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Effect of Meteorological Variables on Temperature Changes in Flowing Streams

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EFFECT OF METEOROLOGICAL VARIABLES ON TEMPERATURE CHANGES IN FLOWING STREAMS

By

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ABSTRACT

A mathematical model for predicting the change in water temperature in a flowing stream as a function of stream geometry and standard weather information was developed and tested. Five field tests were conducted on cold water released from hydro-power stations as it warmed up moving downstream over periods up to 38 hours.

Predictions of temperature changes were made based on (a) weather data from a boat floating with the water, (b) data from a station on the bank, and (c) data from a remote weather station 100 miles away. Agreement between predicted and observed temperature changes was good, even with remote data, when adjustments to compensate for the local micro-climate were made. Computer programs and all data are included. This report was submitted in fulfillment of Project Number 16130 FDQ, Grant Number R-800613, by Vanderbilt University, Department of Environmental and Water Resources Engineering under the sponsorship of the Environmental Protection Agency. Work was completed as of November 1974.

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INTRODUCTION

The demand for energy, particularly electric power, has increased sharply in recent years. As increased electricity is generated to meet this demand, larger amounts of waste heat will be produced. This thermal energy, which must be transferred to the environment, can cause undesirable temperature rises in natural bodies of water when heated cooling water is discharged to them.

This study had as its purpose the construction and verification of an energy budget model for the accurate prediction of temperatures in flowing rivers, based solely on the approximate geometry of the stream and on data normally taken at U.S. Weather Bureau weather stations. The particular model studied was first presented by Raphael (1) and later modified by Thackston (2) for computer analysis of cooling ponds. Further modifications of the model were necessary to adapt it to conditions in flowing rivers.

The original plan of attack was to study rivers which had been heated by thermal discharges. However, no rivers within reasonable distances of Nashville have a mixed temperature rise of more than a few degrees above equilibrium temperature. Since experimental errors might be a large fraction of the small temperature changes occurring in the river, another situation with large temperature changes was sought. The warming of cold water released from the hypolimnion of stratified reservoirs through hydroelectric plants was studied instead. The water released from the stratified reservoirs had a temperature of approximately 50°F in all six field surveys. Since this was well below the equilibrium temperature, which was 80° - 90°F during the daytime, changes in temperature great enough to test the model were encountered.

THE ENERGY BUDGET

The energy budget for water bodies can be written as

$$Q_t = Q_s + Q_a + Q_b + Q_e + Q_c \qquad (1)$$

where Q_t equals total energy transferred, Q_s equals absorbed solar radiation, Q_a equals absorbed longwave atmospheric radiation, Q_b equals longwave back radiation to space, Q_e equals energy lost by evaporation, and Q_c equals energy gained or lost by conduction.

Following the standard thermodynamic convention, energy transferred into the system, which in our case is a small slug of water in the river, is considered positive, and energy lost is negative.

If the earth had no atmosphere, the solar energy received on a flat surface would depend only on the altitude of the sun and the slight fluctuations in total energy radiated from the sun. Fluctuations in solar output are minor and are neglected in this paper. Since the earth has a relatively dense atmosphere, all of the energy incident upon the top of the atmosphere is not received at the surface of a body of water. Part of the radiation is scattered or absorbed by solid particles, gases, and water vapor. In this manner, part of the shortwave, or direct, radiation is transformed into diffuse solar radiation and longwave radiation. Direct solar radiation which is scattered becomes diffuse solar radiation, and that which is absorbed and reemitted becomes longwave, or atmospheric radiation. For the purpose of this study, all three types of incoming radiation must be calculated separately.

Solar Radiation

With clear sky conditions, solar radiation is primarily a function of solar altitude. Moon (3) presented values of direct and diffuse radiation on a flat surface as a function of solar altitude. Upadhyaya (4) fit polynomials to this data by non-linear least squares methods to produce the equations

$$Q_1 = -0.1470\alpha + 0.3023\alpha^2 - 0.008546\alpha^3 + 0.0001271\alpha^4 - 0.000000001012\alpha^5 \qquad (2)$$

$$Q_2 = 1.680\alpha + 0.03178\alpha^2 + 0.0002414\alpha^3 - 0.000000004729\alpha^4 + 0.000000005858\alpha^5 \qquad (3)$$

where Q_1 is the direct solar radiation, Q_2 is the diffuse solar radiation, and α is the solar altitude in degrees above the horizon.

