Riparian Shade and Stream Temperature: A Perspective

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Reductions in salmon populations over the past 20 years have created a sense of urgency for improved management of watersheds, fish habitat and water quality within the Columbia River Basin. One management approach that has gained in popularity is to increase woody vegetation in riparian zones. The intent behind these plantings is to increase bank stability, stream debris and provide shade for stream temperature control (Beschta 1991)

Oregon Department of Forestry (1994) has established forest rules and regulations for riparian zones of 40 live conifer trees per 1,000 feet along large streams and 30 live conifer trees per 1,000 feet along medium streams. Similarly, Oregon Department of Environmental Quality is developing water temperature standards for streams throughout the state. In northeastern Oregon the Upper Grande Ronde River Plan established watershed standards that require meadows to have at least 80% of the banks covered with shrubs, of which, at least 50% should be more than 8 feet tall (Anderson et. al. 1993). These approaches reflect the view that streamside forests profoundly influence habitat structure and food resources of stream systems. Additionally, tree height and distance away from the stream are considered meaningful indicators of aquatic habitat components including wood recruitment and degree of shade (Thomas et. al. 1993).

Activities by man that modify the amount of shade over streams have been associated with changes in water temperature (Brown et. al. 1971). Some researchers have concluded that loss of vegetation in a riparian area due to grazing, logging, or overuse by other activities can be directly linked to undesirable water temperatures due to the loss of shade (Anderson et. al. 1993).

The establishment of vegetation shade along streams to control stream temperature may seem reasonable upon first review. However this is a simplistic view of a complex and dynamic system. The purpose of this paper is to provide a discussion of energy exchange within a body of water and to consider the contribution of vegetation shade to that process. This discussion will occur in two sections: 1) Characteristics of water, water heating, and water cooling, and 2) The creation of woody vegetation shade in riparian areas. This paper is not intended to provide a complete review of the physics of energy exchange, nor will it provide discussions of more complicated forms of energy exchange in streams. Four equations (boxed) are provided as reference material in this paper. They are not required to read the text of this paper.

Characteristics of Water, Water Heating, and Water Cooling

Energy exchange is described by the First and Second Law of Thermodynamics (Halliday and Resnick 1988). These laws tell us that we can transform but not create or destroy energy and that the direction of energy exchange will occur from areas of high concentration toward areas of lower concentration.

The heating of a natural body of water is governed by two primary radiation sources: the sun, and the ambient radiation emitted by the atmosphere and the earth. A representative value for this daily incoming radiation in the temperate zone on a clear summer day would be 332 W m^{-2} of solar radiation and 330 W m^{-2} of ambient radiation (Satterlund and Adams 1992). The distinction between radiation sources is necessary because rock, vegetation, water, road surfaces etc. absorb, emit and reflect radiation differently, and can significantly affect radiation inputs in a given area.

An average of 19% of the solar radiation striking the atmosphere actually reaches the surface of the earth as direct radiation. An additional 28% will arrive at the earth surface as diffuse and scattered radiation (Trewartha 1968). Shade is created by intercepting direct solar radiation and preventing it from reaching the surface of the earth.

Visible solar radiation is predominantly in the range from violet to red (400 nanometers to 700 nm). These wavelengths are mid-range to the total solar radiation that reaches the earth. Water is transparent to visible solar radiation (the radiation is not absorbed) and is least likely to absorb the energy contained in the blue (400 nm) and green (500 nm) color bands (Hollaender 1956). Approximately 95% of visible radiation will penetrate a column of clear water to a depth of 3 feet and over 75% will penetrate to a depth of 30 feet (Hollaender 1956, Sellers 1974). This characteristic permits us to see objects in the water and photosynthesis to occur beneath the surface of the water.

In contrast, water is opaque to near-infrared (700–1,000 nm) and ambient (>1,000 nm) radiation. Nearly 90% of this radiation is absorbed in the top 0.5 inch of a water column and 100% will be absorbed within the top 4.0 inches (Hollaender 1956, Sellers 1974). The absorption of this energy warms the top 4 inches of the water column without directly warming the water at greater depths. These interactions (visible, near-infrared, and ambient radiation) vary with the season of the year, time of day, water turbidity, and surface turbulence.

Energy exchange between water and incoming radiation can be estimated mathematically (Equations derived from Sec. 7-6, Eqn. 21 and Sec. 20-3, Eqn. 3 are provided in the the following box; Halliday and Resnick 1988).

$$\tau = \frac{Q}{P} = \frac{Q}{SA}$$

Where

$$Q = mc\,(T_f - T_i)$$

Here, τ is time (s); **P** is the total energy delivered to the water per second (W); **Q** is the amount of heat deposited in the body of water (J); **A** is the surface area of the body of water exposed to the radiation (m^2); **m** is the mass of the body of water (kg); **c** is the specific heat capacity of water (4,190 J kg^{-1} @ 288°K); $\mathbf{T_f}$ is the final temperature of the body of water (K); $\mathbf{T_i}$ is the initial temperature of the body of water; and **S** is the radiation at the surface of the water (W m^{-2}).

