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The Scientific Basis for Oregon's Stream Temperature Standard: Common Questions and Straight Answers

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"Water temperature is a catalyst, a depressant, an activator, a restrictor, a stimulator, a controller, a killer, one of the most important and most influential water quality characteristics to life in water."

-The Federal Water Pollution Control Administration
U.S. EPA (1986)

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More Questions For the Especially Curious…

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What does the Water Quality Standard for Temperature Say?

The standard for stream temperature says that no measurable surface water temperature increase resulting from human activity is allowed when stream temperatures exceed the criteria, unless allowed under a Department-approved surface water temperature management plan. When the criteria are exceeded a management plan is required for the basin. The plan will describe the management practices, measures and/or control technologies that will be used to reverse the warming trend of the basin, watershed or stream segment. For nonpoint sources, designated management agencies are responsible for plan development, for example: Oregon Department of Agriculture, Oregon Department of Forestry, federal agencies, cities and counties. Plans shall continue to be maintained or improved until the criterion is achieved or until the Department determines that all feasible steps have been taken to meet the criteria and the designated beneficial uses are not being adversely impacted. See further discussion of implementation of the standard below (OAR 340-41-[basin](2)(b), 340-41-026 and 340-41-120 for the rule language).

A source or land manager that follows the criteria of an approved surface water management plan will be considered to be in compliance with the water quality standard rules.

Why is Temperature an Important Water Quality Variable?

Stream temperature is an extremely important water quality variable that has a profound affect on the health of many of Oregon's native aquatic species, including those symbols of our treasured natural heritage, the salmon. Cold water temperatures are a fundamental characteristic of Pacific Northwest aquatic ecosystems, including: anadromous salmon and steelhead, resident trout, amphibians, various macroinvertebrates and others. The purpose of the water quality standard for stream temperature is to protect the health and integrity of aquatic ecosystems and the organisms that once thrived in Oregon waters.

The Purpose of the Water Quality Standard for Temperature

The purpose of the temperature standard, like all water quality standards, is to protect the beneficial uses of the waters of the state and to preserve the health of our aquatic ecosystems. In achieving these purposes, the water quality standards also serve the goal of the federal Clean Water Act: to maintain and restore the chemical, physical and biological integrity of the nation's waters. The beneficial uses most sensitive to water temperature are fish and aquatic life and, therefore, the temperature standard is based on protecting these uses.

The goals of the temperature standard are to prevent or minimize surface water temperature warming caused by human activity and to maintain the "normal" temperature regime through the year. Not only summer daily maximums are a concern to aquatic life, changes in temperature through the year also affect their development and activity. By maintaining or restoring stream side conditions to minimize summer warming and allow the stream to reach its temperature potential, the temperature regime through the year should also be maintained. The same conditions that can prevent heating in the summer can reduce the amount of icing in a stream in the winter, for example.

For streams that exceed the 64°F criteria under natural conditions, there is still a benefit to preventing additional human caused warming. The goal in this case is to minimize the number of stream miles in the watershed and the amount of time during the day and during the summer that fish habitat is impaired due to elevated stream temperature. One way to visualize this is to think of the goal as pushing the point at which the criterion is exceeded downstream as far as possible.

Please refer also to "The Goals of the Water Quality Standard for Stream Temperature," for additional description of the purpose of the surface water temperature standard (Sturdevant, for DEQ, December, 1996).

Why is the Temperature Criterion for General Salmonid Use 64°F?

The criterion in the stream temperature standard for general salmon and trout use is 64°F (17.8°C). The 64°F criterion in the stream temperature standard was established to protect general salmon and trout use during the warm summer months. This criterion applies where those uses occur or are designated beneficial uses for the stream segment. The unit for all the criteria in the standard is the 7-day moving average of the daily maximum temperatures. This means that the average of the daily maximum stream temperatures for the 7 warmest consecutive days during a year, and any other 7-day period, is calculated and compared to the applicable criterion. If the criterion is exceeded a management plan is required.

The 64°F 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. Anadromous cold water species in Oregon include chinook salmon, coho salmon, sockeye salmon and steelhead trout. One or more of these species occur in most of the waters of the State. There are also resident cold water species that occur in many locations throughout the state such as rainbow and cutthroat trout. The life stages that occur in rivers and streams during the warmest summer months (July and August) are primarily juvenile rearing, adult holding in the case of chinook salmon, and even adult migration in the case of summer/fall chinook. During June and September, adult migration and smolt out-migration in some species occurs and spawning may begin in September for spring chinook. A separate spawning criteria (55°F) applies *during spawning periods at locations that support it.*

There are many ways that stream temperature influences salmonids. The most direct and dramatic is when temperatures are so warm they are lethal. Fish will avoid streams with excessive temperatures unless they become trapped. The standard is based not on these directly lethal temperatures (usually above 70°), but on *sub-lethal effects, of which there* are many. Sub-lethal effects can lead to death indirectly, or they may reduce the ability of the fish to successfully reproduce and for their offspring to survive and grow. These sub-lethal effects include an increase in the incidence of disease, an inability to spawn, a reduced survival rate of eggs, a reduced growth and survival rate of juveniles, increased competition for limited habitat and food, reduced ability to compete with other species that are better adapted to higher temperatures (many of these are introduced species) and other adverse effects.

Sub-lethal effects of temperature on salmonids occur gradually as stream temperatures increase. Some of these effects begin when stream temperatures are below 64°F, 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 temperature below 58 to 60°F. At 64°F, 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 60°F 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 any risk to the fish whatsoever, it keeps the risk to a minimal level.

Please refer to the Temperature Issue Paper published by DEQ in June, 1995 for additional information on the temperature requirements of aquatic species in the scientific literature (see Chapter 2 and Appendix D in particular).

The DEQ recognizes that not only summer maximum temperatures are of importance to aquatic biota. The intent is to protect the temperature regime through the year. Built into the standard is the assumption that if stream and riparian conditions are managed such that they meet the summer maximum criteria, those same conditions will protect the temperature regime of the stream through the year.

What are the Other Criteria Based On?

<u>68°F for the Columbia River below river mile 309 and for the Willamette River below mile 50.</u> 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

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these deep lower mainstem reaches temperature varies by depth so that the fish may find acceptable temperatures at depth.

55°F for salmonid spawning, egg incubation and fry emergence. 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. Information on fish occurrence can be obtained from the Oregon Department of Fish and Wildlife.

50°F for native Oregon bull trout. Bull trout have colder temperature requirements than the other salmonids and their distribution is not as broad. Therefore this specific criterion was established to apply only 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°F.

No measurable increase from anthropogenic activities in ecologically significant cold-water refugia. A no measurable increase criteria applies when and where cold water refugia are identified by the Department. These refugia are areas that are ecologically significant because they provide essential cold water to downstream locations or because they are segments critical to the well-being or sustainability of the basin's population of a particular species.

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. Where T&E species occur, additional human caused stressors should not be added. If stream temperatures are an important variable to the species, such as with cold water fish, additional human caused warming should not be added to their environment.

No measurable increase from anthropogenic activities when DO levels are within 0.5 mg/liter or 10 percent saturation for the water column or intergravel DO criterion for a given stream reach or sub-basin. This provision recognizes that temperature and dissolved oxygen are both critical factors to aquatic biota and that they are related to each other. As stream temperatures rise, the water can dissolve less oxygen. If dissolved oxygen levels are marginal, additional stress should not be added to the stream by increasing stream temperatures.

