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Title TEMPERATURE PREDICTION USING ENERGY BUDGET TECHNIQUES ON SMALL MOUNTAIN STREAMS

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This study is part of the Alsea Basin Logging-Aquatic Resources Study research program. It was initiated to determine the applicability of energy budget theory to stream temperature prediction on small forested streams. The study was also designed to evaluate the energy budget technique as a tool in the management of mountain streams for the production of high quality water.

Temperature predictions were made on four stretches of three streams in the Coast and Cascade Ranges in Oregon during the summers of 1965 and 1966. Three of these stretches were forested. The fourth was completely exposed to direct radiation.

Stream temperature change occurring within a stretch of stream was determined by evaluating the radiative, evaporative, and conductive fluxes incident at the surface of the water as it moved downstream. Net radiation was measured directly. Evaporation was computed using a Dalton type equation. Conduction was determined

with the Bowen ratio. These fluxes were then added to determine the net flux. Stream temperature change was computed as:

$$\Delta T = \frac{\text{surface area of stretch} \times Qt \times \text{time}}{\text{streamflow} \times \text{time}} \times 0.000267$$

where ΔT = the change in stream temperature through the stretch in °F.

Qt = the net energy flux at the stream surface in $BTU/ft^2/min$.

time = travel time through the stretch in minutes.

Stream temperature was predicted with varying degrees of accuracy on the four stretches. Tests suggested that the predictions could be improved slightly on long stretches by subdivision of the stretch and by separating data into daytime or nighttime units. Additional tests indicated that under a broken canopy, net radiation estimates, and thus stream temperature predictions, may be improved by measuring, or utilizing in the predictive equation, only the diffuse radiation penetrating the canopy. Integration of the net radiation recorded to include occasional spots of sunlight results in an overestimation of temperature change during sunny periods.

A stream bottom may act as a heat sink during the day and as a heat source at night. This phenomenon was measured on one stretch. This helped explain predictive errors of about 10° F.

The study on the open stretch showed that during the day, conductive and evaporative fluxes were small compared to the radiative flux. This led to modification of the original formula for predicting temperature maxima. This formula is:

$$\Delta T = \frac{\text{Stretch surface area}}{\text{Streamflow}} \times 0.0001$$

This permits field personnel to make estimates of maximum temperature changes attainable by opening a stretch of stream.

TEMPERATURE PREDICTION USING ENERGY BUDGET TECHNIQUES ON SMALL MOUNTAIN STREAMS

by

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TABLE OF CONTENTS

TABLE OF CONTENTS (CONTINUED)

LIST OF FIGURES

LIST OF TABLES

TEMPERATURE PREDICTION USING ENERGY BUDGET TECHNIQUES ON SMALL MOUNTAIN STREAMS

INTRODUCTION

Purpose

The temperature of a stream is a parameter which determines, to a great extent, the suitability of the water as a source for domestic or industrial uses or as a medium for aquatic biota. The influence of temperature upon the quality of a water supply stems from its effect upon a complex series of physical, chemical, and biological relationships. Fisheries biologists have determined many of the ways in which water temperature affects fish, and the ecology of a stream system. Tarzwell and Gaufin (50) were able to demonstrate that temperature changes brought about by man's activity were responsible for significant changes in the ecology of a stream.

Temperature also influences the growth of fish. Donaldson and Foster (13) showed that salmon fry were not able to grow satisfactorily at temperatures much above 70°F. At 73°F, these fish experienced a considerable loss of weight. Temperatures above 78°F were lethal.

Stream temperature may indirectly influence fish life. Brett (7) noted that during the blue back salmon run in 1941, the Columbia River reached a non-lethal temperature of 74.5°F. However, this warm water permitted parasite populations to increase to epidemic levels. The salmon run was almost obliterated.

Changes in the streamside environment, particularly plant cover, may alter the normal temperature patterns in a stream. Unless these changes in water temperature can be predicted, however, research or management personnel must use temperature data recorded after the effects of the environmental changes are noticed to explain these effects. A method of predicting stream temperature would, on the other hand, permit prediction of some of the changes in these temperature related phenomena. A predicting technique also requires detailed evaluation of the variables influencing stream temperature. This permits a more complete understanding of the temperature-environment relationships.

It is the purpose of this dissertation to evaluate the components of the energy budget on sections of small mountain streams and to adapt current temperature prediction theory, formulae, and techniques developed for larger bodies of water to this special situation. In addition, an attempt will be made to evaluate the energy budget as a tool in the management of mountain streams for the production of high quality water.

Scope

This study was initiated to supplement research currently being conducted on the Alsea Basin Logging-Aquatic Resources Study where nine experimental watersheds and a network of temperature stations are maintained. Extensive fisheries biology and stream environment research are also in progress. The research for this dissertation was limited to prediction of stream temperature on sections of small mountain streams typical of those included in the parent study. Research was conducted during the summer months of 1965 and 1966.

Logging activity during 1966 required moving the study site to the H. J. Andrews Experimental Forest in the McKenzie River Basin. The scope of the study remained the same, i. e., the study stream was the same size as those in the Alsea Basin, the equipment utilized for data collection and the predictive method remained unchanged.

HISTORICAL DEVELOPMENT OF THE ENERGY BUDGET AS A TOOL IN THE PREDICTION OF STREAM TEMPERATURE

The first law of thermodynamics, commonly called the conservation of energy principle, states that the internal energy of a system is equal to the heat added minus the work done by the system. For a body at rest, an index of its energy level may be indicated by its temperature, i. e., the average speed of its molecules. From the first law of thermodynamics, it may be seen that as heat, or energy, is added the body must either expend this energy with some form of work or change its energy level, i. e., its temperature.

The conservation principle indicates that energy cannot be destroyed or created by the system or body. It is therefore theoretically possible to account for all of the energy once the input and initial conditions are known. The mathematical statement of the accounting procedure is called an energy budget.

The energy budget for a surface provides a simple illustration of the previous definition. If a surface is defined such that it has an infinitesimal thickness, its mass and heat storage capacity may be assumed zero. Figure 1 illustrates the flow of energy as it strikes the surface. Part of the incident energy (R) is reflected (S). Another portion is transmitted (T) through the plane of the surface. If the media on either side of the surface are differentially heated, energy

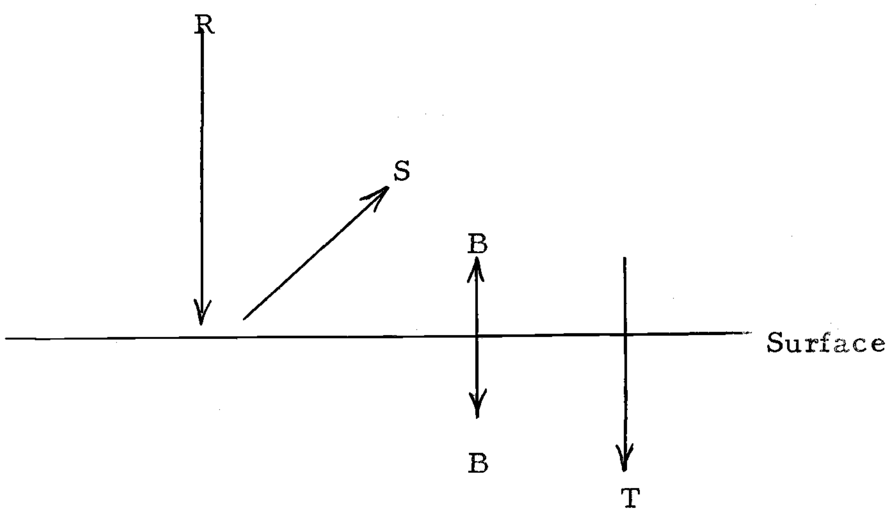

Figure 1. A Simple Energy Diagram For A Surface.

(B) will pass through the surface in response to the temperature gradient. In this simple case, the energy budget might appear as follows:

$$R - S - T \pm B = 0$$

Energy flowing toward the surface is usually labeled positive, that flowing away negative. These same techniques may be applied to a stream surface.

The energy budget for a stream surface however, is more complex. A stream has mass, movement and variable boundary conditions. Since a stream has mass, a storage term is required in its energy budget. Further, energy expended in raising its temperature must be accounted for as well as the energy it radiates as a result of its temperature.

Evaporation and condensation are exclusive dynamic processes occurring at the stream surface. Both processes are extremely important in energy exchange. The stream, like the simple surface, reflects and transmits energy. For shallow, clear, mountain streams transmission of energy to the bottom may be an important part of the energy budget. Reid (43) notes that only 53% of the incident light striking water one meter deep undergoes extinction. The remainder is available for storage in the stream bottom.

Other, less obvious possibilities of energy exchange typify the stream. For swift flowing streams, energy might be exchanged due to shear forces at the stream bottom and banks or at the air-water interface. Tributary waters may also involve energy exchange. Photosynthesizing plants may also add energy to the system. The energy budget for a stream surface might now be written as:

$$R - S - T \pm B \pm E \pm D - L \pm A \pm P + F = 0 \qquad (1)$$

where E, D, L, A, P and F denote energy exchange resulting from evaporation or condensation, heat storage, back radiation, advection, biological activity, and frictional forces respectively. The prediction of stream temperature using an energy budget is therefore complex since all of the above factors may interact to influence the energy level of a stream system. The use of energy budgets to predict stream temperature evolved from less complex theory and techniques originally developed to compute evaporation.

Early Evaporation Studies

Most of the earlier energy budget studies applied to bodies of water were conducted by physicists and oceanographers interested in oceanic evaporation or global heat flux (25, 33, 48). In 1915, Schmidt (46) first attempted to estimate the annual evaporation from oceans utilizing an energy budget. Although the technology of the period forced him to make many assumptions about meteorologic factors now measurable, he was able to make estimates of evaporation.

Other studies dealing with energy budgets of water surfaces followed. From this beginning, engineers and biologists have tried to extend the energy budget technique to reservoirs, rivers, lakes and bodies of water of a much smaller scale.

Until recently, instrumentation was not available for accurate measurement of the meteorologic variables of the energy budget, especially for short periods of time, e.g., hours or even days. Schmidt (46) for example, was forced to make yearly estimates of evaporation because he could not measure changes in energy storage for short periods. He had to assume that the annual change in heat storage in the ocean was zero. Sverdrup (48), in 1931, described the difficulty in conducting evaporation studies without radiation data. He proposed that, in lieu of pyrheliometer records, insolation might be calculated using the solar constant and then corrected using a transmission coefficient for the earth's atmosphere and a "clearness" (cloud) factor. In 1941, Holzman (25) concluded that the heat (energy) balance method for determining evaporation from water bodies, though theoretically precise, was impractical due to problems encountered in measuring the many meteorologic components.

Recent Evaporation Studies

Since 1945, engineers have been using the energy budget as a tool for estimating evaporation from reservoirs. By far the most definitive of these later attempts at estimating evaporation took place at Lake Hefner, Oklahoma. A team of meteorologists and engineers utilizing some of the best equipment available began a study of evaporation and the components of the energy budget over a body of water. According to Anderson (3, p. 91), "the principal objective of the energy budget investigation at Lake Hefner was to determine the utility of the energy budget as a method for computing evaporation from natural bodies of water". Anderson lists some 15 conclusions from the energy budget study. Those pertinent to studies of the energy budgets of streams and rivers are as follows:

1. Indirect computations of solar radiation are useless when computing evaporation.
2. The emissivity of a natural water surface is independent of water temperature and water composition.
3. The Bowen ratio (a ratio of sensible heat transfer to latent heat transfer) is accurate except when the the difference between the atmospheric vapor pressure and that of saturated air at the temperature of the water surface is small.
4. No error is introduced into evaporation computations by neglecting the effects of radioactive diffusivity, the stability of the air, and spray.
5. Energy budget equations, when applied to periods of

greater than seven days, will give a maximum accuracy approaching ± 5% of the mean evaporation if changes in energy storage have been properly evaluated.

M. I. Budyko (8) summarized much of the early work in evaporation estimation completed in Europe and the United States. In addition, Budyko developed several equations for estimation of evaporation based on both heat (energy) budget theory and the concept of turbulent water vapor diffusion. He was able to demonstrate the close correlation and validity of both approaches. Budyko points out that the evaporation rate from a free water surface during periods of absolute calm (wind speed zero) is equal to the evaporation rate in the case of purely molecular diffusion. Evaporation under these conditions is so small that it can be discounted in most energy budget studies.

One of the more recent works dealing with the evaporation term of the energy budget from both land and water surfaces was completed by Fritschen and van Bavel in Arizona (19). The methods and instrumentation utilized in this study were of high calibre. Using lysimeters, they found that on days of similar radiation intensity, the evaporative flux tended to be correlated with wind speed. Like other investigators before them (40, 41), they noted that the rate of evaporation was larger from a wet, bare soil surface than from a free water surface. Their most significant conclusion, from the standpoint of energy budgets for streams, is that with wind speeds less than four to five meters per second, the evaporation was less than 0.02mm of water per hour, the minimum sensitivity of the wetted lysimeters used. It might therefore be concluded that evaporation from the free water surfaces subjected to the same radiation load would be even less at these low wind speeds.

Studies of Thermal Loading of Water Bodies

Engineers have successfully adapted the method of energy budget analysis to evaluating the effect of introducing heated effluents into bodies of water. Langhaar (28), for example, was interested in the design of cooling ponds for industrial effluents. He utilized the energy budget concept to calculate the theoretical heat loss from water in ponds with varying surface areas. Thorne (51) was able to predict the effect of heated effluent on the temperature of a lake. His method was to superimpose the energy budget for an industrial lake (the heated effluent) onto that of a natural lake. Velz and Gannon (53) were concerned with the sanitary implications of heated streams and ponds. Like Langhaar and Thorne, they utilized the energy budget as a tool to predict heat loss. These authors, using energy budget theory, illustrated how a forecast of river temperature profiles might be made after addition of heated effluents to the river. Messinger (32) used an energy budget to predict the dissipation of heat from a thermally loaded stream. He was not able to accurately predict cooling. The error in his calculations was attributed to faulty radiation data. Measurements of radiation were made using a solarimeter mounted on a roof-top platform. This data was then extrapolated to the stream.

Biological Studies

Aquatic biologists have always been concerned with water temperature. Until recently, they have been more interested in the effects of water temperature on organisms than the physical relationships associated with water temperature. Harbeck and Greene (23) recently provided fisheries biologists with a method of estimating maximum temperatures in small lakes and ponds. They utilized a rather crude energy budget which incorporated several macrometeorological averages. Admittedly the method gives a conservative, i.e., high, estimate of maximum water temperature. The authors considered this an advantage, however, since the method was to be utilized in the design of ponds and lakes for fish production and provided a "built-in" safety factor.

River Temperature Prediction

River temperature, and the possibilities for its control, has been of concern to engineers only lately. An increased demand for water usage in the Pacific Northwest, has in recent years, necessitated a closer evaluation of this parameter of water quality. Several authors have illustrated the benefits to fisheries and pollution abatement derived from controlled reservoir releases during summer low flow periods (2, 17, 24). The prominence of water in the Pacific Northwest for recreation and the importance of the anadromous fishery have resulted in several studies relating to stream temperature prediction. Temperature control through regulation of reservoir discharge is now regarded as a practical management tool.

In 1957 and 1958, Burt prepared a series of technical reports dealing with temperature prediction on the Snake and Clearwater River systems (9, 10). These reports were very general in nature and dealt only with gross estimates of the effect of proposed dams on river temperature. The predictions proposed by Burt were based on monthly averages of meteorological parameters reported by the U.S. Weather Bureau at the installation closest to the point of interest. The difficulty of using such data is obvious, since the meteorological environment above a large expanse of water at the bottom of one of the Snake River gorges is likely to be considerably different than that at a distant weather bureau station, for example that at the Lewiston, Idaho airport. However, this is one of the first attempts to predict river temperature in the Pacific Northwest using heat budget theory. Because of its application to the problem at hand, details of Burt's heat budget are given below:

$$Q_s - Q_r - Q_b - Q_h - Q_e + Q_v = Q_t \qquad (2)$$

where Q_s = short wave radiation striking the water surface.

Q_r = short wave radiation reflected back to the sky.

Q_b = net back radiation of long wave energy.

Q_h = heat loss through conduction from water surface to the air.

Q_e = heat loss through evaporation.

Q_v = heat gain through advection.

Q_t = increase or decrease in energy stored in the body of water.

The factor Q_s was obtained using Weather Bureau graphs of short wave radiation. From this value, Q_r was obtained using a hypothetical value for albedo. Net back radiation, Q_b, was computed as the difference between long wave radiation emitted from the water, using Stefan-Boltzmann's law, and the estimated long wave radiation received. Computation of back radiation involved adjustment for cloud cover and height. These values were obtained from the Weather Bureau's mean monthly cloud cover records. Evaporative heat loss was estimated using mass transfer theory and mean monthly averages for wind speed and ambient vapor pressure. Burt also incorporated an exchange coefficient determined by Marciano and

Harbeck (29) at Lake Hefner as a part of the mass transfer study. The formula for finding Q_e is as follows:

$$E = KU(e_w - e_a) \tag{3}$$

$$Q_e = LE \tag{4}$$

F = total depth of evaporation in inches.

where U = wind speed in miles per hour

K = Marciano and Harbeck's coefficient (0.0045)

e_w = saturated vapor pressure at the temperature of the water (mb).

e_a = ambient vapor pressure (mb).

L = heat of vaporization for water at the lake temperature.

Heat exchange by conduction, Q_h, was computed using the Bowen ratio and Q_e above. The Bowen ratio (5), given as:

$$R = \frac{Q_h}{Q_e} = \frac{P}{1000} D \frac{T_w - T_a}{e_w - e_a} \tag{5}$$

was multiplied by Q_e to obtain:

$$Q_h = \frac{P}{1000} 0.61 (T_w - T_a) 0.0045HU \tag{6}$$

where P= barometric pressure in millibars.

T_w = water temperature (°C)

T_a = air temperature (°C)

D = 0.61 = Bowen's "most probable" constant for temperatures in °C, pressure in millibars.

Burt did not attempt to obtain a value for Q_a, the advected energy. He simply states that advection is a function of all the other terms plus the size, shape, and orientation of the reservoir or river and the flow of the river. It would seem that these physical features of the river should influence the other terms as well, invalidating many of the extrapolated meteorological variables. In addition, the value K, used in the evaluation of Q_e, is an empirical value obtained from extrapolated data. The data for the computation of K was obtained 13 miles from the Lake Hefner research site at the Oklahoma City Airport (29). Such coefficients are usually valid only in areas immediately adjacent to the data collection site. It is difficult to extend the application of these coefficients to evaporation computations elsewhere.

In 1962, J. M. Raphael (42) presented a method for the prediction of temperature in rivers and reservoirs. He combined much of the information from the Lake Hefner study, including the exchange coefficient, and Burt's heat budget with a method for "routing" temperature downstream and accounting for advected energy. Raphael proposed dividing a stream into convenient stretches, each of which was treated as homogeneous for a given increment of time.

