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Predicting Temperatures of Small Streams

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Abstract. Hourly temperatures of small streams can be accurately predicted using an energy balance. Micrometeorological measurements are required to assess the environment of the small stream accurately. The temperature-prediction technique was tested on three streams in Oregon. On unshaded stretches, net all-wave radiation is the predominant energy source during the day; evaporation and convection account for less than 10% of the total energy exchange. Conduction of heat into the stream bottom is an important energy balance component on shallow streams having a bedrock bottom. Up to 25% of the energy absorbed by such a stream may be transferred into the bed. Hourly temperature changes of 0–16°F were predicted to within 1°F more than 90% of the time. This technique permits foresters to control water temperature through manipulation of stream-side vegetation.

INTRODUCTION

In recent years, considerable interest has been shown in the prediction of river temperature in the western United States. Large dams may permit regulation of downstream temperature, as well as of flow. Heated industrial effluents also may influence river temperatures. Various techniques have been developed for predicting the extent of this influence. One of the most effective techniques uses an energy budget to predict temperature change.

The purpose of this paper is to illustrate how energy budget techniques may be modified for predicting temperatures of small streams and to indicate the utility of temperature prediction for managing these streams.

Sections of three small streams in western Oregon were selected for study. One section was heavily shaded by Douglas fir, vine maple, and salmonberry and had a gravel bottom. The remaining sections were exposed to direct sunlight; one had a rock bottom, the other a gravel bottom. These conditions are typical of many streams in the forested regions of the Oregon Cascade and Coast Ranges.

The technique most widely used in temperature prediction utilizes some form of energy budget analysis. Estimates of the gains and losses of energy by the body of water are summed to determine the change in stored energy. This value for a known volume of water can then be converted to temperature change.

Accurate estimation of the change in stored energy within a body of water depends upon accurate definition and measurement of the energy inflow and outflow. Equipment limitations restricted early hydrologic application of the energy budget to oceans. Some of the earliest energy budget studies were designed to predict oceanic evaporation. Such estimates were prepared on an annual basis, so that changes in heat storage could be assumed zero and because data on radiation were limited [*Sverdrup*, 1940; *Schmidt*, 1915].

Advances in the development of meteorological equipment permitted extension of the energy budget technique to smaller bodies of water. Energy budget studies for estimation of evaporation at Lake Hefner, Oklahoma [*Anderson*, 1954], were the basis for the models used in later predictions of river temperature. *Burt* [1958] used these models to predict the effect that proposed dams would have on downstream temperatures of the Snake River. *Raphael* [1962] modified the method for incorporating a procedure for routing temperatures downstream. Energy budget terms for the temperature predictions made during these studies by Burt and Raphael were computed with climatic data obtained from the nearest U. S. Weather Bureau station and adjusted for study site location. Coefficients developed at Lake Hefner were used, despite their empirical nature.

Accurate prediction of temperature on small streams requires modification of the techniques used for temperature prediction on large rivers, because small streams have less capacity for heat storage than large rivers. Diurnal fluctuations of 20°F are not uncommon in exposed streams with summer flows of about 1 cfs [*Brown and Krygier,* 1967]. By comparison, the Willamette River, with a mean daily discharge of about 5000 cfs, has a mean diurnal fluctuation in temperature of only 2°F during August, the month of maximum change in temperature [*U. S. Geological Survey, 1965*]. On small streams, therefore, it is necessary to be more precise in defining the energy budget to achieve a given level of accuracy, for example, ± 1°F.

The climatic environment of a small stream is strongly influenced by such environmental features as bankside vegetation and surrounding topography. These factors pose problems in climatic sampling that are more complicated than those encountered on large rivers and reservoirs.

Modification of the environment of a small stream by vegetation and topography, plus rapid response to energy inputs, requires more accurate assessment of the local climate for small streams than for rivers. In turn, microclimatic measurements at the study site are usually needed. It is extremely difficult, for example, to adjust hourly pyrheliometer data of the Weather Bureau for assessment of solar radiation incident at the surface of a forested stream.

Finally, successful prediction of temperature on small streams may require evaluation of energy flow that is insignificant on large rivers. In short, an energy budget for a small stream may include more terms than one prepared for a river.

TEMPERATURE PREDICTION TECHNIQUES

General. Energy budget techniques used for temperature prediction seek to evaluate the net change in the energy level of the stream. A general energy budget equation may be written as

$$\Delta S = Q_{NR} \pm Q_E \pm Q_C \pm Q_H \pm Q_A \quad (1)$$

where ΔS = net change in energy stored;
Q_{NR} = net thermal radiation flux;
Q_E = evaporative flux;
Q_C = conductive flux;
Q_H = convective flux;
Q_A = advective flux.