No measurable increase from anthropogenic activities in natural lakes. The temperature of natural lakes should not be increased above their normal condition by human activity.

Stream Temperature Is Something We All Can Understand

The temperatures of streams and rivers in the Pacific Northwest have been studied in great detail. Research has become more complex as many scientific disciplines have taken an interest in the temperatures of streams and rivers, namely: forest and rangeland science, plant biology, ecology and zoology, watershed hydrology, hydraulic engineering, atmospheric science, meteorology and geology. With such intense scientific study, the understanding of stream temperature dynamics is becoming focused and refined. However, new scientific findings are often presented in complicated jargon and long equations written for other scientists, instead of the general public. The science surrounding stream and river temperatures can indeed be very complicated. However, most of the factors that induce stream temperature change are simple and accessible to any person that has walked along a stream, boiled water, or sat in a bathtub. This paper will try to present the current understanding of water temperature dynamics clearly and concisely. Important terms and words that you should become familiar with are italicized.

The Cycles that Stream Temperature Follows

In general, the temperature regime of streams and rivers occur in two distinct cycles: a seasonal cycle and a daily cycle. In the Pacific Northwest, the seasonal maximum occurs in summer months (July and August), while the winter months offer the coolest stream temperatures (December and January). The daily temperature cycle reaches a maximum in the afternoon, while the daily minimum occurs during the late night or the early morning.

Stream Temperature Monitoring

In order to determine the 7 day moving average maximum, stream temperature must be monitored throughout an entire summer. Data collection should begin in late spring (May or June) and last until the beginning of fall (September or October). To adequately measure the daily maximum, temperature data must be taken frequently throughout each day. Fortunately, new electronic thermometers, called thermistors, have made stream temperature monitoring a simple task. Thermistors are capable of high resolution measurements (±0.2 - 0.4°F) and can record temperature measurements for months at a time. Several academic institutions, government agencies, companies and private citizens have become involved with stream temperature monitoring. Temperature data availability is improving each year. Maximum recording thermometers designed for total immersion are also used, but require daily site visits during the entire sampling period.

Ideally, temperature measurement should occur at several sites along a stream. However, if resources are limited, sampling should focus on the lower stream reaches. Sampling at the headwaters does not provide representative stream temperature data that captures the cumulative impacts of upstream land use activities. In terms of the temperature standard, data collection should occur either at the same location or downstream from the site used for 303(d) listing.

Thermistors should be placed at the bottom of the stream, in the center of the flow and preferably in shade. Pools and stagnant areas should not be sampled. For more information regarding monitoring, contact the DEQ or consult with the DEQ's *Temperature Monitoring Procedural Guidance.*

What Makes Water Have a Temperature?

The temperature of water is an expression of heat energy per unit volume. It takes a certain amount of energy to heat a volume of water, a phenomena known as the *specific heat*. Water has a high *specific heat*, which is to say that it requires the input of large quantities of heat energy to increase the temperature just 1° F (Wetzel 1983). Similarly, water must release large quantities of heat energy before the temperature decreases. To heat a gallon of water 1° F, 2,103 calories of heat energy must be added. Vast quantities of heat energy are required to heat a stream or river.* When water temperature is described in terms of heat energy, the processes that cause a stream to gain or lose heat energy become important.

How Does Heat Energy Enter and Leave a Stream?

There are six processes that allow heat energy exchange between a stream and its environment: *solar energy*, *longwave radiation*, *evaporation*, *convection*, *stream bed conduction* and *groundwater inflow/outflow*. All of these energy processes act in accordance with the laws of thermodynamics with the following consequences:

> *1st Law of Thermodynamics: Energy cannot be created or destroyed*
>
> *2nd Law of Thermodynamics: When two objects at different temperatures are placed in contact with each other, heat flows from the warmer to the cooler object*

These energy processes occur in all streams, rivers, lakes, mud puddles and water troughs. Further, all of these energy processes have been closely studied and are well understood. Each energy process contributes to the total heat energy contained in a stream system. While some have a greater effect than others, all processes are significant because land use activities that impact the stream or its surrounding environment may

* To prevent confusion it should be noted that water temperature can also change in response to work, such as stirring, mixing or shaking. In the context of stream temperature, this paper is primarily concerned with the transfer of heat energy and not energy imparted to water via mechanical/physical means.

result in changing one or more of the energy processes. **Figure 1** depicts the processes that affect the heat energy contained in a stream system. It is important to note that with the exception of *solar radiation*, which can only deliver heat energy, the other energy processes are capable of both introducing or removing heat energy from the stream system.

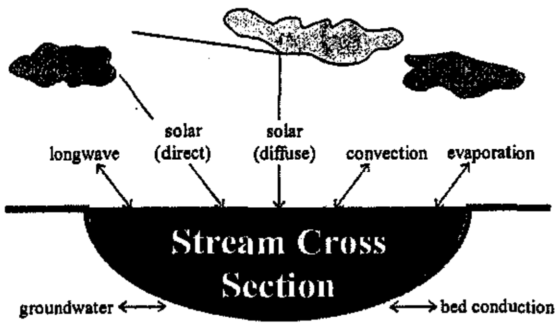
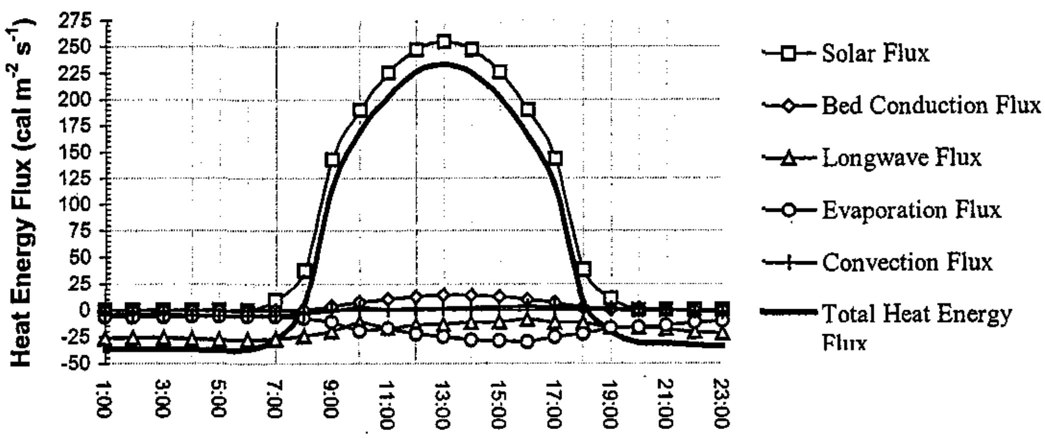


Figure 1. Processes that involve the transfer of heat energy.

The ultimate source of heat energy is *solar radiation*. Secondary sources of heat energy include *longwave radiation*, from both the atmosphere and stream side vegetation, *stream bed conduction*, *convection* and in some cases, *groundwater exchange*. Several processes dissipate heat energy at the air-water interface, namely: *evaporation and back radiation* (*longwave radiation* emitted from the stream surface). Energy is acquired by the stream system when the heat energy entering the stream is greater than the heat energy leaving the stream. When there is an addition of heat energy to the stream, the temperature will increase. The converse is also true. If the effect of the six energy processes results in reducing the total heat energy of the stream, the temperature will decrease. **Figure 2** illustrates the energy processes occurring for an unshaded stream over the course of one clear sky summer day.

