An Improved Temperature Prediction Model for Small Streams

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Abstract

A model for predicting the maximum change in temperature from completely exposing a reach of stream to solar radiation was developed during earlier research. This model, which assumes that net solar radiation is the sole source of energy to the stream, worked well on most streams. In a few cases it worked very poorly. These streams contained either a large proportion of pools or bed rock in the stream bottom. We found that only the flowing portion of the pools should be included in the heat exchange process. We also found that the bed rock stream bottoms can conduct about 20% of the incident solar radiation away from the stream. Reducing our estimates of stream surface area and net heat load according to pool configuration and bed condition provided good estimates of temperature change using the original model.

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Introduction

The composition and productivity of aquatic ecosystems in small streams are determined, in large measure, by the water temperature regime. The temperature regime of a small stream during the summer is determined, in turn, by the amount of solar energy the stream receives. Man can influence the amount of energy received by altering the shade provided by riparian vegetation. Brown (1969) noted a six-fold increase in net all-wave radiation at the surface of streams in clearcuts as compared to those shaded by forest vegetation. Later, Brown and Krygier (1970) reported a 28°F increase in the temperature of a small stream after clearcutting. This increase is directly related to the increase in solar energy received by the stream. Similar increases in temperature following logging have been reported elsewhere (Levno and Rothacher, 1967; Greene, 1950; Meehan, et al., 1969; Patric, 1969).

The importance of temperature as a water quality parameter is reflected in its inclusion in state and federal water quality standards. With this inclusion, land managers must now be able to predict the impact of logging activity on the temperature of adjacent streams in order to comply with the standard. Brown (1969) described a technique for predicting temperature on small streams using micrometeorological measurements obtained along the stream. This technique, while providing accurate predictions of temperature change, is too costly and time

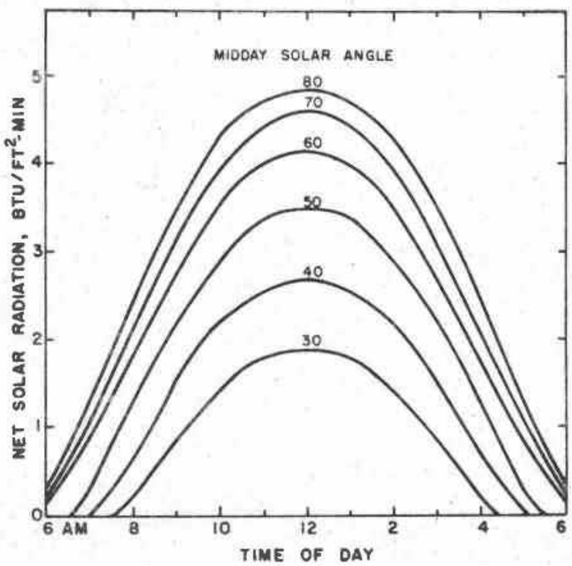

Figure 1. Hourly values for net solar radiation above water surfaces on clear days between latitudes 30° north and 50° north for several solar paths. (After Brown, 1970).

consuming for use by field personnel. An abbreviated technique was devised to alleviate these problems.

The abbreviated temperature prediction model (Brown, 1970) was based on the observation (Brown, 1969) that over 95% of the energy exchange on exposed streams could be accounted for by net radiation alone. The abbreviated technique was thus designed to predict the maximum temperature change expected from completely exposing a given length of stream to sunshine. This is the value required by the water quality standard. Complete exposure is also the condition created by clearcutting, the forest harvest technique most frequently used in the Pacific Northwest.

The model predicts the maximum temperature change (ΔT) in °F expected from completely exposing a reach of stream with a given surface area (A) in square feet, and discharge (D) in (cfs) to an incident heat load (H) in $BTU/ft^2/min$. This relationship can be expressed as:

$$\Delta T = \frac{A \times H}{D} \; 0.000267 \qquad (1)$$

where the constant (0.000267) converts discharge in cfs to pounds of water per minute in order that ΔT may be expressed in degrees Fahrenheit.