For lakes, he noted that the time rate of change in lake temperature is equal to the total heat transferred at the surface plus the product of inflow rate and the temperature difference of inflow and lake water all divided by the mass of the lake. Mathematically this statement is:

$$\frac{dT_w}{dt} = \frac{Q_t A + m_i (t_i - T_w)}{m_w} \qquad (7)$$

where T_w = lake temperature (°F)

t_i = inflow temperature (°F)

t = time

A = surface area of the lake (acres)

m_i = mass of inflow water

m_w = mass of the lake

Q_t = increase in energy stored in the lake (computed using Burt's equation).

For a river, Raphael suggests dividing it into stretches, each of which is treated as a separate "lake". The predicted outflow temperature for a stretch becomes the inflow temperature for the stretch immediately below. The value Q_t in the above formula is computed using mean monthly meteorological averages as proposed by Burt (10).

Raphael made some predictions for 75 miles of a large western river using this method. The flow of this river decreased from 230,000 to 63,000 cfs during the summer. Average stream temperature rose from 59°F in the early summer to a high of 68°F at mid-summer some 95 miles downstream. Although Raphael states that there is "fair correspondence" between computed and observed stream temperatures, the method was not really subjected to a definitive test. First, Raphael had no data for observed temperatures at the end of the 75 mile stretch for which the computation was made. He had, however, stream temperature records for a point 20 miles farther downstream. In the intervening 20 miles, a major tributary entered undoubtedly affecting the stream temperature pattern. A second problem that could lead to discrepancies is that on only one occasion was there ever a temperature difference of two degrees or greater between the initial observation point and the station of record 95 miles downstream.

The State of Oregon, in conjunction with the Corps of Engineers, has conducted several studies to determine the capabilities of several proposed reservoirs for regulation of stream temperature (37, 38). The approach is essentially the same as that of Raphael, and incorporates monthly meteorological data obtained by the Weather Bureau. Although the estimates are hypothetical, they have served as a planning guide in the development of basin-wide water resources in Oregon. The studies have been conducted on large rivers in Western Oregon, e.g., the South Umpqua, the Rogue, and the Coast Fork of the Willamette. The hypothetical reservoir release rates on which estimates were based varied between 100 and 1600 cfs. No studies have been reported which attempted to predict temperatures on smaller streams where the influence of the microenvironment may be greater or to compare predicted and observed temperatures on the larger streams as a check of the method.

Several generalizations may be drawn from the preceding review. None of the studies were concerned with streams having a discharge less than 25 cfs. No attempt was made to measure the microenvironment, or even the macroenvironment, near the stream surface. Most authors used data recorded at the nearest U. S. Weather Bureau station even though no climatic or topographic similarity existed between the recording station and the study site. Seldom did any of the authors attempt to evaluate the error induced by this sort of extrapolation. Neither was any attempt made to determine the local applicability of the Lake Hefner exchange coefficient used in computing evaporation. Finally, the theory developed for stream temperature prediction by many of the recent workers has not been suitably evaluated in the field. It may therefore be concluded that the information regarding stream temperature prediction is far from complete.

DERIVATION OF THE ENERGY BUDGET EQUATIONS

An energy budget for a stream was described as a mathematical procedure used to account for energy entering, leaving and stored in the stream. It may be possible to compile a long list of energy sources and sinks relative to the stream. Many of these would be extremely small, for example the shearing friction at the air-water interface, and would be impossible to measure using available equipment. It will therefore be assumed that only solar radiation, evaporation, condensation, conduction and advection as measured with available instrumentation are effective in altering stream temperature. Symbols used in the equations presented below are usually described only once. A list of all symbols used in this dissertation is included in the appendix for further reference.

The mathematical statement of the energy budget used is as follows:

$$Q_t = Q_{Nr} + Q_e + Q_h + Q_a \tag{8}$$

where: Q_t = net energy flux to storage in stream water

Q_{Nr} = radiative exchange

Q_e = evaporative exchange

Q_h = conductive exchange

Q_a = advective exchange

Each factor in the above equation may be either positive or negative.

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

Net Radiation

Net radiation may be defined as the difference between the total incoming and total outgoing all wave radiation at the stream surface. This value is a measure of the radiation retained in or lost from the stream.

Net radiation was measured directly in this study using a net radiometer. This is a marked improvement over previous studies (1, 9, 10, 42) where net radiation was computed as a function of the solar constant, water temperature, cloud cover, and solar angle.

Using the values obtained from the radiometer, the net amount of energy added to a unit area of the stream was computed using the following formula:

$$Q_{Nr} = 3.68 \times NR \times time \quad (9)$$

where: Q_{Nr} = net radiative energy exchange in $BTU/ft^2/min$

3.68 = a constant for converting langleys/min to $BTU/ft^2/min$

NR = net radiation in langleys/min

time = time intervals in minutes during which the water is subjected to the above radiation load (the stream travel time in the stretch)

Anderson (3) and Raphael (42) have shown that net radiation is by far the most significant source of energy for the stream.

Evaporation

Heat may be added or removed from the stream in response to changes in the state of water at the stream surface through condensation or evaporation. During the summer months, the most significant of these two phenomena is usually evaporation. Anderson (3), Raphael (42) and Tichenor (52) have noted that although evaporation and condensation contribute less to the daily energy flux in a stream than net radiation, they may account for the major energy exchange during the night.

The methods and measurement of evaporation have been the subject of considerable controversy since the early 1900's. Budyko (8) describes three basic methods for determining natural evaporation. These are methods based on:

1. Equations of turbulent water vapor diffusion.
2. The water balance equation.
3. The heat balance equation.

In a review of international evaporation studies, Budyko (8) presents a general equation for the turbulent vapor diffusion method. This equation is presented below.

$$E = \rho_2 \left\{ \int_0^t \left(k \frac{dq}{dz} \right) dt - \int_0^z \left[(q - q_0) + \int_0^t \left(U \frac{\partial q}{\partial x} \right) dt \right] dz \right\} \quad (10)$$

where: E = total evaporation (or condensation)

ρ_2 = air density

t = time

k = turbulent exchange coefficient

q = specific humidity at height z

q_o = specific humidity at water surface

z = height above the water surface

U = wind velocity

x = horizontal distance

Practical limitation of field evaluation prohibited the use of such an equation. First, simultaneous accurate measurement of specific humidity for at least two heights within the zone of turbulence and throughout the length of the stream system is difficult to achieve. Second, the evaluation of the exchange coefficient is also difficult due to similar requirements since:

$$k = l^2\left(\frac{\partial U}{\partial z}\right) = \chi^2(z+z_o)\frac{U}{\ln\frac{(z_1+z_o)}{z_o}} \qquad (11)$$

where: l = mixing length

χ = von Karman's constant (0.38)

z_o = height equivalent to surface roughness

z_1 = height equivalent to mixing length

Water balance equations of the form:

$$E = r - f \pm \Delta_1 \tag{12}$$

may be used where: r = total precipitation or inflow

f = total runoff or outflow

Δ_1 = change in moisture storage

Such equations, while reasonably simple for lakes or reservoirs are difficult to evaluate for streams. For the purpose of this study, precipitation is usually zero and since summer stream flow is solely base flow, inflow occurs throughout the length of the stream as groundwater inflow. This function is difficult to evaluate without an extensive network of groundwater wells or accurate surface gages. Estimating the change in aquifer storage would otherwise require assuming some drawdown rate and distributing this throughout the stream system.

The final general method for evaluation of evaporation from a water surface is the heat balance method. The general equation for this method as described by Budyko (8) is:

$$E = \frac{1}{L}(R - P'' - \Delta_2) \tag{13}$$

where: E = evaporation

L = latent heat of evaporation

R = radiation balance

P'' = total turbulent heat exchange between the water surface and the atmosphere

Δ_2 = change in heat storage.

Further, $\Delta_2 = \rho_1 c_1 \int_o^{\infty} (T_w{}' - T_w{}'')d_z$ (14)

$$p'' = \rho_2 c_p \int_o^{t_o} (K \frac{\partial T_a}{\partial z})dz \qquad (15)$$

where ρ_1 = density of water

c_1 = specific heat of water

ρ_2 = density of air

c_p = specific heat of air

$T_w{}''$ = water temperature at time t_o

$T_w{}'$ = water temperature at time t

k = exchange coefficient

Substituting into equation 13,

$$E = \frac{1}{L} [R - \rho_2 c_p \int_o^{t} (k \frac{\partial T_a}{\partial z})dt - \rho_1 c_1 \int_o^{\infty} (T_w{}' - T_w{}'')dz] \qquad (16)$$

Budyko (8) notes that since the evaluation of k is so difficult, many authors have relied upon the Bowen equation for calculating evaporation by the heat balance method.

The Bowen equation (5) or ratio is essentially a ratio of the heat lost by conduction to the heat lost by evaporation for a water surface. This equation is written as follows:

$$R' = Q_h/Q_e \qquad (17)$$

and $Q_h = \rho_1 c_p \frac{P}{760} (T_w - T_a)$ (18)

$$Q_e = L(\frac{\rho_1 e_w - \rho_2 e_a}{273} \tag{19}$$

Then, $$R' = Q_h/Q_e = 0.61 \frac{T_w - T_a}{e_w - e_a} \frac{P}{1000} \tag{20}$$

where Q_h = heat loss by conduction

Q_e = heat loss by evaporation

c_p = specific heat of air

ρ_1 = density of water

ρ_2 = density of air

P = atmospheric pressure in millibars

T_w = water temperature in °C

T_a = air temperature in °C

L = latent heat of vaporization

e_w = vapor pressure of water in millibars

e_a = vapor pressure of air in millibars

0.61 = Bowen's most probable constant for temperature in °C, pressure in millibars. In terms of heat balance equation 13, Budyko (8) writes this same equation as:

$$\frac{P'}{LE'} = \frac{C_p \frac{\partial Ta}{\partial z}}{L\frac{\partial z}{\partial z}} \tag{21}$$

where P' = rate of turbulent heat exchange between the water surface and the atmosphere

E' = rate of evaporation or condensation

T_a = air temperature

Budyko (8) has shown that the use of the abbreviated heat budget or Bowen ratio, for calculating evaporation is valid only for short periods and not for monthly estimates.

Since the Bowen equation is developed as a ratio, it is difficult to use directly for field estimates of Q_e. The principal reason is that the equation for Q_e (equation 19) does not account for an acceleration of the evaporation process by wind. Several empirical equations have been proposed to correct this deficiency. One of the most successful, utilized during the Lake Hefner studies (3) and also by Penman (40) is in the form of the Dalton equation:

$$E = KU(e_w - e_a) \tag{22}$$

where K = experimental constant

U = wind speed in miles per hour

e_w, e_a = previously defined

From this equation, Q_e may be obtained directly by:

$$Q_e = LE \tag{23}$$

$$\text{or } Q_e = LKU(e_w - e_a) \tag{24}$$

It is evident that the accurate determination of the constant K is an important requirement in this equation. This constant is essentially a locally developed exchange coefficient. Burt (9, 10), Albertson <u>et al.</u> (1), and Raphael (40) all used the constant determined at the Lake Hefner site without regard to this limitation. Tichenor (52), working with evaporation from free water surfaces in controlled environments, was able to show that evaporation computed with this constant was one half of that measured in a wind tunnel. The Lake Hefner constant is 0.00177 for wind speed in miles per hour, vapor pressures in millibars, and evaporation in inches per day. Converting vapor pressure to inches of mercury, doubling K and using 1060 BTU/lb. for the average latent heat of vaporization, Q_e then becomes

$$Q_e = 0.6142\ U\ (e_w - e_a) \qquad (25)$$

where Q_e = heat exchange through evaporation or condensation in $BTU/ft^2/min$.

Conduction

Geiger (21) defines conduction as a heat transfer process which is essentially molecular in nature, i.e., heat energy, or energy of molecular motion, is transferred from molecule to molecule. This process, unlike radiation, requires matter. Geiger calls this process "true heat conduction". A related process is convection. Convection is the result of displacement of masses of fluid, either liquid or gas. As a result, Geiger calls convection "pseudo-conduction". Heat transfer processes above a stream would most likely fall into the latter category. Seldom, if ever, would conditions prevail which would permit "true conduction". True conduction could dominate under conditions of absolute calm and a stream surface having laminar flow conditions. The term conduction, hereafter, will include both "true" and "pseudo-conduction".

The conduction described by the Bowen ratio, equations 18 and 20, applies to both forms of conduction. It is necessary to note, once again, that it can be used only in computations of conduction and evaporation for periods of two to three hours. Once the equation for determining the heat exchange from evaporation has been derived, the Bowen ratio may be used to compute the heat exchange from conduction as follows:

$$R' = Q_h / Q_e = 0.61 \frac{T_w - T_a}{e_w - e_a} \frac{P}{760} \tag{26}$$

Substituting Q_e from equation 25, to include the windspeed term

$$Q_h = 0.61 \frac{T_w - T_a}{e_w - e_a} \frac{P}{760} [\, 0.6142\, U (e_w - e_a)] \tag{27}$$

Simplifying and converting to English units,

$$Q_h = 0.0002\, U\, P\, (T_a - T_w) \tag{28}$$

where Q_h = heat exchange through conduction in BTU/ft^2/min

U = wind speed in mph

P = atmospheric pressure in inches of mercury

T_a = air temperature in ° F

T_w = water temperature in ° F

Advection

Advection may be generally defined as the horizontal transfer of energy from some source outside the area being considered. In terms of the total change in energy occurring at the study site, advected energy is that portion of the total change which may not be attributed to local change (11). For land surfaces, this advection is usually in the form of horizontal transfer of air masses. For streams, advection may also take the form of tributary streams which have a different temperature or energy level than the study stream. In this sense, ground water added throughout the length of the stream also constitutes a source of advective energy.

Two methods may be used to account for the addition of advective energy by flowing water. If the study stream is broken into convenient stretches, all of the tributary waters in the stretch may be mathematically added at the end using a simple mixing ratio to adjust the final predicted temperature (1). Such a ratio may appear as follows:

$$T' = \frac{(Tm)(Fm) + (Tt)(Ft)}{Fm + Ft} \qquad (29)$$

where T' = adjusted temperature

Tm = predicted temperature of the main stream

Tt = temperature of the tributary

Fm = flow of the main stream

Ft = flow of the tributary

Addition of advective energy in this manner is somewhat unrealistic, especially where the travel time in the stretch is lengthy and the advective inputs are large. Equations 25 and 28 reveal that computation of the evaporative and conductive energy fluxes are a function of water temperature. It would seem to be necessary to adjust computed stream temperatures immediately to maintain the validity of these relationships.

A more logical approach is to mathematically break the stretch into sub-stretches, each of which terminates at the point of a surface input or tributary. A mixing ratio such as equation 29 might then be used to obtain more frequent temperature predictions and, as a result, adjusted vapor pressure and temperature gradients. Addition of ground water may be accounted for in a similar manner.

Net Energy Flux

The net energy flux is the sum of the evaporative, conductive, radiative and advective energy fluxes. This may be simply written as: $Qt = Q_{Nr} + Q_e + Q_h + Q_a$. It is important to note that this is the average flux for the period determined by the stream travel time, since each of the above components of the net flux are also averages. Due to the continuously changing stream temperature and continuous addition of ground water as a given parcel of water moves downstream, the use of non-integral relationships for the determination of the components immediately sets some limitations as to the inherent accuracy of the method. Obviously, the closer the substretches approach infinitesimally small segments, the closer will be the evaluation of the net energy flux.

Predicted Temperature Change

The predicted temperature change is simply a function of the net energy flux, the surface area of the stream, the volume of water in the stretch and the time during which the water is subjected to the energy flux. Mathematically, this may be expressed as:

$$\Delta T = \frac{A \times Qt \times \text{time}}{\text{flow} \times \text{time}} \quad (30)$$

In order that the energy output in BTU/ft^2/min may be converted to temperature change in degrees Fahrenheit, equation 30 must be multiplied by a proportionality constant derived through the following dimensional analysis:

$$\Delta T = \frac{\text{Area} \times Qt \times \text{time}}{\text{flow} \times \text{time}} \quad (30)$$

$$\Delta T = \frac{\text{ft}^2 \times \text{BTU/ft}^2\text{min} \times \text{min}}{\text{ft}^3\text{/sec} \times 62.4 \text{ lb./ft}^3 \times 60 \text{ sec/min} \times \text{min}} \quad (31)$$

$$\Delta T = \text{BTU/lb} \times 1/(62.4 \times 60) \quad (32)$$

Since a BTU is defined as the amount of heat required to raise one pound of water one degree Fahrenheit,

$$\Delta T = BTU/lb \times .000267 = {}^\circ F \tag{33}$$

Equation 30 may now be written as:

$$\Delta T = \frac{Area \times Qt \times time}{flow \times time} \times 0.000267 \tag{34}$$

where ΔT = temperature change in °F

A = surface area of the stream stretch in square ft.

Qt = net energy flux in $BTU/ft^2/min$

flow = discharge in cubic feet per second

time = travel time through the stretch in minutes

INSTRUMENTATION AND DATA COLLECTION

Description of the Stream Stretches

Three streams were selected as sites for the stream temperature prediction study. Two of these streams, Deer Creek and Needle Branch, are experimental watersheds of the Oregon State University Logging-Aquatic Resources Study. These streams are in the Alsea River Basin, about ten miles from the Pacific Ocean and are tributary to Drift Creek. A third stream was selected in the Cascade Range of Oregon during 1966 to supplement data gathered on the other two streams. This small stream is a tributary to Lookout Creek in the upper McKenzie River Basin. It is the principal stream in Watershed 3 of the H. J. Andrews Experimental Forest.

