buffers and subsequent mudslides in the H.J. Andrews Experimental Forest by comparing stream temperatures upstream and downstream of the clearcut/mudslide area. The comparison showed an increase in water temperature after flowing through the clearcut/mudslide area. In a different study in the H.J. Andrews, Levno and Rothacher (1967) found summer stream temperatures increased after a watershed was clearcut. Johnson and Jones (2000) looked at historical data on stream temperature through several timber practices, debris flows, and regrowth of riparian vegetation (Figure 10).

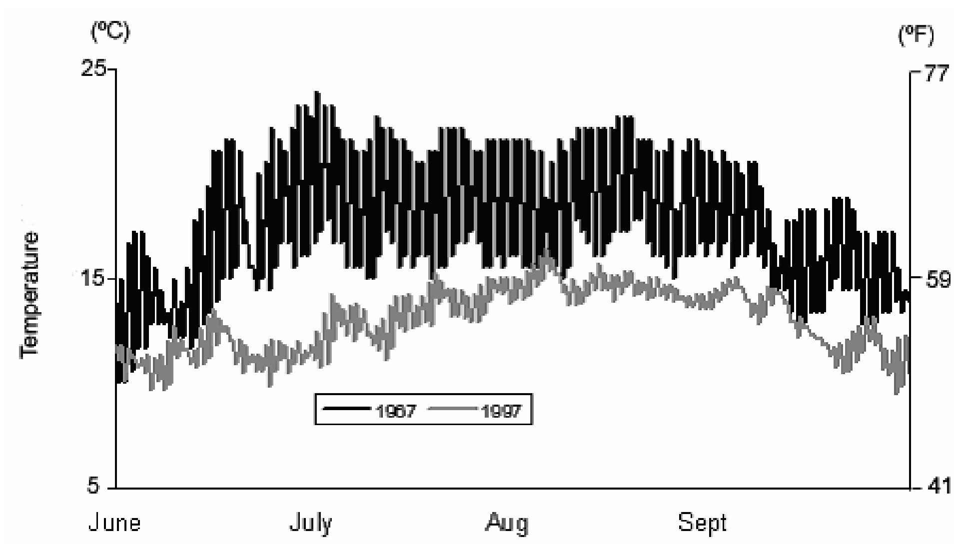

Figure 10. Maximum and minimum daily stream temperatures in summer for a clear-cut basin in 1967 and 1997 in the central Cascades of Oregon. The basin was clear-cut between 1962 and 1966. In 1997, the riparian zone consisted of a dense stand of red alder (Alnus rubra). From Johnson and Jones (2000).

Figure 10 shows the effect of 30 years of riparian vegetation regrowth; mean summer water temperatures in 1997 were lower than in 1967 and temperatures fluctuated much less, correlating with return of riparian vegetation after logging (Johnson and Jones 2000). These and other results of long-term studies indicate that stream temperatures are reduced once riparian vegetation regrows.

<u>Removal of Riparian Vegetation by Fire and Effects on Stream Temperatures</u>

Although the canopies of riparian tree and shrubs are important to moderating stream temperatures, low-growing streamside and upland vegetation also contribute to moderation of stream temperatures. Several studies look at the effects of burning of riparian and upland undergrowth on stream temperatures.

Several studies compared riparian clearcuts to riparian clearcuts that were also burned. Burning after harvest removes more understory vegetation from the site than harvest operations. Levno and Rothacher (1969) and Lynch et al. (1984) showed that burning of the litter and shrubs along stream banks and/or herbicide use after timber harvest leads to an even larger increase in maximum stream temperature. Maximum stream temperatures after clear-cutting a watershed in the H.J. Andrews Experimental Forest increased only 4 ºF [2.2 ºC] after timber harvest; the same stream showed an increase of 12 ºF [6.6 ºF] after the watershed was burned and the channel was cleared of all brush and woody material (Levno and Rothacher 1969). In British Columbia, a controlled experiment compared a clearcut stream to a clearcut/slash burned stream (Feller

1981). Results indicated that summer stream temperatures increased in the clearcut stream and the clearcut/ slash burned stream with the biggest increase occurring in the clearcut/slash burned stream. However, after 7 years, water temperatures in the clearcut/slash-burned stream were still high, while water temperatures in the clearcut stream had started to decrease.

Amaranthus et al. (1989) investigated stream temperatures after a natural fire in southern Oregon. Natural forest fires tend to burn variably across the landscape, leaving a mosaic pattern of severely burned patches, lightly burned patches, and unburned patches. The study measured water temperatures in three adjacent headwater streams before the fire and after the fire. After the fire, riparian shade was provided by topography, surviving riparian vegetation, and dead standing trees. While stream temperatures increased in all three streams after the forest fire, the largest increases occurred in streams with less shade.

Effectiveness of forest buffer strips in protecting water temperatures

Properly designed buffer strips of intact riparian vegetation left along streams after timber harvest activities have been shown to be effective means of providing shade and protection from solar radiation. Adequate buffer strip widths to protect stream temperatures can be highly variable and should account for stream size. Research has found that the height and width of buffer strips should not be set at a specific value or limit as a standard for all streams (IMST 1999).

In the Alsea Watershed Study, Brown and Krygier (1970) reported that 15 to 30 m wide buffer strips left along small streams in the Deer Creek watershed was nearly as effective in maintaining stream temperatures as the intact forest left in the uncut forested watershed, Needle Branch. Aubertin and Patric (1974) reported that no change in stream temperature occurred in a small West Virginia stream when the surrounding forest was clear-cut and a shade strip of 10 to 20 m wide (and 730 m long) was left along the stream.

Brown (1971) cautioned, however, that buffer strips were susceptible to wind damage, and other specific characteristics of the buffer must be used in determining proper widths. Narrow riparian buffer strips exposed to storm winds are highly susceptible to windthrow (trees blown down or stems broken by wind) for 5–10 years after their formation (Steinblums et al. 1984). In northern British Columbia, Macdonald et al. (2003) studied the influence of three variable retention harvesting prescriptions on sub-boreal 1st-order streams. Riparian management areas were 20 and 30 m wide. Management within the riparian management areas was either: (1) low-retention – removal of all merchantable timber within 20 m of the stream; (2) high-retention – removal of large merchantable timber within 10-20 m of the stream; or (3) patch cut – high retention along the lower 60% of the stream and removal of all riparian vegetation in the upper 40% of the watershed. The high-retention treatment did mitigate temperature increases from harvesting; after 3 years of successive windthrow, this treatment reduced the riparian canopy, increased solar radiation reaching the water surface, and increased stream temperatures.

Science Question 3 Conclusions

Conclusion 3-1. Stream temperatures are affected by many environmental factors including, but not limited to, direct and indirect solar radiation, watershed elevation, aspect and topography, regional and seasonal climate, local climate (air temperature, vapor pressure, humidity, wind, etc.), precipitation amounts and timing, channel dimensions, streamflow (water quantity), groundwater inputs, and riparian vegetation.

Conclusion 3-2. Riparian vegetation can reduce stream heating, regulate temperatures by blocking incoming solar radiation, and maintain channel morphology and functioning floodplains. Riparian vegetation has direct and indirect effects on stream temperatures.

- If riparian canopies are removed, large increases in stream temperature may occur.
- The largest increases in stream temperatures after riparian canopies are removed can be expected to occur in small headwater streams.
- Intact riparian vegetation traps sediments, influences watershed hydrology, maintains favorable width-to-depth ratios, and maintains water table depth, thereby indirectly influencing stream temperature.

Conclusion 3-3. Human activities can affect stream temperature by modifying channel morphology, streamflow, surface/subsurface water interactions, and riparian vegetation.

- Channel morphology can be directly and indirectly affected by agriculture, livestock grazing, forest harvest, road construction, urban/suburban development, instream and placer mining, channelizing, diking, rip-rapping, and dredging.
- Streamflow is altered directly by dams, reservoirs and other impoundments, and withdrawals for municipal and irrigation uses.
- Interaction between surface and subsurface waters can be altered by human activities on floodplains and upland areas that affect water movement and storage, by draining of wetlands, and by water impoundments and withdrawals.
- Riparian vegetation directly and indirectly affects the three factors above and is disturbed and degraded by many land use activities including agriculture, livestock grazing, forest harvest, road construction, and urban/suburban development.

Science Question 4. Is the temperature model used by the State of Oregon based on sound scientific principles? How can temperature models be used effectively in water quality actions under the Clean Water Act?

As discussed in this report's introduction, total maximum daily loads (TMDLs) are set, by basin or sub-basin, for each parameter that has been determined to impair water quality. TMDL analysis is the process used to set the total maximum daily loads for each parameter. For heat, the analysis uses available data (current, recent, and historical) each watershed and a Heat Source model that has been calibrated for that watershed. Heat Source simulates stream temperatures in basins based on local climate, topography, elevation, hydrology, natural vegetation, and channel morphology. Most Oregon TMDL documents[28] have used Heat Source, along with available remote sensing and field data, as part of the landscape level analysis of stream temperatures. In the answer to this Science Question, we discuss what models are and how they are used in the TMDL analyses. We evaluate Oregon's Heat Source model and discuss how such temperature models can be used effectively to manage stream temperatures within basins.

Use of Ecological Models in TMDL Analysis
Heat Source is just one tool DEQ uses for stream temperature analyses. The EPA (2003a) recommends that a combination of tools and approaches should be used to estimate natural background temperatures including:

- Comparing degraded streams to less degraded reference streams,
- Using historical stream temperature data,
- Temperature models, and
- Using maps of historical fish distribution to estimate temperatures.

Landscape-level ecological models are recognized tools for TMDL analyses (EPA 2003a; NRC 2001). The NRC (2001) presents categories of models that support the TMDL process, and discusses criteria by which to select appropriate models. The EPA (2003a) categorizes general types of temperature models, and discusses useful applications of different types of temperature models. Ecological models can be categorized as either statistical models or process-based models (EPA 2003a).

Statistical models (empirical models) develop correlations (relationships between variables) based on observed statistical patterns in actual datasets, and are often used in conjunction with non-degraded reference sites (NRC 2001; EPA 2003a). Statistical models become less certain with increasing dissimilarity between the references sites and the assessed area; therefore, statistical models are best applied to small headwater streams or generalized predictions across a large landscape (EPA 2003a).

Process models (simulation models; mechanistic models) quantify natural processes acting on an ecosystem, and are based on mathematical characterizations of current scientific understanding

[28] As of March 15, 2004, fourteen final DEQ TMDL documents approved by EPA have used the Heat Source Model including: Upper Grande Ronde River basin, Upper South Fork Coquille basin, Umatilla River basin, Tillamook Bay watershed, Tualatin subbasin, Little River watershed (in North Umpqua subbasin), Western Hood subbasin, Nestucca Bay watershed, Lower Sucker Creek (Illinois River subbasin), Lobster Creek watershed (Lower Rogue subbasin), Upper Klamath Lake drainage, North Coast subbasins, Alvord Lake subbasin, and Applegate subbasin.

(NRC 2001; EPA 2003a). Process models simulate current river temperatures based on input parameter values. Water temperatures under different management scenarios can be predicted by changing the parameter values.

> "Unlike statistical models, process models do not rely upon data from reference locations, so they can be used for rivers that have no suitable natural reference comparisons available. Thus, process models are well suited for estimating natural conditions for larger streams and rivers. Although powerful, process models are by no means infallible. Errors can arise when there are locally important factors that the model does not address, or when there is a great deal of uncertainty in input parameters that strongly influence model results" (EPA 2003a; p.41).

In recent years, distributed process models have incorporated a high degree of spatial resolution and access Geographical Information Systems, remotely-sensed data, and site-specific data (EPA 2003a).

Oregon's Heat Source Model

Heat Source is designed to simulate water temperatures in river basins. Stream temperature dynamics are represented mathematically and embedded within the larger model; these theoretical representations are supported by scientific literature (listed in Boyd and Kasper 2003). Because each river is thermally unique, the model is re-calibrated (in terms of local climate, topography, elevation, natural vegetation, hydrology, and channel morphology when it is applied to a new river basin. Each basin-specific model represents the major physical determinants of solar heat loading and thermal balances including topographic and vegetative shading. The calibrated model includes all sources of heat (point sources, non-point sources, and natural background heat) affecting stream temperatures in the basin (Boyd and Kasper 2003).

Heat Source can be characterized as a distributed process model, which provides relatively detailed, spatially explicit information across large landscapes. Heat Source is particularly useful in river basins where only a few (or no) reference sites are found.

Climate, topography, and elevation are included in the calibration of the model; however, these environmental factors cannot be manipulated by human actions, and they are not manipulated in the model. Heat Source simulates water temperatures under current basin conditions, and can predict potential stream temperatures under various landscape management scenarios by manipulating basin hydrology (e.g., groundwater inputs, hyporheic flow, stream discharge), riparian vegetation (type, height, width, canopy density), and channel morphology (width and depth).

<u>Simulation of Current Conditions</u>

Stream temperatures are influenced by anthropogenic and natural heat sources (both point and non-point sources) of heat. Human activities can affect heat loading from non-point sources by affecting groundwater, streamflow, channel dimensions, and riparian vegetation (discussed in Science Question 3). Heat Source simulates current stream temperatures based on measured temperatures of all water quality limited streams (and tributaries that may affect those impaired streams) in a river basin.

Two methods of stream temperature measurement are used: 1) forward looking infrared radiometer (FLIR) readings, which are spatially continuous measurements, and 2) thermister readings, which are temporal measurements (at 0.5 to 1.0 hour intervals). These spatial and temporal data are entered stream by stream into Heat Source, calibrating FLIR data with thermister data in the basin (discussion of model calibration is continued in the Calibration of Heat Source Model section). Simulated results are paired with actual results to calibrate the model in terms of stream temperature. Calibration is at the level of pixels, and the sample size of paired results for stream temperature is approximately 2,000 pairs in each Heat Source model (M. Boyd, pers. comm.[29]).