The sign convention shall be positive for energy added to the stream and negative for energy losses.

The equations used to compute the individual fluxes have been derived elsewhere [*Anderson,* 1954; *Marciano and Harbeck,* 1954; *Raphael,* 1962]. A summary of the equations used in this study is given below.

Net thermal radiation is the difference between total incoming and total outgoing all-wave thermal radiation. This flux was measured directly in this study with a net radiometer.

Heat may be added or removed by condensation or evaporation at the surface of a stream. The amount of heat exchanged is a function of the latent heat of vaporization and the vapor pressure gradient at the stream-air interface. The Dalton-type equation, below, assumes horizontal uniformity of all variables [*Marciano and Harbeck,* 1954]:

$$Q_E = kLU(e_w - e_a) \quad (2)$$

where Q_E = evaporative flux, Btu/ft^2 — min;
k = exchange coefficient;
L = latent heat of vaporization;
U = wind speed, miles/hour;
e_w = saturated vapor pressure at the temperature of the stream, inches of mercury;
e_a = ambient atmospheric vapor pressure, inches of mercury.

Selection of a suitable exchange coefficient is difficult for streams sheltered by steep banks, overhanging vegetation, and precipitous topography. *Burt* [1958] and *Raphael* [1962] used a coefficient derived at Lake Hefner, Oklahoma [*Marciano and Harbeck,* 1954]. This coefficient, which uses wind speeds at 8 meters, could not be directly transposed to the environment above a small stream. *Tichenor* [1966] used wind tunnel measurements to compare several methods for computing evaporation. Measured evaporation was consistently twice that predicted using the Lake Hefner coefficient. On this basis, an empirical coefficient twice that derived at Lake Hefner was incorporated in the evaporation computation for this study. The error induced by using this new coefficient could not be precisely defined. However, the conditions used in Tichenor's models were thought to approximate more closely those above a small sheltered stream than did the conditions under which the Lake Hefner coefficient was derived. Substituting the empirical value obtained from Tichenor's model studies and 1060 Btu/lb for the latent heat of vaporization, equation 2 becomes

$$Q_E = 0.6140\,U(e_w - e_a) \qquad (3)$$

Conduction is a heat transfer process whereby heat is transferred from molecule to molecule. This process may occur at the bottom of small clear streams, because thermal energy reaching the stream surface is not strongly attenuated by water only a few inches deep. Conduction is computed as the product of the thermal conductivity and the measured temperature gradient of the bottom material. This may be written as

$$Q_C = K(dT/dz) \qquad (4)$$

where Q_C = conduction, Btu/ft^2 − min;
dT/dz = temperature gradient in the bottom material, °F/inch;
K = thermal conductivity of the bottom material, Btu/ft^2-inch-min-°F.

Conduction was measurable on only one stream in this study where green breccia formed a solid rock bottom. Thermal conductivity values for agglomerate (0.39 Btu/ft^2-inch-min-°F) were substituted for breccia [*Clark,* 1966].

Convection occurs at the stream surface. It results from boundary layer conduction and subsequent transfer of this heat through displacement of masses of fluid. Wind speed and the temperature gradient between the air and water are the driving forces for convective heat transfer at the air-water interface. The Bowen ratio [*Bowen,* 1926] has been used to relate convection to evaporation. This may be written as

$$Q_H = RQ_E$$

$$Q_H = 0.61[(T_w - T_a)/(e_w - e_a)](P/1000)Q_E$$

Substituting Q_E from equation 3 and correcting for temperature in °F

$$Q_H = 0.0002\,UP(T_w - T_a) \qquad (5)$$

where Q_H = convection, Btu/ft^2-min;
0.0002 = exchange coefficient;
R = Bowen constant;
U = wind speed, mph;
P = atmospheric pressure, inches of mercury;
T_w = water temperature, °F;
T_a = ambient air temperature, °F.

Energy may be added to a stream by introducing water at a different temperature. This transfer of energy from some source outside the area being considered is generally termed advection. Advective energy may come from precipitation, tributary streams, or ground-water inflow. If the volume and temperature of this inflow are known, the stream temperature may be adjusted by a simple mixing or temperature-dilution ratio. In this study, reaches were selected where advective inflow could be neglected.