Typical Summer Energy Balance for an Unshaded Stream



Note: Total Heat Energy > 0 Indicates Stream Warming
Total Heat Energy < 0 Indicates Stream Cooling

Figure 2. Stream energy processes experienced during one full day. (data taken from Boyd 1996).

Solar Radiation

In terms of summertime stream heating, the majority of energy is contributed by *solar radiation*, as can be seen in **Figure 2**. Once emitted from the sun, photons travel through space to the edge of the earth's atmosphere. While passing through the atmosphere a portion of *solar radiation* is absorbed and scattered by water vapor and other particulates, while the remainder continues its journey towards the earth's surface (McCutcheon 1989). Some of the radiation that is scattered in the atmosphere eventually reaches the earth's surface and is referred to as *diffuse solar radiation* (Ibqal 1983). The solar radiation that travels through the atmosphere unobstructed is known as *direct solar radiation*. Assuming there are no topographic barriers between the stream surface and the sun, *solar radiation* has one last barrier to pass before reaching the stream surface: riparian vegetation. Depending on the characteristics of stream side vegetation and the time of day, an individual photon may or may not encounter riparian vegetation before arriving at the stream surface. It follows that land use activities that impact riparian vegetation will alter the quality and quantity of shade offered to the stream. When a stream surface is exposed to midday *solar radiation*, large quantities of heat energy will be imparted to the stream system, usually resulting in a dramatic water temperature increase. **The principal source of heat energy for streams is solar energy striking the stream surface directly** (Brown 1970).

Longwave Radiation

A very simple way to understand *longwave radiation* is hold your hand over a warm object (car engine, stovetop, pavement, etc.). When you feel heat from a object without actually touching it, part of the heat that you are feeling is *longwave radiation* emitted from the object. Unlike solar radiation, which occurs only during the daylight hours, *longwave radiation* is continually emitted by all objects (Bedient and Huber 1992). *Longwave radiation* is transmitted from the atmosphere to the stream surface. Further, riparian vegetation can furnish *longwave radiation* to the stream surface. Lastly, the stream surface can emit *longwave radiation*, that serves to cool the stream, while warming the surrounding environment. The summation of the three modes of *longwave radiation* is plotted as one line in **Figure 2**.

Convection

Place your hand on your desk. It feels cold because its temperature is less than that of your hand. Heat energy is transferred from your hand to the desktop. Your hand is warming the desktop and will continue to do so until you lift your hand or the temperature of the desktop begins to approach that of your hand. It is important to note that in order for direct heat transfer to occur, two bodies (your hand and the desk) must be in contact.

In terms of stream temperature, the two bodies in contact are the stream water and the column of air directly above it. When the air column is warmer than the water surface, as is usually the case in the daytime, heat energy will be transferred to the stream, for the same reason that your hand warmed your desk. When air temperature is cooler than the stream, as is often the case at night, *convection* will move the other direction and cool the stream. Heat energy will always travel from a high temperature to a low temperature.

When your lift you hand from the desk, your hand is only in contact with air and you do not feel a temperature because very little heat energy is transferred between the air and your hand. Recall that your desk felt cold to the touch, yet the desk and the air are the same temperature. How can this be? Air *conducts* heat much slower than your desk, limiting the rate of energy transfer. Gases are poor conductors because of their dilute nature (Serway 1990). **In terms of stream heating, energy is transferred between the stream and air at a very slow rate.** Compared to the other energy processes, *convection* results in little energy exchange, as can be seen in **Figure 2**.

Evaporation

As the motion of a water molecule in the liquid phase increases in response to increased heat energy it begins to overcome the molecular attraction to liquid water, causing water molecules to escape as water vapor. Water molecules in the liquid phase require energy to overcome the molecular bonds that bind the liquid molecules. A measure of the internal energy that is necessary to convert liquid water to water vapor is known as the *latent heat of vaporization*. The evaporative process represents a heat energy loss for a stream or river.

Wind assists *evaporation* by removing the escaping water molecules before being forced back into the water surface. This is the same phenomena that encourages people to fan themselves when they are hot. Air movement increases *evaporation*, which in turn, removes more heat energy. Computer modeling has shown that increased wind speeds decreases stream temperature by allowing a stream to shed large quantities of energy via *evaporation* (Boyd 1996).

Stream Bed Conduction

Heat energy exchange between the stream bed and the stream is driven by a temperature difference. Shallow streams, less than eight inches in depth, may allow *solar radiation* to penetrate through the water column and strike the stream bed (Brown 1969). Depending on the composition of the stream bed material, it will absorb and retain some of this solar energy. A stream bed that is comprised of large rocks will retain more energy than a stream bed of sand or small cobble (Beschta and Weatherred 1984). Small cobble or gravel offers a greater surface area for contact with water and thus, for heat transfer. Large cobble or bedrock has less surface area and offers a slower rate of heat transfer. The heat energy that is stored in the stream bed will eventually be released back to the water column. Again, the *conductance* of the stream bed will depend on the composition of the bed material. A stream bed composed of solid rock may retain heat energy for a long period of time and release it back to the stream in the late evening.

Groundwater Inflow/Outflow

Groundwater mixing with streams and rivers has the potential to affect water temperature. A gaining reach is one that has its flow augmented by groundwater, while a losing reach loses a portion of its flow to seepage through the stream bed. Any stream or river in the Pacific Northwest has both gaining and losing reaches. Further, the influence of groundwater changes seasonally. The temperature of groundwater is usually cooler than stream temperatures in the summer months. For this reason, *groundwater mixing* with stream water usually has a cooling influence on summer stream temperatures.

Add Up the Energy Processes and We Know Exactly What Is Happening

Recall **Figure 2**. In addition to the lines that represent the energy processes, the *total energy flux* is also plotted. This line represents the instantaneous summation of all of the energy processes. In simpler terms, if you pick a time on the x-axis and add all of the energy processes you can derive the total amount of energy that the stream is receiving or losing. When the *total energy flux* is negative, the stream is losing energy and the water temperature is cooling. Similarly, when the *total energy flux* is positive, the stream is gaining heat energy and the water temperature is increasing. Remember that streams and rivers follow a daily temperature cycle. The *total energy flux* as depicted in **Figure 2** clearly shows why temperature has a daily cycle. During the nighttime a *negative total energy flux* removes energy from the stream, cooling the water. This continues until the sun rises. Once the sun's intensity is such that the *total energy flux* becomes positive, the stream will begin to warm. Warming continues until the sun's intensity begins to wane in the late afternoon. Eventually the *total energy flux* will become negative and the stream will again begin to cool.

How Do Streams Warm?

We now know that due to the *specific heat* of water, a large quantity of heat energy is required to change water temperature. We also know that when the *total energy flux is positive*, a stream is gaining heat energy. Very few energy processes have the ability to quickly impart the large amount of energy needed to warm water rapidly, with the exception of *solar radiation*. **Figure 2** clearly shows that compared to the other energy processes, *solar radiation* is the predominant process that contributes to daytime heating. Other processes such as *convection* and *longwave radiation* may also introduce energy into the stream, but at much smaller amounts when compared to *solar radiation*. If a stream is completely unshaded, as is the case in **Figure 2,** the *solar radiation* flux has the potential to quickly introduce vast quantities of heat energy, resulting in a rapid increase in water temperature.

