Umpqua Basin Watershed Council

Thermal Transition in Small Streams Under Low Flow Conditions

by
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Executive Summary

This analysis uses a simple steady-state model to estimate the time required for a column of water representative of a typical stream to change temperature when moved from one environment to another. Results from the example indicate that a stream with a 20 cm depth would be over 90% adjusted in less than 8 hours.

A companion study, the Yoncalla Creek Dye Study, shows that effective flow velocities of the order of 50 ft per hour can be expected in small streams under low flow conditions. This means that thermal transition from upstream conditions may occur within 1000 feet.

An important implication is that prevailing stream temperatures in small streams can be strongly influenced by local conditions. As a result, local stream temperature management restoration projects may be very effective in improving stream temperature conditions in many of the small streams in the Umpqua Basin.

Objective and scope of this report

The objective of this report is to examine the manner that stream temperatures change as the water moves downstream from one thermal environment to another. The emphasis of this report is on small streams under low flow conditions.

Background:

Stream temperature is generally recognized as a key parameter used in the assessment and management of aquatic ecosystems. Apparently relatively small changes in the local temperature regime can cause significant changes in the quantity and composition of the aquatic organisms.

In western Oregon elevated stream temperatures are thought to be detrimental to various cold-water fish species that have experienced major population declines. As a result, there is considerable interest in finding ways to effectively manage stream temperature.

It is well know that a stream system consists of a main stem that is supplied by a hierarchical network of smaller tributaries each of which eventually terminates at a source point. A consequence of this pattern is that a change in water quality at a particular point can affect the water quality in a downstream direction.

Studies (UBWC, 1998, 1999) have shown that, in the Umpqua Basin, summer stream temperatures tend to increase in the downstream direction during the seasonal high temperature period. Consequently, the smaller streams become important as a source of cold water for the temperature sensitive species. Also, it should be noted that the maximum temperature typically occurs during the low flow season.

To develop an effective stream temperature management strategy it is essential to understand how far the effects of a particular thermal condition will extend downstream. For example, an opening in the riparian area can caused increased solar heating with associated increases in stream temperature. It is useful to know how far downstream this effect will extend. Likewise, a shade enhancement project could result in lower stream temperatures and it would be useful to know the extent of the benefited area.

The seasonal stream temperature pattern is highly variable, with several thermal processes that add and remove heat from the water. Some of these processes are dependent on the temperature difference between the water and the surrounding environment. The second law of thermodynamics says that the water will tend to adjust to the temperature of the local environment and that the rate of adjustment will be proportional to the difference in temperature. Since the natural system is dynamic, with water flowing and local climatic conditions constantly changing, it is helpful to extract the processes that are dependent on the temperature difference and apply them to a steady-state situation. The problem then reduces to determining the length of time for a column of water to adjust from temperature condition A to temperature condition B. It is helpful to imagine one container of water that has adjusted to the temperature for condition A and another identical container at condition B. When the A container is moved to the B environment the problem then is to determine the time required for the temperature of container A to become indistinguishable from the temperature of container B.

Numerical Analysis:

There are several relevant heat transfer processes that are driven by the difference in temperature between the water and the environment. As heat is transferred, the temperature difference is reduced and the rate of change decreases. In the following analysis the instantaneous difference in the rate of heat loss between A and B is calculated for each process as a function of time to show the relative effect of each process. Initially the difference is 100% or, in this example, 6°C. As more heat leaves A, the difference diminishes as an exponential decay function and finally reaches zero.

In this analysis the temperature of condition B is held constant which represents a steady state condition. This was done to simplify the analysis. However, virtually the same result would be obtained if condition A and B were varying together with time. Likewise, streamflow is immaterial as long as the condition B environment remains constant with respect to the water.

The general formulas and values for the constants were taken from the mathematical model used for the SSTEMP/ SNTEMP computer stream temperature model that was developed for the Cooperative Instream Flow Service group by Theurere, Voos, and Miller (1984).