The predicted water temperature change is then a function of the heat applied and the volume of water heated. That is

$$T_w = (\Delta SA/F)0.000267 \qquad (6)$$

where T_w = predicted temperature change, °F;
ΔS = change in energy storage, Btu/ft^2-min;
A = surface area of study section, ft^2;
F = discharge, cfs;
0.000267 = proportionality constant.

The constant 0.000267 converts discharge from cfs to pounds of water per minute, so that Btu's may be expressed as a temperature change in °F.

Method. The flux evaluation techniques described above were tested on selected reaches of three small streams in Oregon. Deer Creek, in the Coast Range 8 miles south of Toledo, was selected to study temperature change phenomena in forested streams. Overhanging salmonberry and vine maple provided about 80% coverage of the water surface. Douglas fir, 100 feet tall, growing along the banks shaded the stream in early morning and late afternoon. The stream flows from north to south. Sunlight struck the water surface directly from only 1100–1400 hours. Discharge in the 1400-foot study section was about 0.4 cfs. Weirs above and below the reach showed ground-water advection to be negligible. Travel time through the gravel-bottomed stretch was about 2.5 hours.

Reaches of two small streams exposed to direct sunlight were selected to evaluate the prediction technique under conditions of rapid temperature change. A reach of Berry Creek, 10 miles north of Corvallis, provided an opportunity to study temperature change in a gravel-bottomed channel. The 2000-foot study section was located in a meadow. Discharge measurements indicated negligible ground-water advection. Discharge in the study reach was about 0.7 cfs. Travel time was about 45 minutes.

A channel with a solid green-breccia bottom on the H. J. Andrews Experimental Forest near Blue River in the Cascade Range was selected for a second study of exposed streams. The stream was exposed to direct sunlight as it flowed through a clear-cut in the forest. The study reach was 1300 feet in length. The solid bottom prevented any ground-water advection. Discharge through this section was about 0.5 cfs. Travel time was about 1 hour.

Predictions were made at each study site by first measuring the temperature at the upstream boundary of the stretch. The change in energy storage was then evaluated during the travel time through the section. Measurements of net radiation, wind speed, air temperature, and humidity were made at only one point in each study section. Limited equipment prohibited greater sampling. The predicted temperature change was then compared with the observed temperature recorded as the water reached the downstream boundary of the study section.

All meteorological variables used in flux evaluation except barometric pressure were measured on site. Daily barometric pressures were obtained by using Weather Bureau values at Salem or Eugene, adjusted for altitude. Net thermal radiation was measured continuously with a Thornthwaite net radiometer placed about 10 inches above the stream surface. The accuracy of this instrument is about ±5%. Water temperatures were measured continuously at the top and bottom of each study section with a Partlow thermograph to within 0.5°F.

Wind speed was measured continuously with a Raim microanemometer. This anemometer, with a starting speed of about 0.4 mph, was placed 1 foot above the water surface.

Air temperature and humidity were measured with an aspirated psychrometer at 15-minute intervals within 6 inches of the water surface during the day. The more stable nighttime values were recorded with a hair hygrothermograph placed on the bank within 18 inches of the water surface. The accuracy and precision of these instruments are not established.

Temperature gradients within the stream bottoms were measured with copper-constantan thermocouple pairs placed at 1-cm intervals. The thermocouples were simply inserted into the bed of the two gravel-bottomed streams. Large boulders of green breccia, similar to the bed of the rock bottom stream, were fitted with thermocouples to evaluate the heat flow through this material. Small holes were drilled in the samples at 1-cm intervals. One-half of a thermocouple pair was placed in each hole. The holes were partially filled with mercury to ensure good rock-to-thermocouple contact and sealed with a silicon rubber of low thermal conductivity. The rocks were then placed in water baths. Stream temperatures recorded at the study site were simu-

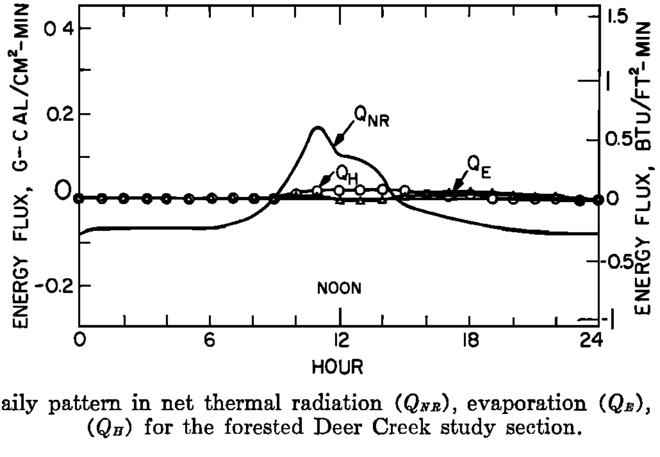

Fig. 1. The daily pattern in net thermal radiation (Q_{NR}), evaporation (Q_E), and convection (Q_H) for the forested Deer Creek study section.