The solar altitude is given by the equation

$$\sin \alpha = \sin \phi \sin \delta + \cos \phi \cos \delta \cos h \tag{4}$$

where Φ is the latitude; δ is the declination of the sun; and h is the hour angle of the sun. Thackston (2) used the above mentioned non-linear least squares method to determine an equation for δ . Data from a solar ephemeris was used.

The equation obtained was

$$\delta = - 23.28 \cos[(2\pi \mathrm{day}/365) + 0.165] \tag{5}$$

where day is the day of the year.

Once sin α was calculated using Equation 4, values of α were determined from the equation.

$$\alpha = \sin \alpha + \frac{\sin \alpha^3}{6} + \frac{3 \sin \alpha^5}{40} + \frac{15 \sin \alpha^7}{337} \tag{6}$$

Total solar radiation is the sum of direct and diffuse solar radiation, Q_1 and Q_2. However, Equations 1 and 2 apply only to clear sky conditions. Furthermore, they assume that no part of the river is shaded from the sky.

The net direct solar radiation becomes

$$Q_3 = Q_1 (1 - s) \tag{7}$$

where s is the portion of the river surface shaded from direct sunlight. This shaded fraction was usually about 5% during daylight hours on the rivers studied.

Net diffuse radiation is corrected for the percentage of the sky blocked from view of the river by the surrounding hills. This number was often substantial because the rivers studied all flowed in rather deep and narrow valleys. Net diffuse radiation became

$$Q_4 = Q_2 (1 - b) \tag{8}$$

where b is the portion of the sky blocked from view of the river.

Total clear sky solar radiation is the sum of diffuse and direct solar radiation. Cloud cover was taken into account by using the relationship

$$Q_s = (Q_3 + Q_4)(1 - 0.0071\ C^2) \qquad (9)$$

where C is the cloud cover in tenths of sky.

Atmospheric Radiation

Considerable difficulties arise in determining a relationship for longwave atmospheric radiation. These difficulties are encountered because the atmosphere is far from homogeneous. Temperature gradients are quite variable from day to day and the distribution of moisture is seldom known to the observer.

Anderson (5) proposed an empirical relationship of the form

$$Q_a = \sigma\ \beta\ (T + 460)^4\ (1 - r) \qquad (10)$$

in which Q_a is the longwave atmospheric radiation, σ is the Stefan-Boltzman constant, β is a constant which is a function of vapor pressure, and the height and type of cloud cover, being higher for greater vapor pressure, greater cloud cover, and lower clouds, T is the air temperature in ^oF, and r is the reflectivity of the water surface.

Plots of β versus vapor pressure, e_a, for particular values of cloud cover were developed by Raphael from Anderson's data. These plots were straight lines of the form $\beta = a + be_a$ for each value of cloud cover in tenths of sky. Thackston utilized these plots by writing them in equation form for each value of cloud cover from 1 to 10. These equations were built into a computer program along with instructions to pick the proper equations for a particular cloud cover.

Since vapor pressure of ambient air is equal to the saturated vapor pressure at the wet bulb temperature, an equation between the latter quantities was obtained by the non-linear least squares procedure. The equation is

$$e_s = \exp[17.62 - 9501/(T_{wb} + 460)] \qquad (11)$$

with the units of e_s being inches of mercury.

Wet bulb temperature, T_{wb}, may be calculated from the relative humidity and air temperature by the equation

$$T_{wb} = (0.655 + 0.36R)\ T_a \qquad (12)$$

Since the reflectivity of the water surface is usually used as 0.03, Equation 10 becomes

$$Q_a = 1.66 \times 10^{-9} \beta (T_a + 460)^4 \qquad (13)$$

Atmospheric radiation can easily be determined by a computer utilizing Equations 11 - 13, given only relative humidity and air temperature. The sequence of operations is as follows:

1. Determine T_{wb} from Equation 12.

2. Plug T_{wb} into Equation 11 to determine e_s, which is also equal to e_a.

3. Use the value of cloud cover to determine the proper equation to use for calculating β. Insert the value of e_a into the proper equation and find B.