In general,

$$\Delta H = H_A - H_B. \qquad \text{eq 1}$$

$\Delta Hw \equiv$ difference in heat loss between A and B Calories/square Cm/hour

$H_A \equiv$ instantaneous rate of heat loss from condition A water
$H_B \equiv$ instantaneous rate of heat loss from condition B water

The difference in the amount of heat lost during a small time interval can be calculated and the corresponding change in temperature of A can be determined. The heat loss for A is then recalculated using the new temperature over the next time interval.

Radiant Exchange:

$$\Delta Hw = \epsilon_w \sigma[(T_A+273.16)^4 - (T_B+273.16)^4] \qquad \text{eq 2}$$

$\Delta Hw \equiv$ difference in heat loss between A and B due to radiated heat.

$\sigma \equiv$ Stephan-Boltzman constant = 0.04879 cal/cm^2/hr/K^4

$\epsilon_w \equiv$ water emissivity = 0.9526

$T_A \equiv$ water temperature condition A

$T_B \equiv$ water temperature condition B

Heat loss due to evaporation

$$\Delta He = 0.086(40+15.0 \cdot Wa)[(Rha(1.0640)^{ATa} - (1.0640)^{Ta}) - (Rhb(1.0640)^{ATb} - (1.0640)^{Tb}] \qquad \text{eq 3}$$

ΔHe ≡ difference in heat loss between A and B

T_A ≡ water temperature condition A

T_B ≡ water temperature condition B

Wa ≡ wind speed (m/sec)

Rha ≡ Relative humidity for condition A

Rhb ≡ Relative humidity for condition B

ATa ≡ air temperature for condition A

ATb ≡ air temperature for condition B

T_A ≡ water temperature condition A

T_B ≡ water temperature condition B

The saturated vapor pressure for condition B was calculated from:

$$e_s \approx 33.8639[(0.00738T + 0.8072)^8 - 0.000019|1.8T + 48| + 0.001316] \qquad \text{eq 4}$$

(Linsley, Kohler, and Paulhus, 1975.)

and used with the relative humidity to calculate the vapor pressure for the air. The saturated vapor pressure for condition A was calculated for each change in temperature and the corresponding relative humidity value was determined as the ratio of the air vapor pressure to the saturated vapor pressure.

Heat exchange due to air convection

$$\Delta Hc = 0.086(3.75 \cdot 10^{-3} + 1.4 \cdot 10^{-3} \cdot Wa)P(T_A - T_B) \qquad \text{eq 5}$$

ΔHc ≡ difference in heat loss between A and B due to air convection

T_A ≡ water temperature condition A

T_B ≡ water temperature condition B

Wa ≡ wind speed (m/sec)

$P \equiv$ atmospheric pressure (mb)

Heat exchange due to Streambed conduction

$$\Delta Hd = K_g[T_A - T_B] / \Delta Z_g \qquad \text{eq 6}$$

$\Delta Hc \equiv$ difference in heat loss between A and B due to streambed conduction