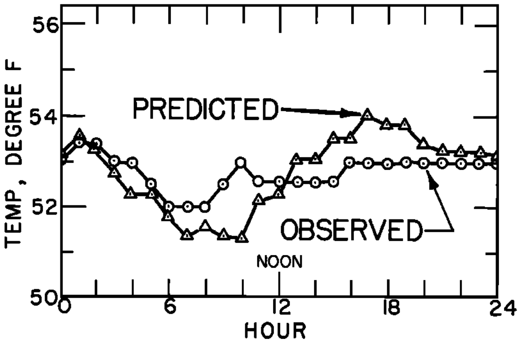

Fig. 2. Observed and predicted hourly temperatures for the forested Deer Creek study section.

lated. Thermocouple output, read with a Leeds and Northrup potentiometer, was converted to temperature gradients with standard thermocouple tables.

RESULTS

A diagram of the energy budget components measured at the forested Deer Creek study site on September 1, 1965, is presented in Figure 1. Comparisons of measured stream temperatures with those predicted from the energy budget values of the previous figure are shown in Figure 2. Predictions were made at hourly intervals; 22 of the 24 predictions made for September 1, 1965, were within 1°F of the measured value. The maximum change in stream temperature observed as the water passed through the study reach was only 1.5°F for the 2.5-hour travel time.

The energy budget components measured at the nonforested Berry Creek study site on May 20, 1967, are presented in Figure 3. Stream temperatures predicted from these values are compared with measured temperatures in Figure 4. Of the 24 predictions made, 23 were within 1°F of the measured value. The maximum change in stream temperature in this instance, however, was 11°F during the 45-minute travel time through the study reach.

Figure 5 illustrates the energy budget com-

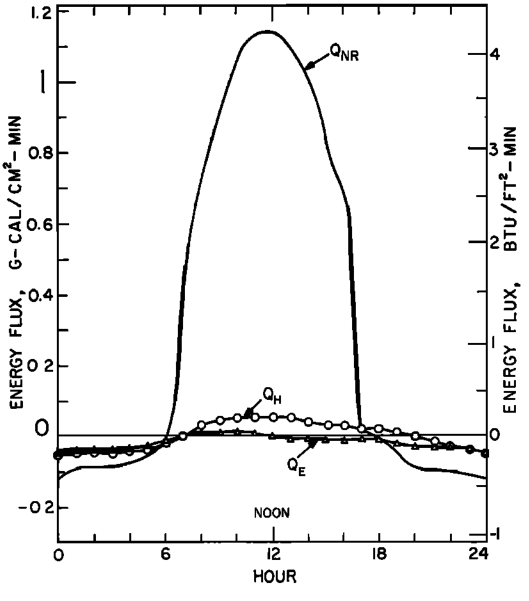

Fig. 3. The daily pattern in net thermal radiation (Q_{NR}), evaporation (Q_E), and convection (Q_H) for the nonforested Berry Creek study section.

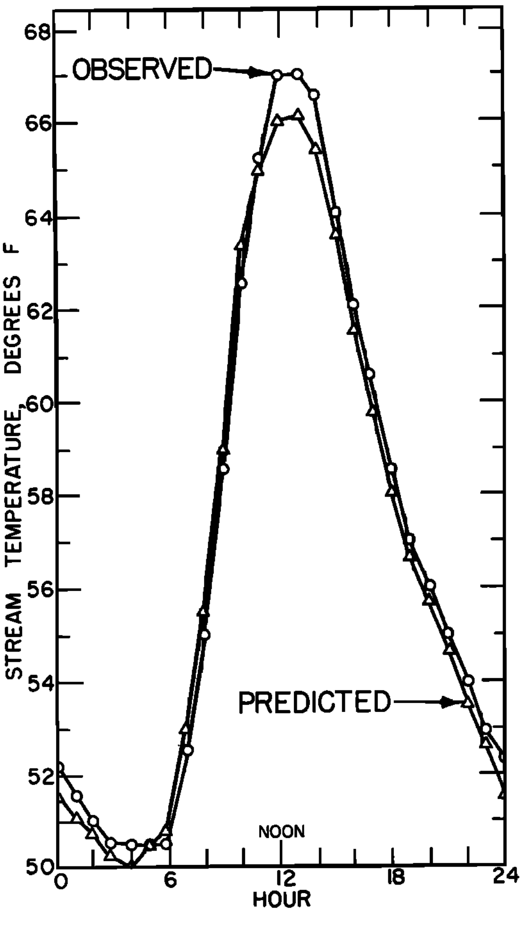

Fig. 4. Observed and predicted hourly temperature for the nonforested Berry Creek study section.