Values for H as a function of travel time through the exposed reach and the midday solar angle are obtained graphically. The family of curves in Figure 1 describes the incoming solar radiation adjusted for reflection as a function of time of day and midday solar angle. Since the model seeks to predict the maximum change in temperature through a reach of stream, it is necessary to obtain the maximum heat

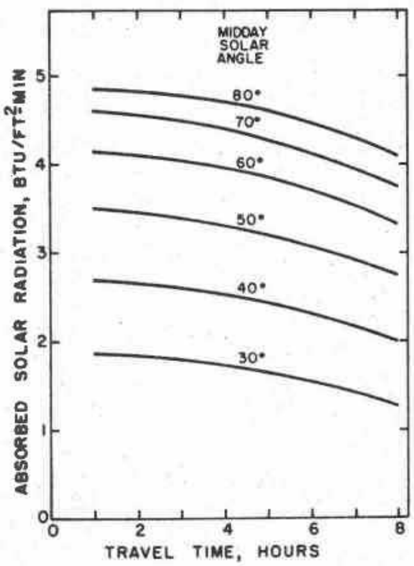

Figure 2. Average net solar radiation absorbed by streams between latitudes 30° north and 50° north on clear days during several periods of exposure to different solar paths. (After Brown, 1970).

input to the stream during the time the water flows through the exposed reach. This has been accomplished by integrating the heat load received about the noon maximum during this travel time. A two hour travel time, for example, would require averaging the incoming radiation from 11 a.m. to 1 p.m. This integration appears graphically in Figure 2. Incorporating midday solar angle as a variable permits these curves to be used over a wide range of latitudes and seasons.

The abbreviated model was applied successfully by field foresters on several streams. Maximum temperature changes of 10-15°F were predicted within 2-3°F. On other streams, the temperature changes predicted by field personnel were far in excess of that observed. This lack of accuracy indicated that further refinement of the model was required before a simplified prediction model could be universally implemented. The fact that the technique worked well on most streams, however, indicated the promise offered by this method.

The objective of this study, therefore, was to redefine and test the temperature prediction model now in use so that it may more nearly become a universal predictor of the effect that clearcutting induces in the temperature regime of small streams.

Stream Surveys

We began the study by making an intensive survey of the streams on which the temperature prediction model proved inaccurate. All of these streams had one of two characteristics in common. The first characteristic was a solid bedrock stream bottom. This characteristic typifies many streams in Oregon's western and southern Cascades where steep topography and high winter flows often combine to scour stream channels to bedrock.

A pool and riffle profile characterized the second type of stream where temperature predictions were inaccurate. The size of pools varied with the streamflow, but in all cases, the pools were large in proportion to the riffle above.

These characteristics determined the nature of the study. The study design consisted of two parts. The first experiments focused upon the influence of the stream bed in heat exchange. Subsequent experiments concentrated on the role of pools in the heat exchange process.

Heat Transfer In Stream Beds

The abbreviated temperature prediction model recognizes only one source of energy for heating the stream--net all-wave radiation. Further, it is assumed that none of this energy will be dissipated by evaporation or convection. Earlier energy budget studies had shown that this assumption was sufficient to account for about 95 percent of the energy exchange (Brown, 1969). Thus, all the heat absorbed by the stream was allocated to increasing its temperature.

Conduction of heat from the stream to the stream bed or transmission of heat through the stream water to the bed was not included in the abbreviated temperature prediction model. Since the prediction of temperature was always greater than that observed on these streams with solid bedrock bottom, a heat sink such as the bed might provide was a logical point to begin study.

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Method

Conduction of heat through a material such as rock is calculated as the product of the thermal conductivity of the rock and its temperature gradient. Thermal conductivity values for the rock types found in the study streams were obtained from standard tables (Clark, 1966).