4. Determine Q_a from equation 13.

In earlier work with the model, the atmospheric radiation was corrected for the percentage of the sky blocked from view of the water surface. However, this procedure gave temperature predictions which were too low. The surrounding valley walls radiate to the water and the attempted correction did not take this radiation into account. By recognizing that the trees and rocks covering the valley slopes radiated just as the atmosphere, better temperature predictions were obtained than by assuming that all longwave radiation came from the visible portion of the sky.

Back Radiation

All bodies which have some thermal energy radiate to the environment. The relationship is quantified by the equation

$$Q_b = \varepsilon\sigma (T_w + 460)^4 \qquad (14)$$

where Q_b is back radiation, ε is the emissivity, about 0.97 for water, σ is the Stefan-Boltzman constant, and T_w is the temperature of the water surface in ^oF.

Evaporation

Much effort has been applied to developing evaporation formulas. Numerous empirical formulas are now in existence. The equation used in this study was

$$Q_e = - C\, U(e_w - e_a) \qquad (15)$$

Q_e is the energy lost by evaporation, C is an empirical coefficient, U is the wind speed in miles per hour, e_w is the saturated vapor pressure of the air at the water surface temperature in inches of mercury, and e_a is the vapor pressure of the air in inches of mercury.

The constant C depends on the geometry of the water surface and its surroundings, the height of wind measurements, and probably other factors. The value of C was determined by the Lake Hefner studies to be approximately 13.9 in the units used here. Note should be taken of the fact that wind speeds at Lake Hefner were measured at 8 meters. Adjustments which were made to correct for different heights of wind measurements in this study are discussed later.

The saturated vapor pressure at the water surface temperature is determined from

$$e_w = \exp[17.62 - 9501/(T_w + 460] \qquad (16)$$

where T_w is the temperature of the water. This equation is the same as Equation 11 with T_w substituted for T_{wb}.

Conduction

Energy is transferred from air to water or water to air by conduction if a driving force in the form of a temperature difference exists. Important factors in this mechanism of energy transfer are air temperature, water temperature, and wind velocity.

Because of the similarity between evaporation and conduction, Bowen developed a relationship between the two known as the Bowen ratio.

$$R = \frac{Q_c}{Q_e} = \left(\frac{C_o(T_w - T_a)}{e_w - e_a}\right)\left(\frac{P}{1000}\right) \qquad (17)$$

P is the barometric pressure in inches of mercury, Q_c is the energy transferred by conduction, and C_o is a constant with a value of 0.61. By making substitutions from the evaporation formula, Equation 17 becomes

$$Q_c = 0.00543\ U\ P\ (T_u - T_w) \qquad (18)$$

Normal approximate barometric pressure can be computed by the relationship,

$$P = \frac{29.92}{\exp\left(\frac{32.15\ E}{1545\ (T_a + 460)}\right)} \qquad (19)$$

in which E is the elevation of the site in feet above mean sea level.

As previously stated, the total energy received on a square foot of water surface is computed from Equation 1. This energy transfer is converted to a temperature change by the equation

$$\Delta T = \frac{Q_t\ \theta}{62.4\ d} \qquad (20)$$

in which ΔT is the temperature change in $^{\circ}F$, Q_t is the average rate of energy transfer in Btu/ft^2-hr, θ is the time interval in hours, and d is the average depth for the time interval.

The steps in the computer program to predict temperature changes of the water body are the following:

1. The initial temperature is given.
2. The average rate of energy transfer by each mechanism is computed using Equations 2 through 19.
3. The total rate of energy is obtained from Equation 1.
4. Equation 20 is used to compute a temperature change.
5. The computed temperature change is added to the previous temperature to give a new water temperature.
6. Steps 2 - 5 are repeated for the total time of the survey.

Although 30-minute time intervals were used for this study, savings in computer time could probably be realized by employing hourly readings.

EXPERIMENTAL WORK

Five field surveys were conducted to test the computer model. Weather data and information pertaining to the geometry of the stream were collected.

All of the surveys were conducted downstream from dams having rather deep impoundments behind them. The discharges had temperature of approximately 50°F. In each case a slug of water was marked with Rhodamine WT dye and followed downstream for up to 36 hours. (See Table 1 for a concise summary of each survey.)