$T_A \equiv$ water temperature condition A

$T_B \equiv$ water temperature condition B

$K_g \equiv$ 0.1419 cal/cm/hr/C

$\Delta Z_g \equiv$ equilibrium depth for the water-streambed interface

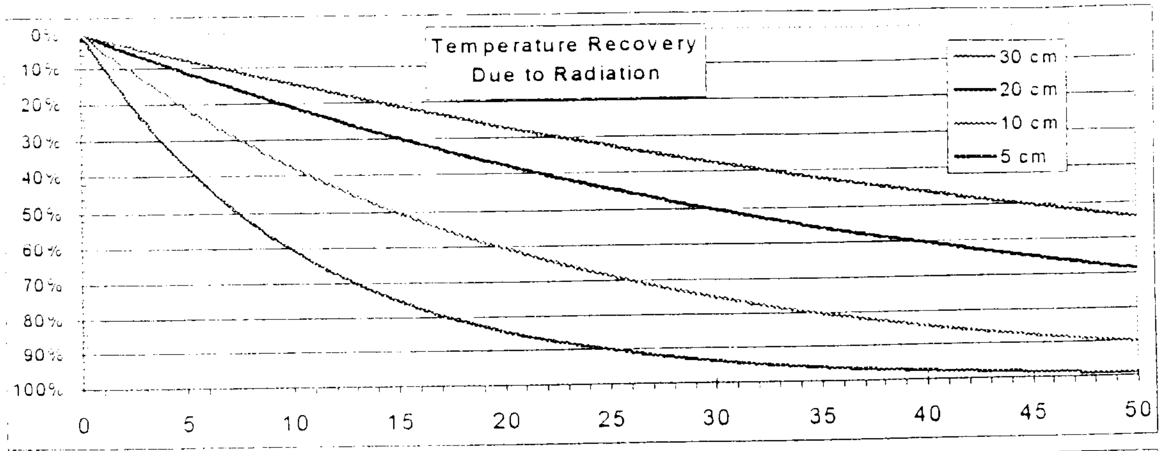
Assumed conditions for this analysis

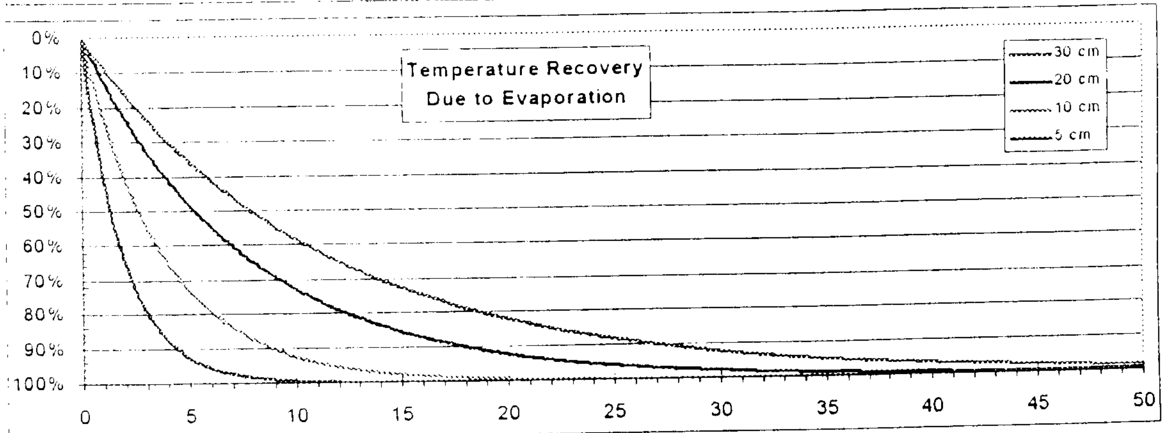
The table shows the assumed values used for this analysis. Since the formulas are set up in a spreadsheet, it is a simple manner use different values to examine different scenarios.

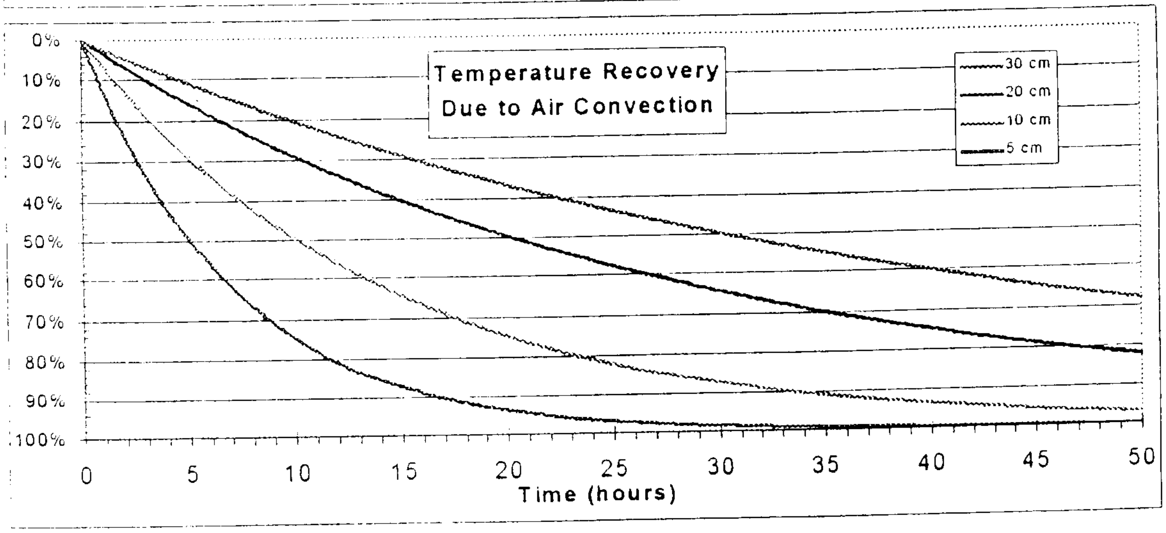
Temperature Condition A (initial)	**26**	**°C**
Temperature Condition B (constant)	**20**	**°C**
Wind Speed	**3**	**m/sec**
Air Temp	**20**	**°C**
Relative Humidity (Condition B)	**60%**	
Sat VP for Condition B	**23.39**	**mbar**
Air VP for Condition B	**14.03**	**mbar**
Air Pressure	**1000**	**mbar**
Streambed conductivity	**0.1419**	**cal/sqcm/hr**
Streambed temperature	**10**	**°C**
Equilibrium Streambed Depth	**1**	**m**