Very little heat exchange at the surface of small streams results from *convection* or *evaporation*. This is important for two reasons. First, high air temperatures cannot be responsible for a rapid rise in temperature. Second, it suggests that the heat added to streams by the sun will not be readily dissipated (Brown 1983). During daylight hours an unshaded stream receives vast amounts of solar energy that rapidly accumulates. However, the processes that dissipate heat energy from the stream do so slowly. The result is that most of the *solar energy* is stored in the stream, causing an increase in water temperature.

How Do Streams Cool?

Streams and rivers cool via three energy processes: *evaporation*, *back radiation*, and if the water temperature is greater than the air temperature, *convection*. The evaporative heat flux across the air-water interface is generally the most significant factor in dissipation of stream heat (Parker & Krenkal 1969). *Evaporation* is the energy process through which streams lose most heat energy and, therefore, contributes most to decreases in stream temperature (**Figure 3**). The human body relies on *evaporation* of skin moisture as a primary method of cooling because *evaporation* is the fastest way to dissipate heat from water. Streams and rivers take advantage of evaporation as well. As water temperatures increase, the rate of evaporation increases serving as a method of cooling.

The second most significant cooling processes is termed *back radiation*. As previously mentioned, *back radiation* occurs when the stream emits *longwave radiation*. As the temperature of water increases, the amount of energy released in the form *of back radiation* also increases. **Figure 3** shows how the magnitude of *back radiation* cooling compares to that of *evaporation* and *convection*.

A third process in which energy leaves the stream system is through *convection*. Quite simply, when the stream is warmer than the air above it, the 2nd law of thermodynamics requires that energy will travel from the stream to the air. Remember that energy will always travel from higher concentrations to lower concentrations. As can be seen in **Figure 3,** *convection* is the least significant of the processes by which streams cool.

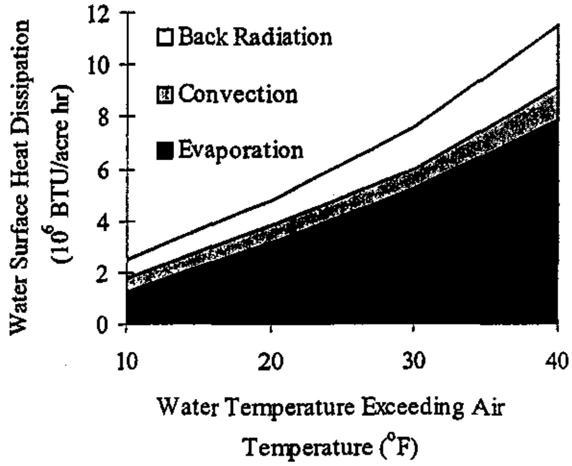


Figure 3. Heat dissipation from water surface by *evaporation*, *back radiation*, *convection* during June (data taken from Parker and Krenkal 1969).

How Stream Temperature Changes

Stream temperature change is explained rather simply. At any instant of time, a stream reach is capable of sustaining a particular water temperature. Water traveling downstream enters a reach with a given temperature. If that temperature is greater than the reach is capable of supporting, the temperature will decrease. If that temperature is less than the reach is capable of supporting, the temperature will increase. Stream temperature change is induced by the energy balance between the stream water and the surrounding environment. It takes time for a water parcel to travel downstream, during which the energy processes drive stream temperature change. In all natural systems both scenarios occur simultaneously. At any particular instant of time, water that enters the upstream portion of a reach is never exactly the temperature that is supported by a reach. And, as the water is transferred downstream, heat energy and hydraulic process induce water temperature change.

If we apply this concept to a watershed, we see that the temperature dynamics behave quite logically. A watershed is comprised of many types of streams and rivers. In general, the upper watershed consists of low flow tributaries. Progressing downstream, tributaries begin to converge and create larger streams, and eventually combine to form a main stem river or stream. The upper portions of the watershed consist of small streams that generally have cooler water temperatures. As water travels down gradient to lower elevations the water warms as heat energy is exchanged between the stream and its surrounding environment. The water in a stream may travel for a long distance before the temperature stabilizes. This is due to the relatively high *specific heat* of water. Simply stated, water temperature changes slowly because large quantities of heat energy are required. When a stream temperature no longer changes it is said to be in equilibrium with its environment. The stream is still experiencing energy exchange, but the rate at which heat energy is entering the stream is equal to the rate at which the stream is

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shedding heat energy. **Figure 4** shows how the temperature regime of a stream reacts as it travels downstream through a watershed.

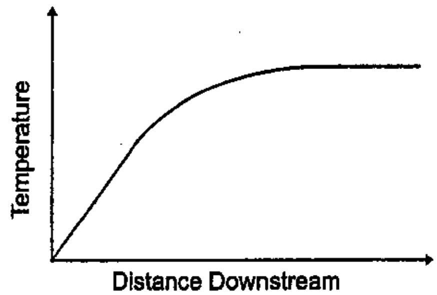

Figure 4. Stream temperature change with respect to downstream distance.

What Are Some Stream Characteristics Important to Temperature?

Several components of the stream system have the potential to significantly affect the energy balance of a stream and thus, the temperature response. Those that are considered most important in maintaining healthy stream temperatures are worthy of discussion.

Stream Surface Shading: How Much Is Enough?

It is important to remember the role that shade plays with respect to stream temperature. Solar energy is a one way heating process for the stream. Heat energy gained from the sun must be dissipated by other energy processes, namely: *evaporation*, *longwave* radiation or *convection*. For this reason, while shade does not cool stream water, it does prevent or reduce heating by *solar radiation*.

In order to assess the ability of riparian vegetation to shield a stream from *solar radiation*, we need to consider the two basic characteristics of shade: *shade duration* and *shade quality*. The length of time that a stream receives shade can be referred to as *shade duration*. The density of shade which affects the amount of radiation blocked by the shade, is referred to as the *shade quality*. To minimize stream heating from *solar radiation* two components of shade must be considered. First, the stream surface shade must persist throughout the day, even when the sun is very high in the sky. Second, the shade must block the majority of the incoming *solar radiation*.

We all know that the earth tilts on its axis away from the sun in the winter and towards the sun in the summer. Days get longer in the summer months and the sun gradually gets higher in the sky. The vertical position of the sun is known as the *solar altitude*. Due to the northern latitude of the Pacific Northwest the sun never really gets directly over head. In fact, the highest that the sun gets in the summer is roughly 70°. When applied to riparian shading of a stream, we can ensure that shade spans the full length of a day if the stream side vegetation is tall enough to block the sun when it is at the highest *solar altitude.*

The *vegetation shade angle* is the angle that exists from the top of the vegetation canopy to the center of the stream surface. As can be seen in **Figure 5**, the interaction between the *vegetation shade angle* and the sun's angle (*solar altitude*) will control the timing and duration of stream shading. Clearly the *vegetation height* and the position of vegetation relative to the stream play a role in determining the *vegetation shade angle*. An increased *vegetation shade angle* will lengthen the duration of shading that is experienced by the stream surface.