Two boats were used, a weather boat and a dye boat. The dye boat established the peak of the dye cloud as often as possible, usually about every hour. Dye concentrations were measured with a fluorometer. The fluorometer was equipped with a pump which circulated river water through the fluorometric cell continually. Two methods were utilized to find the dye peak. The first method was to position the dye boat downstream of the dye cloud and take readings as the cloud passed. When the crewmen felt the peak had been reached, they released a buoy as a marker for the weather boat. The second method of detecting the peak was to take the boat downstream of the cloud and drive it back upstream through the cloud. A buoy was released when the fluorometer readings peaked. This method seemed to give slightly better results.

Additional dye was placed in the river whenever the peaks of the dye curve began to flatten because of dispersion. Plug flow was assumed in the prediction model. Considerable dispersion took place in at least two of the surveys, but this was determined to have no significant effect on the results because of the slight longitudinal temperature gradients in the streams.

River depths were measured by the dye boat with a recording fathometer. A plot of the depth of the river bottom from the water surface was created by driving the boat from one bank of the river to the other. Since only the average depth of the river was necessary, the area within the plot was determined by planimetering and this quantity was divided by the length of the plot to obtain the average depth. Fathometer recordings were made every 30 to 60 minutes.

TABLE 1 - SUMMARY OF RIVER SURVEYS

Survey Date	July 29-1970	August 30-31, 1970	June 12-13-1971	June 26-1971	July 17-18, 1971
River	Cumberland	Cumberland	Holston	Caney Fork	Cumberland
Location	Below Wolf Creek Dam, near Burksville, Kentucky	Below Wolf Creek Dam, near Burksville, Kentucky	Below Cherokee Dam near Jefferson City, Tenn.	Below Center Hill Dam near Carthage, Tenn.	Below Wolf Creek Dam near Burksville, Kentucky
Length of River Surveyed (Miles)	72.5	48.3	50.0	24.0	35.8
Approx. Flow cfs	12,000-20,000	6,000	4,000-12,000	3,000	4,000
Duration of Survey (Hrs)	32.5	35.5	28.5	16.0	33.0
Initial Temperature (°F)	49.5	52.3	51.8	52.1	51.1
Final Temperature °F	54.7	59.7	60.5	59.4	59.3

Two major sources of error were possible with the measurements taken from the dye boat. Dye tracer curves were often quite elongated and the peaks were somewhat flat, making the decision of picking the center of the dye cloud a difficult one. Although errors in individual water temperature measurements were possible because the weather boat was not located on the peak of the dye tracer cloud, the errors are not cumulative. Through the course of a survey both small positive and negative errors probably occurred, making the measured temperature curve somewhat more uneven than it really was.

Depth measurements for a particular stretch of river were probably not representative at times. Wide variations in river depths were encountered within relatively short distances. However, since both the depths and measurements can be assumed to be normally distributed, the average of many measurements should differ only slightly from the actual average depth. Calculated temperature changes are inversely proportional to the depth, so erroneous depth measurements would lead to serious errors in temperature prediction.

Meteorological readings and water temperature were taken every 30 minutes by the crewmen in the weather boat. This boat stayed as close to the dye peak as possible. Since the surface velocities in rivers are slightly higher than average velocities, the dye boat occasionally had to anchor and wait for the peak of the dye cloud to watch up. The weather variables that were recorded were air temperature, relative humidity, cloud cover, and wind speed. The elevation of the horizon from the horizontal, which was used to compute the fraction of the sky blocked from view of the river, the percentage of the water surface shaded from direct sunlight, and the actual water temperature were also recorded. Descriptions of the meterological instruments used are in the appendix.

Air temperature, both wet bulb and dry bulb, were measured using a Bendix aspirated psychrometer. The readings were taken about 18 inches above the water surface. Relative humidity was calculated from wet bulb and dry bulb temperatures by using a psychrometric chart.