To illustrate, assume there is a stationary column of water (12 inches x 12 inches x 12 inches deep at 60°F) that is receiving the radiation amount (average) received at La Grande, Oregon at Noon and 2 PM, 734 W m^{-2} and 674 W m^{-2} respectively (Solar Monitoring Lab. 1987). Also assume that none of the incoming radiation is reflected by the water surface and that none of the radiation can escape once it penetrates the surface of the water column. Given these constraints it would take 16 minutes to raise the temperature of the water column by 1° F at Noon and 17.5 minutes at 2 PM. However to be accurate this estimation would need to be corrected for changes in the water surface reflectance, the transparency of water to visible radiation, heat exchange with other thermal bodies (i.e. soil), and the mixing associated with a stream environment. These factors increase the length of time required to detect a measurable increase in water temperature. If shade were introduced into this example it would intercept direct solar radiation. It would have little influence on diffuse, scattered or ambient radiation sources.

The problem of water cooling is a more complex issue both conceptually and mathematically. Water must convert and radiate its internal energy (in the form of heat) out into the thermal reservoir of the atmosphere. This process is governed by a partial differential equation known as the 'one dimensional heat equation,' or the 'diffusion equation' (Sec. 8-3, Eqn. 8-60, equations are provided as follows; Matthews and Walker 1970).

$$\frac{\partial^2 T}{\partial \mathbf{x}^2} - \frac{1}{\kappa}\frac{\partial T}{\partial \mathbf{t}} = 0$$

Where

$$\kappa = \frac{k}{\rho \mathbf{c}}$$

Here **x** is the position in the water column (m), κ is a constant depending on the thermal conductivity ***k***, the heat capacity **c**, and the mass density ρ.

The solutions to this equation depend strongly on the initial temperature distribution assumed for the body of water, and the temperature of the air mass over the water. For simplicity we will use the water column previously described and assume that there is no heat exchange through the sides or bottom of the water column. In addition, we assume that the water and air each have uniform temperatures (water, 77°F; air, 68°F) before the onset of cooling, then as it cools, a temperature gradient forms between the top (coolest) layer of water, and the deepest (warmest) layer. Given these constraints, the rate of cooling will be a strong function of time and water depth, slowing down as the water and air mass approach the same temperature. In this example, water at a depth of 4 inches will cool only 4.5°F in approximately 1.5 days. This demonstrates that cooling water by diffusion is a relatively slow process. It does not illustrate the influence of stream mixing or any of the more complex thermal exchanges that could occur within a water channel.

This example would seem to be contrary to one's ideas about cooling. When one steps from full sunlight into shade, it appears to be cooler. This is not because of a rapid cooling effect brought on by shade, but rather a manifestation of a human body's response to full sunlight. **Shade does not produce cooling, but rather prevents heating by direct solar radiation.**

If the water is in contact with an energy source (i.e. air, soil, etc.) that has a greater temperature, energy will be transferred into the water body. As a result water traveling through shade will gain energy if the air mass temperature is greater than the temperature of the water.

The Creation of Woody Vegetation Shade in Riparian Areas

Shade creation is bound by a number of constraints. The angle and direction of solar radiation is controlled by global position, time of year and time of day. The greatest solar angle during the summer in the northern hemisphere occurs at Noon on June 21 and decreases on the days preceding and following the summer solstice. Similarly, the greatest daily solar angle occurs at Noon (standard time) and decreases in both the AM and PM.

The greatest intensity of solar radiation occurs when the sun is directly overhead. Deviations from the zenith position reduce the intensity of radiation by spreading energy over a larger surface area (Trewartha 1968, Satterlund and Adams 1992). Therefore the greatest reduction in direct radiation through the use of shade would occur at the time of the greatest solar angle.

An illustration of the influence of the solar angle on shading is provided in Figure 1. In this illustration the trees are 20 and 50 feet in height and July shadows (45° N Lat.) are being cast at 12:00 Noon and 2:00 PM, respectively. The trees are 10 feet from the edge of a 40 foot wide water channel that flows from east to west. Given these parameters the 20 foot tree does not cast a shadow on the water at either time. The 50 foot tree would cast a shadow extending 12 feet into the