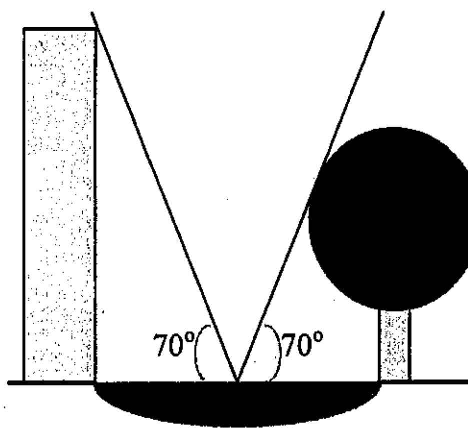

Figure 5. 70° vegetation shade angle.

The stream receives shade when the *solar altitude* is less than the *vegetation shade angle*. Once the *solar altitude* exceeds the *vegetation shade angle*, the stream no longer is shaded. **Figure 6** plots the *solar altitude* for a latitude of 45° N, on June 29, 1996. By comparing the relationship between the *vegetation shade angle* and the *solar altitude* we can determine the timing and duration of shade that a stream will receive. When the *solar altitude* is negative, it is nighttime. From **Figure 6**, we can see that when the *vegetation shade angle* is 45° the stream only receives shade in the early morning and late evening. In fact, the stream is completely unshaded between 9:30 AM and 4:15 PM. This level of shading exposes the stream to six hours and forty-five minutes of *solar radiation*. Further, the *solar radiation* flux is greatest in the unshaded portion of the day (refer to the energy balance for an unshaded stream, **Figure 2**). If the stream were to receive a complement of shade that lasted the entire day length, the *vegetation shade angle* must be increased to 70°, which is roughly equal to the *solar zenith angle* (the *solar zenith* is the highest daily *solar altitude*). With our new understanding of *shade duration*, we can now consider the quality of the shade that is offered to the stream.

The density of the vegetation, or *canopy density*, and the *vegetation width* control the quality of shade that is provided to the stream surface. Shade is enhanced by increasing the chance of collision between incoming photons from the sun and riparian vegetation.

This is accomplished by augmenting the quantity of vegetation in the riparian zone, either by increasing *vegetation density*, and/or increasing *vegetation width*. Wide riparian vegetation corridors and a dense riparian canopies will intercept more solar radiation and increase the quality of shade offered to the stream.

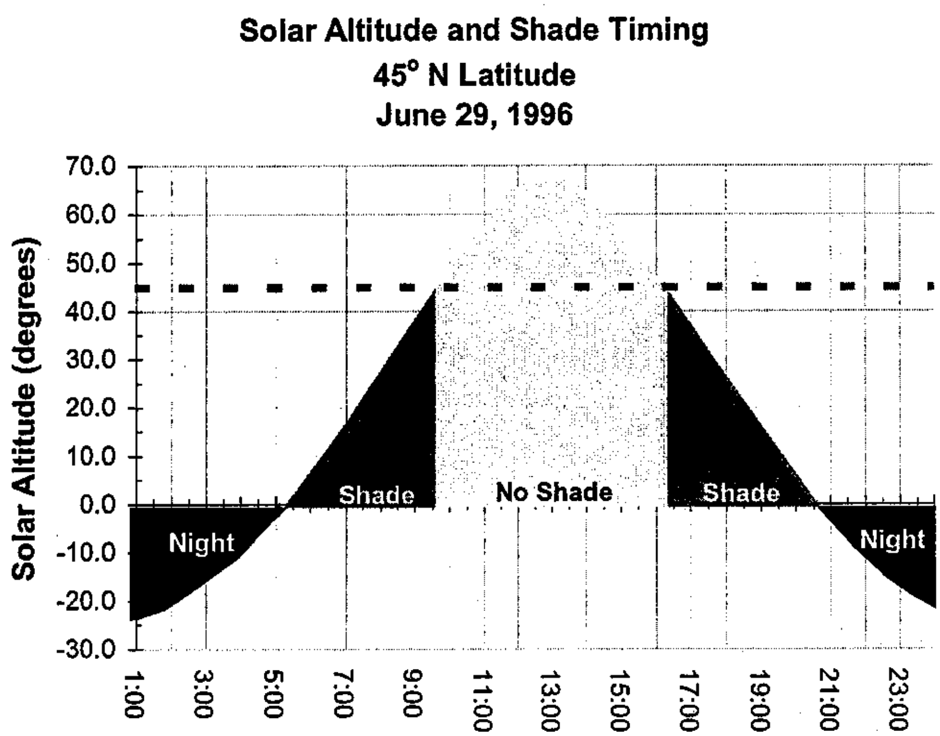

Figure 6. Diurnal solar angle profile and shade timing (Boyd 1996).

Channel Width and Channel Depth

Given that the flow volume is constant, stream widening will result in reduced *channel depth*. The depth of a stream may alter the energy relationship by allowing solar energy to strike the stream bed and thus, increase *stream bed conduction*. As the width of a stream channel increases, so does its surface area. An increased surface area will increase the amount of heat energy exchange that occurs between the stream and it's environment.

A secondary response to increased *stream width* results from the geometric relationship between the *vegetation shade angle* and *vegetation height*. It follows that a wide stream requires taller vegetation to provide adequate shading. Any confusion with this phenomena should be easily remedied by consulting with **Figure 5**. Due to increased surface area and decreased *shade duration*, wide streams experience greater heat energy loads from radiant energy when compared to streams that have a smaller width.

Flow Volume

Stream temperatures are highly dependent on *flow volume*. Streams with *low flow volumes* become extremely temperature sensitive. As the flow rate decreases, the volume of water that is involved in the heat energy balance is reduced. However, the energy processes inherent to the stream environment remain relatively unchanged. The result is that during heating periods the stream water tends to accumulate more energy per unit volume. The daily fluctuation of temperature in a small stream will be far greater than that of a large volume stream or river. Preservation of in-stream flow is helpful in establishing a healthy temperature regime. Water diversions or other means of flow reduction may cause excessive stream temperature increase. Stream flow magnitude is potentially the most significant stream parameter leading to stream temperature change. Note the potential for large temperature change as the flow volume decreases, as depicted in **Figure 7**.

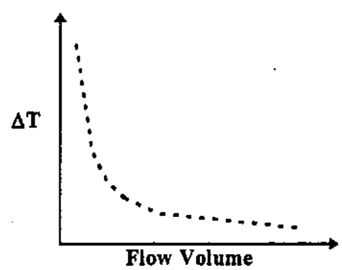

Figure 7. The relationship between stream temperature change and flow volume.

Is There Field Data to Confirm The Scientific Theory?

Some of the largest increases in stream temperatures have been caused by forest practices that removed riparian vegetation. Meehan et. al. (1969) found that an Alaskan stream experienced a 7°F increase in the maximum temperature following a clear cut. While studying clear cut streams, Greene (1950) reported a maximum weekly temperature that was 13°F greater than that recorded on a nearby stream.

The Alsea Watershed Study

Perhaps the most significant study, designed and implemented by Brown and Krygier (1970) to highlight the importance of riparian vegetation for stream temperature control, was part of the Alsea Watershed Study located in the Oregon Coast Range. Two similar watersheds were selected in the Alsea basin. One watershed was left alone as a control, while the other was clear cut from April to July, 1966, fully exposing the stream. Mean monthly maximums increased by 14°F during the summer of 1967, the first year after being logged. **Figure 8** shows the mean monthly maximum stream temperatures of both the clear cut and the uncut control watersheds. On days in which the annual maximum occurred, the daily temperature profile was recorded, as depicted in **Figure 9**.