The temperature gradients within the streambed were obtained by placing thermocouples at one centimeter intervals within the bed material. Large samples of the streambed material were extracted, and a flat surface was cut with a rock saw to provide a reference surface. Holes were drilled beneath this surface with a small rock drill at several intervals. Thermocouples were placed in the drilled holes together with mercury to insure good contact with the surrounding rock and sealed with epoxy cement. The rocks were then replaced in the stream. Thermocouple output was obtained with a Non-Linear Systems digital data acquisition system (Figure 3). The system's digital voltmeter had a one microvolt resolution, permitting us to evaluate the temperature within the rock to within 0.05 °C.

A similar technique was utilized on gravel-bottomed streams. In these streams, however, thermocouples were simply inserted a given depth into the porous gravel medium.

Measurements of incoming solar radiation were made concurrently with the temperature measurements obtained in the stream bed. Solar radiation and net all-wave radiation values were obtained using a Kipp and Zonen solarimeter and a Fritschen miniature net radiometer. Millivolt output from these instruments was also recorded using the data acquisition system. The temperature and radiation sensors were interrogated by the system at 10 minute intervals. Data were recorded

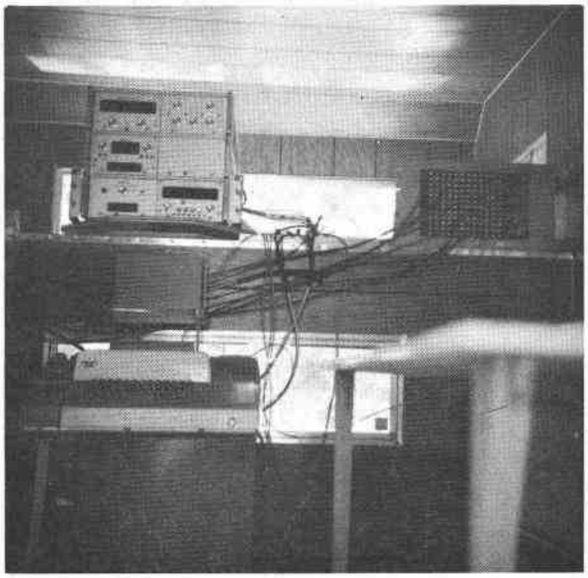

Figure 3. The digital data acquisition system used to measure and record environmental data at the research sites.

on punched tape and translated into real values of temperature and solar radiation using computer programs developed at OSU.

Results

As anticipated, very little heat transfer occurs in the bed of the gravel-bottom stream. The upper 20 centimeters of the gravel beds studied could be considered isothermal. Gradients of 0.05°C or less were observed between the surface and 5 cm. levels. The maximum gradient observed between the surface and 20 cm level was 1.1°C. The principal reason for this isothermal condition seems to be the open porous nature of the gravel. Surface water freely circulates within this 20 cm layer. Conductive heat transfer is restricted by the point-to-point contact between gravel particles together with the efficient heat transfer between particles and the circulating inter-gravel water.

Heat transfer into the bedrock stream bottom is much more efficient. All of the rock types studied had relatively high thermal conductivities. Green breccia, the most common material observed in the study streams of the Cascades, has a thermal conductivity of about 8×10^{-3} cal/cm sec °C (Clark, 1966). Midday temperature gradients of about 0.45°C/cm were observed in the upper layers of the bedrock. Thus, approximately 0.22 cal/min was conducted through the rock. This was about 18% of the incoming heat load. The transfer of heat into the bedrock is plotted in Figure 4 beneath the net radiation observed during the day at one site on Little Rock Creek, Umpqua National Forest.