Data that are entered into each model to simulate current conditions include:

- Groundwater inputs (known springs and groundwater sources),
- Stream discharge, flow augmentation, and water withdrawals,
- Point sources of heat (e.g., industrial discharge),
- Shade (topographic and vegetative),
- Channel dimensions (width, depth, length), and
- Riparian vegetation.

Concerns about FLIR Technology

Heat Source uses FLIR readings (verified with field measurements) to represent current stream temperatures. FLIR technology provides the ability to scan surface temperatures of water over large areas (calibrated with thermometers in the water). FLIR imagery provides pixels that typically range from 20 cm x 20 cm to 30 cm x 30 cm (and, less typically, 100 cm x 100 cm) across the surface of rivers, streams, and lakes. From the surface, FLIR images can detect cold-water spots from springs and tributaries if the water is naturally mixed. FLIR information is spatially continuous. The information is entered into Heat Source, where it is verified stream by stream with temporally continuous data (at half-hourly to hourly time-step) from instream thermisters (which are deep in the water, usually at the bottom of the stream).

In a conceptual paper, Larson et al. (2002) raised some concerns about how FLIR images are interpreted. A discussion in the scientific literature further explored the issue of proper interpretation of FLIR imagery (Beschta et al. 2003; Larson et al. 2003). Overall, FLIR data represent surface water temperatures, which are influenced by near surface water temperatures. Because FLIR data are obtained from surface emittance, they cannot detect temperatures on the bottoms of streams where coldwater pockets may exist. The FLIR approach also does not work for streams in which the riparian canopy covers the water surface. The State of Oregon has evaluated the limitations of FLIR data and uses such data carefully in temperature assessment in the TMDL process. Interpretation of FLIR for use in Heat Source is discussed in detail in Boyd and Kasper (2003).

<u>Estimated Conditions</u>

Heat Source predicts potential stream temperature conditions after improvements in streamflow, tributary inputs, groundwater, and shade from vegetation and stream channel. These predictions are based, in part, on site-potential information from outside the model, which is entered into the model. Heat Source's developers estimate potential adjusted channel dimensions and potential riparian vegetation (based on site potential for height, width, and density) for that basin.

[29] Boyd, Matt. Personal Communication. 2003. Carollo Engineers, Portland, OR.

Effective shade[30] is calculated from the potential channel morphology and riparian vegetation. Heat Source contains an assumption (supported by empirical data) that as shade increases, stream temperatures are moderated at a particular site, as well as with distance downstream.

Heat Source simulates future stream temperatures under potentially restored conditions, and determines the miles of stream segments that would still be too warm to meet water quality standards for temperature. Results from Heat Source indicate that increased streamflow, cool tributary temperatures, groundwater inputs, and improved shading (from riparian vegetation and narrower, deeper channels) are important for maintaining cooler river temperatures (DEQ 2002b).

One may be tempted to use Heat Source to reconstruct historical conditions, as the model is able to describe natural conditions when channel morphology attains equilibrium. However, the model's developer has reservations about using Heat Source by itself for this purpose (M. Boyd, pers. comm.[31]). The IMST believes that if other ancillary information (such as reference streams, historical data on vegetation, fish distributions, and water temperature) is available to help calibrate and crosscheck model results, careful use of the model may provide a good estimate of natural, unmodified conditions.

Historical Information on River Temperatures and Climate Change

Natural stream temperatures in basins may be estimated from historical water temperature data when used in conjunction with modeling. Several historical documents provide data on stream temperatures and salmon abundance in the Columbia River Basin (McDonald 1895; Gilbert and Evermann 1895; Evermann 1896; Stone 1878). These and other historical sources from the 1890s could provide a guideline for estimating current natural background stream temperatures.

Concerns do exist that the current climate in Oregon may be quite different from that of the 1890s (Diaz and Bradley 1995; Mote et al. 2003). Recent precipitation patterns in the Pacific Northwest do appear to be changing. Depending on the region, more or less precipitation is occurring, and seasons of precipitation are shifting (Mote et al. 2003). Researchers have projected the Cascade Mountain (Oregon and Washington) snowpack to decrease as much as 60% based on changes occurring in the snowpack since the 1950's (reported in Service 2004). The decrease in snowpack could significantly decrease summer stream discharges. In addition, Oregon air temperatures appear to have been increasing slightly over the last one hundred years.

Over the last one hundred years in the Northern Hemisphere, scientists have measured a general air temperature increase of less than 1.0 ºC (from 0.1 to 0.8 ºC [0.2 to 1.4 ºF] increase) superimposed on the natural variability of the climate (Diaz and Bradley 1995; Mote et al. 2003). However, the IMST could find no evidence that the effect of slight variations in climate on stream temperatures would be equal to or greater than the documented effects land use impacts have had on stream temperatures in Oregon and other regions. Riparian vegetation canopy

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[30] "…effective shade is defined as the percent reduction of potential solar radiation load delivered to the water surface…the role of effective shade … is to prevent or reduce heating by solar radiation and serve as a linear translator to the solar loading capacities' (DEQ 2002b; p. 102)

[31] Boyd, Matt. Personal Communication. 2003 Carollo Engineers, Portland, OR.

removal has been shown to increase stream temperatures as much as 12.7 ºC [22.9 ºF] in the Pacific Northwest (Moring 1975 listed in Table 7, see p. 87–88).

Evaluation of the Heat Source Model

Prior to development of Heat Source, the 1992–1994 Water Quality Standards Review (DEQ 1995) for the State of Oregon concluded that temperature models in general were useful only at the scale of reaches for interpreting and understanding stream temperatures. The Temperature Subcommittee reported that temperature models available at that time could not accurately predict water temperatures throughout a basin and therefore were not adequate for setting basin-specific standards (DEQ 1995).

Subsequently, the State of Oregon developed Heat Source, which was first applied in 1997 to the Upper Grande Ronde River Subbasin (DEQ 2000a). Heat Source has gone through several iterations. The most current version (version 7.0) is described in detail by Boyd and Kasper (2003). Heat Source has been demonstrated to accurately predict stream temperatures after adjustments based on field data. This is consistent with reviews of other temperature models (Sullivan et al. 1990; Sinokrot and Stefan 1993) that found that these models can be accurate when calibrated with field observations.

<u>Calibration, Validation, Verification, and Sensitivity Analysis</u>

While developing a model, scientists conduct tests to determine the relative performance of that model. The following tests are aspects of rigorous modeling and can be applied to models of natural systems: calibration, verification, validation, and sensitivity (presented in Table 8).

The validity and accuracy of a model may become a concern when the model has important policy and management implications. Consequently, the terms model validation and model verification are also used in a public policy context. As shown in Table 8, definitions of validation and verification vary among scientists, and are sometimes used interchangeably by modelers. Because natural systems are open systems with incomplete data sets and parameters that are not completely known, the measurement of variables contain inferences and assumptions that cannot be validated nor verified in the rigorous way that theoretical systems (closed systems, such as proofs in mathematics) can be validated and verified (Oreskes et al. 1994).

In terms of assessing the accuracy of natural system models, scientists can determine the relative performance of the model with respect to observational data, and consistency with other models of the same site (Oreskes et al. 1994). Consequently, Haefner (1996) suggests that modelers may want to use other terms instead of validation for natural system models such as corroboration, confirmation, or plausible. Regardless of terminology, the IMST recognizes that carefully tested models of natural systems can be appropriately applied to land management situations with important policy implications, thereby providing important information to the decision-making process.

Table 8. Definitions of calibration, verification, validation, and sensitivity analysis.

Test of Model	Definitions
Calibration	Adjustment of the independent parameters of a model to obtain a match between observed data and model results (Oreskes et al. 1994); Pairs of simulated results and actual results are used to calibrate the model (Boyd and Kasper 2003).
Verification	Demonstrating the reliability of a model as a basis for decision-making (Oreskes et al. 1994). Establishes the correctness of an algorithm or computer code (Haefner 1996). To ensure that a model performs as intended; empirical information used to build the model is compared with model results (Herrman et al. 2002; Alsaeedi and Elprince 1999).
Validation	Establishes the legitimacy of a model; indicates that model does not contain obvious errors of logic and accurately reflects the behavior of the real world (Oreskes et al. 1994). Evaluates the quality of a model with respect to the external world and with respect to the objectives of the modeling project (Haefner 1996). To determine how closely a model represents reality (e.g., how accurate a model is); results from the model are contrasted with data from the natural system (Herrman et al. 2002; Alsaeedi and Elprince 1999; Larkin et al. 1995). The comparing of model output with actual data; model performance is consistent with observations (Gardner and Urban 2003) The statistical comparison of measured data to simulated data to assess model accuracy (Boyd and Kasper 2003); however, true validation requires that half of all available data are used to build and calibrate a model, and the other half of available data are used in validation tests; this technique is seldom used by modelers, because modelers typically use all available data to develop and calibrate the model (M. Boyd, pers. comm.[32]).
Sensitivity Analysis	Manipulation of model parameters to test response of the model; a model parameter is varied over a range and model behavior is evaluated (Alsaeedi and Elprince 1999; Haefner 1996; Larkin et al. 1995).

Validation of the Heat Source Model

True validation of a model requires that half of all available data are used to build and calibrate a model, and the other half of available data are used in the validation tests; this technique is seldom used by modelers, because modelers typically use all available data to develop and calibrate a model. Therefore, Boyd and Kasper (2003) describe validation of Heat Source as the

[32] Boyd, Matt. Personal Communication. 2003. Carollo Engineers, Portland, OR.

statistical comparison of measured data to simulated data to assess model accuracy (Boyd and Kasper 2003). Measured (empirical) data are statistically compared to simulated data quantify errors (e.g. average deviation from the mean, standard error, and correlation coefficient). This validation process tests methodology errors in the model, as well as sources of error from data gaps. Most errors in Heat Source appear to be from data gaps. Modeling limitations vary by river basin because Heat Source is limited by the amount of available data for a river basin (DEQ 2002b).

Verification of the Heat Source Model

Haefner (1996) describes verification as establishing the correctness of an algorithm or computer code. Several scientific peer reviews investigated the algorithms in Heat Source and determined that the algorithms were correct for the defined mathematical relationships of natural heat loading and temperature processes (discussion continued in the External Peer Review of Oregon's Heat Source Model section).

Sensitivity Analysis of the Heat Source Model

To test how a model behaves, a sensitivity analysis of model parameters is conducted, where a model parameter is varied over a range and model behavior is evaluated (Alsaeedi and Elprince 1999; Haefner 1996; Larkin et al. 1995). A sensitivity analysis can reveal which interacting factors in a model have greatest influence on the functioning of the model.

When Heat Source is calibrated for a particular basin, sensitivity analyses are conducted (DEQ 2002b). These sensitivity analyses investigate the role of land cover, geomorphology, and streamflow in affecting stream temperature. However, because these sensitivity analyses are stream and basin-specific, they test only application of the model to a particular watershed (M. Boyd, pers. comm.[33]). Additionally, external reviewers have conducted independent sensitivity analyses of earlier versions of Heat Source (discussed in the External Peer Review section).

Summary of Heat Source Model Performance Tests

Heat Source undergoes tests to determine the relative performance of the model: calibration, verification, validation, and sensitivity. Scientific peer review verified the model's algorithms. Basin-specific calibration, validation, and sensitivity analysis take place each time the model is applied to a new river basin. These tests take place in the following steps:

1. Input of basin-specific empirical data,
2. Calibration of model to basin-specific data,
3. Statistical validation of model based on available empirical data, and
4. Sensitivity analysis of model parameters as they relate to the river basin.

<u>External Peer Review of Oregon's Heat Source Model</u>

When Heat Source was presented in 1996 as part of a Master of Science thesis, it was evaluated and approved by an academic committee (Boyd 1996). As DEQ further developed the model for use, a national peer review was conducted in 1999 (DEQ 1999). Five reviewers commented on the mathematics and theory in Heat Source and made detailed suggestions. These improvements were incorporated into the model, and more sensitivity analyses were conducted. In general, the

[33] Boyd, Matt. Personal Communication. 2003. Carollo Engineers, Portland, OR.

reviewers found the model to be mathematically sound and a helpful advance in comprehensive stream temperature assessment (DEQ 1999).

In addition, CH2M Hill (1999) subcontracted a review of Heat Source (version 5.5) used in the Upper Grande Ronde River Subbasin TMDL (DEQ 2000a). Sensitivity tests indicated that the model performed as expected, and reasonably predicted water temperature conditions in the river basin (CH2M Hill 1999). However, CH2M Hill (1999) noted three problems with Heat Source at that time: 1) the model did not consider air temperature changes correlated with elevation; 2) the model did not include the cooling effects of groundwater inputs; and 3) the model had an anomaly in measurement of downstream water temperatures. All of these problems have been corrected in subsequent versions of Heat Source (Boyd and Kasper 2003) In general, CH2M Hill determined that Heat Source adequately represents thermal processes in streams, but the model requires large input of basin-specific data, which could limit its application to some river basins.

Since 1999, Heat Source has continued to be modified and developed. The most current version (v. 7.0) can simulate longer periods of time to include variable hydrological conditions (Boyd and Kasper 2003). The most recent application of Heat Source was for the Upper Klamath Basin Temperature TMDL (DEQ 2002b).

IMST Evaluation of Heat Source

As part of our evaluation of Heat Source for use in TMDL analysis, the IMST has compared the Heat Source to eight desirable model selection/evaluation criteria suggested by the NRC (2001) (Table 9). NRC (2001; p. 77) also points out that "TMDL model choice is currently hampered by the fact that relatively few models have undergone thorough uncertainty analysis. Post-implementation monitoring at selected sites can yield valuable data sets to assess the ability of models to reliably forecast response".