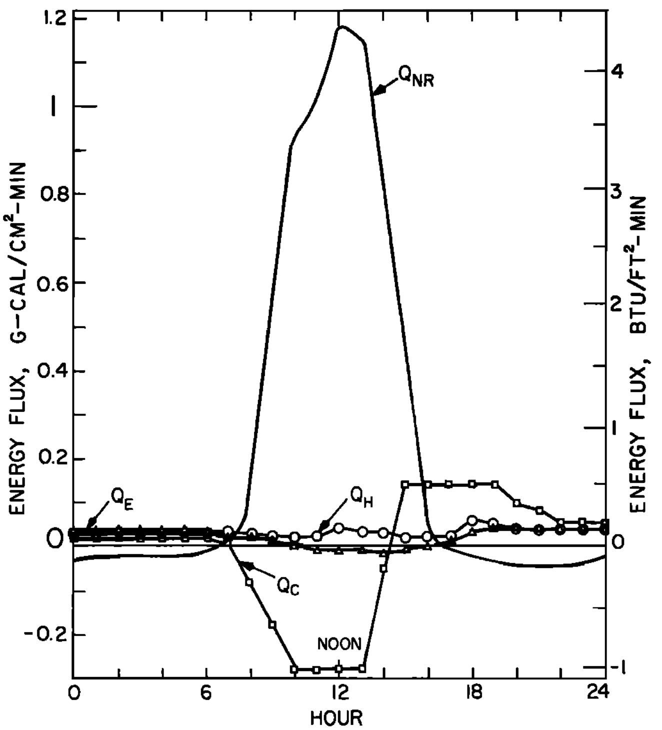

Fig. 5. The daily pattern in net thermal radiation (Q_{NR}), evaporation (Q_E), convection (Q_H), and conduction (Q_C) for the nonforested H. J. Andrews study section.

ponents measured on the study section in the H. J. Andrews Experimental Forest. Stream temperatures predicted from these values are compared with measured temperatures in Figure 6. Of the 24 predictions made for May 20–21, 1966, 21 were within 1°F. The maximum increase in water temperature during the 1-hour travel time through the study stretch was 16° F.

DISCUSSION

The results indicate that the energy budget technique outlined earlier is an acceptable tool for predicting temperature on small streams. The technique permits prediction of large and small temperature changes.

The data illustrate the necessity of on-site meteorological measurements for accurate temperature prediction on small streams. As an example, the predictions at 1600, 1700, and 1800 hours at the H. J. Andrews study section are in error by 5.5, 4.3, and 2.0°F, respectively. These are thought to be errors in sampling, because only one radiometer was available to measure net thermal radiation during this study. For the period 1600–1800, the stream was only partially shaded by surrounding topography and vegetation, but the radiometer was in full shade. Later in the afternoon, as the proportion of shade increased, the prediction error decreased. Errors in the opposite direction would have occurred had thermal radiation data from unshaded Weather Bureau installations been used to predict stream temperature.

The variability in the percentage of water surface shaded on many forested streams also makes on-site climatic measurement a necessity. In the early phases of the work reported here, temperature predictions attempted on streams having a discontinuous forest canopy were accurate only at night, late afternoon, or early morning. Sampling the thermal radiation flux with one radiometer where the stream surface was dappled with moving spots of sunlight proved to be a difficult task. Adjusting Weather Bureau radiation data to these conditions would have been even more difficult. The success of the temperature predictions made for all three study streams reported here is certainly related to the