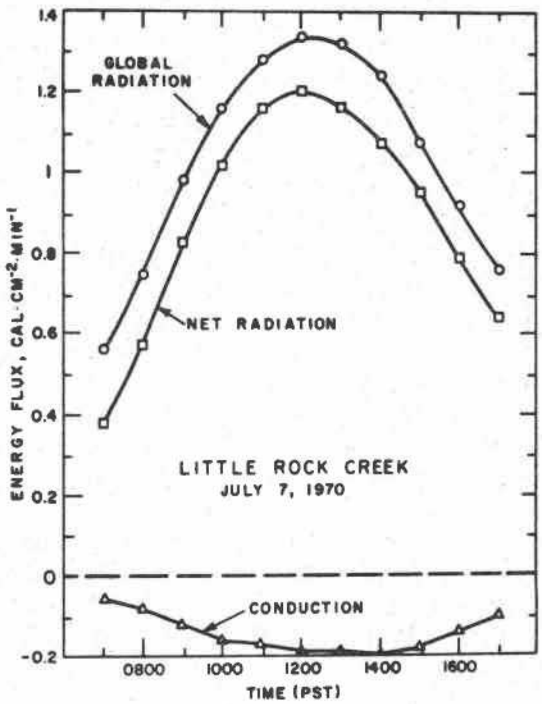

Figure 4. Heat transfer into the bedrock bottom of Little Rock Creek, Umpqua National Forest, Oregon during a clear day in July, 1970.

Conclusion

Streambed composition can significantly influence heat transfer in small streams and thereby affect the accuracy of temperature predictions made using the abbreviated model. Heat transfer by conduction in porous gravels, the most common bed material in small streams, is very small compared to the incoming radiation on exposed streams. The accuracy of temperature predictions on gravel bottom streams made using the abbreviated model would not be affected. On those few streams where bedrock is the principal bottom type, 15-20% of the net all-wave radiation absorbed by the stream may be lost to the bed. Not accounting for this heat loss will provide predictions of temperature change much higher than observed.

Heat Transfer In Pool and Riffle Streams

Small forest streams often contain pools which are large in proportion to the width of flowing stream. The presence of such pools raise several questions about how heat exchange varies as a function of stream configuration. How does circulation in a pool influence stream temperature? Should all of the pool's surface area be included in the computation of surface area for the reach? These questions became more interesting when we found that many small streams on which the temperature prediction model failed contained a series of such pools. This portion of our study was divided into two parts. The first part focused upon thermal stratification in pools. The second part investigated flow patterns in pools to determine the active or flowing portion.

Method

Thermal stratification in pools was studied using thermocouples and the digital data acquisition system. A series of thermocouples was placed across the middle of the study pools perpendicular to the flow path and just beneath the water surface. Thermocouples were positioned such that both the flowing portion and circulating portion of the pools were sampled. Later, thermocouples were used to obtain the vertical temperature profile of several pools. Finally, a complete temperature profile of one large pool (Figure 5) was obtained by traversing a thermistor across the pool in the surface foot. Transects were made at 10 foot intervals over the length of the pool and from bank to bank. This was followed by vertical profiles made at selected points within the pool.

Flow patterns in pools were studied using Rhodamine B fluorescent dye. Dye dispersion was recorded on both black and white and color infrared film using a Wratten 12 filter. A sequence of photographs was taken to follow the dye cloud as it moved through each pool. Areas of flow, stagnation and circulation in each pool were readily discernable from these photographs. Further, these areas were easily measured using cross-sectional data for each pool.

Results

Our continuous measurements of surface water temperature in several exposed pools showed that there was no stratification across pools perpendicular to the direction of flow. Even in the largest pool (Figure 5), which contained significant areas of stagnant water, surface temperatures did not vary more than 0.05°C, which was the precision of our measurement system.