The IMST finds that the use of Heat Source in Oregon's TMDL process is based on sound scientific principles and incorporates the major physical factors that affect stream temperatures. The process currently used by the State of Oregon to assess stream temperatures and address human activities affecting temperature is based on sound scientific principles and utilizes one of the best temperature models available.

Several other stream temperature models have been developed for use in the Pacific Northwest, such as:

- Forest Science Project stream temperature model (Lewis et al. 2000),
- SSTEMP and SNTEMP (Bartholow 1995),
- MNSTREM (Sinokrot and Stephan 1993),
- TEMP84 (Beschta and Weatherred 1984), and
- Brown's Model (Brown 1972).

Table 9. IMST's evaluation of Heat Source with respect to NRC's (2001) criteria for selecting and evaluating water quality models for use in TMDL analysis.

NRC Model Selection Criteria	IMST Evaluation of Heat Source Model
1. The model focuses on the water quality standard.	1. Heat Source focuses on the water quality parameter, temperature.
2. The model is consistent with scientific theory.	2. External peer reviews and IMST review determine that Heat Source is consistent with this criterion.
3. Model prediction uncertainty is reported. "To date, we are aware of no thorough error propagation studies with the mechanistic models favored by EPA (by thorough, we mean that all errors and error covariance terms are estimated and are plausible for the application)" (NRC 2001; p. 75).	3. Heat Source does not appear to meet this NRC criterion. The Oregon TMDL process does account for uncertainties and variability in available data (e.g. uses conservative assumptions about groundwater inputs) entered into the model.
4. The model is appropriate for the complexity of the situation.	4. Heat Source contains all major parameters identified by the external peer reviewers and the IMST that are appropriate for temperature analyses in basins.
5. The model is consistent with the amount of data available.	5. Heat Source contains all relevant data for each river basin and is consistent with the amount of data available.
6. The model results are credible to stakeholders.	6. Results of Heat Source are scientifically credible, however, their credibility to stakeholders is difficult to assess. The IMST is unable to evaluate all stakeholder concerns.
7. Cost for annual model support is an acceptable long-term expense.	7. Thus far, Oregon has been able to support utilization of Heat Source; however, the IMST is unable to evaluate the future financial and political support by the State.
8. The model is flexible enough to allow updates and improvements.	8. Heat Source has been updated and improved since its creation and is flexible to allow future updates and improvements.

Additional models have also been reviewed by Sullivan et al. (1990). One way to determine the relative performance of a model is to compare that model with other models (for the same sites). The IMST suggests that results from Heat Source be compared to other models as a form of validation, corroboration, confirmation, or determining plausibility.

Although sensitivity tests have been conducted on Heat Source each time it was applied to a new basin, these basin-specific sensitivity tests were just for calibration. And, although CH2M Hill (1999) conducted an independent sensitivity analysis of an earlier version, no independent sensitivity tests have been conducted on the 7.0 version. The IMST suggests further sensitivity tests be conducted on Heat Source.

Heat Source has been evaluated by DEQ and in an external review by CH2M Hill. IMST feels that it would be beneficial to submit Heat Source and model evaluation results to appropriate peer-reviewed scientific journals for independent review and publication. This will give the model credibility with the broader scientific community, perhaps provide ideas and tools for others facing similar issues, and provide rigorous peer-review of the model.

IMST also recommends DEQ to use Heat Source and the initial databases for each TMDL analysis to document the performance of the model before any adjustments are made to improve the goodness of fit for specific basins. The State collects necessary data from each basin prior to running the model in the TMDL process. The model outputs could be compared to the observed temperature patterns in the basins. These comparisons of model temperature patterns to observed temperature patterns from each basin could be documented, made available to the public on the DEQ website, and eventually synthesized after all TMDL assessments have been completed. An additional form of evaluation would be to apply several major temperature models to selected Oregon basins and to include this analysis in the overall synthesis described above.

Applications of Heat Source

The IMST finds that Heat Source is based on sound scientific principles and is currently being applied effectively in the appropriate manner. Heat Source should not be used (and is not used) to set basin-specific numerical water quality standards for temperature, but should continue to be used to guide actions in the TMDL process for each river basin.

As discussed earlier, Heat Source utilizes local vegetation and channel information (based on field sampling combined with remote sensing) to provide descriptions and general locations of each vegetation type found in the basin of study. At site-potential, each vegetation type provides different degrees of channel stability, groundwater infiltration, and solar interception. Heat Source uses effective shade as a surrogate for the suite of ecological influences provided by riparian vegetation.

<u>Regional Framework for Site Potential Vegetation</u>

One of the strengths of Heat Source is that, if it is used along with regional frameworks for site potential vegetation, the model has the ability to predict patterns of temperatures at stream network scales. These predictions permit a more rigorous determination of whether a particular site can attain Oregon’s water temperature standards.

Application of Heat Source requires determination of the potential height of riparian vegetation that would be effective in shading streams. Broad regional assumptions about historical vegetation patterns can be verified through historical maps of land cover (e.g., General Land Office maps from 1850-1870; US Forest Service maps from 1905-1940). Regional experts can provide finer resolution of site potential vegetation based on site characteristics (e.g., soil type, soil moisture, stream size, elevation, slope, geology, stream discharge, disturbance regimes). Establishment of explicitly designated reference systems, regional site potential, and peer review of the classification system will strengthen application of models such as Heat Source.

<u>Landscape Perspective for Restoration</u>

Heat Source allows resource managers to assess the degree to which temperatures could be affected by land use or restoration efforts. One of the major advantages of using a landscape-level model that can assess river networks is the ability to determine where changes in land use practices and restoration activities would have the greatest positive effects on stream temperatures.

In addition, Heat Source can identify alternative practices that could attain the desired outcome and, in some cases, provide additional desired outcomes. One example would be mitigation for thermal loading in urban areas. Local riparian recovery might provide relatively little improvement for large lowland rivers. Municipal thermal loading can still be detrimental and require some form of mitigation. Riparian protection by urban areas in sensitive upstream areas outside urban areas could provide desired thermal benefits and provide additional benefits to habitat for aquatic and terrestrial communities.

Public Concerns About the Application of the Heat Source Model

As acknowledged in the Oregon Administrative Rules (OAR), riparian vegetation is known to play several roles that ultimately reduce stream heating (control of erosion that widens streams, moderation of solar heating, and infiltration of water into the soil profile), and State law requires that agricultural activities allow development of riparian vegetation to control water pollution (OAR 603-095-0440).

If a landowner believes that Heat Source has not described the vegetation on their land accurately (and therefore effective shade at site-potential is inaccurate), the landowner may present their concern to ODA. Personnel from ODA then investigate the site to determine site-specific differences and work with the landowner for a voluntary solution. In the OARs, ODA is directed to seek voluntary adoption of Best Management Practices; ODA is to pursue enforcement actions only after reasonable attempts at voluntary solutions have failed (OAR 603-095-0030).

Enforcement actions have taken place with violations of point source pollution of nutrients (e.g., excess nutrients from Confined Animal Feeding Operations). However, the IMST asked ODA if Heat Source or TMDL process had been used to force any landowner to take an action on their land to protect or restore stream temperature. We were told that the agency knows of no circumstances when the State of Oregon required an agricultural landowner to take a mandatory action to protect or restore stream temperature. Concerns over environmental conditions, including stream temperature, have led to the development of the Oregon Forest Practices Act and riparian rules for private forest landowners. No such regulations exist for agricultural, rural, or urban landowners. The IMST is not suggesting that regulatory approaches for protecting and restoring common resources are inappropriate. We are simply pointing out that much of the current debate over stream temperature and the TMDL process is driven by fear more than the existence of regulatory restrictions.

IMST Summary of Applications Heat Source Model

Heat Source is a tool that explores physical relationships, develops hypotheses, and tests the effects land management decisions may have on stream temperatures at the basin or sub-basin scale. Ecological models have limitations when they are applied to real ecosystems, because models, while attempting to understand the impact or interactions of certain environmental factors, simplify complex ecosystems. However, Heat Source is based on sound scientific principles and has a high spatial resolution that attempts to include all complex processes in a river basin. Heat Source has managerial value, particularly to point out significant landscape factors that affect streams and to test these effects under various modeled conditions.

Science Question 4 Conclusions

Conclusion 4-1. Heat Source, the temperature model used by the State of Oregon, is scientifically sound. The direct and indirect influences of climate, topography, elevation, riparian vegetation, channel morphology, hydrology, and point sources are accounted for in Heat Source, which can predict patterns of stream temperature at river network scales.

Conclusion 4-2. Further sensitivity analyses should be conducted on the current version of Heats Source (7.0) to evaluate the performance of this version of the model. In addition, the model should be compared with the output from several major stream temperature models to assess the performance of Heat Source. Other approaches to evaluating the consistency of model output with observed stream temperatures should be conducted by DEQ.

Heat Source is peer-reviewed. A sensitivity analysis conducted by external reviewers on version 5.5 of the Heat Source found the model to perform as expected and to reasonably predict water temperatures in the Upper Grande Ronde River Subbasin. An independent sensitivity analysis has not been conducted on the current version, 7.0.

The IMST recommends evaluation of the relative performance of Heat Source with respect to other similar models. The IMST recommends that Heat Source be submitted for journal publication.

Conclusion 4-3. Temperature models, such as Heat Source, should not be used to set basin-specific temperature standards, but can be used to develop basin-specific total maximum daily loads for heat.

Heat Source is based on sound scientific principles and is being applied effectively in the appropriate manner. Heat Source should not be used (and is not used) to set basin-specific numerical water quality standards for temperature, but should, instead, be used to guide actions in the TMDL process for each river basin. The temperature standard serves as a yardstick to determine whether beneficial uses may be impaired as a first step in deciding whether actions are needed to improve stream temperatures. The model is an appropriate tool for determining how the state should implement basin plans in response to the determination of stream reaches that do not meet the standard. It can identify the degree to which we can expect temperature to recover and general areas of the watershed that provide more temperature recovery.

Development of Heat Source for stream temperature has been a major advance that increases Oregon's ability to manage streams and riparian areas. Modeling of stream temperatures provides insights on how various environmental factors and their interactions may affect water temperature. Models assist in comparing management options.

Conclusion 4-4. Oregon's TMDL process (public process, analysis of sources of elevated stream temperature, and Water Quality Management Plans) is conducted at the basin

scale, which is consistent with a landscape approach. Therefore, the IMST concludes that the State's application of the TMDL process and Water Quality Management Plans is appropriate for implementation of the water temperature standards at a landscape scale.

The TMDL process used by the State of Oregon to assess stream temperature and address the human activities that affect stream temperature includes both basin-specific empirical data and modeling. The model used in the TMDL process for developing watershed management plans for stream temperature is peer-reviewed, is based on sound scientific principles, and incorporates the major physical factors that determine stream temperature.

Science Question 5. What are the benefits of alternative watershed and stream evaluation methods to 1) identify appropriate actions or 2) effectively involve the public?

In the answer to this question, we discuss how several watershed and stream evaluation methods might benefit restoration activities aimed at improving stream temperature at both site and landscape scales. We briefly describe several assessment methods, discuss the utility of the methods for evaluating stream health and potential for restoration, and evaluate the possibility of using stream assessments to better involve the public in progressing toward healthier streams. None of these methods were developed specifically to evaluate sources of elevated stream temperatures. However, as we discuss in more detail below, stream assessments may be useful to the State to evaluate the potential of different sites to contribute to the rehabilitation of stream temperature regimes. We also review opportunities for Oregon to use these or similar tools in "the TMDL process" and during the implementation of basin Water Quality Management plans.

Relationship of Temperature Restoration, Channel and Riparian Condition, and Stream Assessment Techniques

The utility of riparian and stream assessments to temperature restoration is based on the assumption that improving riparian and channel conditions will lead to restoration of stream temperature regimes. IMST bases this assumption on the well documented relationship between riparian and channel degradation and elevated stream temperature (see Science Question 3; Figures 7 and 8 on p. 77 and 81, respectively). We are currently limited to case studies to determine the relative effect restoration methods may have on stream temperature regimes. For example, a case study in Bear Creek, (central Oregon) documented less variable stream temperatures after 22 years of management aimed at rehabilitating the stream channel (Figures 11 and 12). Maximum stream temperatures less closely followed ambient air temperature after channel restoration (Figures 14 and 15). The Oregon Plan monitoring program presents the opportunity to examine the effects of channel restoration on temperature regimes with greater replication.

Because stream and riparian conditions have often changed (e.g. altered plant communities or stream morphology, lowered water table), stream rehabilitation does not always involve returning channels to historical (i.e., pre-European settlement) conditions. However, the IMST concludes that restoring functional riparian plant communities, floodplain inundation processes, and channel dimensions will have beneficial effects for stream temperature as well as the entire stream ecosystem.