Cloud cover was estimated by eye and reported as tenths of the sky covered. Table 2 indicates that estimates

TABLE 2 - CLOUD COVER ESTIMATES FROM NASHVILLE AND BOAT

Survey	Day	Average Cloud Cover, Tenths	
		Boat	Nashville
Cumberland #2	July 29, 1970	1.36	2.46
	July 30, 1970	2.42	2.74
Cumberland #3	Aug. 30, 1970	2.90	6.66
	Aug. 31, 1970	5.80	5.35
Caney Fork	June 26, 1971	0.30	0.70

made from the boat were considerably lower than those reported by a U.S. Weather Bureau weather station approximately 100 miles from the survey sites. Part of this error can probably be attributed to lack of skilled weather observers. A larger part of the error is probably due to the geometry of the situation. During the survey considerable fractions of the sky were blocked from view of the water surface by the surrounding hills.

Because of the vertical thickness of scattered clouds, equally spaced clouds near the horizon will appear denser than those directly overhead, because the observer cannot see the sky through the holes between the clouds. These denser looking clouds, which were visible to Weather Bureau observers at the relatively flat terrain at the weather stations, were blocked from the view of the observers in the boats and on the river bank. Thus, cloud cover reported by project observers was usually lower than that reported at nearby U.S. Weather Bureau stations.

Dense woods covered large portions of the banks of the rivers studied. Since portions of the river were usually shaded, some of the direct solar radiation was prevented from reaching the water's surface. This fraction of the water's surface shaded was estimated by eye and ranged from 0 to 10 percent.

Weather stations were set up in the vicinity of the river during each survey. Wind speed and direction, air temperature, and relative humidity were measured and recorded with automatic instruments. Cloud cover was estimated by an observer at the site. Since much of this data was of rather low quality, and some was missing, primarily due to equipment failures, it was not carefully analyzed. However, the estimated values of cloud cover tended to be higher at the bankside stations than estimates made from the boat on the river. This could have been caused by the bankside observer's ability to see more of the sky, particularly the portion near the horizon, where scattered clouds look denser than they actually are, than the observers in the boats, whose view was partially blocked by trees on the riverbank and the adjacent hills and bluffs.

CHARACTERISTICS OF STREAMS BELOW HYDROELECTRIC INSTALLATIONS

The project was undertaken with the view that the heat transfer mechanisms for the warming up of cold water should be the same as the cooling of heated water, with the heat flowing in opposite directions. This appears to be the case. However, problems with discharges from deep reservoirs in Tennessee and Kentucky were encountered which were not entirely anticipated.

The three streams studied have cut rather narrow and steep-sided valleys. The valleys of the Cumberland and Caney Fork rivers have maximum depths of approximately 400 feet, while the valley of the Holston River is no more than 200 feet deep. All three streams exhibit well-developed meander patterns, with nearly vertical cliffs on the outside of the meanders and moderate areas of flood plain within.

The cold discharges, approximately 50^{o}F in the summer months, radically change the microclimate of the river valleys below deep reservoirs. A tremendous cooling effect is exerted on the adjacent air by the cold water. When the air is cooled to the dew point, fog banks begin to form. As soon as the sun's energy is blocked out by hills and vegetation, patches of fog begin to form over the water surface. These patches rapidly change to thick fog banks during the early evening hours. By morning the entire valleys are covered with thick blankets of fog. When the air is warmed to above the dew point by solar energy in the morning, these fog banks are dissipated.

Cooling of the lower layers of air within the river valleys create temperature inversions with very stable atmospheric conditions being the result. Temperature measurements made on the Caney Fork River about 2 miles below Center Hill Dam are presented in Figure 1 and 2. These measurements were made in May, 1972. Figure 1 indicates that relatively large differences in air temperature exist within small vertical distances adjacent to the river. Lapse rates on a rather typical spring night are shown in Figure 2. Lapse rates are highest in the late afternoon and early evening, as is illustrated by both figures.