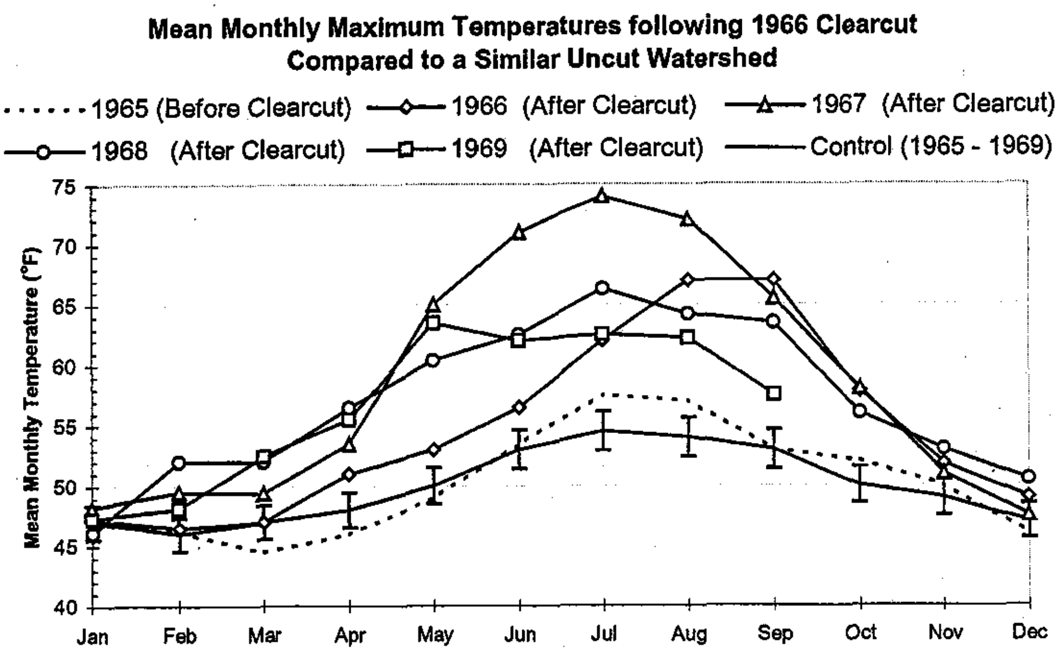

Figure 8. Mean monthly maximum temperatures for the clear cut and uncut control watersheds (data taken from Brown and Krygier 1970).

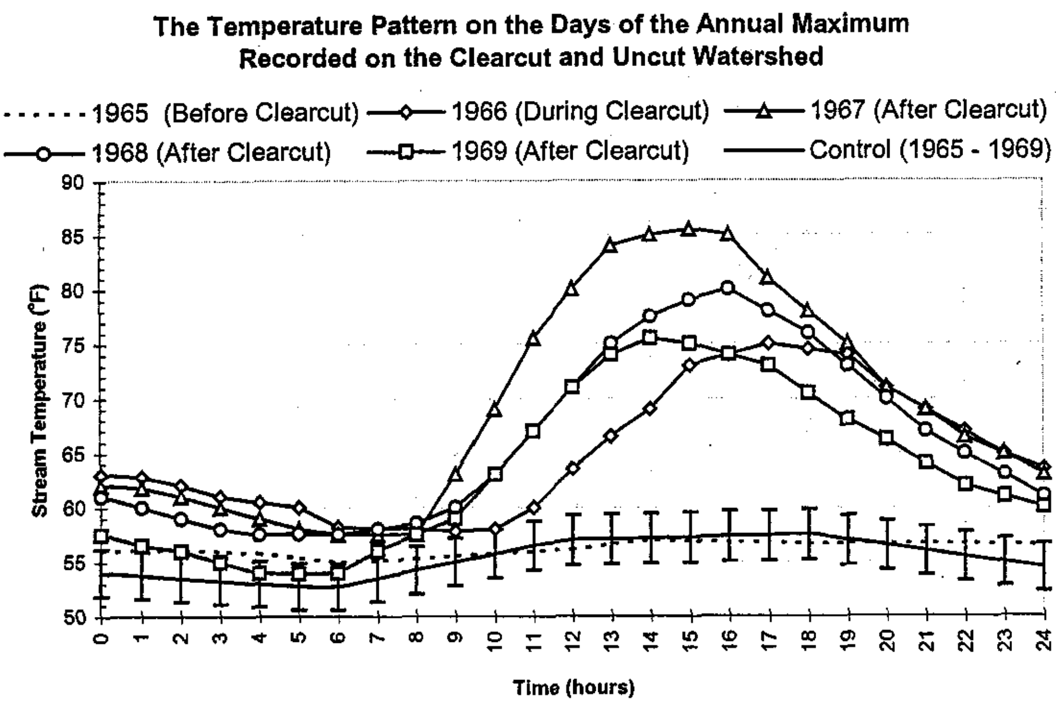

Figure 9. The daily temperature profiles on the days of the daily maximum record for the clear cut and uncut control watersheds (data taken from Brown and Krygier 1970).

The results from the Alsea Watershed Study clearly demonstrated the importance of riparian vegetation in shading the stream surface and reducing the solar energy input. Brown (1983) determined summertime solar energy input for both a shaded and unshaded stream and demonstrated the importance of shade in reducing the heat energy contributed by the sun.

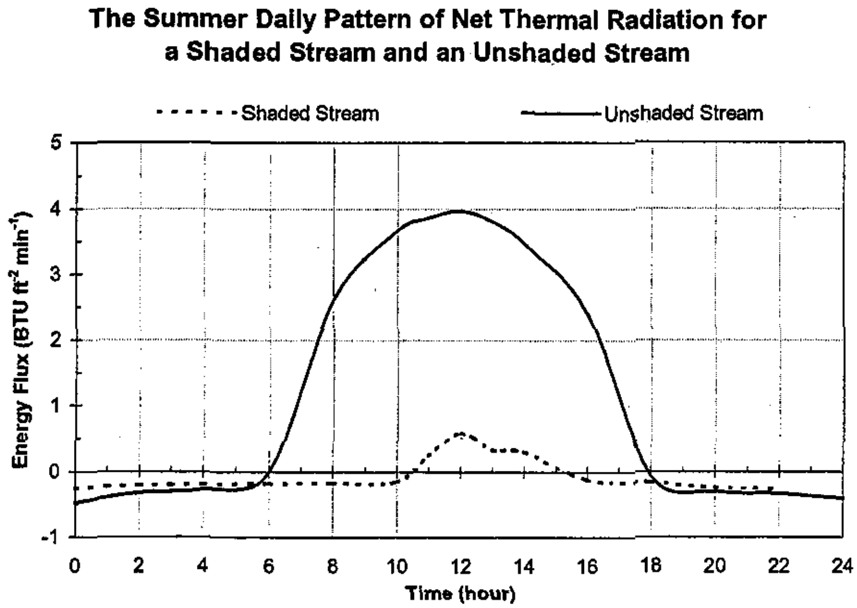

Figure 10. The summer daily pattern of net thermal radiation for a shaded and an unshaded stream (data taken from Brown 1983).

