The Natural Heating and Cooling of Water

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In accordance with an Environmental Protection Agency (EPA) mandate established by the Clean Water Act (1972), many states of the Pacific Northwest are establishing water temperature standards and regulations to protect their most sensitive beneficial uses of water.

In application, a number of state regulations are being established that apply equally from head waters to state borders, regardless of stream or river location. This approach has raised questions about the appropriateness of the standards and whether they take into account 'natural' temperature fluctuations.

If the intent of a regulation is to maintain water temperatures within the range of natural temperature fluctuations and prevent heating by anthropogenic sources, then the natural pattern of heating and cooling must be established. The purpose of this paper is to provide a perspective regarding factors that must be taken into consideration to determine 'natural' temperature fluctuations for water bodies.

Climate as a Driver of the Thermal Environment

The first step in this process is to recognize the influence of global climate on the thermal environment of a stream. From a global perspective the Earth's atmosphere gains energy from the ocean and land masses. Differential heating of these surfaces by the Sun creates pressure systems, climatic patterns, and ocean currents that circulate over the globe redistributing energy and water. As a result, the rise of average surface-air temperatures typically lag 4 to 8 weeks behind the period of maximum solar radiation (summer solstice), shifting the period of maximum summer heating from June into July and August (Trewartha 1968).

On a watershed scale, both air and soil serve as large thermal reservoirs that are directly influenced by these global patterns of heating and cooling. These reservoirs are large in comparison to flowing streams. In many respects their relationship resembles a narrow layer of water flowing between two hot water bottles. In this situation one would anticipate that the temperature of the layer of water would be dependent upon, not independent of the temperature of these thermal reservoirs, and would provide a direct influence on the upper and lower temperature limit that water can achieve.

Energy Exchange and Natural Systems

Energy exchange is described by The First and Second Law of Thermodynamics (Halliday and Resnick 1988). These laws state that we can transform but not create nor destroy energy and that energy exchange occurs from areas of high temperature toward areas of lower temperature.

Table 1 provides an illustration of the temperature patterns that can be observed in Northeastern Oregon in the summer between a stream and its associated soil and air mass. During summer, air typically warms during the day to temperatures that are greater than the temperature (62°F) maintained beneath the soil surface (1 ft. depth). The water and soil, having a lower temperature receives energy from the air and sun as a day progresses. The daily temperature pattern of the water in a stream then is determined by its initial temperature at sunrise, the volume of water (depth), surface area, and how long it is exposed to the sun, air and soil.

Table 1. Temperature pattern of the air, water, and soil (1 ft. depth) in a riparian environment in NE Oregon at 3,000 ft. elevation in August.

Time	Air °F	Water °F	Soil °F
7 AM	57	57	60
8	55	57	60
9	58	58	60
10	61	59	60
11	64	60	60
11:30	63	61	60
NOON	63	61	60
1	67	62	60
2	68	63	60
3	70	65	60
3:30	72	67	61
4	72	67	61
5	73	67	61
6	74	67	61
7 PM	68	66	61
7:30	64	66	61
8	61	65	61
9	56	64	62
10	54	63	62
11	50	62	62
12	48	62	62

Air temperature can be used as an indicator of the thermal environment surrounding the layer of water. If the difference between the air temperature and the water temperature is large we can expect the rate of water heating to be more rapid than when the difference is small. Table 1 illustrates the daily pattern of warming that occurs in the thermal environment that surrounds a stream and the lag time that exists between daily peak solar radiation and maximum air, water, and soil temperature. Throughout the day, water temperature increases at a rate that is influenced by the temperature of the air mass. This phenomenon occurs on all streams at all elevations. The size of the difference between air temperature and water temperature (the gradient) influences how fast water will heat and cool.

Should Streams Heat as You Move to Lower Elevations?

The daily temperature range of a stream is influenced by the environment through which it flows. Streams originating at high elevations in mountainous regions, flow through a warming environment as the water flows to lower elevations. For most people this warming trend is observed in changes in air temperature. The rate of air temperature change typically ranges between 3.2°F and 5.5°F per 1,000 feet of elevation (Satterlund and Adams 1992) and is described as the adiabatic rate of heating and cooling. Similarly a pattern of temperature change can be observed in the soil (1 ft. depth) as you travel from high to low elevations.