Deer Creek

Deer Creek was chosen as the first study site for the summer of 1965. The watershed contained an extensive system of thermographs and stream gages in conjunction with other studies and was reasonably accessible. The watershed was heavily forested at the time of the study. Western red alder grew along the stream and provided an almost continuous canopy in the upper portion of the

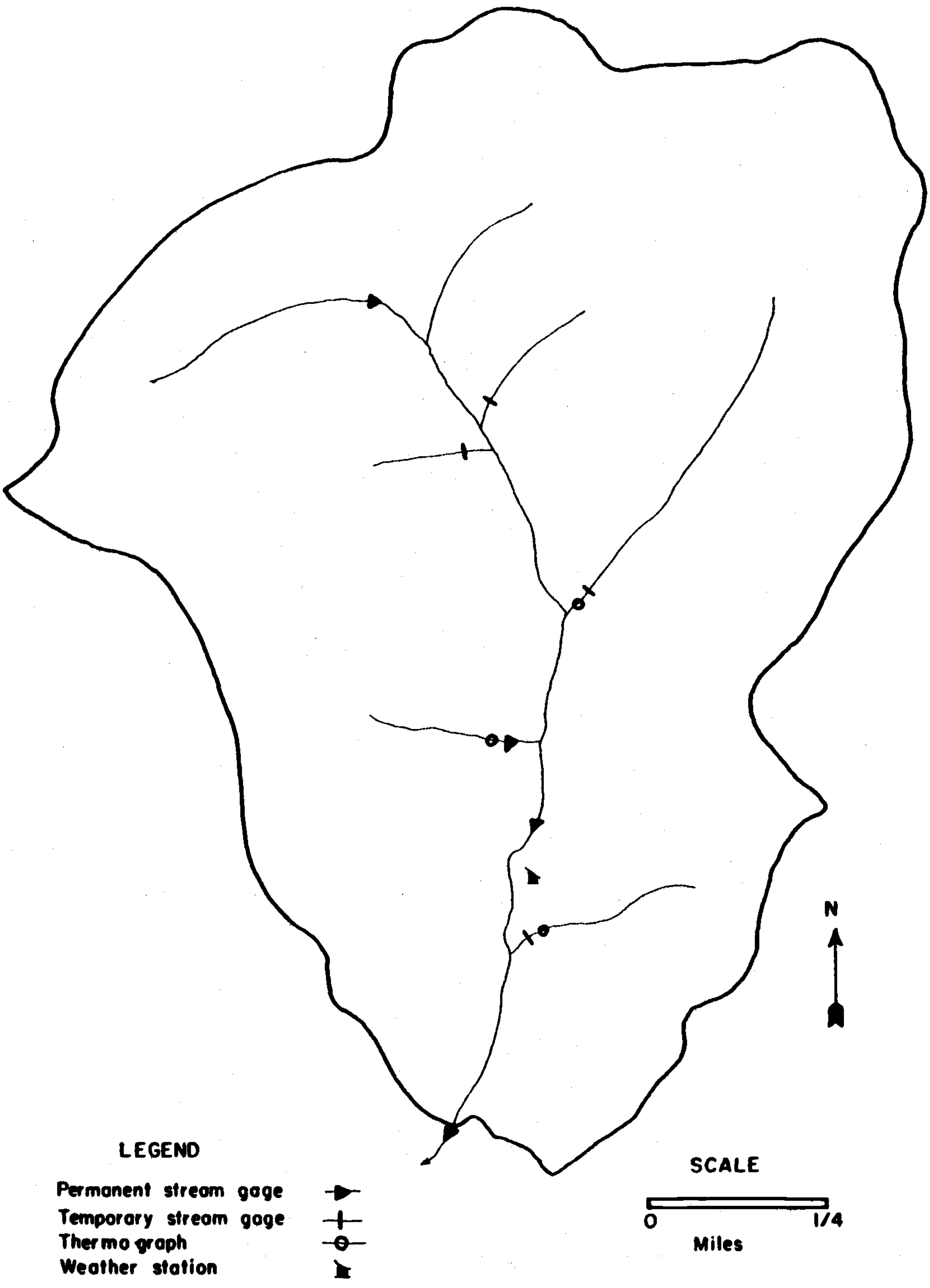

Figure 2. The Deer Creek Instrumentation System.

watershed. The lower 1200 feet of the stream was topographically shaded until midday. Even during midday it was partially shaded by salmonberry bushes growing along the bank. The sections of the watershed away from the stream were primarily covered with 100 year-old Douglas-fir. The upper portion of the stream flows through a flat, broad meadow. Even though the surrounding hillsides are steep, topographic shading is negligible within three hours after sunrise.

Two stream stretches were selected in Deer Creek. One included the lower 1200 feet of stream which drops 60 feet in elevation. This section is turbulent and swift flowing. The travel time is about two hours (0.17 fps) for normal summer low flow. The second stretch selected was within the upper mile of stream and has a different pattern of flow. The stream meanders through rather flat meadows and has a series of small, shaded pools and riffles. The summer flow velocity is, as expected, very low and averages about 0.04 fps in the upper mile. Figures 3 and 4 illustrate the differences in vegetation and streamflow pattern between the upper and lower reaches of Deer Creek. The discharge in Deer Creek, as measured at the U.S. Geological Survey gage at the bottom, dropped to about 0.4 cfs during August and September.

Figure 3. The Upper Stretch (Stretch II) of Deer Creek

Figure 4. The Lower Stretch (Stretch I) of Deer Creek

Needle Branch

The stream temperature prediction study was shifted to Needle Branch during April, 1966. The stream section studied was very similar to the upper section of Deer Creek in that alder and salmonberry provided shade for most of the stream. However, the surrounding topography was much steeper and the stream bottom was much narrower. Streamflow during April was about 0.5 cfs. The stream velocity averaged about 3 fps. through the 1800 foot stretch. Summer discharge on this stream often drops below 0.1 cfs. Measurements were conducted during the spring to take advantage of these higher flows and faster travel times.

H. J. Andrews Experimental Forest

The study site was shifted to a stream in the Cascade Mountains in order to test the prediction equations in an environment providing higher stream temperature fluctuations. The study was initiated in May, 1966. A large mud slide in Watershed 3 of the H. J. Andrews Experimental Forest had removed all of the debris and much of the alluvium from the stream channel during the floods occurring in 1964-1965. The channel was scoured to bed rock through a clear cut resulting in a stream that was exposed to direct sunlight for about 1300 feet (Figure 5). Discharge was measured at

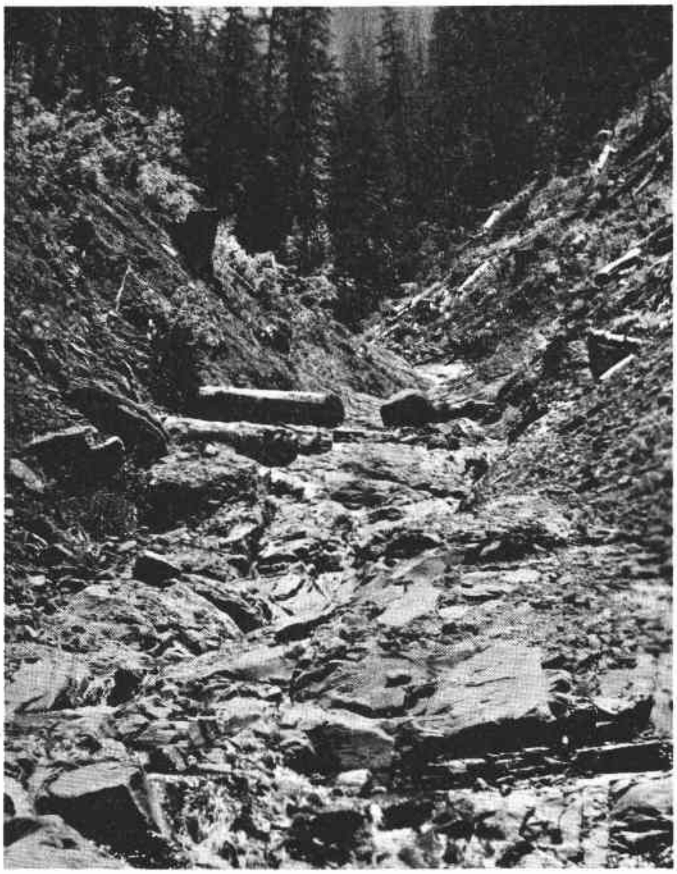

Figure 5. The H. J. Andrews Experimental Forest Study Section

bottom of the watershed with a trapezoidal flume maintained by the U.S. Forest Service. Discharge during the early summer months is about 0.4 cfs. The velocity in the open clear cut is about 0.4 fps. The flow is extremely turbulent through this stretch. The water depth in the upper region is approximately 0.5-1.0 inches. Low flow, shallow water depth and exposure provided maximum opportunity for rapid and extreme temperature fluctuations.

Instrumentation and Data Collection Procedures

Both hydrologic and climatic data were collected to determine the magnitude of the previously developed prediction equations (equations 9, 25, 28, 34). The instrumentation used is described below. The choice of instruments for measurement of each variable was dictated by the degree of accuracy and precision required, the necessity for making measurements at remote locations without alternating electrical current, and a restricted budget.

Hydrologic Instrumentation

Water Temperature. Water temperature data were used in assessing the temperature gradient in equation 28, the vapor pressure gradient in equation 25, and in evaluating the accuracy of each prediction.

Water temperature was measured with Partlow model TR thermographs. These instruments utilize a continuous mercury filled capillary and sensing bulb. The expansion or contraction of this mercury column activates the recording pen arm. The sensing element is a large mercury-filled bulb 5/8 inch in diameter and nine inches long. Thermograph charts with one degree Fahrenheit graduations were used. This permitted interpolation to 0.5° F. The chart drive utilizes a seven day spring wound clock. These instruments were field calibrated. Daily checks were made on each thermograph after field placement with a mercury-in-glass laboratory thermometer graduated in tenths of a degree Fahrenheit. Adjustment of the temperature recorders was seldom necessary. The time constant for this instrument is less than five minutes.

Discharge. Discharge data, in cubic feet per second, were inserted directly into equation 34 for computing ΔT. Discharge is essentially an estimation of the volume of water affected by the net energy flux.

Discharge was measured at several points within the Deer Creek study area (Figure 2) using six 60° V-notch weirs, one 120° V-notch weir and a broad crested, V-notch weir built by Oregon State University and maintained by the U.S. Geological Survey. Calibration data was available for the U.S.G.S. weir and daily stage measurements were recorded for reference. Four tributary streams were gaged using temporary plywood weirs fitted with steel

60° V-notch plates. Discharge through these weirs was obtained by measuring the head above the weir crest with a specially constructed plastic triangle, designed to fit the notch. This device was marked in hundredths of a foot and permitted a direct measurement of head to within 0.005 ft. Two permanent gaging stations were fitted with a 60° V-notch plates and measured in a similar manner. Discharge through the one 120° V-notch was measured using a staff gage. The discharge of several small tributaries was measured volumetrically using a graduated bucket and a stop watch. The accuracy of the formula used to compute discharge from the V-notch weirs was periodically checked using this method.

Discharge at the Needle Branch and H. J. Andrews study sites were obtained directly from the permanent gages at the bottom of these watersheds. These two gages are maintained by the U.S. Geological Survey and the U.S. Forest Service respectively. The gage at Needle Branch is a broad-crested V-notch weir. The Forest Service gage is a trapezoidal flume. Since the Needle Branch and H.J. Andrews stretches contain no significant tributaties, the measured discharge at the gage was assumed to be representative of the discharge through the stretch. The character of the stream channels prohibited installation of small, temporary weirs at the upper end of the study stretches. The use of only one measurement point necessitates an assumption that there is no groundwater addition in the stretch. Such an assumption is probably valid in the H. J. Andrews study area because of the bed rock stream bottom and the lack of evident seepage. On Needle Branch, this assumption is not entirely valid. Studies the previous year on an equivalent distance in Deer Creek indicate that although the volume of such groundwater input is probably small, the proportion may be significant. Groundwater discharge was estimated at 0.1-0.2 cfs for the entire stream or approximately 25% of the total discharge in the two stretches on Deer Creek.

Travel Time. Stream travel time, the time required for water to flow a given distance along the stream gradient, is an important component in the computation of stream temperature change (equation 34). This time interval determines the total amount of energy reaching the water, when multiplied by the rate of energy flux, and also the amount of water affected by the net flux. Travel time through a study stretch was obtained at the beginning of a study and repeated only after noticeable changes in discharge occurred. Travel time was measured using DuPont Rhodamine B dye. This fluorescent dye is mixed with acetic acid to a specific gravity of 1.05. After introduction of the dye at the top of a stretch, samples were obtained at the bottom of the stretch for laboratory analysis. Long stretches were subdivided to correspond with those substretches used in computing stream temperature (see Data Processing, Chapter V) by determining travel times between tributaries. After laboratory analysis with a fluorometer, concentration of Rhodamine dye was plotted against the time elapsed between introduction of the dye and sample collection. The peak of this concentration-time curve was taken as the travel time for the study stretch or substretches and was estimated to be within ten to 15 minutes of the true travel time for a stretch or substretch. The accuracy of the travel time estimates was within 10% since the travel time through most substretches or stretches was two to four hours.

Surface Area. All three study stretches were within larger research areas and a part of surveyed stream systems. Cross sections of the streams were taken at 25-foot intervals along these measured distances to obtain surface area.

Climatic Instrumentation

Net Radiation. Measurement of net radiation provides data for solution of equation 9 for the net radiation flux, an important component of the energy budget equation. Net radiation was measured with a model 602 net radiation system produced by C. W. Thornthwaite Associates Laboratories. This system consists of a portable microvolt recorder and a Fritschen miniature net radiometer (18). The recording system utilizes the galvanometer photoelectric feedback principle in conjunction with a transistorized amplifier. This amplifier requires less than ten milliamps at 12 volts D.C. Solar radiation is recorded on a Rustrak miniaturized chart recorder having a sensitivity of one milliamp at full scale deflection.

The Fritschen miniature net radiometer has a thermal transducer sensor. The transducer is encased in two hermetically sealed plastic radiation windows. The transducer surfaces have been sprayed with flat black paint giving uniform response to both short and long wave radiation. The output of this transducer is from 3-5 mv/ly/min with a resistance of 1-4 ohms. Fritschen (18) and Reifsnyder and Lull (44) note that the response time for this instrument is about two seconds. The system is factory calibrated, i.e., each radiometer is calibrated with a given recorder. In addition, each radiometer has its own calibration so that utilization of other recording systems is possible. The calibrations on the radiometer recorder systems were checked with a microvoltmeter and were found to be both accurate and precise.

The system gives a read-out directly in ly/min, printed onto a contact type strip chart. This chart permits interpretation of net radiation to within 0.02 langleys. For days of continuous, uniform radiation, i.e., completely clear or completely cloudy, the chart is quite easy to read or interpret. During periods of erratic radiation, e.g., partly cloudy days or under a moving tree canopy, the chart becomes extremely difficult to interpret due to the rapid movement of the pen along the chart in response to spots of sunlight passing over the sensor.

A few problems have been encountered using this instrument in the field. First, the radiation windows are ideal collecting surfaces for dust and dirt, and more importantly, dew. Therefore, the radiation windows required cleaning early each morning prior to the time direct sunlight reached the stream bottom. Another problem is the power requirement. A 12 volt car battery will provide enough power for only about four to five days of continuous operation. Stockpiling batteries was necessary to insure continuous recording.

Adequately sampling the meteorological microenvironment is a difficult task in mountainous, forested areas. The sampling problem was compounded by a lack of equipment, principally net radiometers. During the 1965 study conducted on Deer Creek, only one net radiometer was available for sampling radiation on about two miles of nonuniformly forested stream. Practical, rather than statistical considerations dictated the sampling procedure. The Thornthwaite net radiation system is best used from a fixed station. Frequent movement of the recorder invites mechanical difficulties not easily corrected. As a result, an instrument shelter was constructed and placed along the stream. Placement of the shelter was determined by measuring the tree crown density along the stream using a Lemon crown densiometer. This hand-held device is a hemispherical mirror engraved with a grid. A rough estimate of mean canopy cover was then the basis for placement of the radiometer, and therefore the other meteorological instruments on Deer Creek, under the assumption that crown cover would modify the fluxes more than any other physiographic parameter.

The solar radiation sampling task was further complicated during the 1966 study at Needle Branch. The study was initiated in early April shortly after the alder and salmonberry began to leaf out. Three radiometer systems were used but the patchwork of shade and moving spots of sunlight was almost impossible to sample adequately. At this time, the spots of sunlight occupied up to 50% of the stream surface; much more than they had on Deer Creek the previous year.

The problem of adequately sampling radiation was simplified during the H. J. Andrews study. Here, the stream channel was exposed throughout the entire length of the study stretch. Differential topographic shading is not really a problem, since the entire stretch is either completely exposed or shaded within about 30 minutes.

Air Temperature and Relative Humidity. Air temperature and relative humidity provide basic data for solution of the temperature and vapor pressure gradients in equations used to compute evaporation and conduction (equations 25 and 28). The basic instrument for measurement of air temperature and relative humidity was a Belfort hygrothermograph. These instruments are not very responsive to rapid fluctuations in air temperature or relative humdiidty, but at night such changes are not common. The hygrothermographs were checked in the evening and early morning with an aspirated psychrometer. The night-time hygrothermograph record was then used as the principal source of night air temperature and relative humidity data. The daytime record was used only as a supplement to the more accurate aspirated psychrometer data which were obtained periodically throughout the day. The difficulty with using a hygrothermograph or psychrometer is that only point estimates of humidity and air temperature may be made. Accurate horizontal and vertical gradients cannot be determined using this type of equipment.

Wind Speed. Although equations 25 and 28 used for computing evaporation and conduction are modifications of the Bowen ratio (equation 20), they are written in the form of the Dalton equation (equation 22) and include a wind speed factor. It is evident that wind speed must be evaluated accurately if the evaporative and conductive fluxes are to be accurately computed. The importance of these fluxes during periods of low radiation has been described (p. 20).

During the 1965 research season, one large, conical cup, contact type anemometer with a 3.0 mph starting speed was used to measure wind speed on both stretches of Deer Creek. This instrument, with a rated accuracy of ±1.5 mph, was unsatisfactory for measuring the low wind speeds near the stream surface. A Raim microanemometer was later purchased for use during 1966 and was utilized on Needle Branch and the H. J. Andrews study. This cup anemometer contains a transistorized light chopper which produces an impulse each revolution. The rated accuracy is ± 2% and the starting speed is 0.3-0.5 mph. An Esterline-Angus event recorder was used to record the output from the anemometers.

Barometric Pressure. Barometric pressure is a component of the conductive equation. Usually, barometric pressure varies less than two inches of mercury during a day. Such variation would represent only about a 6% change in the total atmospheric pressure. As a result, a less precise instrument was required for measuring barometric pressure. The instrument chosen was a Baroscribe barograph. Barometric readings were taken to the nearest tenth of an inch of mercury using this instrument. Prior to installation, this instrument was checked against a more accurate barometer at the U.S. Weather Bureau office at Oregon State University.

DATA PROCESSING

Chart Reduction to Digital Data

Data reduction for the energy budget equation was based upon the travel time in each stretch. The meteorological parameters in the equation were averaged over this time period. Mathematically, this permits starting parcels of water at the top of a stretch at hourly intervals and subjecting them to an environment which is the average of that occurring during the time of flow in the stretch. In this manner, hourly temperature predictions are made for each stretch. Mean values for wind speed, air temperature and relative humidity were obtained directly from recorder charts. Average ambient vapor pressure was then obtained using psychrometric tables (30). Saturated vapor pressures at water temperature were obtained using the recorded water temperature at the start of the stretch. Water temperature at the beginning and end of the stretch and of each tributary were likewise obtained directly from thermographs.