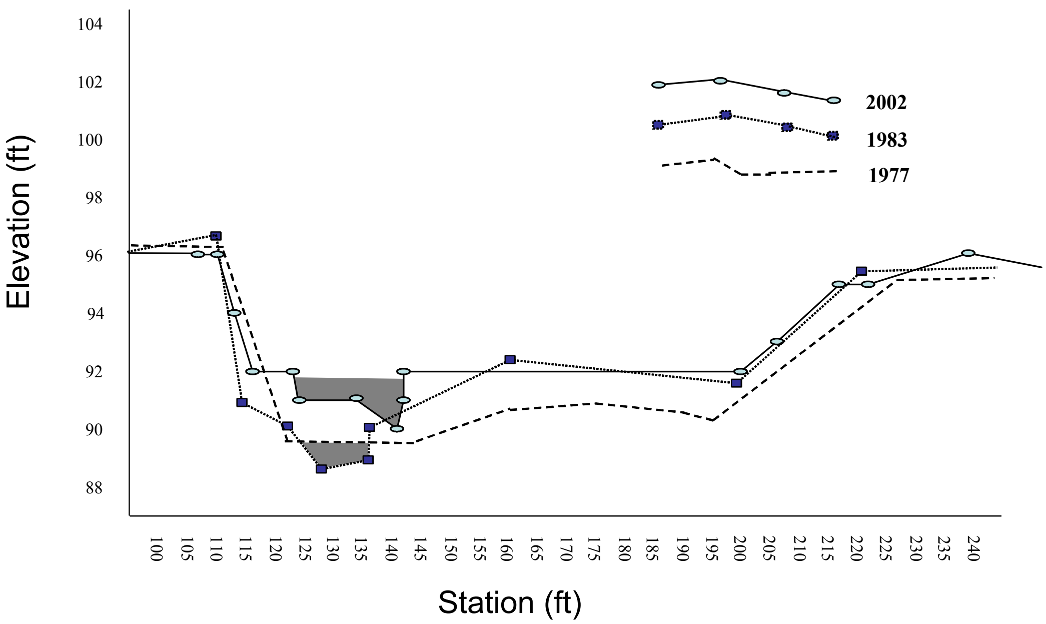

Figure 11. Schematic drawing depicting change in channel profile of Bear Creek (central Oregon) between 1977 and 2002. Dark grey shaded area represents the channel at low flow. Sediment deposition between 1977 to 1983 provided deeper gravel beds that allowed subsurface exchange with surface waters and augmented the thermal benefit of shading provided by riparian vegetation. Based on unpublished data collected by Bureau of Land Management, Prineville, OR. (W. Elmore, pers. comm.).

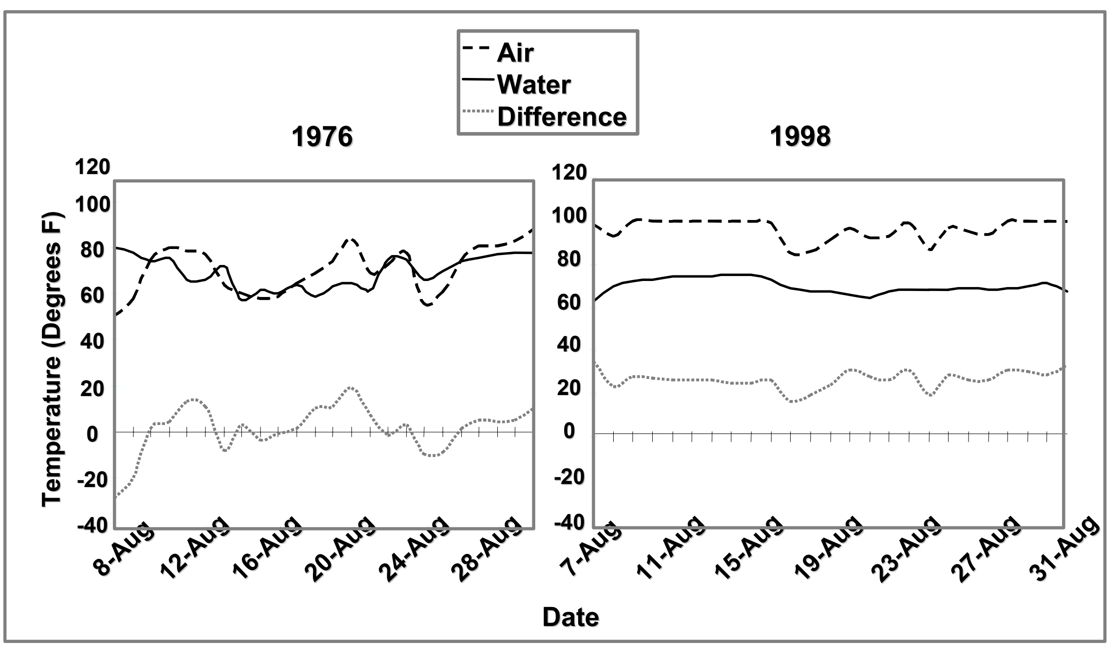

Figure 12. Air temperature and maximum water temperatures in Bear Creek, central Oregon in 1976 versus 1998 (W. Elmore, unpubl. data).

Evaluation / Classification Tools

Site-specific stream evaluation methods generally assess the condition of channel morphology or riparian vegetation (including riparian species composition). Scientists and managers have developed these methods for technical classification or for stream management objectives other than stream temperature monitoring or restoration. IMST is not aware of any stream evaluation methods developed specifically to address restoration of stream temperature regimes. However, assessments developed for other purposes can play an important role in protection and restoration of stream temperature regimes. As we will describe, assessments are useful in determining historical, current, and possible future conditions in a stream reach.

When restoring aquatic and riparian conditions, each watershed and stream reach is unique (based on soil, climate, topography, etc.). Taking these site-specific attributes into account can greatly benefit restoration. Site potential has been described as "the highest [ecological] functional status attainable on a site..." Barrington et al. (2001, p. 1666). The IMST recognizes that this concept of site potential is useful to restoration success, and should be considered when planning restoration projects. In application, some sites probably cannot reach true site potential due to physical constraints imposed on the landscape by humans. Site capability, on the other hand, takes into account human infrastructure constraints, such as power-lines, roads, and ditches. In practical terms, site capability is the highest state attainable for a given stream, given the legal and jurisdictional constraints of the land manager (Prichard et al. 1998; Barrington et al. 2001).

Site-specific assessments are a means to evaluate site potential and site capability of a stream reach, and can help to scientifically evaluate:

- Causes of elevated stream temperature,
- Probable effectiveness of proposed restoration actions.

Many site-specific assessment techniques are dependent on understanding the potential vegetation and hydrology at a site. To determine expected conditions, scientists and managers often turn to local reference sites with minimal human impacts. When sites with minimal human impacts are not available, reference conditions (expected conditions) can be defined by groups of regional experts including botanists and hydrologists. General reference conditions are based on experts' knowledge of geomorphology, soils, hydrology, and plant associations. Therefore, general reference conditions may be less accurate than those determined by visiting local sites with minimal impact. Nevertheless, IMST concludes that using regional experts is an acceptable methodology to define reference conditions in the absence of appropriate reference sites.

Tools to understand the expected ecological characteristics within a region can be of great benefit to land managers when assessing site potential and site capability. Anderson et al. (1998) have developed a regional description of the ecological provinces of Oregon, in which they provide descriptions of ecological sites within each province and the potentials for vegetation growth in each ecological site. The Oregon Watershed Enhancement Board (OWEB) has also compiled descriptions of the ecoregions of Oregon as an appendix to the Oregon Watershed Assessment Manual (Watershed Professionals Network 1999). Two major riparian vegetation classifications have been completed for eastern Oregon, and one covers parts of both eastern and western Oregon. Riparian Zone Associations for Deschutes, Ochoco, Fremont, and Winema

National Forests (Kovalchik 1987) and Mid Montane Wetland Plant Association of the Malheur, Umatilla, and Wallowa-Whitman National Forests (Crowe and Clausnitzer 1997) were specifically prepared for eastern Oregon. Riparian Ecological Types of the Gifford Pinchot and Mt. Hood National Forests, Columbia River Gorge National Scenic Area only covers the Columbia River east of the crest of the Cascade Mountains.

Site-specific assessments do not replace the need for watershed assessment or for monitoring of restoration projects. Watershed assessment involves examining aquatic and riparian conditions at the scale of watersheds. A watershed assessment is complementary to site-specific assessment techniques because the larger spatial scale can help to prioritize among projects to provide the maximum benefit to a stream or watershed (Watershed Professionals Network 1999). Watershed assessments can also help to identify upland land uses that may be causing elevated stream temperature (Watershed Professionals Network 1999). Monitoring involves systematic collection of data over time. DEQ monitors stream temperature to determine which reaches are warmer than criteria in State water quality standards. However, evaluating the effectiveness of restoration techniques for improving stream temperature will also be important. This type of monitoring is called effectiveness monitoring. Effectiveness monitoring asks the basic question, “Was the action (e.g. permit conditions, restoration) effective in attaining or maintaining the desired future conditions and in meeting objectives?” (Kershner 1997, p. 117).

In the sections that follow, we give examples of stream assessment and classification systems. In the text that follows, our intention is not to evaluate the strengths of each methodology to achieve its original purpose. Rather, we wish to illustrate some existing site-specific assessment techniques that the State of Oregon might further develop or modify to guide stream temperature restoration. Many other established stream evaluation methods exist, but are not included in this section.

Rosgen methodologies

The Rosgen stream classification key (Rosgen 1996) is based upon geomorphology and stream form and classifies the physical channel structure of a stream (Figure 13). The Rosgen method does not describe biological components of a riparian system; instead, stream potentials are classified in terms of channel form, entrenchment, width/depth ratio, sinuosity ratio, gradient, and bed morphology. The Rosgen stream classification system does not includes an assessment of how changes in channel from expected conditions may affect stream temperature. Several federal agencies use Rosgen methodologies to classify stream reaches on public land in the western United States.

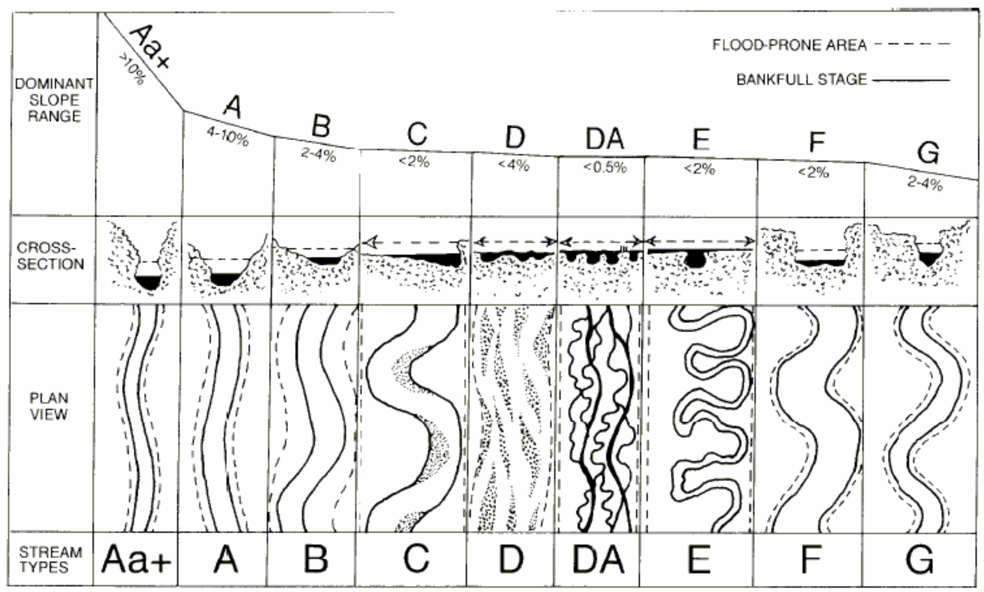

Figure 13. Stream types defined in the Rosgen stream classification system. Streams are categorized by channel form, width/depth ratio, sinuosity, gradient, and bed morphology (Rosgen 1996).

<u>"Greenline" approach</u>

The "greenline" approach (Winward 2000) classifies stream bank stability in relation to vegetation types. In this approach, a botanist describes plant communities along a 363+ ft. transect along the "greenline" of both streambanks (Figure 14). A greenline is defined as, "The first perennial vegetation that forms a lineal grouping of community types on or near the water's edge. Most often it occurs at or slightly below the bankfull stage." (Winward 2000, p. 3).

The botanist quantifies vegetation by plant community types that have been defined in a regional plant assessment. Winward (2000) has assigned relative values, or stability classes (1–10, least to greatest), to rank the soil-holding capability for the roots of vegetation community types of the Intermountain West including eastern Oregon. When these values are weighted according to their frequency of occurrence along a greenline, a measure of the relative bank stability of the reach is obtained, which also varies from 1 to 10. If repeated every 3–5 years, this approach can be used as part of a monitoring program (Winward 2000). The approach is applicable to western Oregon, but riparian plant communities would need to be evaluated for their soil-holding capability. Greenline methodologies do not include an evaluation of how changes in plant communities or bank stability affect stream temperature.

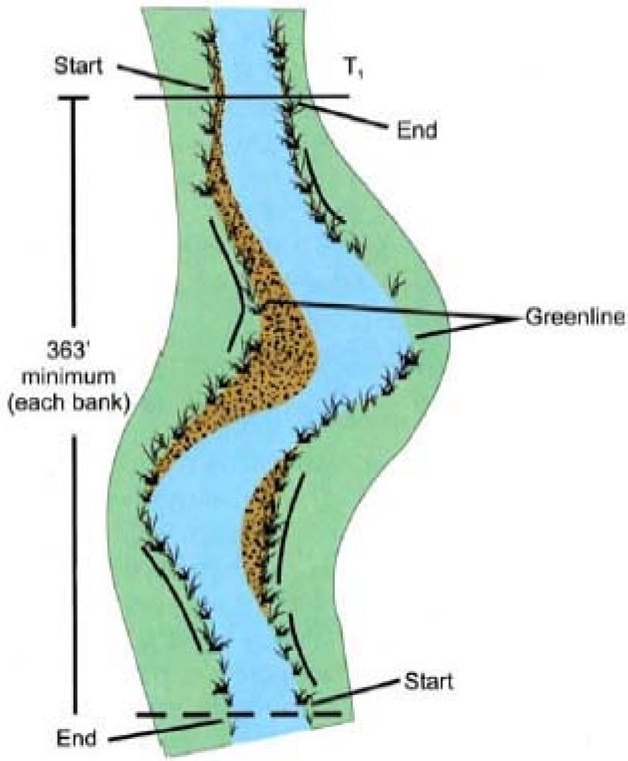

Figure 14. A 363-foot measurement taken along the greenline at the edge of a stream and repeated on the opposite streambank. Illustration from Winward (2000).