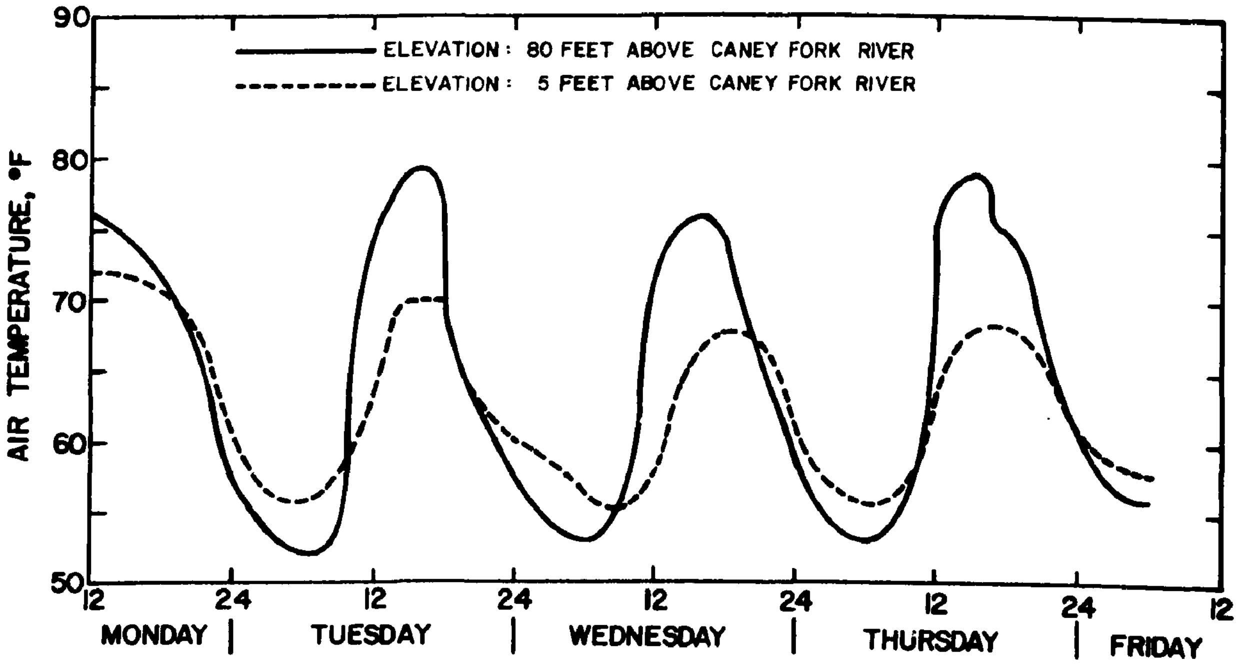

FIGURE 1 - VARIATION OF AIR TEMPERATURE OVER CANEY FORK RIVER AT TWO ELEVATIONS

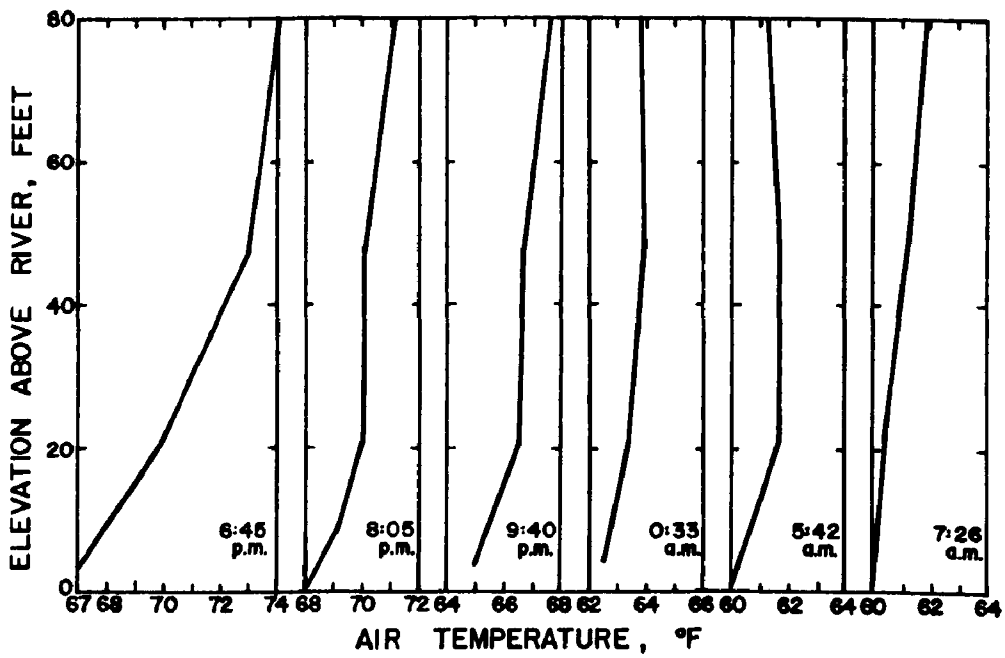

FIGURE 2 - VARIATION OF LAPSE RATE OVER CANEY FORK RIVER WITH TIME

Since relative humidity at constant vapor pressure is a function of air temperature, the relative humidity would be expected to be greater at lower elevations in the valley. That this is the case is illustrated by Figure 3. Note that, although the relative humidity is higher at lower elevations, the total amount of moisture in the air at various heights can remain the same.