Average radiation values incident upon the water as it passed through each stretch were also obtained. Brechtel (6), in evaluating the effect of light in a forest stand in Germany, found that the only effective means of accounting for light incident at the forest floor was to measure only the diffuse light. In the same manner, attempts to account for the energy added by moving sunspots did not contribute to the accuracy of the energy budget. Obtaining average radiation values for the studies on Deer Creek and Needle Branch therefore entailed neglecting those portions of the recorded radiation which represented a spot of sunlight moving onto a radiometer. This was accomplished by truncating the peaks on the strip chart caused by these spots of sunlight. Figure 6 illustrates this technique. A comparison of predicted stream temperatures using this technique and by including the peak radiation as a part of the average incident radiation is given in the following chapter. Radiation measurement at the H. J. Andrews Experimental Forest required integration of the full trace since the stream was completely exposed.

Data Analysis

The meteorological and hydrologic data together with physiographic measurements of the stream were placed on punch cards for analysis by an IBM 1410 computer. The Fortran IV program used in data analysis is placed in Appendix II along with a flow chart illustrating the various steps in the computation of predicted stream temperature. Briefly, the program performs the following operations.

First, the data for a given stretch and time period is incorporated into the energy budget formulae given in Chapter III (equations 9, 25, 28, 34). For a stretch of stream with no surface tributaries,

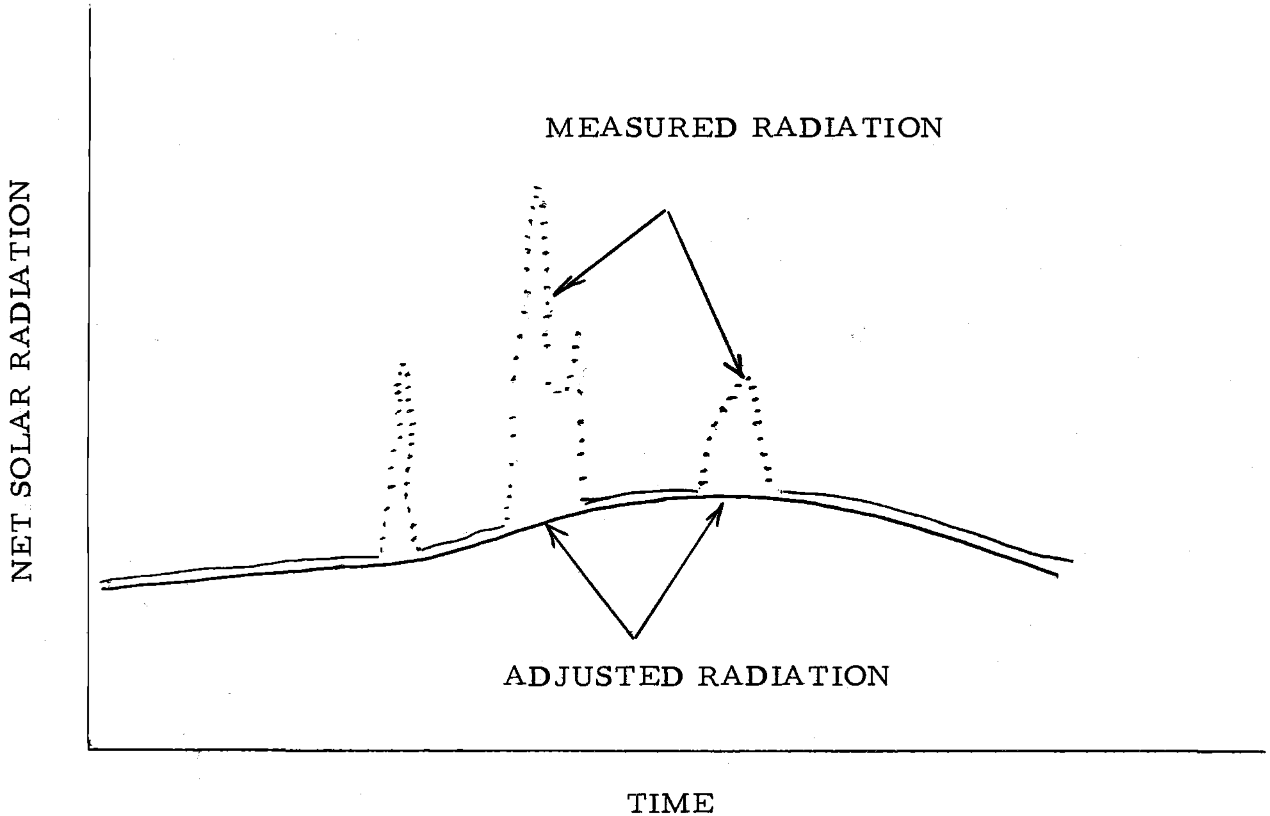

Figure 6. Estimation of Diffuse Solar Radiation By Adjusting Recorded Net Radiation.

such as lower Deer Creek, Needle Branch or the H. J. Andrews sections, the program then computes a single predicted temperature.

For stretches containing surface tributaries, such as upper Deer Creek, the program mathematically divides the stretch into substretches. The lengths of the substretches are determined by the location of the tributaries. The tributaries mark the end of an upstream substretch and the beginning of a downstream substretch. The upper boundary of the uppermost substretch and the lower boundary of the bottom substretch coincide with the upper and lower stream stretch boundaries. This is done mathematically by including the surface area of the substretch, the travel time within each substretch and the discharge and temperature of each tributary in the input data. The program then computes the outflow temperature of each substretch, adding the tributary flow at the end, using the mixing ratio method (equation 29). The computed outflow temperature of an upper substretch then becomes the inflow or start temperature of the substretch immediately below. The outflow temperature of the lowest substretch is then the predicted temperature for the stretch which could then be compared with measured water temperature.

RESULTS AND CONCLUSIONS

Deer Creek Study, 1965

Deer Creek was subdivided into two stretches. Boundaries for these stretches were selected to correspond with changes in the physiography of the channel described in detail in Chapter IV. The lower stretch (stretch I) extended from the U.S.G.S. gage at the bottom through the canyon 1400 feet upstream. The upper stretch (stretch II) extended from this point another 2000 feet upstream.

Four weeks of data were collected on Deer Creek from August 30 through September 24, 1965. Only the results from a few days of record will be presented here since the relationship between predicted and observed stream temperature is rather constant for a given stretch.

Stretch I

Predicted and observed stream temperature are given in Figure 7 for stretch I during three days. Table A in Appendix I includes the energy budget values as well as observed and predicted temperatures for these same time periods. The travel time through this stretch was about three hours. Of the 72 predictions made during these three days, 61 were within 1 °F and all but four were within 1.5 °F. August 31 and September 3, 1965 were clear and sunny. September

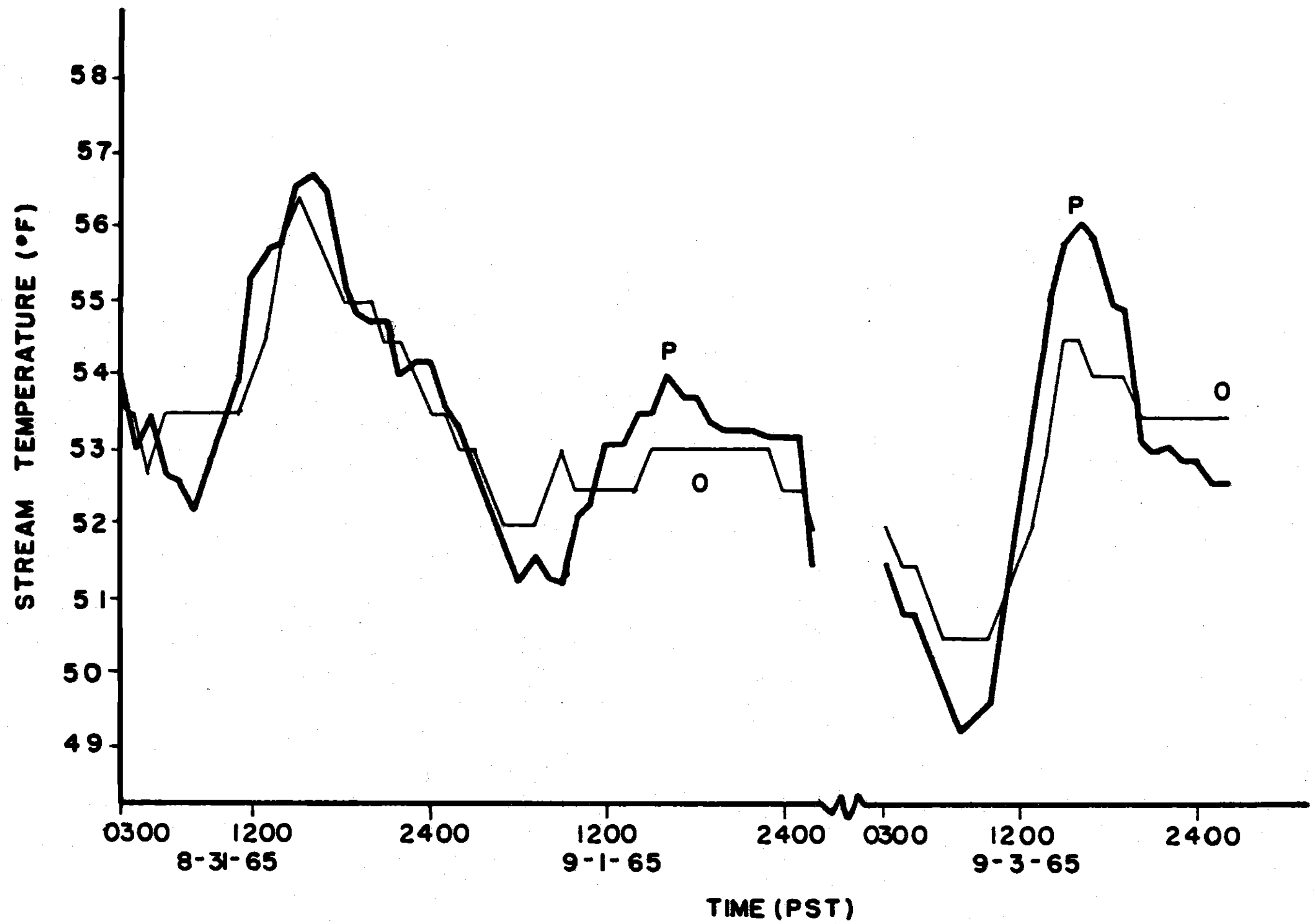

Figure 7. A Comparison of Observed (O) and Predicted (P) Stream Temperatures for Stretch I, Deer Creek During 1965.

1, on the other hand, was overcast and cool.

The accuracy of the predictive method on this stretch may be attributed to the hydrologic simplicity of the stretch. Stream temperature in this stretch is most directly a function of microclimate and not groundwater or surface water advection. Stretch I contains no tributary streams nor does it flow over deep alluvium.

In this short stretch, stream temperature follows the hourly radiative flux very closely during periods of positive radiation. Comparing the radiative flux with the column listing the observed ΔT in Table A, Appendix I, demonstrates this fact. During these periods, elimination of the evaporative and conductive fluxes from the prediction causes less than one degree error in the predicted stream temperature. During periods when the radiative flux was directed away from the water surface, the magnitudes of the evaporative and conductive fluxes were often equal to the radiative flux. Neglecting the conductive and evaporative members of the energy budget resulted in differences of 1-2.5°F between predicted and observed temperatures. Such a difference is quite significant since the observed change in temperature through the stretch was only 1-2°F for the travel time involved.

The difficulty of accurate interpretation of the anemometer records for 1965 was immediately apparent. The instrument has a rated starting speed of 3 mph and a rated accuracy of ±1.5 mph.

Usually, the record indicated no wind movement whatsoever during the night and early morning indicative of the low wind speeds over the stream. The record often indicated midday wind speeds of 0.3 to 1.0 mph. True wind speed using these records was difficult to determine.

Manipulation of the wind data with the aid of the computer revealed that a wind speed of 1.0 mph both day and night increased the accuracy of the predictions under a variety of radiative conditions. Wind speeds of unity were selected to permit the vapor pressure or temperature gradients, rather than an estimated wind speed, to determine the magnitude of the evaporative and conductive fluxes.

Stretch II

The predicted and observed hourly stream temperatures for stretch II are illustrated in Figure 8. These predictions cover the same series of days described earlier for stretch I. The digital data are presented in Table B, Appendix I. The travel time is 18 hours for this stretch as compared to travel times of less than three hours for the other stretches. Only nine of the 72 predictions made for this stretch were within 1 °F of the observed temperature. Predictive errors ranged from +5 °F to -8 °F. The question is posed: Why less accuracy of prediction in stretch II as compared to stretch I?

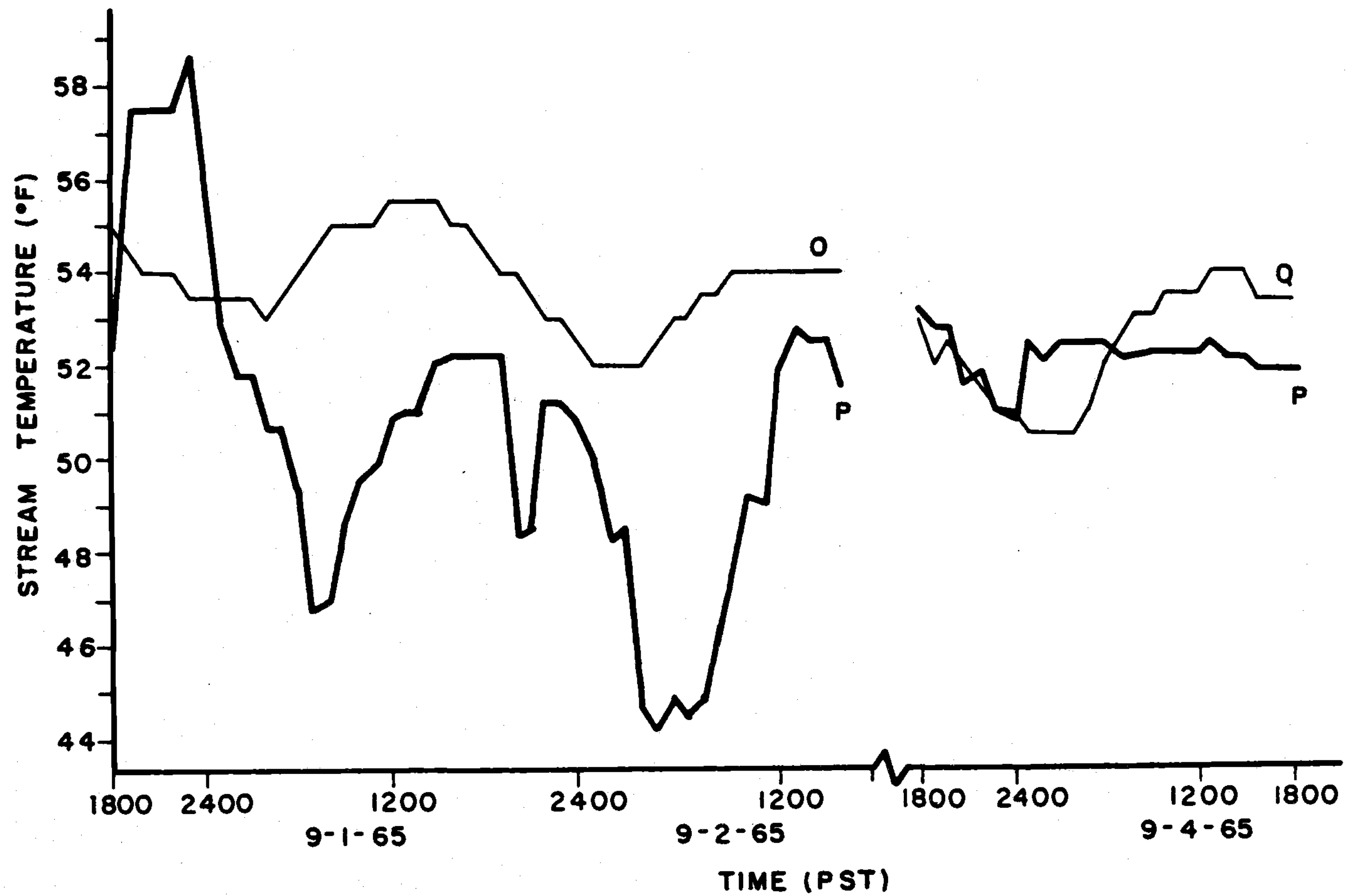

Figure 8. A Comparison of Observed(O) and Predicted (P) Stream Temperatures for Stretch II, Deer Creek During 1965.

One reason may be that stretch II is hydrologically more complex than stretch I. Groundwater discharge undoubtedly affected the accuracy of the predictions made for this stretch. Significant groundwater advection is indicated by the alluvial nature of the channel, frequent surface tributaries and occasional seeps evident along the bank. Even with the crude gaging devices on Deer Creek, groundwater discharge was estimated at 20-30% of the total discharge in the two study stretches.

Predictive errors may also be related to the equation for computing temperature change. This equation (equation 34) is given as:

$$\Delta T = \frac{A \times Qt \times time}{flow \times time} \times 0.000267$$

If the low discharge and large surface area of stretch II are inserted into the above equation, it reduces to:

$$\Delta T = 23.39 \times Qt$$

Changing Qt 0.1 BTU/ft^2/min would produce a change in the predicted temperature of 2.3° F. An error of about 0.02 ly incurred while averaging incident radiation over the 18 hour travel time could produce such a change. Errors of 0.16 inches of mercury in computing the vapor pressure gradient or 16° F in computing the temperature gradient for the evaporative and conductive fluxes could influence the prediction in a like manner.

The error most likely to occur is in the radiation member of

Qt. The problem associated with reducing the radiation data was compounded on this stretch by a sampling problem discussed earlier. Accurate temperature prediction is unlikely under these circumstances.

The type of data reduction on stretch II also affected the accuracy of the prediction. All meteorologic data included in the predictive equations were averaged over an 18 hour period corresponding to the stretch travel time as also applied to the other experimental stretches. The validity of using long term averages has been questioned by other authors engaged in energy budget research. Tanner (49) found that separation of daytime and nighttime meteorologic measurements was necessary before an accurate evapotranspiration estimate could be made using an energy budget. If average values for the various components in the equations were obtained by combining both daytime and nighttime measurements, actual evapotranspiration was seriously underestimated using his energy budget equation. Tanner notes that without the separation described above, low vapor pressure and temperature gradients during the late evening, nighttime, and early morning hours carry undue weight when averaged with data for the shorter daytime period. Budyko (8) has shown that serious errors result from using long term averages of meteorologic variables in the Bowen equation, even when these values are obtained by frequent measurement.

A simple analysis was performed to determine if separating the stretch into segments corresponding to the substretches described earlier would improve the temperature prediction. The variables in the predictive equations were obtained using meteorological data averaged during the time period for which the water was in a given substretch. This subdivision of the stretch was merely a crude first approximation of a prediction incorporating integrated variables.

A mechanical sample of the data included in the continuous prediction was taken in order to compare predictions made using data averaged over short periods, and applied to substretch temperature predictions, with predictions made using data averaged for the 18 hour period corresponding to the travel time for the stretch as a whole. Predictions were made at four hour rather than one hour intervals. This information is contained in Table 1. Outflow temperatures were computed for each substretch in the following manner. The uppermost substretch had an eight hour travel time. An outflow temperature was predicted using data covering this eight hour period. The outflow temperature of this substretch then became the inflow or start temperature of the substretch below. The same technique was continued through the stretch. The last outflow temperature could then be compared with both the observed temperature and the predicted temperature computed using 18 hour averages.