Steamboat Creek Basin

In a 1969 study conducted in the Steamboat Creek basin (Umpqua Basin, Oregon) substantial increases in stream temperature were identified by measuring water temperature above and below clear cuts. The most dramatic measurement found a 14.4°F temperature increase that occurred in roughly 3/4 of a mile (1280 meters) on Cedar Creek, a tributary of Steamboat Creek (Brown et. al. 1971). The relatively high stream temperatures were directly related to the removal of shading vegetation over and along the creek (Hostetler 1991). Since the 1969 logging, temperature records have been maintained to track the recovery of the basin. The temperature records, as depicted in **Figure 11,** clearly show that the temperature of Cedar Creek has gradually decreased (Hostetler 1991). As riparian vegetation continues to increase the quality and quantity of shade offered to the Steamboat basin, stream temperatures are expected to continue to decrease. It should be noted that it has taken over twenty years for the basin stream temperatures to recover.

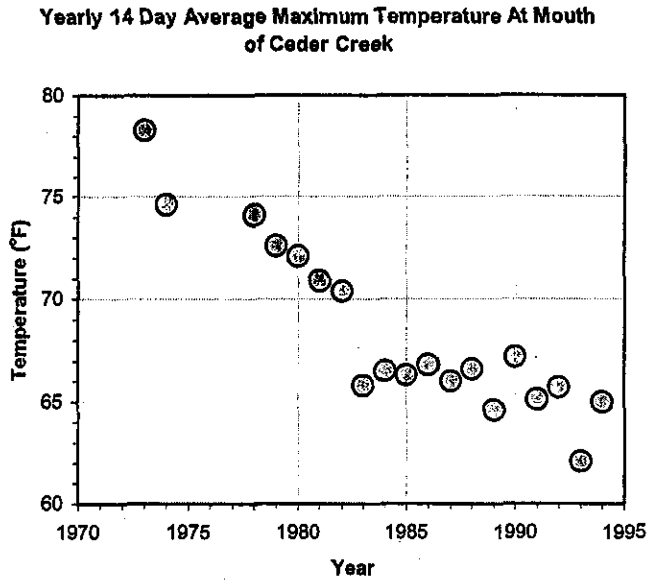

Figure 11. Yearly 14 day maximum stream temperatures at the mouth of Cedar Creek (data provided by Michael Jones in conjuction with the Umpqua National Forest).

Camp Creek: A Tributary to the John Day River

Camp Creek, a tributary to the John Day River, is located in northeastern Oregon's Blue Mountain Range. An interesting study undertaken by Claire and Storch (1977) investigated grazing along the banks of Camp Creek and the effects it had on stream temperature. A section of Camp Creek that had been grazed summer long was fenced in 1964 to exclude livestock from grazing riparian vegetation. Prior to fencing, this section of Camp Creek had no vegetation canopy over the stream, virtually no shrubs or woody vegetation in the riparian zone and stream banks were exposed. After ten years of changed management (4 years of total livestock exclusion, followed by limited riparian grazing), the fenced portion of Camp Creek had changed drastically. Alders, willows, shrubs and other woody species provided over 75% shade to the fenced section of stream, where ten years prior no shade existed. Downstream from the livestock exclusion area, conditions remained the same: little woody riparian vegetation, exposed stream banks and nonexistent stream surface shading.

Claire and Storch (1977) found the maximum stream temperatures in the fenced section of Camp Creek to be 12°F lower than the maximum temperatures recorded in the unfenced section downstream (66° and 78°F, respectively). The daily stream temperature fluctuations for each section are shown in **Figure 12.** The grazed stream segment experienced a daily stream temperature change that was twice that experienced by the fenced section of Camp Creek. The recovered stream section also showed increased cold-water fish numbers, as shown in **Figure 13**. Game fish populations in the fenced stream section were over three times that of the unfenced section of Camp Creek.

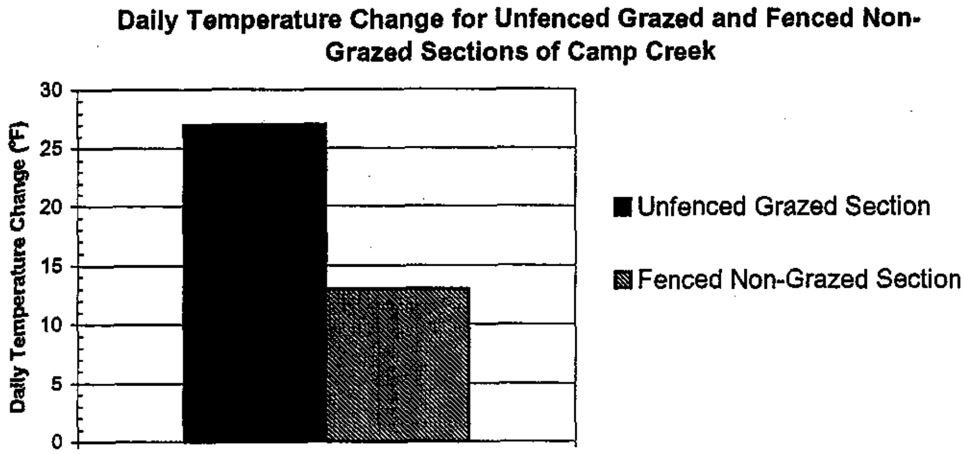

Figure 12. Daily temperature change for fenced non-grazed and unfenced grazed section of Camp Creek, a tributary for the John Day River (data taken from Claire and Storch, 1977).

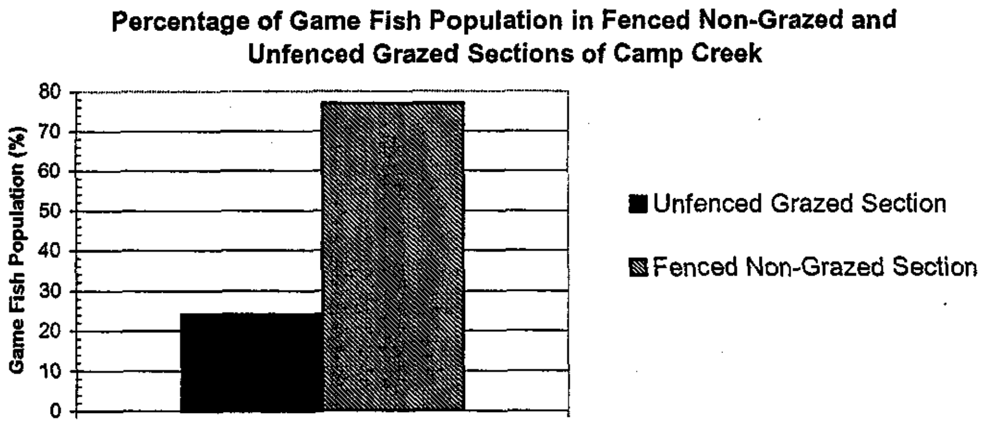

Figure 13. Cold water game fish as a percentage of total fish population inventoried in the fenced non-grazed and the unfenced grazed section of Camp Creek, a tributary for the John Day River (data taken from Claire and Storch, 1977).