Proper Functioning Condition

Proper Functioning Condition (PFC; Prichard et al.1998) is a nationally accepted protocol used on US Forest Service (USFS) and Bureau of Land Management (BLM) lands to determine if a stream has the physical ability to withstand a moderately high flood event without deteriorating. PFC does not evaluate fish habitat, riparian vegetation, or deviation from historical stream temperature regimes, but rather evaluates how stream reaches function hydrologically. The assessment can provide information on whether a riparian-wetland area is physically functioning in a manner that will allow the maintenance or recovery of values such as fish habitat or livestock forage (Prichard et al. 1998).

The process of assessing PFC involves reviewing existing information, analyzing the PFC definition in the context of a local stream, and assessing functionality using a multidisciplinary team. Each step is important because it provides a foundation and a certain level of understanding necessary to complete the assessment. Existing information that provides a basis for assessing PFC includes existing classification documents, inventories, aerial photos, topographic maps, management plans, and any other pertinent information useful for establishing capability and potential. Assessing functionality involves a seventeen-step evaluation of hydrologic, vegetation, and erosion/deposition criteria, which enable the team of evaluators to make a reasoned and professional judgment of the hydrologic and habitat potentials of a stream to withstand a moderately high flood event without deteriorating. Guidance on the use of local reference sites and visual images of desired conditions allow the approach to be applied to a variety of location conditions.

Information from previously described methodologies can be used in conjunction with the PFC assessment. For example, PFC documentation recommends Rosgen methodologies for stream classification to assess existing and potential hydrologic condition of the stream reach (Prichard et al. 1998). The greenline approach is recommended when quantitative information on vegetative stability or community types are needed (Winward 2000).

A major limitation of PFC is that it has never been compared to direct measures of channel structure or hydrologic responses (NRC 2002). The NRC (2002) points out that confidence in the application of PFC would be strengthened if agencies already using the technique (e.g., BLM, USFS, USDA Natural Resources Conservation Service) validated the approach. IMST agrees that validation based on field observations would greatly strengthen the credibility of this approach.

Involving the Public

<u>Importance of Public Involvement in Stream Temperature Restoration</u>

Factors that cause elevated stream temperatures (including erosion and sedimentation, stream morphology, riparian condition, and groundwater flow patterns) are highly complex and interrelated (see Science Question 3). Restoration of stream temperature will consequently require a suite of restoration activities and management changes in upland and riparian areas, and in streams. We conclude that temperature impacts in streams can rarely be fully addressed at the site or reach scale, despite the shortcoming that stream restoration activities are almost always carried out in individual sites or reaches. The challenge will be coordinating these site-specific activities to achieve stream restoration goals for watersheds or basins. For situations where elevated stream temperature is a result of non-point source pollution, restoration of stream temperature will often require a continued commitment over decades. The degraded state of many Oregon streams is a cumulative result of years of multiple land use activities. Likewise, stream restoration is a slow process. Where flow regimes have been altered and channel morphology and riparian vegetation have been degraded, we may need to wait years to decades to see stream temperatures restored to levels that are beneficial to salmonids

Given the long time frame and large spatial extent necessary for restoring stream temperature regimes, participation by landowners and community groups is essential to minimize the non-point sources of elevated stream temperature across the landscape. Therefore, the most important part of Oregon's water quality management is what happens on the ground --- the many actions of citizens that influence the environment and water temperatures. Individuals and groups undertake protection and restoration activities over small spatial extents. The IMST finds that it is important for individuals to be shown how their work and efforts fit into a larger picture. The State of Oregon needs to develop methods for expanding that landscape comprehension, and increase participation by more groups of people, in order to affect a change over a much larger geographic area.

Value of Stream Assessment Techniques to Increase Public Involvement

The National Riparian Service Team[34] has trained people in PFC methodology in order to increase public understanding of riparian ecology and management. Between 1996 and 2001, approximately 10,000 individuals in 325 sessions were trained in PFC. Van Riper (2003) evaluated the effectiveness of the training sessions by surveying a subset of workshop participants (n=147 respondents). The study found that over 85% of participants reported increased knowledge of 1) the relationship between stream attributes and processes, 2) determining a functional rating for riparian areas, and 3) determining limiting factors. The importance of developing a common technical understanding to successful riparian restoration is logical. However, this alone is not enough to encourage the type of cooperative management that is necessary to restore stream temperature regimes at the watershed scale. When asked about the relative importance of barriers to cooperative riparian restoration and management, technical issues were ranked last (Van Riper 2003; Figure 15). "Lack of Communication/Trust" was ranked very highly (Figure 15, indicating that a common vocabulary among stakeholders may improve restoration project success (Van Riper 2003). Van Riper also concluded that other National Riparian Service Team programs, particularly programs that emphasized conflict resolution among stakeholders, may be more effective in actually improving riparian health.

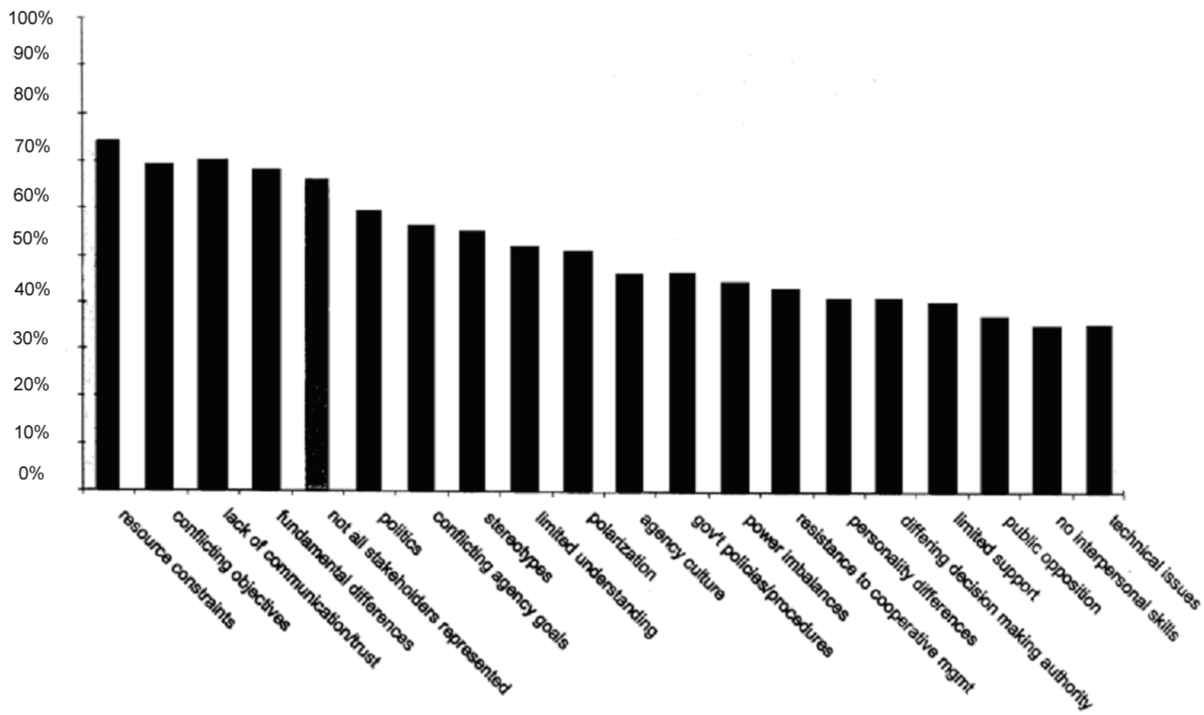

Figure 15. Barriers to cooperative riparian restoration and management as identified by PFC workshop survey respondents as "extremely serious" and "somewhat serious" (from Van Riper 2003).

[34] The National Riparian Service Team is a cooperative program of the US BLM, USFS, and USDA Natural Resources Conservation Service.

Reference-based stream assessment techniques (such as PFC), may serve as a "communication tool", by providing an opportunity for communities to come to a common understanding of restoration goals (NRC 2002). As the NRC points out,

> "...to the extent that [reference] sites can be placed in a successional sequence, they may be used effectively for insights into restoration goals. These sites provide excellent opportunities for locally 'grounding' the available science, thus providing a knowledge base for restoration needs. Finally, reference sites can serve as demonstration areas where scientists, managers, regulators, and interested citizens can interact on a common footing when addressing restoration needs and priorities and the potential for successfully attaining restoration goals" (NRC 2002, p.320).

Current Use of Site-specific Assessment Techniques in TMDL Implementation
In 1993, Oregon Senate Bill 1010 authorized ODA to develop Agricultural Water Quality Management (AgWQM) Area Plans to address water pollution from agricultural and rural lands with water quality limited streams. These plans are the mechanism to address the percentage of the TMDL load allocated for agricultural lands. In addition, these plans are the mechanism to address other requirements for water quality management plans on agricultural lands in Oregon, including ground water management.

ODA has developed AgWQM Area rules that specify or prohibit conditions in Oregon basins needed to protect water quality. Common to all AgWQM Areas is a rule requiring land management that will allow the establishment and growth of riparian vegetation consistent with the capability of the site. For example, the rules for the lower Deschutes River basin state, "...by January 1, 2005, agricultural management or soil-disturbing activities that preclude establishment and development of adequate riparian vegetation for streambank stability and shading, consistent with site capability, are not allowed." (OAR 603-095-0600). ODA is also currently using the concept of site capability in the AgWQM program in these general ways (M. Barrington, pers. comm.[35]):

- Providing technical assistance to landowners,
- Voluntary compliance and outreach,
- TMDL model refinement.

ODA is presently refining the protocol for assessing site capability in AgWQM Areas (ODA 2003). The draft protocol covers field methods and spatial data analysis. The field methods specify a modified greenline transect (based on Winward 2000), a method for measuring stream shading, a rating system for streambank condition, and a method for assessing channel form. ODA reports using techniques that are consistent with PFC (Prichard et al. 1998) methodology, and relies on both published literature and local expert knowledge concerning plant associations to verify site assessments of riparian site capability (M. Barrington, pers. comm.[36]).

Oregon Department of Forestry (ODF) is the state agency with responsibility for implementing TMDL load allocations for forest lands. ODF is not conducting assessments of channel or riparian condition on streams that have been identified as impaired for temperature (T. Lorenson,

[35] Barrington, Mack. Personal Communication. 2003. ODA, Salem, OR.
[36] Barrington, Mack. Personal Communication. 2003. ODA, Salem, OR.

pers. comm.[37]); instead, ODF relies on compliance with Oregon's Forest Practices Act to manage water quality and to carry out responsibilities identified in TMDLs (ODF/DEQ 2002).

What are the Choices for the State of Oregon?
When restoring stream temperatures, managers need to determine both current and potential conditions of streams and riparian areas. Assessments provide managers a technical basis for selecting appropriate restoration activities. None of the techniques presented in this discussion were specifically developed to address stream temperature; however, the State may be able to modify or select elements from them in order to develop techniques aimed at maintaining or improving stream temperatures.

Understanding expected (or reference) conditions in streams and riparian areas across Oregon is also fundamental to selecting appropriate restoration activities. The State of Oregon should develop a scientifically sound "reference system" describing potential riparian vegetation in the various ecoregions in Oregon. Such a reference system would identify likely native plant communities for sites based on locations adjacent to streams, position in river network, soils, moisture, channel morphology, elevation, aspect, and other local edaphic conditions. Regional riparian plant ecologists could develop such a system. Peer review of the final determination of expected site-potential vegetation across regions of the state would help to ensure the scientific rigor of the system.

Science Question 5 Conclusions

Conclusion 5-1. When restoring aquatic and riparian conditions, including stream temperature regimes, each watershed and stream reach is unique (based on soil, climate, topography, etc.). Accounting for these site-specific differences can greatly benefit restoration programs.

Conclusion 5-2. Site-specific assessment techniques are a means to evaluate the unique characteristics of a site relevant to restoration.

Conclusion 5-3. Many site-specific assessment techniques are dependent on understanding the expected vegetation and hydrology at a site. To determine expected conditions, scientists and managers often turn to local reference sites with minimal human impacts. When these reference sites are not available, conditions can be defined by groups of regional experts.

Conclusion 5-4. We are currently limited to case studies to determine the effects of channel restoration on temperature regimes. However, based on the well-documented relationship between riparian and channel degradation and elevated stream temperature, IMST concludes that restoring stream and riparian characteristics will often improve stream temperature.

[37] Lorensen, Lorensen. Personal Communication. 2003. ODF, Salem. OR.

Conclusion 5-5. Where water temperature limits salmonid recovery, restoration activities or changes in land uses that lead to reestablishing natural flow regimes, erosion rates, and riparian plant communities should be promoted.

Specifically, the following activities are consistent with this approach:

- Restoration of stream width-to-depth ratio
- Restoration of riparian vegetation
- Restoration of hydrologic features (meanders, wet meadows, wetlands)
- Protection of coldwater refugia along mainstem migration corridors (tributary junctions).

Conclusion 5-6. Oregon Plan monitoring presents the opportunity to examine the effects of channel restoration on temperature regimes. Individual restoration projects could provide replication in studies evaluating the effectiveness of restoration practices on restoring stream temperature regimes.

Conclusion 5-7. Given the long time frame and large spatial extent necessary for restoring stream temperature regimes, participation of landowners, community groups, and state & federal partners is essential to minimize the non-point sources of elevated stream temperature across the landscape.

Conclusion 5-8. IMST agrees with NRC (2002) that confidence in the application of PFC would be strengthened if the approach was validated.