It is difficult to determine from the data in Table 1 whether

Table 1. A comparison of predicted and observed stream temperature for Stretch II, Deer Creek using short term and 18 hour averages of meteorologic data.

Date	Start time (PST)	End time (PST)	Observed temperature (°F)	Short term prediction (°F)	18 hour prediction (°F)
8-31	0000	1800	55.0	53.5	52.3
	0400	2200	54.0	52.8	57.6
	0800	0200[a]	53.5	53.7	53.0
	1200	0600[a]	53.5	52.0	50.6
	1600	1000[a]	55.0	49.8	48.6
	2000	1400[a]	55.5	52.2	51.0
	2400	1800[a]	55.0	53.3	52.2
9-01	0400	2200	53.5	53.3	48.4
	0800	0200[a]	52.0	52.3	49.6
	1200	0600[a]	52.5	54.0	44.2
	1600	1000[a]	53.5	52.3	46.4
	2000	1400[a]	54.0	50.0	49.0
	2400	1800[a]	54.0	49.7	50.0
9-03	0400	2200	52.0	52.2	53.2
	0800	0200[a]	51.5	51.5	51.8
	1200	0600[a]	52.0	49.1	50.5
	1600	1000[a]	53.5	47.1	48.9
	2000	1400[a]	54.0	51.4	52.2
	2400	1800[a]	53.5	52.2	51.5

[a]End time occurs the following day.

or not short term predictions are better than 18 hour predictions. Considering the table as a unit, it can be seen that 16 of the 19 predictions made using short term data are better than those using 18 hour data. The improvement however, must be considered in light of the data reduction problems described earlier for the 18 hour stretch. Fourteen of the 18 hour predictions differ from the short term predictions by only one or two degrees. A small rounding error during reduction of the radiation data could account for this difference.

The data in Table 1 were also analyzed statistically as a unit. A T test comparing the short term and 18 hour predictions showed that there is insufficient evidence to indicate any difference between the means of the two predictive methods. The standard error of the estimate obtained when comparing the short term predictions with the observed temperature was slightly lower than that obtained after making a similar comparison with the 18 hour predictions. This seems to indicate that the short term prediction is a better estimator of observed temperature than is the 18 hour prediction.

All of the above analyses seem to indicate that subdividing a stretch for more accurate data analysis may provide a better prediction of stream temperature, but the degree of improvement is slight.

Another analysis was performed on the data in Table 1 to determine whether separation of nighttime and daytime measurements improved the temperature prediction. The travel times for the upper, middle, and lower substretches on stretch II are eight, six, and four hours respectively. The daytime radiative flux on Deer Creek became positive between 0700 and 0800 and became negative again between 1600 and 1700. This information permitted selection of predictive intervals during which each substretch was subjected to either a daytime or a nighttime environment. The short term predictions made for the periods 0400 to 2200 and 0800 to 0200 meet these requirements. For the 0400 to 2200 prediction period, the upper substretch prediction was made with data averaged during the interval 0400 to 1200, a predominantly daytime period. The middle substretch prediction was made during the interval 1200 to 1800, also from predominantly daytime data. The final substretch prediction was made during the interval 1800 to 2200 with nighttime data. The predictive periods for the substretches during the 0800 to 0200 interval may be followed in a like manner. The predictive periods for the substretches during the 0800 to 0200 interval are even better separated into day or night periods.

It is difficult, again, to determine from the data presented in Table 1 whether separation of nighttime and daytime measurements improved the prediction. The three 0400-2200 predictions and the three 0800-0200 predictions are all within 1 °F of the observed temperature with one exception. The 0400-2200 prediction for August 31 is 1.2°F below the observed temperature. Three of the 18 hour predictions are within 2°F of the observed temperature. If the data reduction problem described earlier is considered, these differences may not have any physical significance, even if they are statistically so. A T test comparing the means of the short term and 18 hour predictions for the 0400-2200 and 0800-0200 time intervals showed that there is insufficient evidence to indicate any difference between the means of these two methods. Another test for the standard error of the estimate indicated that the predictions based on data separated into daytime and nighttime groups were closer to the observed values than those based on data averaged for the 18 hour period. Although separation of data into daytime and nighttime periods intuitively seems to give a better prediction of stream temperature, conclusive proof will require more data than is presented in Table 1.

Needle Branch Study, 1966

The study on Needle Branch began early in April, 1966. Predicted and observed stream temperature are compared in Figure 9 using the adjusting and integrating techniques for determining net radiation described earlier in Chapter V. This information is presented in a digital form in Table C, Appendix I along with more detailed energy budget data. Since only radiation was varied in these two types of predictions, the conductive and evaporative fluxes are

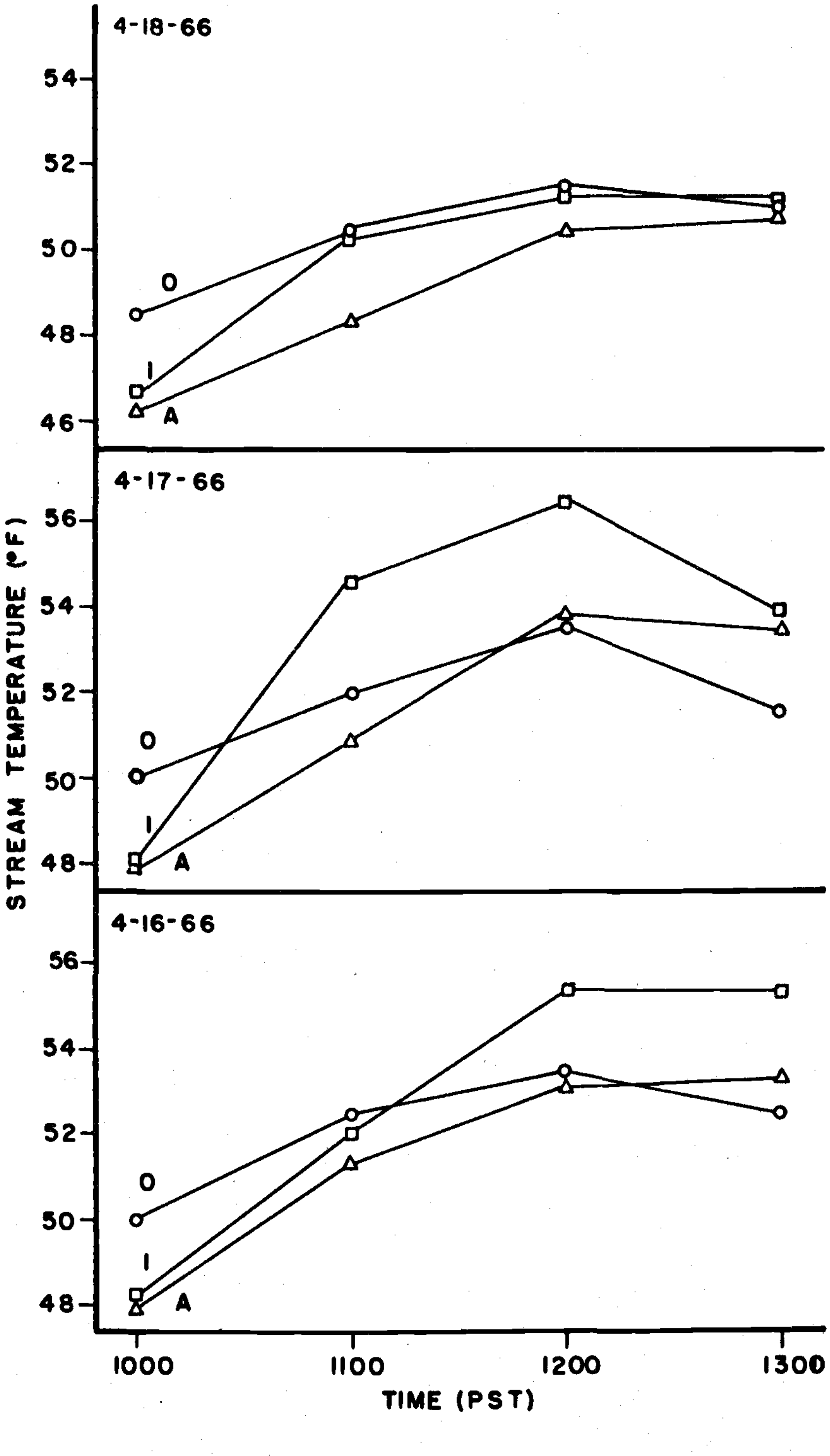

Figure 9. A Comparison of Observed (O) and Predicted Stream Temperatures on Needle Branch for April 16, 17, and 18, 1966 Using Integrated (I) and Adjusted (A) Net Radiation.

reported only once in this table. Travel time for this study stretch was two hours. Twelve hourly predictions were made during April 16, 17, and 18. Seven predictions were within 1.5°F using the adjusting technique and four were within 1.5°F using the integrating technique.

A more difficult sampling problem was encountered on this stretch than had been encountered the year before on Deer Creek. The alder and salmonberry leaves were just beginning to open during the period of measurement. Even with three net radiometers, the distribution of solar radiation in the stretch was difficult to determine.

The data in Table C, Appendix I, were compared statistically. This comparison revealed that there is a statistical difference between the means of the predictions made using the net radiation adjusting technique and those made using the integrating technique. The standard errors of the estimate were ±1.11°F when using the adjusted data and ±1.68°F when using the integrated data indicating that on the whole, the adjusted net radiation data provides a better prediction of stream temperature. With such a small sample and such small differences, the statistical significance of these errors is subject to question.

The data were also compared in a more general manner. April 16 and 17 were hot, sunny days with very little wind. April 18 was windy and partly cloudy. The data illustrate the requirement for definitive interpretation of radiation records. Using integrated radiation values for the hot sunny days generally produced an overestimation of stream temperature change. The same technique applied to the partly cloudy day permitted a fairly accurate estimation of this change. During cloudy periods, the radiometers were, in effect, measuring diffuse radiation which was probably fairly uniform throughout the stretch.

The adjusting or truncating technique for analyzing radiation charts gives better estimates of stream temperature changes during the sunny days than the integrating technique. Using this technique in all instances, however, may produce considerable error in the predicted stream temperature. Adjusting radiation values during April 18, the partly cloudy day, results in an underestimation of stream temperature change, since the radiation recorded was already somewhat diffuse in nature. The integrated predictions were consistently better than the adjusted predictions during April 18.

A statistical check of the data verified these observations. Two T tests revealed that the means of the two predictive methods for both the sunny days and the cloudy day were significantly different. The standard errors of the estimate for both types of days indicated that during the sunny days, the predictions incorporating adjusted solar radiation data were better estimators of the observed temperatures. During the cloudy day, the reverse was true. The small sample sizes and the small magnitude of the differences in standard errors again prevented definite conclusions.

The energy fluxes computed on this stretch illustrate the necessity for accurate evaluation of evaporation and conduction. Evaporation for example, may be only one fifth of the radiative flux during the midday hours, but during the early morning hours, evaporation exhibits a much more significant role in the total heat flux. For example, the 1000 hour prediction for May 17 included values of 0.34 BTU/ft^2/min for the evaporative flux and only 0.25 BTU/ft^2/min for the radiative flux computed using the integration technique. The 1200 hour prediction for the same day included values of 0.40 BTU/ft^2/min for the evaporative flux and 1.93 BTU/ft^2/min for the radiative flux computed using the integration technique.

H. J. Andrews Experimental Forest Study, 1966

Predicted and observed stream temperature for three sunny days in May, 1966 on Watershed 3 of the H. J. Andrews Experimental Forest are shown in Figures 10 and 11. This data is also presented in Tables D and E of Appendix I. This study stretch is completely exposed and has a travel time of about one hour. Diurnal temperature fluctuations of 20°F have been recorded on this stream. During the study, temperature changes of 16°F were recorded within the

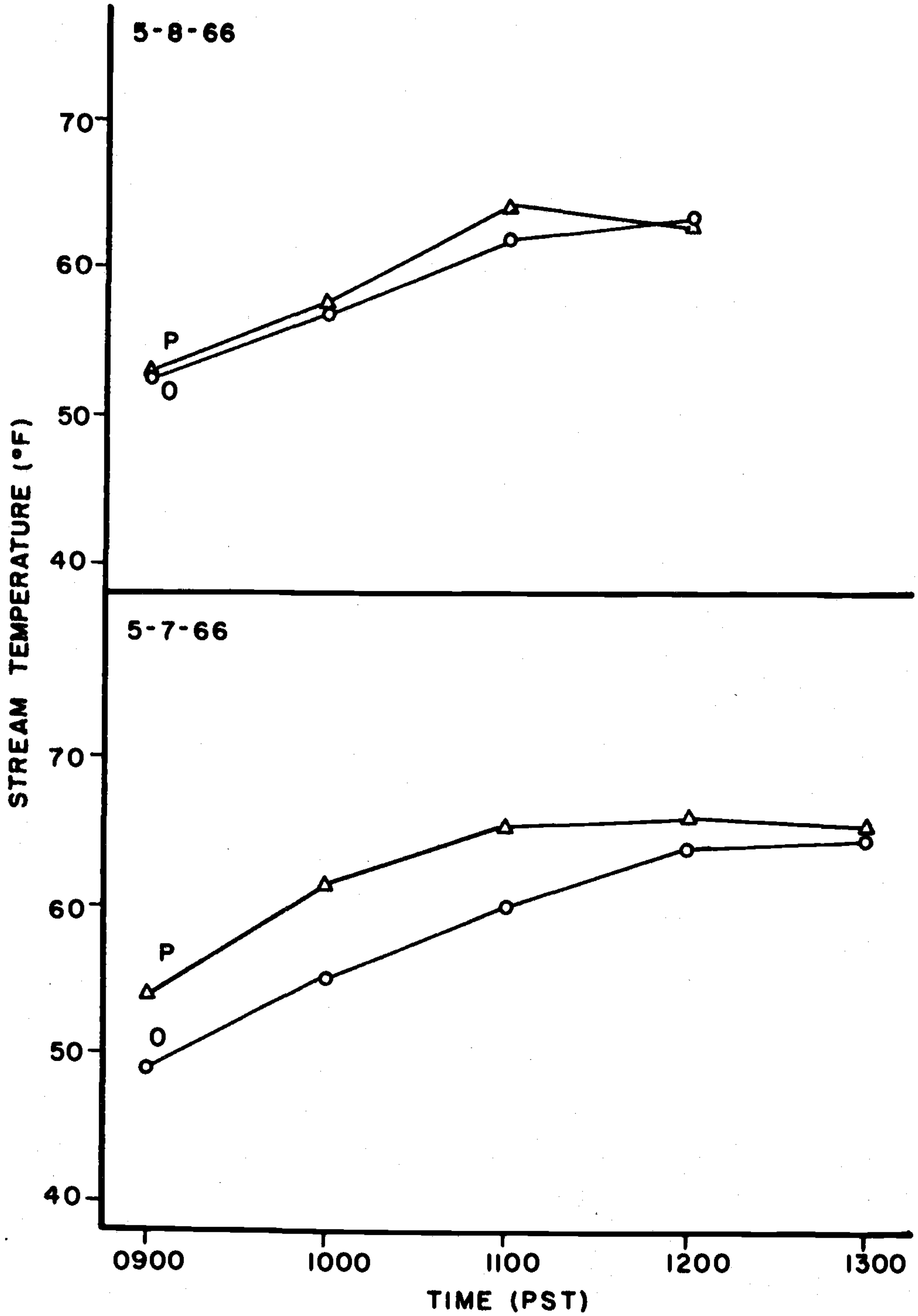

Figure 10. A Comparison of Observed (O) and Predicted (P) Stream Temperature for the H. J. Andrews Study During May 8 and 9, 1966.

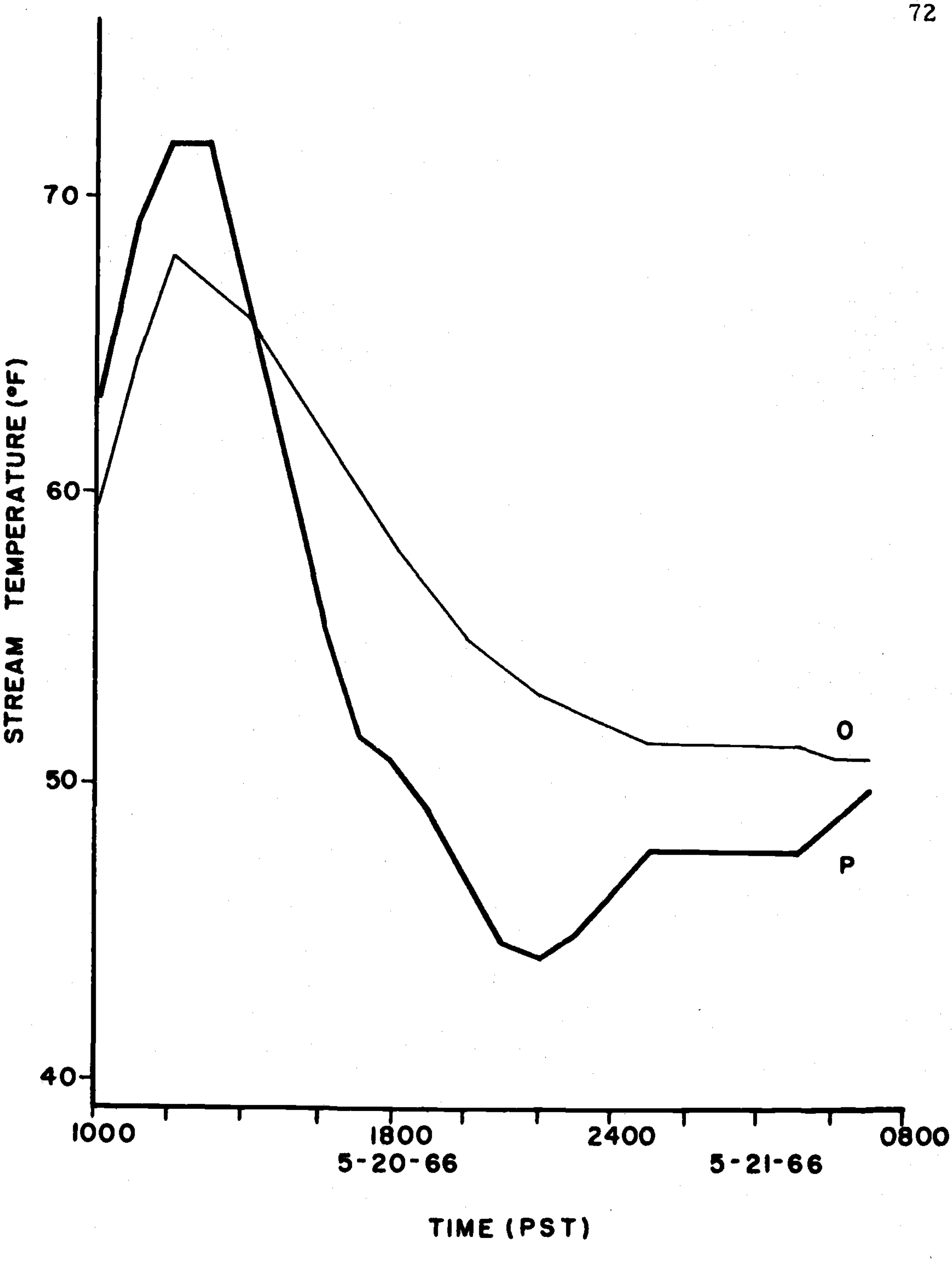

Figure 11. A Comparison of Observed (O) and Predicted (P) Stream Temperatures for the H. J. Andrews Study During May 20 and 21, 1966.

study stretch. Nine predictions for rising stream temperature are made for two of these days. These predictions are illustrated in Figure 10. Data for the third day were collected to follow the nighttime stream temperature decline as well as the morning rise. Twenty-two hourly predictions made using this data are illustrated in Figure 11. Of the 31 predictions made for the three days, five were within 1 °F of the observed temperature and nine were within 2 °F. The magnitude of the predictive errors ranged from -9.3 °F to 6.6 °F.