Figure 1 shows daily low water temperatures at two elevations on the same stream. These water temperatures were recorded each day at 6 am during August. Water temperatures taken at 6 am have stabilized with the thermal environment of the watershed overnight and approach ambient conditions. In this example the differences between the water temperatures observed at the two elevations on a daily basis, fall within the anticipated differences of the adiabatic rate. The differences between the recorded low temperatures, are between 3.2°F and 5.5°F per 1,000 feet of elevation difference.

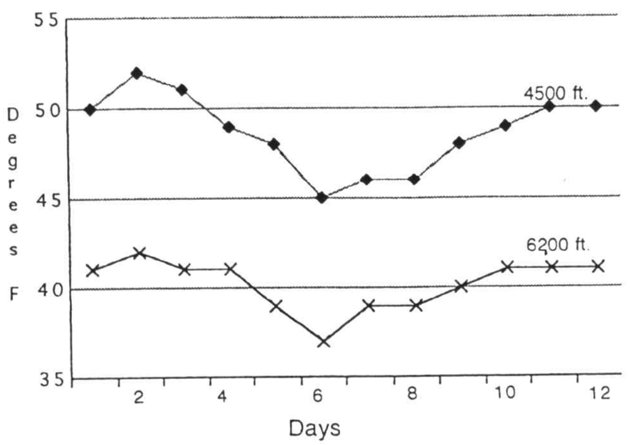

Fig. 1 *Daily low water temperatures measured at two elevations for 12 consecutive days in August at 6 am.*

Combining Elevation and Flow

Figure 2 shows water temperature data taken on the same stream as it drops approximately 1,700 feet in elevation and travels 4.1 miles. If a tennis ball was maintained in the current of the stream at 6,200 feet it would take 4 hours for it to reach the 4,500 ft. elevation with a stream flow of 1.5 ft/sec. In this example air temperature increased at a rate that falls within the anticipated adiabatic rate of 6.4°F to 11°F during the 4 hour time period.

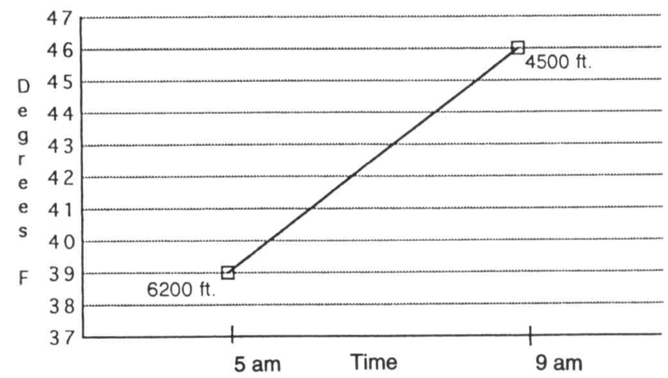

Fig. 2. *Water temperature increase over a 1,700 ft. elevation drop and a 4 hr. flow period. Temperatures were recorded at 5 and 9 am with air temperature differences of 47°F and 58°F respectively.*

If we were to continue to observe the pattern of air temperatures, we would find that the top and bottom locations increase 10°F and 20°F between 9 and 10 am respectively. Water during that same period increased only 1 degree at each location. This is a daily phenomena that occurs on clear summer days. At 10 am the sun reaches an altitude in the sky when maximum solar heating begins to take place.

Generally air heats slowly between 5 am and 10 am while the water remains fairly constant. By 10 am when air temperature increases 10°F to 20°F due to the increased solar angle, a steep gradient is established between the air and water temperatures. During the next 5 hours the water temperature increases 2–3 degrees each hour depending on the increase in the thermal environment as indicated by air temperature during the same time period.

Water temperature data collected at a single site can only describe a volume of water at a specific time as it flows over the thermometer's location. To understand how much that volume of water heats during a day, at least 2 sites must be monitored. The natural heating and cooling of water within a watershed can then be described using rate of flow to estimate the influence of the thermal environment on water during a time period.