If Oregon adopts PFC methodology, we encourage the State to work with federal agencies (BLM, USFS, and USDA Natural Resources Conservation Service) to validate the methodology in Oregon. If the State of Oregon adopts any aquatic or riparian classification/assessment methodologies, the methods should be validated or calibrated for the specific objectives for which they are to be used.

RECOMMENDATIONS

The science questions previously answered in this report provide the basis for these recommendations. In general, our approach was to develop and answer each science question and then summarize our findings and conclusions for each question. Our specific recommendations are developed from our findings and conclusions. In some cases a specific recommendation is drawn narrowly from a specific finding and conclusion, but in many cases the recommendations resulted from a synthesis across several findings and conclusions. For this reason the order in which recommendations appear do not correlate with the order in which material was covered in the science questions. The recommendations are grouped into broad subject areas for convenience. The order is not intended to imply priority. We consider each recommendation important to accomplishing the mission of the Oregon Plan.

IMST recommendations are based on our assessment of the best available science as it pertains to salmonid and watershed recovery and the management of natural resources. Recommendations are directed to one or more agencies or entities that have the ability to implement or to affect changes in management or regulation that are needed for implementation. It should be noted that the IMST looks beyond an agency's *current* ability to implement the recommendations because current legal, regulatory, or funding situations may need to change. It is the belief of the IMST that if an agency agrees that a recommendation is technically sound and would aid the recovery of salmonid stocks and watersheds, the agency would then determine what impediments might exist to prevent or delay implementation and work toward eliminating those impediments. The Team also assumes that each agency has the knowledge and expertise to determine how best to identify and eliminate impediments to implementation and to determine appropriate time frames and goals needed to meet the intent of the recommendation. In addition, the IMST recognizes that an agency may already have ongoing activities that address a recommendation. Our inclusion of such an "overlapping" recommendation should be seen as reinforcement for needed actions.

Senate Bill 924, which created the IMST, specifies that agencies are to respond to the recommendations of the IMST, stating "(3) If the Independent Multidisciplinary Science Team submits suggestions [recommendations] to an agency responsible for implementing a portion of the Oregon Plan, the agency shall respond to the Team explaining how the agency intends to implement the suggestion [recommendation] or why the agency does not implement the suggestion [recommendation]". Once agency responses are received, the IMST reviews the scientific adequacy of each response and if further action or consideration by the agency is warranted. The IMST's review of responses is forwarded to the Governor and the State Legislature. State agencies are expected to respond to IMST recommendations within six months after a report is issued.

IMST recommends the following:

Recommendation 1. IMST recommends the Oregon State University (OSU) Extension Service and relevant state agencies develop a coordinated education and information distribution system for citizens, watershed councils, and special interest groups on the topic of elevated stream temperature. We recommend that OSU Extension Service conduct

workshops to summarize current relevant scientific information to be included in educational programs.

The IMST concludes that the State's water quality standards for temperature and its TMDL process for coordinating watershed management for water temperature are rigorous and some of the most advanced in the western United States. Recent regional guidance from EPA acknowledges the validity of Oregon's approach and recommend similar approaches for other states. In spite of the scientific acceptance of Oregon's water quality criteria and analytical methods, concerns continue to be raised by certain sectors of the public. Some of these concerns appear to be more intense in Oregon than other states in the western United States.

Educational programs on stream temperature could improve public understanding of the science and management direction of the State of Oregon. We recommend that the State of Oregon convene workshops to be organized and facilitated by OSU Extension Service and IMST. Participants would include members of relevant state agencies. The workshop participants would agree upon consistent scientific findings related to stream temperature and aquatic ecosystems, modeling, and management alternatives. These scientific findings could be linked to the validity of current water quality management policies of the State. These findings and policy assessments would be disseminated through written products and oral presentations by OSU Extension Service throughout the State of Oregon. OWEB could play a role in funding and disseminating this information, while the Oregon Plan Outreach Team could be involved in sharing this information with watershed councils and other Oregon citizens.

Recommendation 2. IMST recommends that Oregon Department of Environmental Quality (DEQ) continue systematic evaluation of the performance of Heat Source, the model that is used in total maximum daily load (TMDL) planning for stream temperature.

In addition the model should be compared with the output from several major models of stream temperature to assess the performance of Heat Source. Other approaches to evaluating the consistency of model output with observed stream temperatures should be conducted by DEQ.

2a. IMST recommends that DEQ conduct a sensitivity analysis of the major factors included in the Heat Source model.

Continued, systematic evaluation of model sensitivity would improve the DEQ's application of the model in the total maximum daily load (TMDL) process. Sensitivity analysis conducted to resolve the relative influence of various factors in the Heat Source model would improve the model's application to the TMDL process as well as improve it's credibility to critics. A sensitivity analysis would allow the State to explicitly identify the relative influence of the major factors that determine stream temperature within the model. In addition to questions about elevation and air temperature, sensitivity analysis could explore the relative influences of the four major factors that are affected by human land use activities ─ shading by vegetation, stream discharge, channel morphology, and surface/subsurface exchange. A sensitivity analysis should help resolve some of the concerns throughout Oregon about the relative importance of various factors at different locations along stream networks. In addition, studies to understand processes in the stream energy balance (radiative transfer; evaporation, convection, and advection of heat in the atmosphere; conduction of heat in the streambed) would provide useful information for model refinement. To our knowledge, there has only been one sensitivity analysis of the overall functioning of Heat Source conducted to date.

2b. DEQ should publish the comparisons of the goodness of fit between Heat Source Model predictions and independently observed water temperature data for analyses conducted in the TMDL process

IMST also recommends DEQ to use Heat Source and the initial databases for each TMDL analysis to document the performance of the model before any adjustments are made to improve the goodness of fit for specific basins. The State collects necessary data from each basin prior to running the model in the TMDL process. The model outputs could be compared to the observed temperature patterns in the basins. These comparisons of model temperature patterns to observed temperature patterns from each basin could be documented, made available to the public on the DEQ website, and eventually synthesized after all TMDL assessments have been completed. An additional form of evaluation could be the application of several major temperature models to selected Oregon basins and included in the overall synthesis described above.

Recommendation 3. IMST recommends that Oregon Department of Fish & Wildlife (ODFW) and Oregon Department of Environmental Quality (DEQ) conduct or fund studies of temperature requirements and/or use of coldwater habitat by redband trout, Lahontan cutthroat trout, and other temperature-sensitive aquatic species occurring in more arid areas in the state.

Relatively few studies are available on fish species restricted to more arid areas of Oregon. Information used for determining temperature requirements for redband trout and Lahontan cutthroat trout, and other fish species, are often extrapolated from data collected on taxa that are closely related but may have considerably different distributions and habitat requirements. The risks of setting and changing standards for these arid area species based on extrapolated data are not known; therefore, Oregon needs to acquire more species-specific information. DEQ has funded several studies (noted in text), but these still represent a small number of studies. These future studies should also examine species other than trout that may have colder temperature requirements. Future improvements in the temperature standard will require a larger number of rigorous studies of aquatic responses in arid regions.

3a. IMST recommends the State of Oregon and DEQ to examine the thermal requirements of species that may not be protected by the existing water quality standard (i.e., coldwater species).

Examples of organism for which existing studies indicate the potential for colder thermal requirement include tailed frogs (*Ascaphus truei*), torrent salamanders (*Rhyacotriton cascadae*), and Pacific giant salamanders (*Dicamptodon tenebrosus*). DEQ and ODF could review the State's sensitive species list for other species that may warrant additional study and consideration.

Recommendation 4. IMST recommends that the Oregon Watershed Enhancement Board (OWEB) develop consistent guidance on assessment of current conditions of stream and riparian areas relative to elevated stream temperature.

This assessment methodology could integrate useful elements of various existing classification methods including Oregon Plan watershed assessment and monitoring protocols. Such a methodology would also require a system for determining reference conditions for streams and riparian vegetation across Oregon.

4a. IMST recommends that the State of Oregon adopt methods to evaluate stream and riparian conditions as part of programs to protect and restore stream temperature.

After evaluation methods are adopted and implemented, the State should monitor the effectiveness of stream assessment relative to improvements in stream temperature. The State should also evaluate the effectiveness of stream assessment in improving communication among stakeholders.

When restoring stream temperature, managers need to determine both current and potential condition of streams and riparian areas. Assessments provide a technical basis for managers to select appropriate restoration activities. Various existing stream and riparian assessment methods evaluate different channel and riparian features that affect stream temperature. Current Oregon Plan monitoring and watershed assessment guidelines address some of these factors (e.g., riparian condition and channel condition), as well as direct measurement of stream temperature.

OWEB should develop consistent guidance on stream and riparian assessment for agencies and groups addressing stream temperature problems. IMST does not know of an existing classification system that meets this need, but integration of several existing approaches could provide a scientifically rigorous context for determining current and potential conditions. Collectively, this assessment methodology could be used by agencies, professionals, watershed councils, schools, and other citizen groups determining appropriate restoration activities for streams with elevated temperature. Once an assessment program has been implemented, the State should assess whether the assessment system has achieved intended outcomes such as 1) improving stream temperature and 2) improving communication among stakeholders.

4b. IMST suggests development of a classification system for determining riparian reference conditions and riparian plant associations for all regions in Oregon. They should be peer-reviewed to assure their validity for each region.

Any guidance on stream and riparian assessment for agencies and groups addressing stream temperature problems would require a scientifically sound reference system describing potential riparian vegetation across Oregon. The State of Oregon needs to identify and protect sites with minimal human impacts for reference. A reference system would identify likely native plant communities for sites based on location adjacent to streams, position in river network, soils, moisture, channel morphology, elevation, aspect, and other local edaphic conditions. Where reference sites are not available, regional riparian ecologists should develop general descriptions of site-potential riparian vegetation; peer-reviewed classifications have already been completed for several regions of the State. IMST recommends scientific evaluation and screening of proposed approaches to determining reference conditions, as well as peer review of the final determinations of site-potential vegetation. In addition, the State should validate any stream/riparian assessment system that is developed from this process.

4c. IMST recommends the State of Oregon support efforts to coordinate management of stream temperature among stakeholders and across jurisdictional boundaries.

Stream assessment, management, restoration, and monitoring activities should be coordinated in order to protect and/or restore thermal regimes at a landscape scale. The State of Oregon should support coordination among state and federal agencies, professionals, landowners, watershed councils, schools, and other citizen groups.

Recommendation 5. IMST recommends that Oregon Watershed Enhancement Board (OWEB) and Oregon Department of Environmental Quality (DEQ) should jointly monitor effectiveness of protection and restoration activities aimed at improving stream temperatures. OWEB and DEQ should coordinate with other state agencies involved with temperature issues including ODA, ODF, and ODFW.

Under the Oregon Plan for Salmon and Watersheds, OWEB and DEQ should monitor the effectiveness of protection and restoration programs at improving stream temperature. Oregon Plan monitoring provides an opportunity to examine the effectiveness of stream temperature restoration practices with replication.

Recommendation 6. IMST recommends that the Oregon Water Resources Department (OWRD) should continue to promote protection of instream water flows for fish and aquatic life.

Reductions in stream discharge increase the potential for warming streams and rivers. The State should use existing water laws to protect existing flows to the degree possible. Several methods are already available to OWRD including protecting existing instream flows, leasing water rights, purchasing water rights, and encouraging conservation of water, especially for irrigation and industrial water withdrawals.

Numerous programs in the state and federal government as well as private resource conservation groups provide incentives and compensation to landowners for water conservation. Other programs provide funds for purchasing water rights or acquiring lands that are critically important in maintaining natural flow regimes. These programs also provide a basis for acquiring or protecting important coldwater refugia. OWRD and other relevant agencies should work with DEQ in Water Quality Management Plans and emphasize water conservation measures that are within their authority and responsibility. Short and long-term climatic variations and an apparent warming trend that could lead to diminished summer streamflows, make water conservation efforts critical to salmonid recovery.

Recommendation 7. IMST recommends that Division of State Lands (DSL) and Oregon Department of Agriculture (ODA) should emphasize and implement programs to restore wetlands for use as natural water storage systems.

Wetlands provide important sites for retaining water during floods and both storing and slowly releasing water during dry periods. Wetland conservation actions can influence stream temperatures and should be considered in Water Quality Management Plans for basins. All relevant state agencies should identify actions that they can take or encourage in the development of each Water Quality Management Plan. ODA should encourage and promote off-stream livestock water systems to protect and preserve riparian areas and their functions as water storage and release systems. Off-stream livestock water systems encourage livestock to spend less time in riparian areas seeking water.

Recommendation 8. IMST recommends that the Governor's Natural Resource Office and the Oregon Legislature complete and implement a statewide program of riparian protection and restoration. The Oregon Riparian Policy should be expanded and used as a framework for restoring the riparian resources of the State of Oregon.

All state agencies that have authority for land use practices and resource use should implement actions that promote the protection of existing riparian areas and restoration of riparian areas to local site potential wherever possible. Every assessment of riparian areas in the State of Oregon has concluded that a large portion, if not the majority, of our natural riparian plant communities have been converted to other land uses or shifted to young plant communities. Riparian vegetation along small to medium streams throughout the State of Oregon, both east and west of the Cascades, plays an important role in reducing the warming of surface waters. In May 2002, the State of Oregon finalized a "Statewide Management Riparian Policy". In a June 17, 2002 letter to agency directors and members of agency commissions and boards, Governor John Kitzhaber characterized this policy as his informal direction to state agencies; the policy and was not issued as an executive order or rule, nor was it intended to be self-executing. However, he did list his expectations for agencies and their boards or commissions to follow and to be completed by October 31, 2002. Governor Kitzhaber recommended all agencies to implement the measures contained in the Riparian Policy, but aggressive review of agency actions and application of this policy should be a high priority for the Governor's Natural Resource Office and relevant committees of the Oregon Legislature. This 2002 Riparian Policy builds a strong foundation for agencies but more work needs to be done in order to institutionalize the policy and to make it an effective tool in resource management.