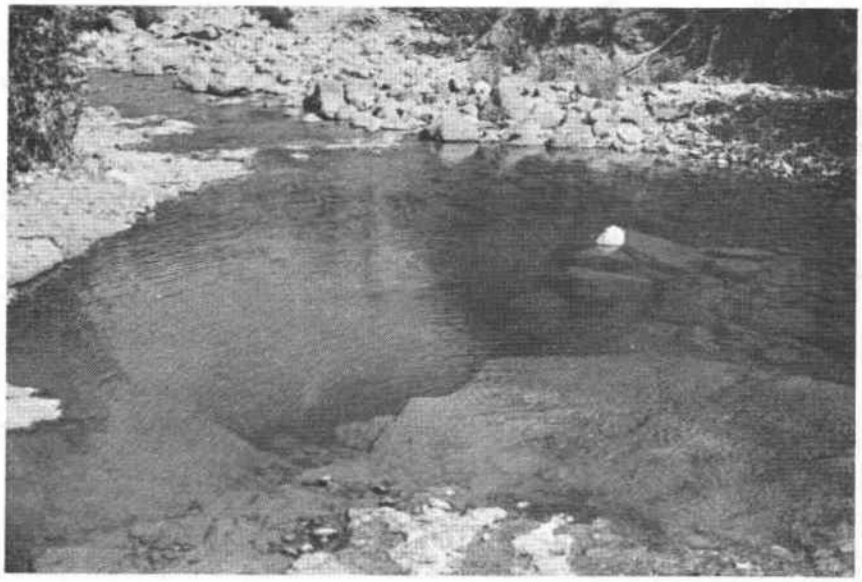

Figure 5. A large pool in Little Rock Creek, Umpqua National Forest, Oregon. This pool is 50 feet long and 34 feet wide.

We observed vertical stratification in only one study pool (Figure 5). Stratification in this pool was caused by the nature of the streambed as the stream entered the pool. The stream entered as a waterfall. The plunge pool was fully contained in a bed-rock scour hole which emptied onto a rock ledge. Thus, heated water entering the pool from the clearcut upstream flowed onto the surface of the pool with little chance for mixing. Mixing was further inhibited by an extremely strong temperature gradient, created in part by this entrance condition. Beneath the surface foot, which was fully mixed, the temperature dropped 6.5°C in four feet. Thus, inflow water was contained within a very restricted portion of the pool. This conclusion is supported not only by the temperature profile data, but from observations of dye clouds as well. It was evident that the dye did not move below the one-foot level.

Temperature stratification of this degree in a relatively shallow pool seemed unusual. Yet other measurements of temperature stratification in pools of nearby streams revealed similar temperature profiles. Hall[1] described temperature gradients of 6-7°C in pools with configurations similar to our study pool.

A gradient of about 0.2°C was observed from the inflow to the outflow of the largest study pool (Figure 5). As expected, the smallest pools showed no temperature gradient in the direction of flow.

Our studies of flow patterns in pools indicated that usually only a small portion of the pool contained flowing water. The flow pattern in a pool was generally determined by the character of the inlet. In these small streams, channel banks or obstacles in the stream were often sufficient to determine the inflow condition.

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[1]Hall, James - Personal communication

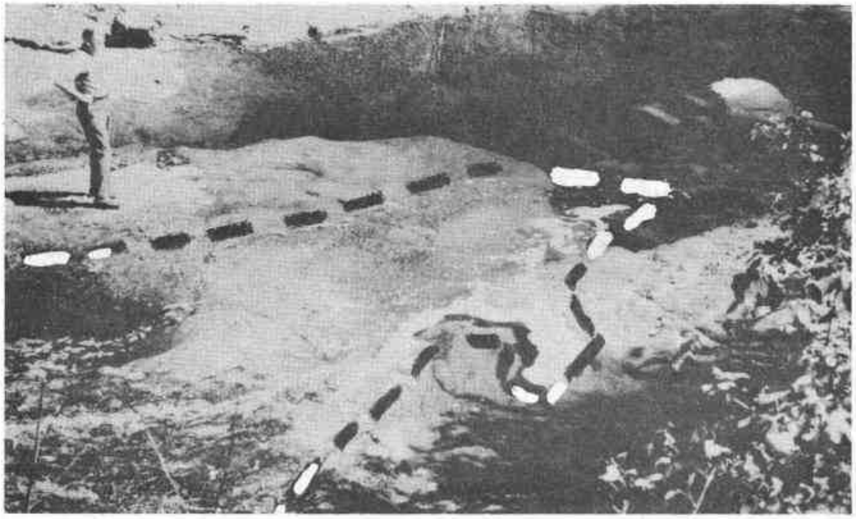
The largest study pool (Figure 5) was on Little Rock Creek and was about 34 feet wide. Dye was injected into the inflow water and observed as it moved through the pool. The average width of this dye cloud was only 8 feet. Only about one-third of the pool, therefore, contained flowing water. The photo sequence in Figure 6 depicts this dye dispersion.