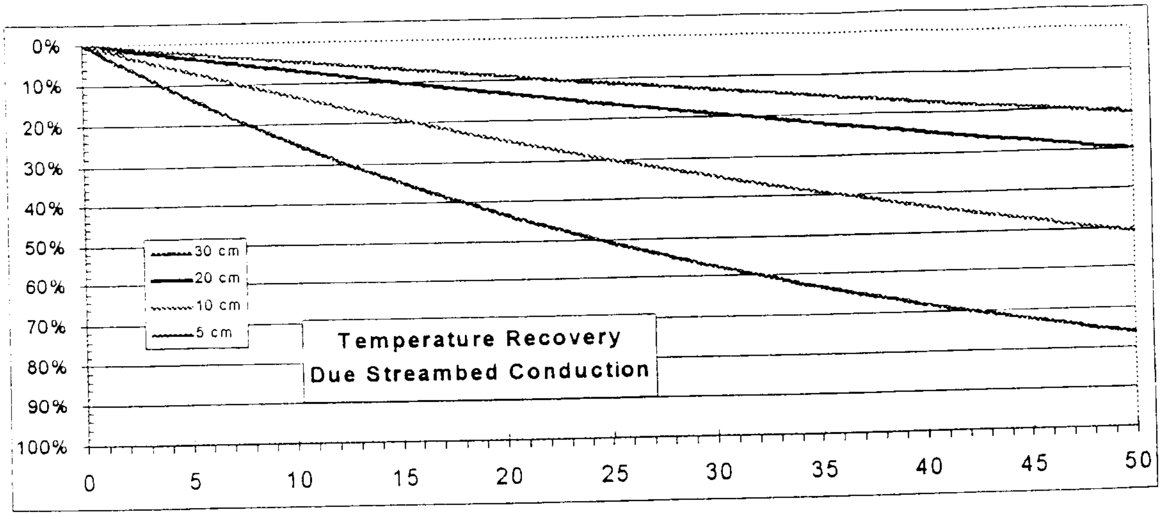
Results

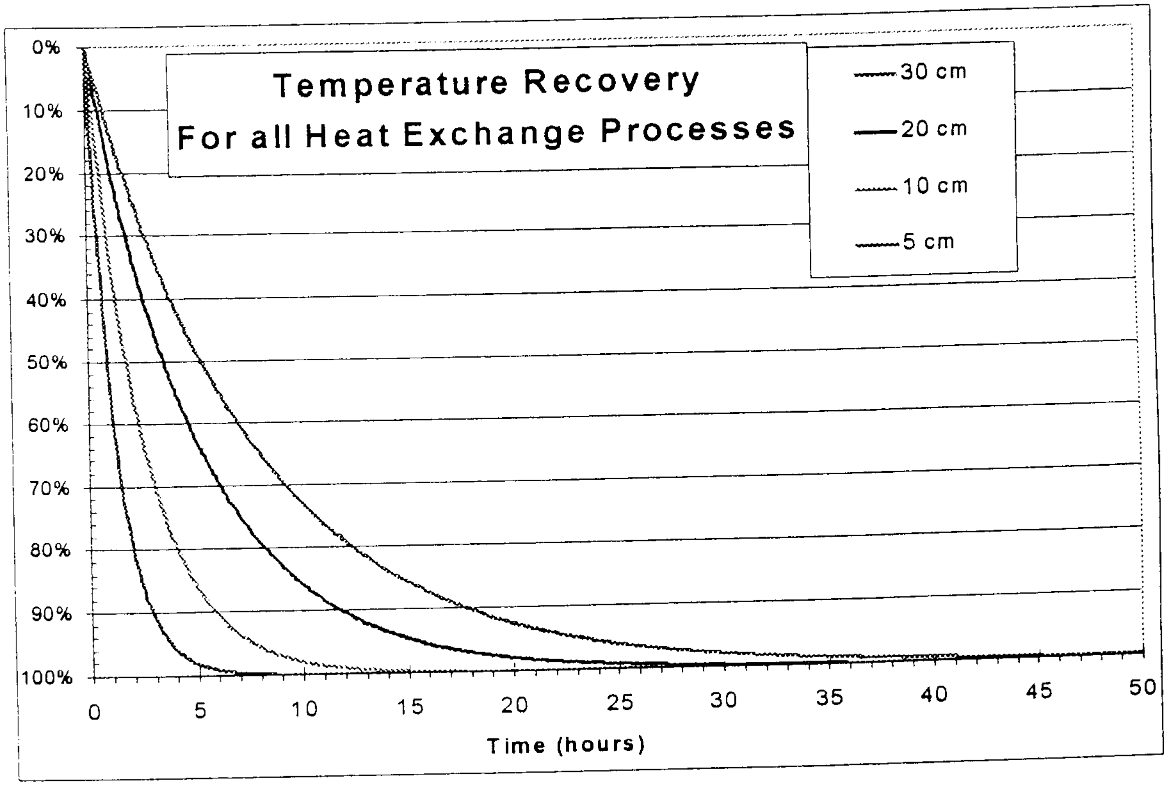
The charts show the decay curves for each of the individual processes and for the net result.


Temperature Recovery
Due to Radiation
30 cm
20 cm
10 cm
5 cm
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
0
5
10
15
20
25
30
35
40
45
50


Temperature Recovery
Due to Evaporation
30 cm
20 cm
10 cm
5 cm
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
0
5
10
15
20
25
30
35
40
45
50


Temperature Recovery
Due to Air Convection
30 cm
20 cm
10 cm
5 cm
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
0
5
10
15
20
25
30
35
40
45
50
Time (hours)





Implications

This analysis indicates that most of thermal effect of a transition will be effectively completed within 10 hours for small streams. To determine the transition distance it is necessary to know how fast the heated water is moving downstream.

The attached report, Yoncalla Creek Dye Study, shows that effective flow velocities on small low gradient streams can be in the order of 50 ft/ hour. During the Yoncalla study the streamflow was about 0.2 cfs. While several of the pools were quite deep (i.e. 3 feet) the flow depth in the riffle areas was typically a few inches. Assuming an effective depth of 20 cm the chart shows that 90% of the temperature change would occur within 10 hours or 500 feet.

While Yoncalla Creek may be slow, it is not believed to be exceptional. While more information on effective stream velocities would be helpful, it is the writer's belief that, for most of the small streams under low flow conditions, the effective temperature transition zone is less than 1000 feet.

The management implications are significant because it indicates that stream temperature management improvements along a small stream can be effective in spite of conditions further upstream. The information also implies that the prevailing stream temperature of these small streams at a given location is determined, for the most part, by local conditions.

For More Information

The Excel spreadsheet used for this analysis is available as well as data, reports, and pictures of the Yoncalla Creek Study and the Umpqua Stream Temperature Characterization Studies. Contact:

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Cited References

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