The discrepancies in observed and predicted stream temperature are illustrated in both figures. These differences are most apparent in Figure 11, a 24 hour comparison of predicted and observed stream temperature. These differences are not explainable in terms of measurement errors for wind speed or the vapor pressure and temperature gradients. Measurement of these variables and incident radiation was not complicated by time, distance, or vegetation as at the other sites.

On this study stretch, the radiation flux is responsible for almost all of the energy flux at the stream surface. Solar radiation intensities were two to three times those recorded at Needle Branch or Deer Creek. During the day, conductive and evaporative fluxes are less than 10% of the radiative flux.

The predicted stream temperature during the morning hours is much higher than that observed. During the evening hours the reverse is true. A possible explanation for this difference was heat transfer into and from the bedrock of the stream bottom; a radiation component not accounted for in the basic energy budget equation used at the other sites.

In order to obtain some estimate of the significance of this unaccounted energy flux, a small experiment was devised to approximate the amount of heat flow through the bedrock by utilizing the thermal conductivities reported for these types of rocks and by measuring the thermal gradients in the rocks throughout the day.

The rock in the stream bottom through the clear cut is either tuff or breccia. These two rocks have highly variable thermal conductivities as a result of their magmatic origin. The thermal conductivity of tuff was obtained directly from the International Critical Tables (35). It was necessary to assume that the thermal conductivity of breccia was similar to conglomerate since the above tables did not contain values for breccia.

A sample of each rock was obtained and thermocouples inserted. The thermocouples were constructed from plastic coated, 16 gauge, copper-constantan wire produced by the Minneapolis-Honeywell Company. Smaller wire was not immediately available. Use of such large wire required drilling 3/8 inch holes in the rocks for insertion of the thermocouples. As a result, placement of the thermocouples immediately under the surface was not possible. Two thermocouples were joined by the constantan leads permitting measurement of the gradients between two points beneath the rock surface. One thermocouple pair was placed in the tuff and breccia samples to measure the gradient between the rock surface and one centimeter below. An additional pair was inserted in the breccia to measure the gradient between one and three centimeters beneath the rock surface. Only one pair was placed in the tuff since the sample was only about $8 \times 8 \times 8$ in. and was full of fracture seams. The thermocouples were sealed in the rocks with an epoxy glue.

The rocks were placed in the stream and allowed to acclimate for two weeks. Heat flow through the rocks was then measured on a hot sunny day similar to those days during which the energy budget studies had been conducted. Table 2 contains data collected during this heat flow study. In addition, the temperature gradients recorded in the rocks are converted to approximate temperature corrections for stream temperature prediction by the energy budget technique using the thermal conductivity data described above.

The direction of heat flow is indicated in this table as well. This permits temperature correction in the proper direction. For example, a positive voltage difference indicates heat flow into the rock and thus requires a negative correction in the stream temperature predicted by the energy budget since this represents heat going

Table 2. Heat flow measurements through a bedrock stream bottom, H. J. Andrews Experimental Forest, from 0930 to 1900 June 14, 1966.

Time (PST)	Water temp. (°F)	Voltage Diff. (μv)			Temp. Gradient (°C)			Thermal conduct.[b]		Approx. temp. corr. (°F)	
		Tuff	Breccia		Tuff	Breccia		Tuff	Breccia[c]	Tuff	Breccia
		A[a]	A	B[a]	A	A	B				
0930	63.5	+32	+36	+22	0.8	0.9	0.6	0.004	0.006	-2.59	-4.2
1030	68.0	+24	+34	+39	0.6	0.8	1.0			-1.9	-2.5
1130	73.0	+19	+30	+35	0.5	0.8	0.9			-1.6	-2.5
1230	77.0	+16	+32	+43	0.4	0.8	1.0			-1.2	-2.5
1330	77.0	+6	+8	+23	0.15	0.2	0.6			-0.5	-0.6
1430	74.3	-5	-17	-20	0.15	0.4	0.5			+0.5	+1.2
1530	70.9	-8	-12	-10	0.2	0.3	0.25			+0.6	+0.9
1900	57.8	-5	-13	-12	0.15	0.3	0.3			+0.5	+0.9

[a] A = gradient between approximately 0.5 and 1.5 cm. below rock surface.

B = gradient between approximately 1.5 and 3.5 cm. below rock surface.

[b] Given in cal $cm^{-2} sec^{-1} (^{\circ}C\ cm^{-1})^{-1}$ by International Critical Tables (35).

[c] Values are for conglomerate.

into the rock and not into the stream.

Visual comparison of the corrections listed in Table 2 with the discrepancies between the observed and predicted temperature curves in Figure 11 clearly indicates that these corrections are not sufficient to account for the differences in the two curves. These low corrections seem to be explainable, however, in terms of the experimental design described above.

Placement of the topmost thermocouple only a few millimeters from the upper surface of the rock was not possible. It was necessary to drill the hole at least 0.5 to 0.75 cm. away from the surface to prevent fragmentation of the rock surface. In addition, the hole itself was 3/8 inch or about 1 cm. in diameter. This probably placed the thermocouple another 0.5 cm away from the surface. A higher gradient, and thus greater computed heat transfer, would probably have been measured if these upper thermocouples could have been placed closer to the surface.

Another factor which might have contributed to thermal gradients lower than anticipated was the epoxy glue used to seal the thermocouples inside the rocks. The epoxy has a thermal conductivity of about 0.001 cal $cm^{-2} sec^{-1} (°C\ cm^{-1})^{-1}$ or about 20% of the conductivity of the rocks. The epoxy would not only integrate the temperatures on all sides of the hole, but would respond less quickly to temperature changes in the surrounding rock. Near the surface, where the energy flux is most rapid, slower response to temperature changes by the epoxy could account for a portion of the lower than anticipated gradient.

Although the gradients measured in the rock did not fully account for the discrepancy between predicted and observed stream temperatures noted during the earlier study, these gradients were always in the right direction. That is, the rock did, in fact, act as a heat sink during the early morning and a heat source at night. This seems to confirm the hypothesis put forward earlier that significant amounts of energy may be stored in the stream bottom in certain circumstances and, if not taken into account, may cause large errors in a prediction of stream temperature using the simple equations given earlier.

DISCUSSION

General

During this study, stream temperature predictions were made under a variety of physiographic and climatic conditions. Stretch I, Deer Creek was forested but temperature prediction was not complicated by groundwater or surface water advection. Stretch II, Deer Creek contained three surface tributaries and considerable groundwater advection. This forested stretch also had an 18 hour travel time which complicated temperature prediction. Needle Branch was physiographically similar to Stretch II, Deer Creek, but not uniformly shaded by vegetation. The study stretch at the H. J. Andrews Experimental Forest was completely exposed to direct solar radiation. In addition, the bedrock stream bottom played an important part in the heat exchange of the stream. The energy budget approach seems to be a valid technique for temperature prediction under all of these conditions. Since this method may be used for prediction, it seems to offer more as a research or management tool than other methods which only characterize stream temperature patterns in a general way by lengthy statistical description or through correlation with nearby streams.

The energy budget approach is one of separation and description of the various energy fluxes incident at the stream surface. As a result, the technique requires a more detailed knowledge of the stream system and the pertinent microclimate than is required for a correlation analysis of stream temperature. At a minimum, this entails measurement of such climatic variables as solar radiation reaching the stream surface, air and water temperatures, relative humidity, and wind speed near the water surface. In addition, the influence of groundwater and any tributaries to the stream must be determined along with the discharge and surface area of the stream.

The influence of the microenvironment on the temperature of small, and especially forested, streams is paramount. Vegetation for example, may significantly modify the macroenvironment. Overstory vegetation may reduce the solar radiation received, as well as wind movement, producing a thermostatic effect on stream temperature fluctuations. The maximum diurnal fluctuation on Deer Creek was only 3.8°F as compared to a 17°F fluctuation on the H. J. Andrews study stream. The difficulty encountered in predicting temperature on the H. J. Andrews study without some idea of the effect of the bedrock stream bottom on heat exchange is another case in point. This infers that stream temperature cannot be accurately predicted using such macrometeorologic data as is commonly reported by the U.S. Weather Bureau. It also infers that the method cannot be applied to small streams without considerable effort by the researcher to adequately sample and describe the microenvironment of the stream system. This study has shown, for example, the differences between the relative magnitudes of the evaporative and conductive fluxes on an open or on a forested stream. On an open stream, these fluxes may be so small compared to the radiative flux that they may be considered inconsequential when predicting stream temperature. On a forested stream, these fluxes may all be of the same magnitude during the day. At night, evaporation and conduction may account for most of the energy exchange at the stream surface. The requirements for evaluating the evaporative and conductive parameters in these situations are evident, and would distinctly apply for lengthy stream systems with longer travel times.

Problems Encountered

The principal problems encountered during the study were associated with adequately sampling solar radiation and with inadequate equipment. During 1965, only one net radiometer system was available for use. The problem of adequately sampling the most important, and spacially most variable component, of the energy budget was therefore difficult. Definitive measurement of the low wind speeds under a canopy of alder was hampered by an inadequate anemometer during the first year. Neither was it possible to spacially sample windspeed. Finally, an accurate relative humidity-air temperature record would have been very helpful in evaluating more closely some of the evaporative and conductive fluxes. At Stretch II, Deer Creek, these fluxes were relatively large compared to the radiative flux because of the overstory vegetation. A more precise definition of the vapor pressure and temperature gradients within this stretch would have considerably improved the temperature predictions.

Evaluation of groundwater inflow and continually changing vapor pressure and temperature gradients were three other problems not fully solved in this study. These three parameters are concerned with evaluating water advection, evaporation, and conduction, respectively. All are essentially integral relationships. Groundwater advection within a stretch, for example, was necessarily determined as the difference between the discharge at the start of the stretch, plus the discharges of all the surface tributaries, and the discharge at the bottom of the stretch. This was mathematically distributed equally throughout the stretch and then added as a slug at the end of a substretch along with surface advection.

In a similar manner, the vapor pressure and temperature gradients were determined using the average ambient vapor pressure and air temperatures recorded using substandard instrumentation. The saturated vapor pressure was determined using the water temperature recorded at the start of the stretch, which, in turn, was included in the computation of the temperature gradient. These gradients are seldom representative of the conditions at the stream surface since the water temperature, and thus both gradients, is continually changing in response to all of the energy fluxes throughout the stretch.

The approximations for groundwater advection and the vapor pressure and temperature gradients were used in the study for one reason. The relative simplicity of the sampling systems and the sampling network did not seem to permit an extrapolation of data necessary to evaluate these changes as an integral relationship. The meteorological sample was a point sample taken with psychrometers that were not capable of providing a continuous record or with a hygrothermograph that was not sufficiently responsive to rapid changes in the environment. In addition, no other means was available for measuring or estimating the groundwater input. It was logistically infeasible to construct more gaging stations. As a result, the short cuts described above were accepted as a practical compromise in full awareness of the theoretical limitations imposed. This study indicates that for short stretches of stream or for long stretches suitably subdivided, these compromises may not statistically affect the accuracy of the prediction. Subdivision of a long stretch is, in fact, a crude attempt at obtaining a closer approximation of the integral.

Application

This study was included as a part of the Alsea Basin Logging-Aquatic Resources Study where temperature is being studied because of its importance as a physical parameter determining the suitability of water for domestic or industrial consumption or as a medium supporting aquatic life. One of the major purposes of the temperature prediction study is to provide a tool for forestry and fisheries personnel which would aid in prediction of the effects of a timber harvest operation on stream temperature.

The influence of temperature on the ultimate quality of a given water supply depends upon a wide range of physical, chemical and biological interrelationships. If stream temperature could be predicted, biologists would be better equipped to evaluate a harvest operation in terms of its effect upon these interrelationships and thus the ecology of the stream. Cairns (12), for example, showed the effect of temperature changes on diatom and algae populations. Tarzwell and Gaufin (50) were able to describe the ecological implications of altering stream and lake temperature regimes. A prediction of the effect of a harvest operation on stream temperature, then, would permit biologists to make a better estimate of detrimental effects or benefits of logging, i.e., the effect on the stream ecosystem.

The importance of being able to predict stream temperature may be illustrated by some examples of fishery studies conducted solely for the purpose of relating water temperature to fish mortality. Trout seem to be able to withstand higher stream temperatures than salmon. Needham (36) and Embody (16) for example, describe lethal temperatures for brook, brown, and rainbow trout ranging from 75° F to 83° F. Brett (7) and Donaldson and Foster (13) list the upper lethal temperature range for several species of salmon fry as 73° F to 78° F. Brett also noted that in 1941, the Columbia River reached a record high temperature of 74.5° F. Parasite populations increased rapidly and almost obliterated the blue back salmon (Oncorhynchus nerka) run. Temperatures such as those recorded and predicted during the H. J. Andrews study approach the lethal limit for many of these fish.

In the Pacific Northwest, the anadromous fishery must coexist with the logging industry. This industry is becoming increasingly aware of its role in influencing the various water oriented resources of forested regions. Hopefully, application of some of the work presented in this paper will give the forest manager, as well as the aquatic biologist, another tool for evaluating some of these influences.

Application of the formulae and techniques for research purposes involves considerable effort and expenditure for equipment. The energy budget approach to stream temperature prediction has considerable merit, however, as a practical tool if some modifications are made in the formulae and care is taken to apply the technique only in limited situations.

The previous chapter discussed the dominant role of incident solar radiation in effecting stream temperature changes on an open stretch of stream (H. J. Andrews study). During the mid-day hours of 1000 to 1400, the radiative flux was 20-30 times as great as the evaporative and conductive fluxes combined. It would therefore seem possible to use the heat energy of solar radiation as the sole index of stream temperature in similar physical circumstances, i.e., where the area in question is fully exposed to direct solar radiation.

Systems for measuring and recording solar radiation are expensive and often difficult to maintain. Refinement of the energy budget technique to measuring only net radiation may still not be sufficient if the method is to be used as a management tool by field personnel in forestry or fisheries. Field personnel however, are more likely to be interested in predicting temperature maxima rather than the complete temperature cycle since these maxima exert the greatest influence on the quality of the water for industrial and domestic consumption or as a medium supporting aquatic life. For maxima further reduction of the predictive equation is possible.

A reasonable estimate for maximum net solar radiation during the midsummer months at midday is about 1.2 ly at 45°N latitude. This assumes reasonable values for incoming short wave radiation as 1.3-1.4 ly (34), incoming longwave radiation as about 0.5-0.6 ly (20) and backradiation from water between 10°C and 25°C as about 0.5-0.6 ly computed using the Stefan-Boltzmann law. Midday reflection from a water surface is quite low and will be assumed about 0.1 ly or about 5-6% of the incoming radiation (21). Values of about 1.2 ly were in fact, measured during the H. J. Andrews study.

The maximum change in temperature within a stretch of stream may now be roughly computed using the physical characteristics of an open stretch of stream rather than the meteorological variables of the microenvironment. The only other requirement is that the opening on the stream be traversed within three to four hours or the time during which the assumption of a 1.2 ly radiation load is valid. In other words, the travel time through the open stretch must not be longer than the time during which the stretch is exposed to full sunlight. If this requirement is not fulfilled, the maximum temperature may occur somewhere within, and not at the end of, the stretch. Furthermore, if a longer travel time, and thus a longer stretch, is used in this abbreviated computation, excessively high predictions will be obtained.

Assuming a value of 1.2 ly for net radiation, and thus a Qt value of 1.2 ly, permits solution of equation 34 for temperature change in terms of stream surface area (A) and flow. That is,

from equation 34,

$$\Delta T = \frac{A \times Qt \times \text{time}}{\text{flow} \times \text{time}} \times 0.000267 \qquad (34)$$

Then

$$\Delta T = \frac{A \times 1.2 \times 3.68 \times \text{time}}{\text{Flow} \times \text{time}} \times 0.000267$$

and

$$\Delta T = \frac{A}{\text{Flow}} \times 0.001 \qquad (35)$$

The stream's surface area (A) and flow or discharge rate are the only parameters required to compute ΔT, the stream temperature change. This general formula may then be used without incurring a great deal of expense for meteorological equipment. A knowledge of some of the physical characteristics of the stream is required including normal temperature patterns, the placement of the planned clearing, and shading provided by surrounding topography during the critical midday hours.

If large amounts of advected energy in the form of groundwater are added to the stream or if significant amounts of energy are transferred into the stream bottom, equation 35 will overestimate the amount of stream temperature change. For planning purposes, this conservative estimate may be of some value, in that a safety factor is automatically included.

Research Needs

It is evident from the foregoing discussion that a great deal of additional research is necessary before a complete definition of the energy budgets for small streams in forested situations may be obtained. Some of the more striking requirements, on the basis of this study, are briefly given below.

The data collection for this thesis was restricted by the poor accessibility of the study sites. It was necessary to use portable equipment and either spring driven or D. C. powered recorders. This restricted the type of equipment available and necessitated, in all instances, a graphic rather than digital read-out of measured values. Analysis of several weeks of charts is extremely exacting and often results in considerable error. It is also difficult to obtain integrated values. Sophisticated multi-chaneled equipment could not be included in the study. Values for wind speed and aspirated air temperature and ambient vapor pressure, for example, were taken at only one point above the stream. If such values could have been obtained continuously for more than one elevation, more precise estimates of the evaporative and conductive members of the energy budget could have been made. In short, this information would have permitted computation of a local exchange coefficient.

These needs could have been fulfilled with a large, permanent installation serviced by either a generator or regular line A. C. power. This would permit installation of a wide range of refined instrumentation and tape punch recording equipment, thus permitting direct data reduction using a computer.