Confinement of flow to a limited portion of the pool was observed in pools of many streams in the southern Cascades and the Coast Range. In many of the streams studied, discharge was below 0.10 cfs. Pool sizes were proportionately smaller than the pool shown in Figure 5, but flow restriction of the same magnitude was observed.

Conclusions

Predicting the temperature change between two points on a stream combines estimation of heat inputs and a routing procedure for adding this heat to a given unit of water as it passes between the points in question. Until now, it has been assumed that small streams are fully mixed and that all water within the channel participates equally in the heat exchange-temperature change process. Our study has shown that this is not the case.

Pools in small streams must be considered similar to small impoundments in the way water moves through them. Only a limited portion of the water within the pool is active in the transfer of heat downstream. In a reservoir, regulation of the outflow volume and the depth from which water is extracted determine the flow pattern and temperature in the reservoir. In small streams, the inlet configuration and pool dimension seem to provide a similar regulation. While pool surface area and volume may influence the mean temperature of a pool, the a.



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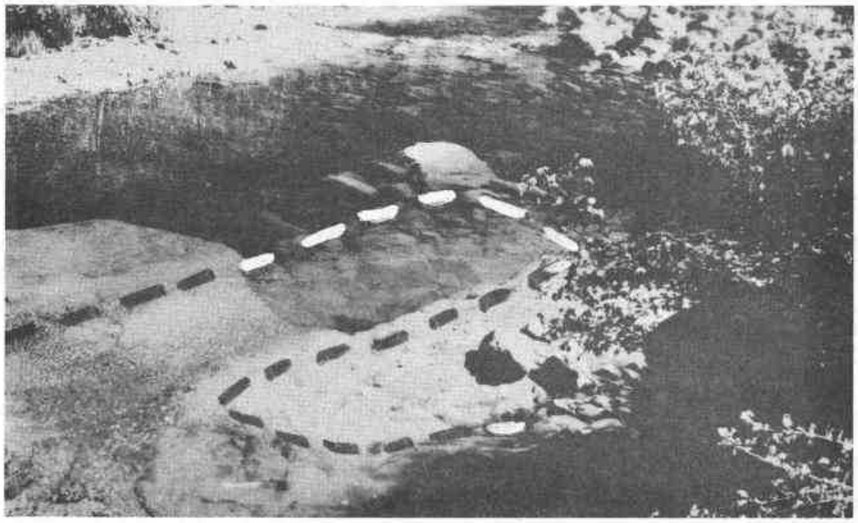