Time and Temperature Gradients

At any point along the stream the gradient between air temperature and water temperature will vary from hour to hour. Maximal heat transfer occurs when the gradient is steepest.

Generally water at higher elevations accumulates energy at a different rate than those at lower elevations (Fig. 3). Higher elevations have lower water temperatures at sunrise and greater average gradients during the day. This might

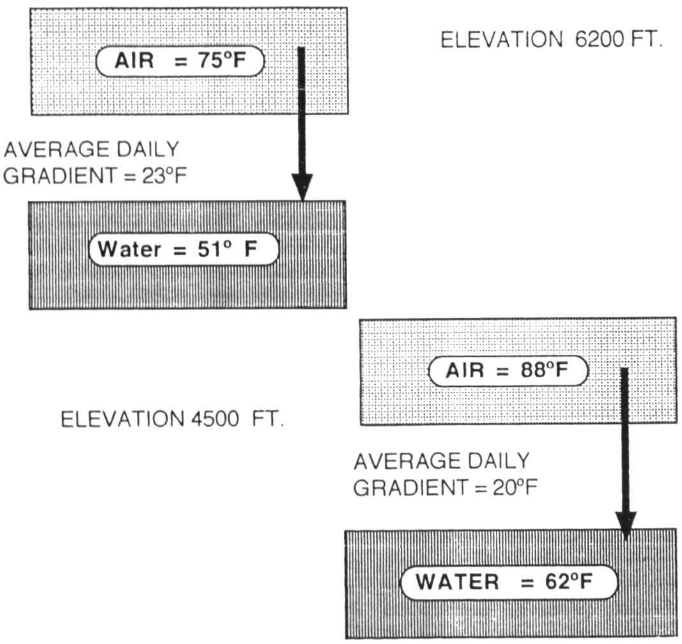

Fig. 3. *Gradients of the difference between air and water temperature at 2 elevations. The arrows represent the thermal gradient from air to water at 2 pm. The average daily gradient is the average of the air and water temperature differences measured at hourly intervals.*

suggest that the water temperatures would be higher than a similar body at lower elevations. This is not the case. Water heating at higher elevations is restricted to a short time period. This is due to a rapid thermal cycling of the local environment which results in less energy accumulation. Given this, water temperatures at lower elevations will have a greater increase in temperatures than those at higher elevations.

When all these processes are combined (elevation, time, rates of heating and cooling, and the difference between air temperature and water temperature) the framework of the thermal environment in which a stream is flowing is described. However, as recognized in the principles of thermodynamics and the examples provided in this paper, modification of one or more of the thermal sources will result in a different rate of heating or cooling.

Observations

1. Climates produce weather systems that determine the patterns of heating and cooling within a watershed environment.

2. Water temperatures are influenced by the thermal reservoir that surrounds the water body. Air temperature can be used as an index of that thermal environment. Air and stream temperatures, at a minimum, must be measured at each data collection site to establish the relationship between the stream and its environment.

3. A portion of stream temperature change can be associated with the thermal environment and rates of adiabatic temperature change. The lower elevations not only have warmer water, but they have warmer air temperatures on a daily basis. The adiabatic rates of air mass temperature change is 3.2°F to 5.5°F difference for each 1,000 ft. of elevation.

4. The difference between the air temperature and the water temperature influences the rate at which the water will warm or cool. The smaller the differences are between air and water temperature the longer it will take for the water to heat or cool.

5. The rate of flow of a stream must be determined to understand the entire process of how a stream heats and cools. Flow determines how long a body of water is influenced by a particular thermal environment. Downstream air temperatures are warmer than upstream because of lower elevations. Flow rates must be monitored during each sample period, between each monitoring site to establish how long the water is exposed to a thermal environment.

6. Two measurements are required at a minimum to estimate the thermal evolution of a stream: 1) the flow rate and, 2) the gradient between air and water temperature. The rate of flow determines how long the water is exposed to a particular air mass (at a specific temperature). The gradient determines the rate at which heat energy is transferred.

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