Implications for Policy
The issue of the effects of land use practices on stream temperature has generated extensive and sometimes intensely critical debate in Oregon over the last few years. After the publication of the Final Issue Papers (DEQ 1995), a number of people in Oregon questioned the assumption that streams in Oregon have warmed as a result of land use practices, and have questioned whether *riparian vegetation* significantly influences stream temperature.

Recent debate in Oregon has been intense regarding the relative importance that *shade* has on influencing stream temperatures (Larson and Larson 1996; Beschta 1997; Larson and Larson 1997). The arguments against the importance of shade have been aided by short-term, limited scope studies on shading containers or irrigation. Researchers have also attempted to determine the relative importance of shade in relation to other watershed features, including features that are not affected by human activities (such as elevation, aspect, gradient, etc.; Carr et al. 2003; Krueger et al. 2003; Borman and Larson 2003).

The IMST finds that there is little scientific debate about the many factors that influence the heating and cooling of streams. The IMST concludes that only four major factors that influence stream temperature–riparian shade, channel morphology, discharge, and subsurface exchange–are modified by human actions. IMST has found that the vast majority of published studies document that riparian shade has a significant effect on stream temperature. Additionally, riparian vegetation also plays a major role in influencing other factors that, in turn, affect stream temperature. For example, plant roots are important because they keep stream banks from eroding and channels from becoming wide and shallow. The scientific literature reviewed by the IMST indicates that removal of vegetation along small- to medium-sized streams usually results in increased surface water temperature. In addition, most scientists agree that riparian vegetation provides many benefits to stream and terrestrial ecosystems, in addition to shading streams (IMST 2000). Therefore, despite the level of public controversy, the IMST does not find substantial scientific disagreement on the topic of the importance of riparian vegetation to maintaining stream temperatures.

Some Oregon citizens have criticized the State's water quality standards and implementation process, and believe that the burden of proof to list a stream as temperature impaired should be on the government. The burden of proof is already on DEQ because DEQ must document records of thermal conditions before a stream reach can be placed on the 303(d) list. A formal process also exists for assessing streams individually for removal from the 303(d) list based on data and modeling; however, some Oregon citizens have stated that general opinions from the local community about past temperatures and occurrence of beneficial uses should be a sufficient basis for removal of streams from the 303(d) list. IMST believes local knowledge can provide valuable information, but without empirical scientific evidence, local knowledge is insufficient.

IMST suggests the following actions:

- Honest scientific inquiry needs to continue. We have extensive knowledge to guide restoration efforts, but some questions remain about both ecological processes and appropriate management practices. Clearly stating and answering these questions will help the State to better manage our resources and develop appropriate social guidance.

- Riparian zone management should be implemented. IMST has repeatedly called for “big picture” (landscape scale) views of salmonid restoration because of the enormous extent of the problem. At the same time IMST recognizes that site-specific details will dictate the exact physical and ecological potentials at a given location. Implementation of regulations and voluntary programs should carefully consider the landscape context and potential of specific sites.
- Over-appropriation of water in Oregon streams is a problem that needs to be resolved. Oregon water rights law establishes that older water rights are to be filled before newer water rights. The majority of consumptive water rights in Oregon are older than the priority dates established for instream water rights, increasing the tendency for water left in streams to be heated above the historical range of conditions.
- Equity issues should be addressed as well. In many cases, landowners are already doing a wonderful job of ecological management. Those cases should be celebrated. This sort of recognition could provide incentive and peer support to proper land stewardship. Financial incentives to offset potential losses of value or income, which may happen with various kinds of setback rules and/or non-use requirements, should be vigorously explored. “Riparian Bill” and “Farm Bill” kinds of technical and financial assistance programs, conservation easements, buy-out programs, etc. should also be explored.
- The State should continue to involve Oregon citizens in stream restoration and the TMDL process. By adopting an approach that allows citizens to become vested in the process and the potential benefits of stream restoration, we have a hope of achieving water quality goals. Landowners, scientists, agency managers, and public citizens should find ways of working together in mutual respect (as was accomplished in recent TMDL assessments, the Malipai Working Group, Bridge Creek, and many watershed council programs and projects).
- Strong educational programs should be implemented. Education and outreach are the best, long-term tools we have at our disposal. The OSU Extension Service is a rational leader for this action. Education is always an important element in effective conservation and restoration. Different state entities charged with public education need to deliver consistent messages about stream temperature, and to clarify these complex issues, rather than complicate them.

Explaining complex scientific results to the public is an ongoing challenge for educational institutions. The public should not be surprised that scientists do not necessarily agree on all issues. Scientific studies of ecological systems are confounded by the unique combinations of factors (geology, soils, geographic orientation, watershed shape and size, elevation, ambient conditions, climate and weather, as well as a myriad of other features) that often serve to make results site-specific or increase variance in population studies.

The daunting task for land managers is to collate the numerous facets of science into rational plans for on-the-ground action. IMST has repeatedly voiced the strong call for a landscape level view of watershed and salmonid recovery---at the same time recognizing that site-specificity will dictate nuances within that big picture.

In some cases, citizen groups have criticized Oregon’s temperature standard, and suggested that the standard is “bogus” or not supported by science. Groups have also criticized efforts to restore riparian vegetation as unnecessary and ecologically unsound. IMST finds these criticisms to be incorrect, misguided, and damaging to Oregon's resources in the long-term. IMST encourages all citizens, agencies, and politicians to move beyond these arguments, and to move forward with the protection and restoration of streams and riparian areas for the numerous important ecological and social functions of these critical features of Oregon's landscape.

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Appendix A. SUMMARY OF SCIENTIFIC STUDIES ON PREFERENCE AND AVOIDANCE TEMPERATURES OF SALMONIDS COMPILED BY EPA REGION 10 TEMPERATURE WATER QUALITY CRITERIA GUIDANCE DEVELOPMENT PROJECT (SAUTER ET AL. 2001).

Bull trout (*Salvelinus confluentus*)

Life stage	Location; wild/hatchery	Aquatic system	Preferred field temp °F (°C)	Acclimation temperature °F (°C)	Temperature regime	Citation
juvenile	Throughout NW bull trout range; wild	stream	42.8–48.2 (6–9) AWAT ≤55.4–57.2 (≤13–14) MDMT	N/A	natural	Reiman and Chandler 1999
juvenile	Lake Pend Oreille, ID; wild	stream	46.04–57.02 (7.8–13.9) MDMT	N/A	natural	Saffel and Scarnecchia 1995
juvenile	Lake Pend Oreille, ID; wild	stream	46.4–48.2 (8–9) instantaneous	N/A	natural	Bonneau and Scarnecchia 1996
juvenile	Flathead River, MT; wild	stream	≤60.62 (≤15.0)unknown	N/A	natural	Fraley and Shepard 1989
juvenile & adult	Columbia River, Kootenay, BC, Canada; wild	stream	53.6 (12.0) MDMT 51.26 (10.7) MDAT 52.88 (11.6) MWMT 50.36 (10.2) MWAT	N/A	natural	Haas, unpublished manuscript[38]
adult-spawning	Flathead River, MT; wild	stream	≤50 (≤10.0) unknown	N/A	natural	Fraley and Shepard 1989
adult-upstream migration	Blackfoot River, MT; wild	stream	63.86 (17.7) DAT	N/A	natural	Swanberg 1997

Cutthroat trout (*Oncorhynchus clarki*)

Life stage	Location; wild/hatchery	Aquatic system	Preferred field temp °F (°C)	Acclimation temp	Temperature regime	Citation
juvenile & adult	Lake Pend Oreille drainage, ID; wild	stream	50–57.2 (10–14) instantaneous	N/A	natural	Bonneau and Scarnecchia 1996

[38] Haas, G.R. Unpublished manuscript. Maximum temperature and habitat mediated interactions and preferences of bull trout (*Salvelinus confluentus*) and rainbow trout (*Oncorhynchus mykiss*). British Columbia Fisheries, Fisheries Research and Development Section, University of British Columbia, Vancouver, BC, Canada.

Rainbow trout (*Oncorhynchus mykiss*)

Life stage	Location; wild/hatchery	Aquatic system; feeding	Acute preference temp °F (°C)	Acclimation temp °F (°C)	Temperature regime	Citation
juvenile	New and East Rivers, VA, USA; hatchery	tank; starved (see text above on feeding)	52.9°F [51.1–53.1] (11.6°C [10.6–11.7]) 54.7°F [54.5–56.1] (12.6°C [12.5–13.4]) 57.9°F [57.9–59.2] (14.4°C [14.4–15.1]) 62.4°F [61.2–62.4] (16.9°C [16.2–16.9]) 64.5°F [64.2–65.6] (18.1°C [17.9–18.7]) 68.2°F [67.5–69.1] (20.1°C [19.7–20.6]) 71.6°F [70.5–72.5] (22.0°C [21.4–22.5])	42.8 (6) 48.2 (9) 53.6 (12) 59 (15) 64.4 (18) 69.8 (21) 75.2 (24) (see text on acclimation below)	stable	Cherry et al. 1975
juvenile-1 month 6 months 10 months 12 months	Ontario, Canada; hatchery	tank; unknown	62.7 (17.08) 62.5 (16.92) 64.2 (17.88) 59.4 (15.21) 62.4 (16.91) 62.9 (17.20) 60.4 (15.75) 51.7 (10.95) 58.7 (14.82) 55.1 (12.85) 47.1 (8.40) 50.4 (10.20)	50 (10) 59 (15) 68 (20) 50 (10) 59 (15) 68 (20) 50 (10) 59 (15) 68 (20) 50 (10) 59 (15) 68 (20)	stable	Kwain and McCauley 1978
Life stage	**Location; wild/hatchery**	**Aquatic system; feeding**	**Avoidance temp °F (°C)**	**Acclimation temp**	**Temperature regime**	**Citation**
juvenile	New and East Rivers, VA, USA; hatchery	tank; starved	< 41>55.4 (<5 >13) < 46.4 >59 (<8 >15) < 51.8 >62.6 (<11>17) < 55.4 < 66.2 (<13 >19) < 55.4 < 66.2 (<13 >19) < 60.8 >73.4 (<16 >23) < 66.2 >77 (<19 >25)	42.8 (6) 48.2 (9) 53.6 (12) 59 (15) 64.4 (18) 69.8 (21) 75.2 (24)	stable	Cherry et al. 1975
Life stage	**Location; wild/hatchery**	**Aquatic system; feeding**	**Final preference temp °F (°C)**	**Acclimation temp**	**Temperature regime**	**Citation**
subyearling	Otterville, Ontario, Canada; hatchery	tank; fed	71.6 (22)	N/A	stable	Javaid and Anderson 1967
subyearling	Otterville, Ontario, Canada; hatchery	tank; starved	64.4 (18)	N/A	stable	Javaid and Anderson 1967
subyearling	Campbellville, Canada; hatchery	tank; fed	64.4–66.2 (18–19)	N/A	stable	McCauley and Pond 1971

Life stage	Location; wild/hatchery	Aquatic system; feeding	Final preference temp °F (°C)	Acclimation temp	Temperature regime	Citation
juvenile	Waterloo County, Ontario, Canada; hatchery	tank; unknown	52.3 (11.3)	N/A	stable	McCauley et al. 1977
adult	unknown	tank; unknown	55.4 (13)	N/A	stable	Garside and Tait 1958
adult	New and East Rivers, VA, USA; hatchery	tank; starved	64.4 (18)	N/A	stable	Cherry et al. 1975
adult	New and East Rivers VA, USA; hatchery	tank, starved	66.6 (19.2)	N/A	stable	Cherry et al. 1977
Life stage	**Location; wild/hatchery**	**Aquatic system**	**Final field preference temp °F (°C)**	**Acclimation temp °F (°C)**	**Temperature regime**	**Citation**
juvenile & adult	Columbia River, Kootenay, BC, Canada; wild	river	57.6 (14.2) MDMT	N/A	natural	Haas, unpublished manuscript [39]
adult	Horsetooth Reservoir, Colorado; unknown	reservoir	66.0–69.9 (18.9–21.1) ATU	N/A	natural	Horak and Tanner 1964
adult	Lake Michigan; unknown	lake	61.7 (16.5) unknown	N/A	natural	Spigarelli 1975 (as cited in Sauter et al. 2001)

[39] Haas, G.R. Unpublished manuscript. Maximum temperature and habitat mediated interactions and preferences of bull trout (*Salvelinus confluentus*) and rainbow trout (*Oncorhynchus mykiss*). British Columbia Fisheries, Fisheries Research and Development Section, University of British Columbia, Vancouver, BC, Canada.