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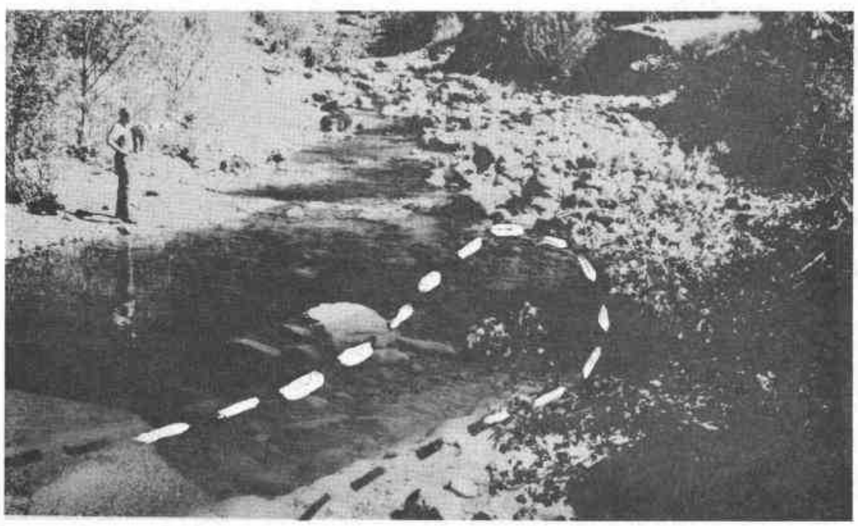

Figure 6. Dispersion of Rhodamine dye through the study pool in Little Rock Creek. Path of the dye cloud is shown with dashed line. Sequence progresses from head (a) to tail (c) of pool.

outflow temperature is primarily a function of the configuration of flowing water within the pool.

The largest study pool on Little Rock Creek (Figure 5) had a temperature gradient of 0.20°C (about 0.4°F) between the inflow and outflow during midday. The predicted temperature change using the full surface area of the pool was about 0.75°C (1.5°F). Using the width of the dye cloud to calculate pool surface area, the predicted temperature change was 0.25°C (about 0.5°F). It is evident that the kind of error incurred by including total pool surface for this one pool is magnified in streams that are composed of a series of such pools.

Field Application

The results of our studies on heat transfer in streams with bedrock channels and in pools was used to predict the temperature change observed as water flowed through a clearcut on Little Rock Creek in the Umpqua National Forest. This reach of stream had been used by field personnel to test the simplified temperature prediction equation (equation 1). The predicted temperature change was far in excess of that observed (Brown, *et al*., 1971). This reach was chosen to test our new information about temperature prediction methodology because it incorporated all of the conditions which caused error. The stream bottom was bedrock and the channel contained a series of large pools.

Predictions of temperature change on Little Rock Creek were made in a clearcut which exposed 1,100 feet of stream. Foresters estimated the average width of this reach of the stream to be 16.8

feet. Discharge was measured as 0.96 cfs. The heat input was estimated to be 4.1 BTU/ft^2/min using tables in Brown (1970. The temperature change predicted using these data and equation 1 was 21°F. The observed temperature change through the reach was only 6°F.

We concentrated our efforts in the upper 640 feet of this same reach. This reach contained most of the solid rock bed condition and all of the large pools. We deducted 20 percent of the incoming heat load to account for conduction losses into the bedrock bottom. For a similar solar angle, the incoming heat load was reduced from 4.1 to 3.4 BTU/ft^2/min. We estimated stream width by following a dye cloud through the reach, measuring its width every 15 feet. Average stream width was estimated to 12.3 feet or 25 percent less than the year before, even though the discharge was greater (1.11 cfs) than measured the previous year (0.96 cfs). Our prediction of temperature change through the shorter reach was 5°F using revised estimates of heat load and stream width. The observed temperature change was 4°F.

Conclusions

This study has enabled us to draw several useful conclusions about the nature of heat transfer in small forest streams and the application of this information to the problem of stream temperature prediction.

1. About 20 percent of the net radiation may be transferred to the bed of exposed streams where the streambed is composed of bedrock. Accurate temperature predictions on such streams will require a 20 percent reduction of H in equation 1. No adjustment of H is required on gravel-bottom streams.

2. All pools are not fully mixed. Only the flowing portion of the pool should be included in the calculation of surface area. The average width of a reach can best be estimated by following a dye cloud through the reach taking frequent measurements of its width.

3. The basic form of the temperature prediction model (equation 1) is valid. With the adjustments noted above, it is possible to predict the maximum temperature change expected by fully exposing a small stream to within 2-3°F of that observed, even on streams with bedrock bottoms and many large pools.

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