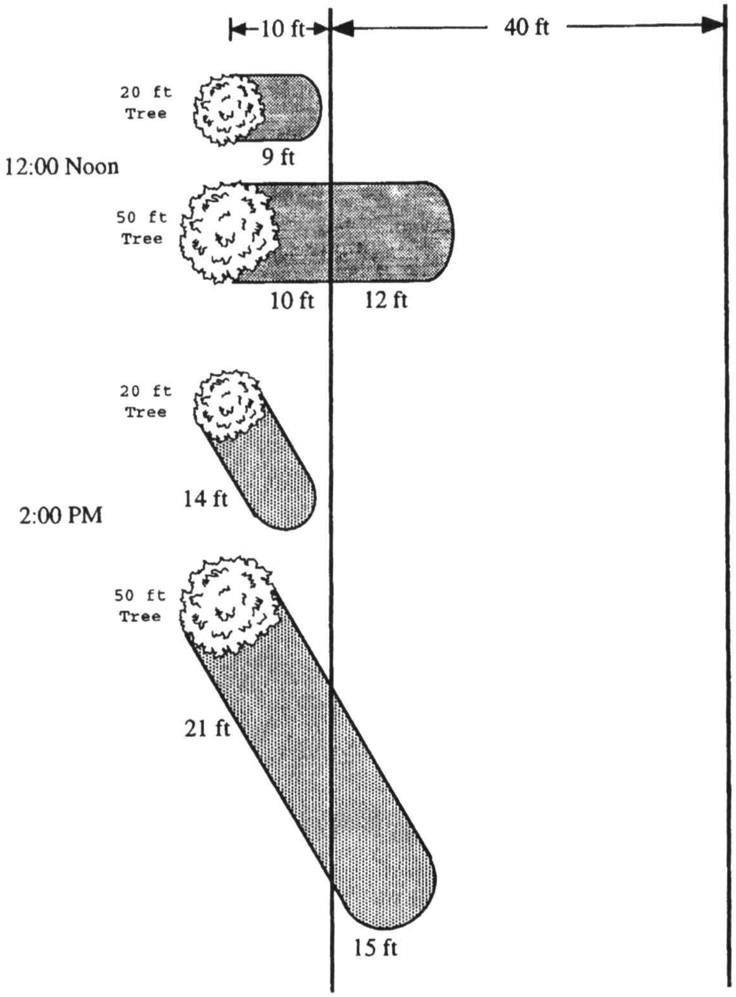

Fig. 1. *Shadows cast by 20 and 50 foot trees in July (45° North Latitude) at 12:00 noon and 2:00 PM along a 40 foot wide stream channel flowing east to west. Shadow lengths are measured along the centerline of the shadow. The trees are planted 10 feet from the stream channel.*

channel at noon and 15 feet into the channel at 2:00 pm. The implication of this illustration is that a 'windbreak' of 50 foot trees would expose 60 to 70% of the water to direct solar radiation.

Observations and Conclusions

Based upon the above discussion there are a number of observations that can be made. The capacity of a stream to buffer against temperature increase is directly influenced by water volume and the size of the surface area that is exposed to the energy source. This capacity can be modified directly through the addition of snowmelt and interflow. Similarly, over-night low air temperature will modify the daily temperature range of a stream by influencing pre-dawn water temperature.

The specific heat of water allows water to absorb considerable amounts of energy before its temperature will increase. Similarly, a warmed stream must release significant amounts of energy before cooling can take place. The minimum temperature that water can be cooled will be the lowest temperature in the local environment (i.e. air or stream bank temperature). This means that it will be difficult to cool a stream in a warm environment. This statement is true whether the stream is shaded or not.

It is true that shade can be used to intercept direct solar radiation over water. However, in reality this interception will yield only limited benefit in many situations. Total surface radiation is comprised of solar radiation (direct, diffuse and scattered) and ambient radiation. Direct sunlight only accounts for approximately 20% of the total, and as a result, shaded areas can receive up to 80% of the total radiative energy available at the surface. Furthermore the ability of woody vegetation (the physical limitation of height growth) to shade a stream decreases with increasing stream width. The value of shade is further influenced by the structure and orientation of the woody vegetation that creates the shade. A stream running east or west will have an entirely different shading pattern than one running north or south. Shade generated from a tall canopy of cottonwoods with an open understory will result in a different shading influence (i.e. canopy closure and air movement) than a mixed conifer community with multiple vegetation strata. Shade generated by the topography and/or stream channel will also contribute different levels of shading and exposure for water. Consequently, shade standards should indicate the amount of shade needed, not the quantity and size of woody vegetation.

Woody vegetation is only one component in a riparian ecosystem. Its importance is dependent upon site conditions and is site specific. Watershed attributes such as air mass characteristics, elevation gradient, adiabatic rate, channel (water) width and depth, water velocity, surrounding landscape, and interflow inputs all influence water temperature and can be of equal or greater importance to stream temperature than vegetation shade.

The history of land management in riparian zones includes periods of channelization, tree removal, the development of stream structures, the removal of large woody debris, and corridor fencing. All of these management strategies, like the current desire to control stream temperature with vegetation shade, were intended to meet a recognized land management need. Unfortunately the application of a standardized management strategy that does not account for the dynamic nature of a riparian zone will likely lead to more failures than successes. Land management decisions need to be site specific and they need to be made by qualified land managers. Streamside vegetation can improve bank stability, increase habitat for some species of wildlife, and serve as a component in the system as a whole, but shade does not control stream temperature.

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