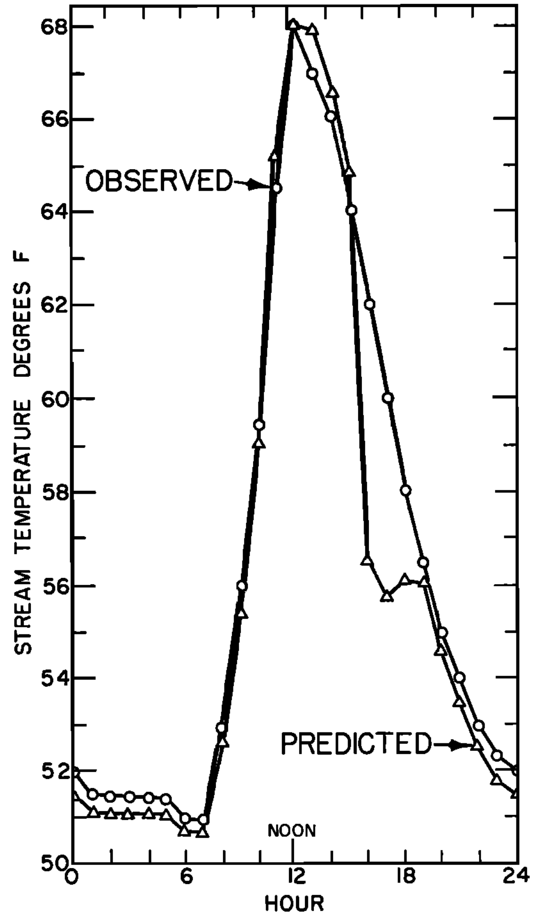

Fig. 6. Observed and predicted hourly temperatures for the nonforested H J. Andrews study section.

uniformity of net thermal radiation patterns within each study stretch. The north-south orientation of overhanging vegetation on Deer Creek, for example, provided either full shade or, for a very short period, uniform exposure to direct sunlight.

The data indicate the general nature of the heat-exchange characteristics of these small streams. Net thermal radiation is the predominant source of energy for the stream. Evaporation and convection seem to play a minor role in establishing the temperature of an exposed stream, especially at midday, when most of the net thermal radiation is going into storage.

The phenomenon of bottom conduction, such as that measured on the rock-bottomed stream of the H. J. Andrews Experimental Forest (Figure 5), has not been considered elsewhere. Consideration of this energy budget component was essential for accurate temperature prediction. The rock acted as an energy sink during the midday hours and as an energy source later in the day.

In contrast, gravel bottoms seem to be insignificant energy sinks. Although temperature gradients were measured in the gravel-bottomed stream, thermal conductivities of the water-gravel mixture, approximately 0.05 Btu/ft^2-inch-min-°F, were too low to provide any heat exchange that noticeably affected the predictions.

The rapid response of the exposed streams to large inputs of energy is shown in Figures 4 and 6. Hourly temperature changes of 4–6°F exceed the diurnal changes recorded on many large rivers.

Temperature prediction may be used as a first step in predicting the effect of man's activity on the aquatic ecosystem of a body of water. A technique similar to the one described here has been used to predict the thermal effect of dams or of adding heated effluents to rivers [*Burt,* 1958; *Delay and Seaders,* 1966; *Duttweiler,* 1962]. In the Pacific Northwest, and in other forested regions as well, this technique may be used to predict the effect of logging on the temperature and temperature-related changes in the ecosystem of small streams.

Many of the streams on forested watersheds provide habitat for valuable game fish. In Oregon, small streams like those studied as part of this research provide the majority of the spawning and rearing habitat for salmon, steelhead, and trout. The sensitivity of these species to temperature changes has been well documented.

Clear-cutting is a typical logging practice in many forests of the western states. Temperature prediction can be used as a tool to determine the maximum or allowable length of stream to be exposed by clear-cutting on watersheds supporting fish populations. Further, it can be used to predict the downstream temperature effect of a proposed clear-cut. As water-quality criteria become more definitive, temperature prediction may become an invaluable tool for meeting these criteria on small watersheds scheduled for timber harvest.

The technique should also find application in the management of small municipal watersheds. Timber harvest, usually clear-cutting, is common on most of the municipal watersheds in the Northwest. If temperature criteria are used to determine the maximum allowable stream exposure, many of the problems from taste, odor, and color associated with warm water algal blooms may be avoided.

Finally, the temperature prediction technique, developed to predict excessive increases in stream temperature, will be useful in attempts to increase the productivity of forested streams with suboptimal temperature regimes. Increased temperatures often induce increases in primary production [*Cairns,* 1956] beneficial to fish and other aquatic organisms. Temperature regulation on a small, heavily shaded stream could be achieved by working backwards through the prediction formulas. The maximum change in temperature desired would ultimately determine the size and number of openings required.

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