The importance of stream surface shading to the thermal health of streams and rivers is demonstrated in all three studies: the Alsea watershed study, Cedar Creek and Camp Creek. The Camp Creek study is not to intended to implicate grazing as a land use practice. Instead, it is included to demonstrate of the importance of riparian shading in reducing the rate at which streams heat and cool. The Alsea watershed and the Cedar Creek studies are not presented to indict forest practices. However, these studies show that the reduction or removal of stream surface shade leads to increased summertime stream temperatures. What is clear from these studies is that shade is an important stream component, regardless of the topographic region in Oregon: coastal, valley, Cascade, high desert and rangeland.

energy processes, namely: *evaporation*, *longwave radiation*, and in some cases, *convection*. Unfortunately, *solar radiation* has the potential to deliver vast quantities of energy that can heat a stream rapidly. Land managers should focus on two main components. First, streams must experience long duration quality shade. Second, the stream surface area exposed to *solar radiation* should be reduced by augmenting bank stability, which in turn, will decrease channel width. In terms of channel morphology and riparian vegetation, unhealthy stream temperatures are a symptom of a degraded stream system.

How Does the Water Quality Standard for Stream Temperature Relate to Natural Stream Temperature? Surely Some Streams Have Always Gotten Warmer than 64°F.

The standard does not attempt to mimic "natural" stream temperatures or the stream temperatures that existed prior to the time European settlers and their livestock began to influence the landscape, more than 150 years ago. Rather the standard is based on the available body of science describing the temperature requirements and preferences of the state's native aquatic biota.

There are several reasons why we chose not to reconstruct historic temperatures and base the standard on what we thought each stream could attain under ideal or natural circumstances. First, there is a lack of data on historic stream temperatures. While there may be some data contained in old journals and archives, this information is not readily available. Routine stream temperature monitoring and record keeping began relatively recently, well past the time human activities began to influence watershed and stream characteristics.

Second, we now have models that can accurately simulate temperature for stream and river reaches, but whole basin models are not yet as reliable for large scale simulations. Additionally, such models require a large amount of data which was unavailable during the standard review process.

Finally, the purpose of the standard is to protect the beneficial uses. Therefore our approach was first, to identify the beneficial uses of Oregon waters most sensitive to temperature, which are the aquatic species; and second, to base the temperature criteria on the available science on the requirements of those uses.

Some streams in our state have likely always reached a summer maximum temperature greater than 64°F. The number of such streams is unknown. We do not expect, through management, to attain a maximum of 64°F for every stream. This is why the standard is crafted such that exceeding the criteria triggers development of a management plan. The goal of the plan is to reduce stream warming and reach the criteria, but where this is not possible, there is a provision in the standard to allow adoption of stream specific criteria. The temperatures achieved when all feasible steps are taken becomes the criterion for a first step is to evaluate the cause of the violation. For streams where human activity contributes to stream warming, management plans or TMDLs must be established. The water quality management plan or TMDL begins with an assessment to further define the problem and it causes and then lays out a strategy to bring the stream into compliance with the water quality standard.

What Is Expected of Land Managers?

Land managers are expected to follow the water quality management plan for stream temperature applicable to their watershed/sub-basin. If the plan is being implemented and appropriate land management practices, measures or controls are being utilized, the individual land owner or manager will be considered in compliance with the water quality rules for temperature, even if the stream flowing through or adjacent to their property exceeds the criteria.

Landowners who are willing to participate in the development of management plans will have the opportunity to do so by working with the designated management agency responsible for the plan development. DMAs will commonly be the Oregon Department of Agriculture, the Oregon Department of Forestry, cities, counties, and federal land management agencies such as the USFS or BLM. Management plans for private agricultural lands will be developed through the Agricultural Water Quality Management Plan (SB1010) process under the Oregon Department of Agriculture.

What Is a Water Quality Management Plan for Temperature?

A Water Quality Management Plan for temperature is a plan that describes how land managers will take actions (measures, management practices, control technologies) to minimize the impacts of human activity on stream temperature. The plans may take the form of describing watershed and streamside conditions to be achieved or avoided and then identify the management practices or actions land managers can choose to achieve those conditions. In other cases, particular practices may be identified, such as in the state's Forest Practices Act rules.

More Questions For The Especially Curious...

Eastern Oregon Has a Different Climate, So Shouldn't Stream Temperature Criteria Be Different than for Other Parts of the State?

Answer: The criteria in the standard are based on the needs of the salmon and trout that reside in streams throughout much of Oregon. The information available at this time does not warrant different criteria for Eastern Oregon salmon and trout populations based on the needs of the fish. In addition, many streams in Oregon, regardless of region, topography and climate, have the potential to meet temperature standards if they are adequately vegetated and shaded.

The criteria in the temperature standard are based on the needs of the beneficial uses most sensitive to temperature - aquatic organisms. The available information does not adequately show that salmon and trout populations in Eastern Oregon have temperature requirements different from those same species in Western Oregon to warrant a different criteria in the standard. If evidence becomes available to show that there are local exceptions to this, basin specific criteria can be established that will supersede the general criteria.

The energy processes that induce water temperature change can be applied to all streams and rivers in the State of Oregon. Unhealthy summertime stream temperatures are the result of excessive exposure to *solar radiation* stemming from the absence of long duration quality stream surface shade and, perhaps changes in channel morphology and streamflow as well. Regardless of which region you are located in the State of Oregon, riparian zones are highly productive areas that are capable of sustaining healthy riparian vegetation. Many streams in Oregon, regardless of region, topography and climate, have the potential to meet temperature standards if they are adequately vegetated and shaded.

What Is the *Adiabatic Lapse Rate* and How Does It Relate to Stream Temperature?

Answer: Based on the current level of scientific understanding, the adiabatic lapse rate does not cause unhealthy stream temperatures.

The air above the surface of the earth has a weight that is exerted on whatever is below, a condition measured and reported as *atmospheric pressure*. It follows that at higher elevations the *atmospheric pressure* decreases. Therefore a rising parcel of air will expand and a descending parcel of air is compressed. It takes energy to compress air. The physical effort, referred to as *work*, required to compress air is transferred into heat energy. After a few minutes of inflating a tire, notice that the pump warms. The mechanical *work* done to compress the air is partially expressed as heat energy.

Conversely, expanding air will release heat energy and cool. The process in which air is compressed and heated or expanded and cooled, without heat exchange caused by mixing with the surrounding air, is called *adiabatic.* The rate at which unsaturated air cools by *adiabatic* lifting is approximately 1°C/100 meters (≈1°F/182 feet) is called the *dry adiabatic lapse rate* (Brooks et. al. 1993). Increasing amounts of water vapor in the air, known as the *relative humidity*, will decrease the *adiabatic lapse rate*. Less cooling will result from expanding humid air; less warming results from compressing humid air. A humid air column may change 3°F per 1000 feet, while a dry air column may change 5.5°F per 1000 feet.

So how does the *adiabatic lapse rate* relate to unhealthy stream temperatures? The *adiabatic lapse rate* has very little to do with unhealthy stream temperatures. Instead the adiabatic lapse rate explains that air temperatures are generally warmer at lower elevations. *Adiabatic processes*, however, are not responsible for excessive stream temperatures. In no way can *adiabatic processes* be linked to large daily stream temperature fluctuations that require the exchange of vast amounts of heat energy. The energy process in which the *adiabatic lapse rate* influences water temperature, namely air-water *convection*, simply cannot deliver the large quantity of heat energy required to cause rapid temperature change.

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