A part of the energy budget not thoroughly investigated in this study is the amount of heat transfer and storage in the stream bottom. This aspect of the energy budget may prove to be the most important sink for energy and should be considered by aquatic researchers. One of the most important phases in the life cycle of an anadromous fish is the time spent in the stream bottom gravels in the egg or as a small fry. Heat transfer and storage in the stream bottom is probably a function of bed material since this regulates the interchange of gravel and surface water and the degree of particle contact. The complexities of this intra- and intergravel heat exchange necessitate a separate study incorporating rather sensitive heat flux instrumentation.

Finally, some means must be found for obtaining a better estimate of solar radiation under an irregular canopy of trees. It would be extremely interesting to compare a spacially integrated radiation load with a point sample of diffuse radiation. This integrated radiation load might be obtained by either moving a radiometer down the stream in some manner at a rate equal to the travel time of the average water particle or by sampling radiation very intensely with a large number of radiometers. Measuring just diffuse radiation, as in this study, does not provide exact values for incident radiation, especially under an extremely variable canopy. The difference between net radiation at the stream surface with and without cover, if known for different types and densities of cover would serve to evaluate the effect of cover removal.

A meteorological installation, such as the one described earlier, would permit a complete revision of the study and the approach described in this thesis. A detailed measurement of each component of each flux could then be made. In this manner, a better picture of the energy budget of the water surface, and changes incurred by land treatment, might be obtained. Speculation about prediction errors would not be so necessary.

SUMMARY

This study is part of the Alsea Basin Logging-Aquatic Resources Study research program. It was initiated to determine the applicability of energy budget theory to stream temperature prediction on small forested streams. The study was also designed to evaluate the energy budget technique as a tool in the management of mountain streams for the production of high quality water.

Temperature predictions were made of four stretches of three streams in the Coast and Cascade Ranges of Oregon during the summers of 1965 and 1966. Three of these stretches were forested. The fourth stretch was completely exposed to direct radiation.

Previous water temperature investigations by engineers and physicists were devoted to evaporation and water temperature investigations on large bodies of water. Stream temperature prediction theory was not thoroughly field tested in these earlier studies.

Stream temperature change occurring within a stretch of stream was determined by evaluating the radiative, evaporative and conductive fluxes incident at the surface of the water as it moved downstream. Net radiative flux was measured directly in this study. The evaporative flux was computed with the following Dalton type equation:

$$Q_e = 0.6142\,U(e_w - e_a)$$

where Q_e = evaporative flux at the stream surface in $BTU/ft^2/min$

U = wind speed in mph

e_w = saturated vapor pressure at the water temperature in inches of mercury.

e_a = ambient vapor pressure in inches of mercury.

The conductive flux was computed using the Bowen ratio. The equation for the conductive flux is:

$$Q_h = 0.0002\ U\ P\ (T_a - T_w)$$

where Q_h = conductive flux at the stream surface in $BTU/ft^2/min$

P = barometric pressure in inches of mercury

T_a = air temperature in °F

T_w = water temperature in °F

These fluxes were added to obtain the net energy flux, Qt. Stream temperature change was then computed as:

$$\Delta T = \frac{A \times Qt \times time}{flow \times time} \times 0.000267$$

where T = temperature change through the stretch in °F

A = surface area of the stretch in ft^2

Qt = net energy flux at the stream surface in $BTU/ft^2/min$

flow = streamflow in cfs

time = travel time through the stretch in minutes

Advection from surface or groundwater was added with a simple mixing ratio.

The meteorologic data were measured at the prediction site with portable equipment. The analog data were converted to digital values for computer analysis.

Stream temperature was predicted with varying degrees of accuracy on the four study stretches. Stretch I, Deer Creek was a forested stretch with a two hour travel time. Temperature prediction was not complicated by groundwater or surface water advection. Seventy two predictions were made during a three day period. All but four were within 1.5 °F of the observed temperature.

Stretch II, Deer Creek was a forested stretch with an 18 hour travel time. This stretch contained three surface tributaries and considerable groundwater advection. Only nine of the 72 predictions made during a three day period were within 1 °F of the observed temperature. Predictive errors ranged from +5 °F to -8 °F. The stretch was subdivided to determine if another data reduction technique would improve the prediction. In addition, predictive periods were selected to facilitate separation of data into daytime or nighttime groups. Neither technique substantially improved the predictions.

Needle Branch was a forested stretch with a two hour travel time. Sampling net solar radiation was complicated on this stretch by an irregular canopy. Net radiation was estimated using two techniques of chart analysis. One technique incorporated all net radiation measured. This method gave more accurate results during a cloudy day. The other technique was an attempt to estimate only diffuse net radiation. Spots of sunlight on the radiation record were disregarded. This method gave more accurate results during sunny days. Statistically, the differences in the predictions provided by the two techniques was slight.

The study stretch on the H. J. Andrews Experimental Forest was completely exposed to solar radiation. Travel time through the stretch was only one hour. The maximum temperature change recorded as the water traveled through the study stretch was 16° F. Measurement of solar radiation, which accounted for over 90% of the daytime energy exchange, posed no problem. Prediction of temperature was complicated by heat storage in the bedrock stream bottom. An experiment showed that the rock acted as a heat sink during the day and a heat source at night, explaining the high daytime predictions and the low nighttime predictions.

The H. J. Andrews study showed that during the day, the conductive and evaporative fluxes were small compared to the radiative flux. This led to modification of the original formula for predicting temperature maxima. This formula is:

$$\Delta T = \frac{\text{Surface Area}}{\text{Streamflow}} \times 0.001$$

This permits field personnel to make estimates of maximum temperatures attainable after opening a stretch of stream.

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APPENDICES

APPENDIX I

Table A. A comparison of observed and computed stream temperature for Stretch I of Deer Creek during 1965.

Date	Time (PST)	Conductive flux BTU/ft^2/min	Evaporative flux BTU/ft^2/min	Radiative flux BTU/ft^2/min	Observed temp. °F	Predicted temp. °F	Observed ΔT °F	Predicted ΔT °F
8-31	0300	0	0	1.25	53.8	54.0	-1.0	-0.8
	0400	-.03	-.04	-.25	53.5	53.0	-1.0	-0.5
	0500	-.01	-.01	-.25	52.7	53.5	-0.5	0.3
	0600	-.01	-.01	-.25	53.5	52.7	-0.5	-1.3
	0700	-.01	-.02	-.25	53.5	52.6	-0.5	-1.4
	0800	0	0	-.25	53.5	52.2	0	-1.3
	0900	.01	.01	-.14	53.5	52.9	0	-0.6
	1000	.01	.02	-.07	53.5	53.3	0	-0.2
	1100	.03	.05	0	53.5	53.9	0	0.4
	1200	.05	-.01	.32	54.0	55.3	0.5	1.8
	1300	.11	-.01	.46	54.5	55.7	1.5	2.7
	1400	.16	-.02	.32	56.0	55.8	2.5	2.3
	1500	.18	-.04	.35	56.5	56.5	2.5	2.5
	1600	.17	.02	.25	56.0	56.7	1.5	2.2
	1700	.16	.04	.11	55.5	56.5	0.5	1.5
	1800	.04	.06	-.11	55.0	55.0	0	0
	1900	.04	.06	-.14	55.0	54.8	0	-0.2
	2000	.03	.05	-.14	55.0	54.7	0	-0.3
	2100	.01	.02	-.18	54.5	54.7	-1.0	-1.2
	2200	.01	.01	-.21	54.5	54.0	-0.5	-1.0
	2300	0	0	-.25	54.0	54.2	-1.5	-1.3
	2400	-.01	-.01	-.25	54.0	54.2	-1.5	-1.3
9-01	0100	-.02	-.03	-.25	53.5	53.6	-1.5	-1.4
	0200	-.02	-.04	-.28	53.5	53.3	-1.5	-1.7
	0300	-.02	-.03	-.28	53.0	52.8	-1.5	-1.7
	0400	-.02	-.04	-.28	53.0	52.3	-1.0	-1.7
	0500	-.03	-.04	-.28	52.5	52.3	-1.5	-1.7
	0600	-.03	-.04	-.28	52.0	51.8	-1.5	-1.7

Table A. (Continued)

Date	Time (PST)	Conductive flux BTU/ft²/min	Evaporative flux BTU/ft²/min	Radiative flux BTU/ft²/min	Observed temp. °F	Predicted temp. °F	Observed ΔT °F	Predicted ΔT °F
9-01	0700	-.02	-.03	-.28	52.0	51.3	-1.0	-1.7
	0800	-.02	-.03	-.25	52.0	51.6	-1.0	-1.4
	0900	-.01	-.01	-.21	52.5	51.3	0	-1.2
	1000	.01	.01	-.18	53.0	51.2	1.0	-0.8
	1100	.02	.04	.04	52.5	52.1	0.5	+0.1
	1200	.04	.06	-.04	52.5	52.3	0.5	0.3
	1300	.04	.05	.04	52.5	53.1	0	0.6
	1400	.04	.05	.04	52.5	53.1	0	0.6
	1500	.04	.06	0	52.5	53.5	-0.5	0.5
	1600	.04	.07	0	53.0	53.5	0	0.5
	1700	.04	.07	0	53.0	54.0	-0.5	0.5
	1800	.04	.07	-.07	53.0	53.7	-0.5	0.2
	1900	.03	.05	-.14	53.0	53.7	-1.0	-0.3
	2000	.03	.05	-.21	53.0	53.4	-1.0	-0.6
	2100	.02	.04	-.21	53.0	53.3	-1.0	-0.7
	2200	.02	.04	-.21	53.0	53.3	-1.0	-0.7
	2300	.02	.04	-.21	53.0	53.3	-1.0	-0.7
	2400	.02	.03	-.21	53.0	53.2	-1.0	-0.8
9-02	0100	.02	.03	-.21	52.5	53.2	-1.5	-0.8
	0200	.02	.03	-.21	52.5	53.2	-1.5	-0.8
9-03	0300	-.01	-.02	-.28	52.0	51.5	01.0	-1.5
	0400	-.01	-.01	-.32	51.5	50.8	-1.0	-1.7
	0500	-.02	-.02	-.32	51.5	50.8	-1.0	-1.7
	0600	-.02	-.02	-.32	51.0	50.2	-1.0	-1.8
	0700	-.02	-.02	-.32	50.5	49.7	-1.0	-1.8
	0800	-.02	-.02	-.32	50.5	49.2	-0.5	-1.9
	0900	-.01	-.02	-.28	50.5	49.5	-0.5	-1.5
	1000	0	0	-.18	50.5	49.6	0	-0.9

Table A. (Continued)

Date	Time (PST)	Conductive flux BTU/ft^2/min	Evaporative flux BTU/ft^2/min	Radiative flux BTU/ft^2/min	Observed temp. °F	Predicted temp. °F	Observed ΔT °F	Predicted ΔT °F
9-03	1100	.02	.02	0	51.0	50.8	0.5	0.3
	1200	.10	.11	.21	51.5	52.6	1.0	1.1
	1300	.15	.15	.35	52.0	53.7	1.5	3.2
	1400	.20	.20	.42	53.0	55.0	2.0	4.0
	1500	.23	.19	.35	54.5	55.8	2.5	3.8
	1600	.24	.25	.25	54.5	56.1	2.0	3.5
	1700	.22	.24	.07	54.0	55.9	1.0	2.9
	1800	.19	.29	.07	54.0	55.0	1.0	2.0
	1900	.16	.27	-.14	54.0	54.9	0.5	1.4
	2000	.04	.08	-.18	53.5	53.2	0	-0.3
	2100	.04	.07	-.21	53.5	53.0	0	-0.5
	2200	.02	.04	-.25	53.5	53.1	-0.5	-0.9
	2300	.01	.02	-.25	53.5	52.9	-0.5	-1.1
	2400	.01	.02	-.25	53.5	52.9	-0.5	-1.1
9-04	0100	.02	.02	-.21	53.5	52.6	0	-0.9
9-05	0200	.02	.02	-.21	53.5	52.6	0	-0.9

Table B. A comparison of observed and computed stream temperature for Stretch II of Deer Creek during 1965.

Date	Time	Conductive flux BTU/ft^2/min	Evaporative flux BTU/ft^2/min	Radiative flux BTU/ft^2/min	Observed temp. °F	Predicted temp. °F	Observed ΔT °F	Predicted ΔT °F
8-31	1900	.01	-.03	-0.02	55.0	52.3	1.0	-1.7
	2000	.06	.14	-0.02	54.5	57.5	0.5	3.5
	2100	.06	.14	-0.02	54.0	57.5	0	3.5
	2200	.07	.15	-0.02	54.0	57.6	.5	4.1
	2300	.07	.15	-0.02	54.0	57.6	0.5	4.1
	2400	.08	.17	-0.02	53.5	58.6	-.5	4.6
9-01	0100	.04	.07	-0.02	53.5	56.2	-1.5	1.2
	0200	-.01	-.05	-0.03	53.5	53.0	-2.0	-2.5
	0300	-.03	-.09	-0.04	53.5	51.8	-2.5	-4.2
	0400	-.03	-.10	-0.06	53.5	51.7	-2.5	-4.3
	0500	-.05	-.13	-0.06	53.0	50.6	-3.0	-5.4
	0600	-.05	-.13	-0.07	53.5	50.6	-2.5	-5.4
	0700	-.06	-.17	-0.09	54.0	49.4	-2.0	-6.6
	0800	-.04	-.15	-.14	54.5	46.8	-1.5	-9.2
	0900	-.06	-.12	-.18	55.0	47.0	-1.0	-9.0
	1000	-.05	-.11	-.11	55.0	48.6	-.5	-6.9
	1100	-.02	-.08	-.11	55.0	49.5	0	-5.5
	1200	-.02	-.06	-.11	55.0	49.8	0	-5.2
	1300	-.01	-.03	-.11	55.5	50.9	.5	-4.1
	1400	0	-.02	-.11	55.5	51.0	1.0	-3.5
	1500	0	-.02	-.11	55.5	51.0	1.0	-3.5
	1600	.02	.01	-.11	55.5	52.0	1.0	-2.5
	1700	.03	.03	-.11	55.0	52.2	1.0	-2.8
	1800	.03	.03	-.11	55.0	52.2	1.0	-2.8
	1900	.03	.03	-.11	54.5	52.1	0.5	-2.9
	2000	.03	.03	-.11	54.0	52.1	0	-2.9
	2100	.04	-.16	-.11	54.0	48.3	0	-5.7
	2200	.05	-.14	-.11	53.5	48.4	0	-5.1
	2300	.02	.01	-.11	53.0	51.2	-.5	-2.3

Table B. (Continued)

Date	Time	Conductive flux BTU/ft^2/min	Evaporative flux BTU/ft^2/min	Radiative flux BTU/ft^2/min	Observed temp. °F	Predicted temp. °F	Observed ΔT °F	Predicted ΔT °F
9-01	2400	.02	.01	-.11	53.0	51.2	-.5	-2.3
9-02	0100	.01	-.01	-.11	52.5	50.9	-1.5	-3.1
	0200	-.01	-.06	-.11	52.0	49.6	-2.5	-4.9
	0300	-.04	-.11	-.11	52.0	48.3	-3.0	-6.7
	0400	-.04	-.10	-.11	52.0	48.5	-3.0	-6.5
	0500	-.05	-.12	-.25	52.0	44.7	-3.0	-10.3
	0600	-.06	-.14	-.25	52.5	44.2	-2.5	-10.8
	0700	-.06	-.14	-.25	53.0	44.8	-2.0	-10.2
	0800	-.06	-.13	-.25	53.0	44.4	-2.0	-10.6
	0900	-.05	-.12	-.25	53.5	44.7	-1.5	-10.3
	1000	-.02	-.03	-.25	53.5	46.4	-1.0	-8.1
	1100	-.01	-.03	-.22	54.0	47.6	-0.5	-6.9
	1200	-.01	-.03	-.14	54.0	49.2	-0.5	-5.3
	1300	-.01	-.02	-.14	54.0	49.0	0	-5.0
	1400	0	-.01	-.14	54.0	51.9	0	-2.1
	1500	0	-.01	-.14	54.0	52.7	0	-1.3
	1600	0	0	-.14	54.0	52.5	0.5	-1.0
	1700	0	0	-.14	54.0	52.6	0.5	-0.9
	1800	.01	.01	-.12	54.0	51.3	1.0	-1.7
9-03	1800	.01	.01	-.05	53.0	53.2	-1.0	-0.8
	1900	.03	.02	-.07	52.0	52.9	-1.5	-0.6
	2000	.03	.02	-.08	52.5	52.7	-1.0	-0.8
	2100	.03	.01	-.12	52.0	51.6	-1.5	-1.9
	2200	.03	.01	-.12	51.5	51.8	-2.0	-1.8
	2300	.03	.01	-.17	51.0	51.0	-3.0	-3.0
	2400	.02	.01	-.16	51.0	50.9	-3.0	-3.1
9-04	0100	.02	.04	-.13	50.5	52.4	-3.5	-1.6
	0200	0	0	-.08	50.5	52.1	-3.5	-1.9

Table B. (Continued)

Date	Time	Conductive flux BTU/ft^2/min	Evaporative flux BTU/ft^2/ min	Radiative flux BTU/ft^2/min	Observed temp. °F	Predicted temp. °F	Observed ΔT °F	Predicted ΔT °F
9-04	0300	0	0	-.08	50.5	52.4	-4.0	-2.1
	0400	0	-.01	-.08	50.5	52.4	-4.0	-2.1
	0500	0	-.01	-.08	51.0	52.4	-3.5	-2.1
	0600	0	0	-.01	52.0	52.4	-2.5	-2.1
	0700	0	0	-.01	52.5	52.2	-2.0	-2.3
	0800	0	0	-.07	53.0	52.2	-1.0	-1.8
	0900	0	0	-.07	53.0	52.3	-1.0	-1.7
	1000	0	0	-.05	53.5	52.3	0	-1.2
	1100	.01	-.02	-.06	53.5	52.3	0	-1.2
	1200	.02	-.02	-.06	53.5	52.1	0	-1.4
	1300	.02	0	-.06	54.0	52.4	..5	-1.1
	1400	.03	0	-.06	54.0	52.2	1.0	-0.8
	1500	.04	.02	-.06	54.0	52.2	1.5	-0.3
	1600	.04	.02	-.06	53.5	51.9	1.5	-0.1
	1700	.04	.02	-.06	53.5	51.9	1.5	-0.1
	1800	.04	.02	-.06	53.5	51.9	1.5	-0.1

Table C. A comparison of predicted and observed stream temperature for Needle Branch using two techniques.