Steelhead trout (*Oncorhynchus mykiss*)

Life stage	Location; wild/hatchery	Aquatic system	Preferred field temp °F (°C)	Acclimation temp	Temperature regime	Citation
juvenile-subyearling	South Umpqua River, OR; wild	river	59 (15.0) DMAT	N/A	natural	Roper and Scarnecchia 1994 (as cited in Sauter et al. 2001)
juvenile-yearling	South Umpqua River, OR; wild	river	64.04 (17.8) DMAT	N/A	natural	Roper and Scarnecchia 1994 (as cited in Sauter et al. 2001)
Life stage	**Location; wild/hatchery**	**Aquatic system**	**Avoidance field temp °F (°C)**	**Acclimation temp**	**Temperature regime**	**Citation**
juvenile	northern California; wild	stream	≥73.4 (≥23)	N/A	natural	Nielsen et al. 1994

Spring chinook salmon (*Oncorhynchus tshawytscha*)

Life stage	Location; wild/hatchery	Aquatic system; feeding	Acute preference temp °F (°C)	Acclimation temp °F (°C)	Temperature regime	Citation
subyearling	Dungeness, WA; hatchery	tank; unknown	53.6–55.4 (12–13) (all acclimation temps)	41, 50, 59, 68, and 73.4 (5, 10, 15, 20, and 23)	stable	Brett 1952
Life stage	**Location; wild/hatchery**	**Aquatic system; feeding**	**Final preference temp °F (°C)**	**Acclimation temp °F (°C)**	**Temperature regime**	**Citation**
subyearling	Dungeness, WA; hatchery	tank; unknown	53.1 (11.7)	N/A	stable	Brett 1952
smolt	Little White Salmon N.F.H.; hatchery	tank; satiation	62.1 (16.7)	increasing temp acclimation, 3.6 (2) per month, range: 46.4–57.2 (8–14)	stable	Sauter 1996
Life stage	**Location; wild/hatchery**	**Aquatic system**	**Preferred field temp °F (°C)**	**Acclimation temp °F (°C)**	**Temperature regime**	**Citation**
adult	Lake Michigan; hatchery	lake	63.1 (17.3)	N/A	natural	Spigarelli 1975 (as cited in Sauter et al. 2001)

Fall chinook salmon (*Oncorhynchus tshawytscha*)

Life stage	Location; wild/hatchery	Aquatic system; feeding	Preferred temp °F (°C)	Acclimation temp °F (°C)	Temperature regime	Citation
subyearling	upriver bright stock from Little White Salmon N.F.H.; hatchery	tank; satiation	63.1 (17.3)	increasing temp acclimation, 3.6 (2) per month, range: 53.6–57.2 (12–14)	stable	Sauter 1996
smolt	upriver bright stock from Little White Salmon N.F.H.; hatchery	tank; satiation	51.6 (10.9)	60.8 (16)	stable	Sauter 1996

Pink salmon (*Oncorhynchus gorbushka*)

Life stage	Location; wild/hatchery	Aquatic system; feeding	Final preference temp °F (°C)	Acclimation temp °F (°C)	Temperature regime	Citation
subyearling	Dungeness, WA; hatchery	tank; unknown	53.1 (11.7)	N/A	stable	Brett 1952
Life stage	**Location; wild/hatchery**	**Aquatic system; feeding**	**Preferred field temp °F (°C)**	**Acclimation temp °F (°C)**	**Temperature regime**	**Citation**
juvenile-subyearling	Dungeness, WA; hatchery	tank; unknown	53.6–56.3 (12–13.5)	41, 50, 59, 68 and 73.4 (5, 10, 15, 20 and 23)	stable	Brett 1952

Coho salmon (*Oncorhynchus kisutch*) (Continued on next page)

Life stage	Location; wild/hatchery	Aquatic system; feeding	Acute preference temp °F (°C)	Acclimation temp °F (°C)	Temperature regime	Citation
subyearling	Nile Creek, BC, Canada; hatchery	tank; unknown	53.6–57.2 (12–14)	41, 50, 59, 68 and 73.4 (5, 10, 15, 20 and 23)	stable	Brett 1952

Coho salmon (continued)

Life stage	Location; wild/hatchery	Aquatic system; feeding	Final preference temp °F (°C)	Acclimation temp °F (°C)	Temperature regime	Citation
subyearling	Bockman Creek, WA; wild	starved 24 hr prior to experiment	52.9 range: 44.6–69.8 (11.6 range: 7–21)	50 (10)	stable	Konecki et al. 1995
subyearling	Bingham Creek, WA; wild	starved 24 hr prior to experiment	69.8 range: 42.8–60.8 (9.9 range: 6–16)	50 (10)	stable	Konecki et al. 1995
adult	Lake Erie; hatchery	tank; unknown	52.5 (11.4)	unknown	stable	Reutter and Herdendorf 1974
Life stage	**Location; wild/hatchery**	**Aquatic system**	**Preferred field temp °F (°C)**	**Acclimation temp °F (°C)**	**Temperature regime**	**Citation**
adult	Lake Michigan; hatchery	lake	63.1 (17.3)	N/A	natural	Spigarelli 1975 (as cited in Sauter et al. 2001)

Chum salmon (*Oncorhynchus keta*)

Life stage	Location; wild/hatchery	Aquatic system; feeding	Acute preference temp °F (°C)	Acclimation temp °F (°C)	Temperature regime	Citation
juvenile-subyearling	Nile Creek, BC, Canada; hatchery	tank; unknown	53.6–57.2 (12–14) (all acclimation temps)	41, 50, 59, 68 and 73.4 (5, 10, 15, 20 and 23)	stable	Brett 1952
adult-migration	unknown	stream	44.6–51.8 (7–11) unknown	N/A	natural	Groot and Margolis 1991
Life stage	**Location; wild/hatchery**	**Aquatic system; feeding**	**Final preference temp °F (°C)**	**Acclimation temp °F (°C)**	**Temperature regime**	**Citation**
subyearling	Nile Creek, BC, Canada; hatchery	tank; unknown	57.4 (14.1)	N/A	stable	Brett 1952

Sockeye salmon (*Oncorhynchus nerka*) (Continued on next page)

Life stage	Location; wild/hatchery	Aquatic system; feeding	Acute preference temp °F (°C)	Acclimation temp °F (°C)	Temperature regime	Citation
juvenile-subyearling	Issaquah, WA; hatchery	tank; unknown	53.6–57.2 (12–14)	5°, 10°, 15°, 20° and 23°C	stable	Brett 1952

Sockeye salmon (*Oncorhynchus nerka*) (Continued)

Life stage	Location; wild/hatchery	Aquatic system	Acute avoidance temp °F (°C)	Acclimation temp °F (°C)	Temperature regime	Citation
juvenile	Great Central Lake, BC, Canada; wild	lake	< 39.2 >64.4 (< 4 >18)	N/A	natural	LeBrasseur et al. 1978
Life stage	**Location; wild/hatchery**	**Aquatic system; feeding**	**Final preference temp °F (°C)**	**Acclimation temp °F (°C)**	**Temperature regime**	**Citation**
subyearling	Issaquah, WA; hatchery	tank; unknown	58.1 (14.5)	N/A	stable	Brett 1952
Life stage	**Location; wild/hatchery**	**Aquatic system**	**Final field preference temp °F (°C)**	**Acclimation temp °F (°C)**	**Temperature regime**	**Citation**
subyearling	Babine Lake, BC; wild	lake	51.1 (15) ± 9 (5) DAT	N/A	natural	Brett 1971
smolts yearling & adult adult	Cultus Lake, BC; Wild Horsetooth Reservoir, CO; hatchery; Okanagan Reservoir, WA; hatchery	lake reservoir; Okana-gan reservoir	51.1–55.0 (10.6–12.8) DAT	N/A	natural	Foerster 1937; Horak and Tanner 1964; Major and Mighel 1966 (as cited in Sauter et al. 2001)

Appendix B. STUDIES OF PHYSIOLOGICAL EFFECTS OF TEMPERATURE ON SALMONIDS COMPILED BY EPA REGION 10 TEMPERATURE WATER QUALITY CRITERIA GUIDANCE DEVELOPMENT PROJECT (MCCULLOUGH ET AL. 2001).

Table B-1. Selected growth optima for salmonids determined from feeding on full rations.

Species	Optimum growth temperature (°C)	Reference
Chinook salmon (*Oncorhynchus tshawytscha*)	15	Banks et al. (1971) as cited by Garling and Masterson (1985)
	17	Clarke and Shelbourn (1985)
	19	Brett et al. 1982
	20	Marine (1997)
Sockeye salmon (*Oncorhynchus nerka*)	15	Brett et al. 1969
Coho salmon (*Oncorhynchus kisutch*)	15	Everson (1973) as cited by Sullivan et al. (2000)
Rainbow trout (*Oncorhynchus mykiss*)	17.2–18.6	Hokanson et al. (1977)
	16.5	Wurtsbaugh and Davis (1977)
	15	Grabowski (1973)
	15	Railsback and Rose (1999) as cited in McCullough et al. 2001
Redband trout (*Oncorhynchus mykiss*)	20	Sonski (1983b)
Brook trout (*Salvelinus fontinalis*)	12.4–15.4	McCormick et al. 1972 as cited in McCullough et al. 2001
Lake trout (*Salvelinus namaycush*)	12.5	Edsall and Cleland (2000)
Brown trout (*Salmo trutta*)	13.9	Elliott and Hurley (1999)
	13.1	Elliott et al. (1995)
Atlantic salmon (*Salmo salar*)	18	Siemien and Carline (1991)
Arctic char (*Salvelinus alpinus*)	14	Jobling (1983)
	15.1	Larsson and Berglund (1997)
European grayling (*Thymallus thymallus*)	17.3	Mallet et al. (1999)
Bull trout (*Salvelinus confluentus*)	12–16	McMahon et al. (1999)

Table B-2. Temperatures that have been linked to impairment of smoltification, ability of smolts to migrate, or survival during smolt migration.

Species	Temperature (°C) threshold for impairment	Reference
Chinook	12	Wedemeyer et al. (1980)
	17–20	Marine (1997)
	12	Wedemeyer et al. (1980)
Coho	15	Zaugg and McLain (1976)
	12	Wedemeyer et al. (1980)
	15	Adams et al. (1975)
Steelhead	>13	Hoar (1988)
	>12.7	Adams et al. (1975)
(summer steelhead)	>13.6	Zaugg et al. (1972) as cited by Zaugg and Wagner (1973)
	12	Zaugg (1981)
Sockeye	12–14	Brett et al. (1958)

Table B-3. Studies that identify thermal blockages to adult salmon migration.

Species	River	Temperature cited as blocking migration	Reference
Chinook, sockeye, steelhead	Columbia	71–75°F (21.7–23.9°C)	Fish and Hanavan (1948)
Spring chinook	Clearwater, Idaho	69.8°F (21°C)	Stabler (1981)
Spring chinook	Tucannon	69.9°F (21.1°C)	Bumgarner et al. (1997)
Spring chinook	Willamette	69.8–71.6°F (21–22°C) (at oxygen >3.5 mg/L)	Alabaster (1988)
Summer chinook	Snake	69.8°F (21°C)	Stuehrenberg et al. (1978) as cited by Dauble and Mueller (1993)
Fall chinook	Sacramento	66.2–69.8°F (19–21°C) (oxygen ~5 mg/L)	Hallock et al. (1970)
Steelhead	Snake	69.8°F (21°C)	Strickland (1967) as cited by Stabler (1981)
Sockeye	Okanogan	69.8°F (21°C)	Major and Mighell (1967) as cited in McCullough et al. 2001
Sockeye	Snake	71.9°F (22.2°C)	Quinn et al. (1997)
Sockeye	Okanogan	73°F (22.8°C)	Hatch et al. (1993)
Sockeye	Fraser	64.4–71.6°F (18–22°C)	Macdonald et al. 2000

Table B-4. Upper incipient lethal temperature (UILT) of various juvenile salmonids.

Common Name	Origin (river/lake)	Acclimation Temp. (°C)	UILT (°C)	Reference
Chinook salmon	Dungeness Hatchery, WA	20, 24	25.1, 25.1	Brett (1952)
	Sacramento River	21.1	24.9	Orsi (1971, as cited by California Department of Water Resources 1988)
Coho salmon	Nile Cr. Hatchery, British Columbia	20, 23	25.0, 25.0	Brett (1952)
Sockeye salmon	Issaquah Hatchery, WA	20, 20, 23	23.5, 24.8 24.3	McConnell and Blahm (1970) (as cited by Coutant 1972) Brett (1952)
Chum salmon	Nile Cr. Hatchery, British Columbia	20, 23	23.7, 23.8	Brett (1952)
Pink salmon	Dungeness Hatchery, WA	20, 24	23.9, 23.9	Brett (1952)
Rainbow trout	Lake Superior	16	25.6	Hokanson et al. (1977)
	France	24	26.4	Charlon et al. (1970)
	Lakes Erie, Ontario, Huron , Superior	15	25–26	Bidgood and Berst (1969)
		24	25	Cherry et al. (1977)
		24?	26	Stauffer et al. (1984)
	Ontario	20	25.9	Threader and Houston (1983)
		20	26.7	Alabaster (1964) (as cited by Threader and Houston 1983)
	Summerland Hatchery, British Columbia	11	24	Black (1953)
	Firehole River, MT Ennis Hatchery Winthrop Hatchery	24.5, 24.5	26.2, 26.2	Kaya (1978)
		24.5	26.2	

Common Name	Origin (river/lake)	Acclimation Temp. (°C)	UILT (°C)	Author(s)
Redband trout	Parsnip Reservoir, Oregon	20, 23 ºC	27.4, 26.8 ºC	Sonski (1983a)
	Parsnip Reservoir, Oregon	20, 23 ºC	26.2, 26.2 ºC	Sonski (1984)
	Firehole River, Wyoming	20 ºC 23 ºC	27.2 ºC 26.3 ºC	Sonski (1984)
	Wytheville rainbow	20, 23 ºC	26.8, 27.0 ºC	Sonski (1984)
Atlantic salmon	England	20 ºC	23.5 ºC	Bishai (1960)
Brown trout	England	20 ºC	23.5 ºC	Bishai (1960)
		23 ºC	25.3 ºC	Frost and Brown (1967)
		?	23 ºC	Cherry et al. (1977)
	England	20 ºC	26.3 ºC	Alabaster and Downing (1966) (as cited by Grande and Andersen 1991)
Brook trout	Ontario	20, 24 ºC	25.3, 25.5 ºC	Fry et al. (1946)
		?	24 ºC	Cherry et al. (1977)
Lake trout	Ontario	20 ºC	24.0–24.5 ºC	Fry and Gibson (1953)
Arctic grayling	Montana	20 ºC	25 ºC	Lohr et al. (1996)
	Alaska	?	24.5 ºC	LaPerriere and Carlson (1973) (as cited by Lohr et al. 1996)