Date	Time (PST)	Adjusted radiation		Observed temp. °F	Integrated radiation		Evap. flux BTU/ft²/min	Conduc. flux BTU/ft²/min	Observed ΔT °F
		Net rad. BTU/ft² / min	Predicted temp. °F		Predicted temp. °F	Net rad. BTU/ft²/min			
4-16	1000	0.21	47.8	50.0	48.2	0.32	.03	.15	3.5
	1100	0.77	51.3	52.5	52.0	0.98	-.04	.24	4.5
	1200	0.88	52.7	53.5	55.4	1.69	-.09	.29	4.5
	1300	1.05	53.3	52.5	55.3	1.65	.01	.34	4.0
4-17	1000	0.17	47.8	50.0	48.0	0.25	-.19	.34	3.5
	1100	0.63	50.9	52.0	54.6	1.72	-.20	.41	4.0
	1200	1.12	53.8	53.5	56.5	1.93	-.11	.40	3.5
	1300	0.95	53.4	51.5	53.9	1.09	-.05	.40	2.5
4-18	1000	0.21	46.2	48.5	46.6	0.32	-.16	.15	3.0
	1100	0.56	48.3	50.5	50.1	1.09	-.30	.26	4.0
	1200	1.05	50.4	51.5	50.8	1.20	-.41	.33	4.5
	1300	1.05	50.8	51.0	51.2	1.16	-.60	.37	3.0

Table D. A comparison of predicted and observed stream temperature for Watershed 3, H. J. Andrews Experimental Forest.

Date	Time (PST)	Evaporative flux BTU/ft^2/min	Conductive flux BTU/ft^2/min	Radiative flux BTU/ft^2/min	Observed temp. °F	Predicted temp. °F	Observed ΔT °F	Predicted ΔT °F
5-20	1000	.005	.06	3.34	59.5	63.1	12.0	15.6
	1100	-.03	.07	3.69	64.5	69.1	12.5	17.1
	1200	-.04	.13	4.27	68.0	71.9	16.0	19.9
	1300	-.02	.12	4.12	67.0	71.8	14.5	19.3
	1400	-.009	.11	3.01	66.0	66.8	13.5	14.3
	1500	-.03	.09	1.79	64.0	62.0	10.5	8.5
	1600	0	.09	0.36	62.0	55.5	8.5	2.0
	1700	.02	.07	-0.36	60.0	51.8	7.0	-1.2
	1800	.12	.21	-0.72	58.0	50.7	5.5	-1.8
	1900	.15	.18	-1.08	56.5	49.2	4.0	-3.3
	2000	.16	.16	-1.43	55.0	46.9	3.0	-5.1
	2100	.16	.15	-1.79	54.0	44.7	2.5	-6.8
	2200	.17	.14	-1.79	53.0	44.2	2.0	-6.8
	2300	.12	.12	-1.43	52.5	45.0	2.0	-5.5
	2400	.16	.13	-1.08	52.0	46.4	2.0	-3.6
5-21	0100	.13	.11	-0.72	51.5	47.8	1.5	-2.2
	0200	.13	.11	-0.72	51.5	47.8	1.5	-2.2
	0300	.13	.11	-0.72	51.5	47.8	1.5	-2.2
	0400	.13	.11	-0.72	51.5	47.8	1.5	-2.2
	0500	.13	.11	-0.72	51.5	47.8	1.5	-2.2
	0600	.14	.13	-0.36	51.0	48.6	2.0	-0.4
	0700	.07	.13	0.00	51.0	49.9	2.0	0.9

Table E. A comparison of predicted and observed stream temperature for Watershed 3, H. J. Andrews Experimental Forest.

Date	Time (PST)	Evaporative flux BTU/ft^2/min	Conductive flux BTU/ft^2/min	Radiative flux BTU/ft^2/min	Observed temp. °F	Predicted temp. °F	Observed ΔT °F	Predicted ΔT °F
5-7	9	-.09	.15	2.11	49.0	54.0	3.0	8.0
	10	-.07	.43	3.19	55.0	61.6	6.5	13.1
	11	-.14	.54	3.75	60.0	65.4	10.0	15.4
	12	-.18	.56	3.97	64.0	66.6	13.5	16.1
	13	-.005	.40	3.37	64.5	65.4	13.0	13.9
5-8	9	-.01	.03	1.08	52.0	52.6	3.5	4.1
	10	-.01	.06	2.04	57.0	57.7	7.0	7.7
	11	-.26	.72	3.23	62.0	64.1	10.0	12.1
	12	-.01	.07	2.63	63.5	62.9	10.5	9.9

APPENDIX II

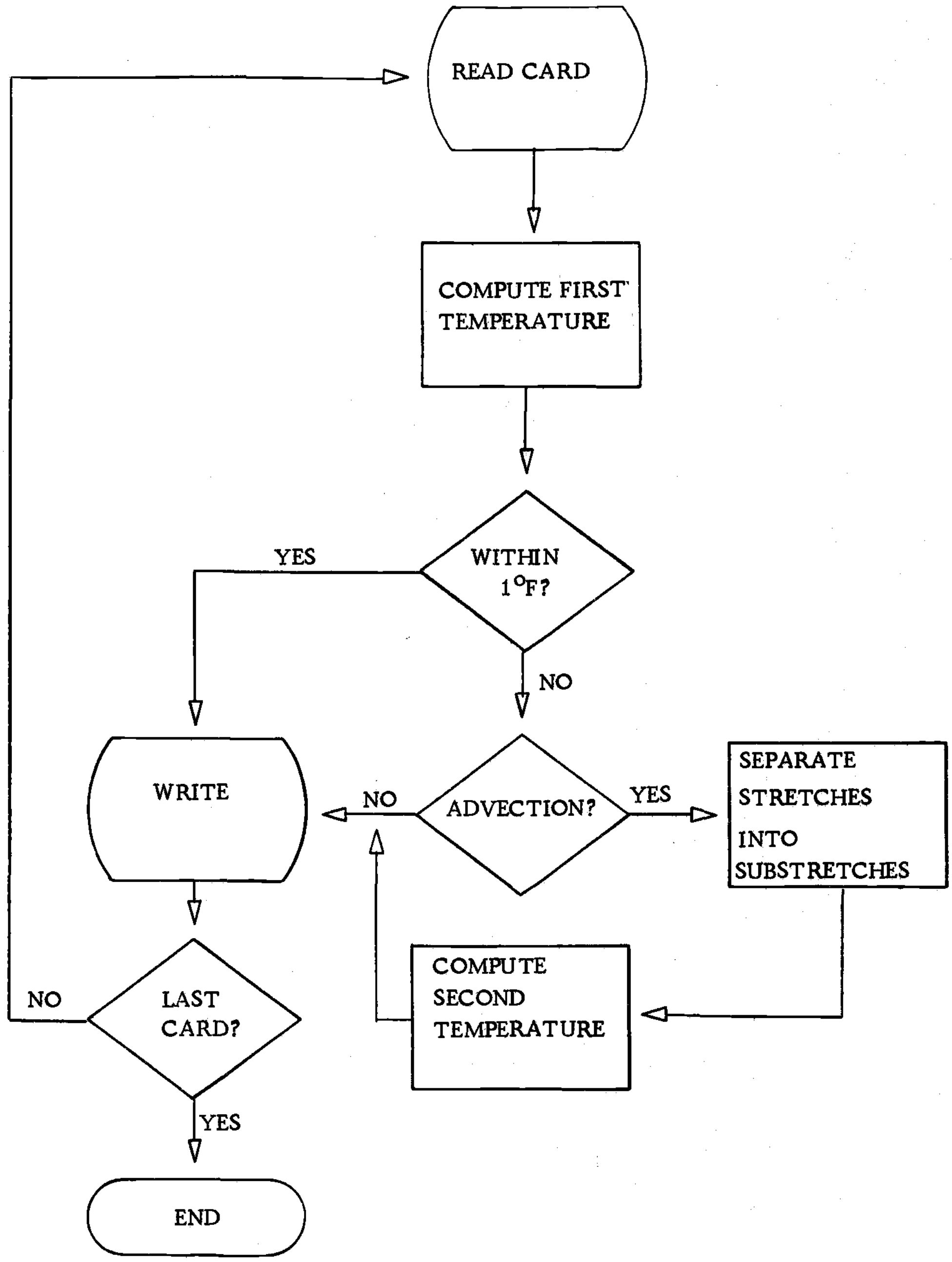

Figure 12. A Flow Chart For the Stream Temperature Prediction Computer Program.

```
 1      FORMAT(F5.2, I2, F2.0, F5.3, F5.2, 2F4.3, 3F4.1, F5.0
      C  F4.2, F4.1, F4.0, F4.1, F4.2, F3.0, F5.0, 7X, I1)
 201    FORMAT(F5.2, I2, F2.0, F4.1, F4.2, F3.0, F5.0, F4.1,
      C  F4.2, F3.0, F5.0)
 101    FORMAT(1H, F5.2, 3X, I2, F4.0, 3X, F6.2, 2X, F5.2, 3X,
      C  I2, 2X, F5.1, 3F7.2)
 6      READ(1, 1)D, IS, R, ZR, WS, EW, EA, TW, TA, P, AR, FL, OBST,
      C  TIME, TEMPA, FLA, TIMA, ARA, ID
        IF(ID)7, 12, 7
 7      READ(1, 201)D, IS, R, TEMPB, FLB, TIMB, ARB, TEMPC, FLC,
      C  TIME, ARC
 12     QZR=3.68 *ZR*TIME
        IK=1
        QE=0.6142*WS*(EA-EW)*TIME
        QH=0.0002*(TA-TW)*TIME*WS*P
        QT=QZR+QE+QH
        DT=((AR*QT)/(FL*TIME))*0.000267
        T1=TW+DT
        OCT=OBST-TW
        IF(FLA)2, 2, 3
 2      WRITE(2, 101)D, IS, R, T1, OBST, IK, OCT, QZR, QE, QH
        WRITE(3, 101)D, IS, R, T1, OBST, IK, OCT, QZR, QE, QH
        GO TO 100
 3      ADV=(FLA*TEMPA)+(FLB*TEMPB)+(FLC*TEMPC)
        F=FLA+FLB+FLC
        T2=((T1*FL)+ADV)/(FL+F)
        IF(ABS(T2-OBST)-1.)5, 5, 4
 4      IF(ADV)5, 5, 21
 5      WRITE(2, 101)D, IS, R, T2, OBST, IK, OCT, QZR, QE, QH
        WRITE(3, 101)D, IS, R, T2, OBST, IK, OCT, QZR, QE, QH
        TO TO 100
 21     QZRA=3.68 *ZR*TIMA
        IK=2
        QEA=0.6142*WS*(EA-EW)*TIMA
        QHA=0.0002*(TA-TW)*TIMA*WS*P
        QTA=QZRA+QHA+QEA
        DTA=((ARA*QTA)/(FL*TIMA))*0.0002670
        T1=TW+DTA
        ADV=FLA*TEMPA
        T2=((T1*FL)+ADV)/(FL+FLA)
        IF(TEMPB)22, 22, 30
 22     IF(TIME-TIMA)23, 23, 24
 23     WRITE(2, 101) D, IS, R, T2, OBST, IK, OCT, QZRA, QEA, QHA
        WRITE(3, 101) D, IS, R, T2, OBST, IK, OCT, QZRA, QEA, QHA
        GO TO 100
 24     QZRAP=3.68 *ZR*(TIME-TIMA)
        IK=2
        QEAP=0.6142*WS*(EA-EW)*(TIME-TIMA)
        QHAP=0.0002*(TA-T2)*WS*P*(TIME-TIMA)
        QTAP=QZRAP+QEAP+QHAP
        TQR=QZRA+QZRAP
```

```
      TQE=QEA+QEAP
      TQH=QHA+QHAP
      DTAP=(((AR-ARA)*QTAP)/((FL+FLA)*(TIME-TIMA)))*
     C 0.000267
      T2A=T2+DTAP
      WRITE(2,101)D,IS,R,T2A,OBST,IK,OCT,TQR,TQE,TQH
      WRITE(3,101)D,IS,R,T2A,OBST,IK,OCT,TQR,TQE,TQH
      GO TO 100
30    QZRB=3.68*ZR*TIMB
      IK=2
      QEB=0.6142*WS*(EA-EW)*TIMB
      QHB=0.0002*(TA-T2)*TIMB*WS*P
      QTB=QZRB+QEB+QHB
      DTB=((ARB*QTB)/((FL+FLA)*TIMB))*0.0002670
      T3=T2+DTB
      ADV=FLB*TEMPB
      T4=((T3*(FL+FLA))+ADV)/(FL+FLA+FLB)
      IF(TEMPC)35,35,40
35    IF(TIME-(TIMA+TIMB))36,36,37
36    TQR=QZRA+AZRB
      TQE=QEA+QEB
      TQH=QHA+QHB
      WRITE(2,101)D,IS,R,T4,OBST,IK,OCT,TQR,TQE,TQH
      WRITE(3,101)D,IS,R,T4,OBST,IK,OCT,TQR,TQE,TQH
      GO TO 100
37    QZRBP=3.68*ZR*(TIME-(TIMA+TIMB))
      IK=2
      QEBP=0.6142*WS*(EA-EW)*(TIME-(TIMA+TIMB))
      QHBP=0.0002*(TA-T4)*WS*P*(TIME-(TIMA+TIMB)
      QTBP=QZRBP+QEBP+QHBP
      DTBP=(((AR-(ARA+ARB))*QTBP)/((FL+FLA+FLB)*
     C (TIME-(TIMA+TIMB))))*0.000267
     C 0.000267
      T4B=T4+DTB
      TQR=QZRA+QZRB+QZRBP
      TQE=QEA+QEB+QEBP
      TQH=QHA+QHB+QHBP
      WRITE(2,101)D,IS,R,T4B,OBST,IK,OCT,TQR,TQE,TQH
      WRITE(3,101)D,IS,R,T4B,OBST,IK,OCT,TQR,TQE,TQH
      GO TO 100
40    QZRC=3.68*ZR*TIMC
      IK=2
      QEC=0.6142*WS*(EA-EW)*TIMC
      QHC=0.0002*(TA-T4)*TIMC*WS*P
      QTC=QZRC+QEC+QHC
      DTC=((ARC*QTC)/((FL+FLA+FLB)*TIMC))*0.000267
      T5=T4+DTC
      ADV=FLC*TEMPC
      T6=((T5*(FL+FLA+FLB))+ADV)/(FL+FLA+FLB+FLC)
      IF(TIME-(TIMA+TIMB+TIMC))42,42,43
42    TQR=QZRA+QZRB+QZRC
      TQE=QEA+QEB+QEC
```

```
      TQH=QHA+QHB+QHC
      WRITE(2, 101)D, IS, R, T6, OBST, IK, OCT, TQR, TQE, TQH
      WRITE(3, 101)D, IS, R, T6, OBST, IK, OCT, TQR, TQE, TQH
      GO TO 100
43    QZRCP=3.68 *ZR*(TIME-(TIMA+TIMB+TIMC))
      IK=2
      QECP=0.6142*WS*(EA-EW)*(TIME-(TIMA+TIMB+TIMC))
      QHCP=0.0002*(TA=T6)*WS*P*(TIME-(TIMA+TIMB+TIMC))
      QTCP=QZRCP+QECP+QHCP
      DTCP=(((AR-(ARA+ARB+ARC))*QTCP)/((FL+FLA+FLB+FLC)*
     C (TIME-(TIMA+TIMB+TIMC))))*0.000267

      T6C=T6+DTCP
      TQR=QZRA+QZRB+QZRC+QZRCP
      TQE=QEA+QEB+QEC+QECP
      TQH=QHA+QHB+QHC+QHCP
      WRITE(2, 101)D, IS, R, T6C, OBST, IK, OCT, TQR, TQE, TQH
      WRITE(3, 101)D, IS, R, T6C, OBST, IK, OCT, TQR, TQE, TQH
100   CALLCRDEND(LT)
      IF(LT.NE.2) GOTO6
60    CALL EXIT
      END
```

LIST OF SYMBOLS

A = surface area of the body of water

a = air temperature

B = energy transferred due to thermal gradients

c_l = specific heat of water

c_p = specific heat of air

D = Bowen's most probable constant (0.61)

E = total depth of evaporation

E' = rate of evaporation or condensation

e_a = ambient vapor pressure

e_w = saturated vapor pressure at the water temperature

F_m = flow of the main stream

E_t = flow of the tributary stream

f = total runoff or outflow

K = Anderson's exchange coefficient (0.0045)

k = turbulent exchange coefficient

L = heat of vaporization for water at the lake temperature

l = mixing length

m_i = mass of inflow water

m_v = mass of the body of water

NR = net solar radiation

P = barometric pressure

LIST OF SYMBOLS (CONTINUED)

p' = rate of turbulent heat exchange between the water surface and the atmosphere

p'' = total turbulent heat exchange between the water surface and the atmosphere

Q_a = heat exchange through advection

Q_b = net back radiation of long wave energy

Q_e = heat exchange through evaporation

Q_h = heat exchange through conduction

$Q_{N.r}$ = net radiation exchange

Q_r = short wave radiation reflected back to the atmosphere

Q_s = short wave radiation striking the water surface

Q_t = net energy flux

q = specific humidity at some height z

q_o = specific humidity at the water surface

R = incident energy

R' = Bowen's R

r = total precipitation or inflow

S = reflected energy

T = transmitted energy

T' = adjusted water temperature

Ta = air temperature

LIST OF SYMBOLS (CONTINUED)

Tm = predicted temperature of the main stream

Tt = temperature of a tributary

Tw = water temperature

Tw' = water temperature time t

Tw'' = water temperature time t_o

t = time

ti = inflow temperature

U = wind speed

x = horizontal distance

z = height above water surface

z_o = height equivalent to surface roughness

z_1 = height equivalent to mixing length

Δ_1 = change in soil moisture storage

Δ_2 = change in heat storage

ΔT = predicted temperature change

ρ_2 = air density

ρ_1 = density of water

χ = von Karman's constant (0.38)

FORMAT KEY

D = date

IS = stretch

R = run

ZR = net radiation (Langleys)

WS = wind speed (miles per hour)

EW = saturated vapor pressure at water temperature (inches of mercury)

EA = ambinet vapor pressure (inches of mercury)

TW = water temperature (degrees Fahrenheit)

TA = air temperature (degrees Fahrenheit)

P = barometric pressure (inches of mercury)

AR = surface area of the stream stretch (square feet)

FL = discharge (cubic feet per second)

OBST = observed temperature at the end of the stretch (degrees Fahrenheit)

TIME = travel time through the stretch (minutes)

TEMPA = temperature of the first tributary (degrees Fahrenheit)

FLA = discharge of the first tributary (cubic feet per second)

TIMA = travel time from start to first tributary (minutes)

ARA = surface area from start to first tributary (square feet)

ID = card code

TEMPB = temperature of the second tributary (degrees Fahrenheit)

FORMAT KEY (CONTINUED)

FLB = discharge of the second tributary (cubic feet per second)

TIMB = travel time between the first and second tributaries (minutes)

ARB = surface area between the first and second tributaries (square feet)

TEMPC = temperature of the third tributary (degrees Fahrenheit)

FLC = discharge of the third tributary (cubic feet per second)

TIMC = travel time between the second and third tributaries (minutes)

ARC = surface area between the second and third tributaries (square feet)