Wind speeds measured in the river valleys were much lower than those at surrounding weather stations. There appear to be two primary reasons for this phenomenon. Weather stations are usually located at airports, which are usually flat and treeless. In constrast, the rivers studied were in relatively deep and tortuous valleys. The atmospheric stratifaction in the valleys, particularly at night, also helped to reduce air movement. Wind speeds at Nashville and on the Cumberland River are contrasted in Figure 4.

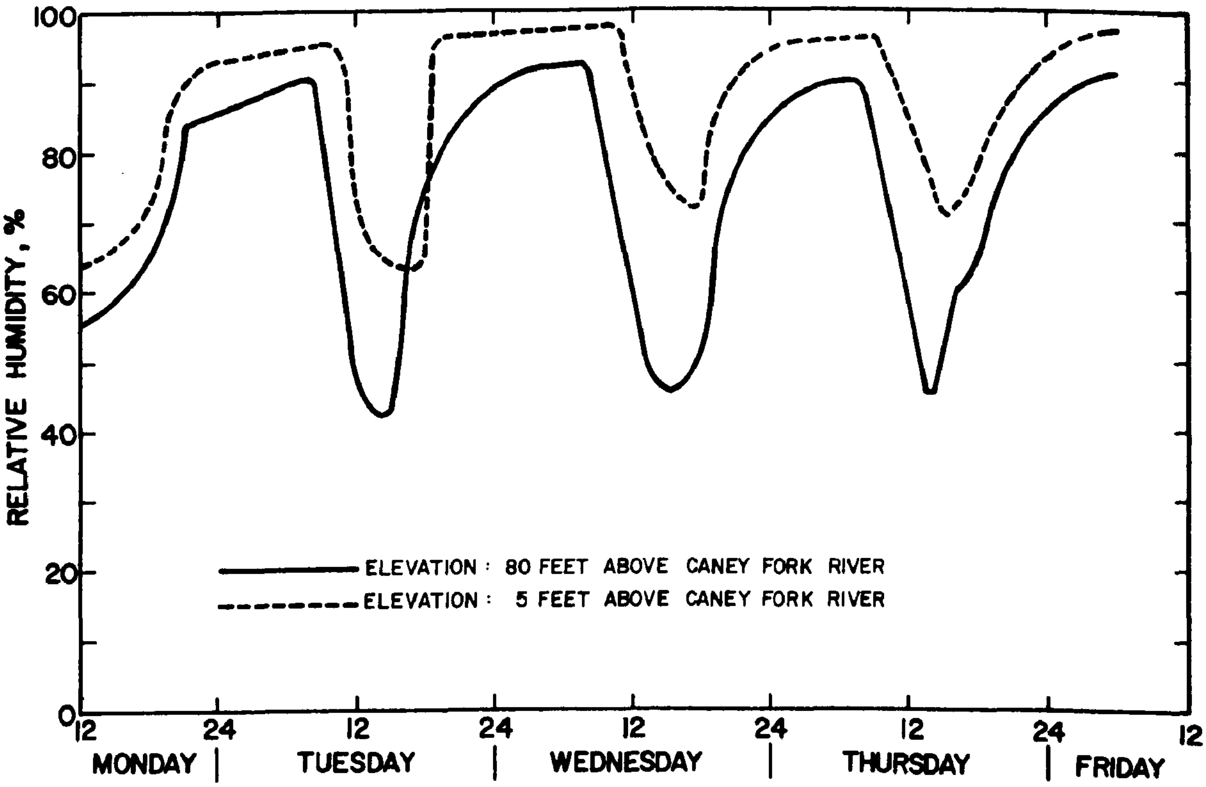

FIGURE 3 - VARIATION OF HUMIDITY AT TWO ELEVATIONS OVER CANEY FORK RIVER

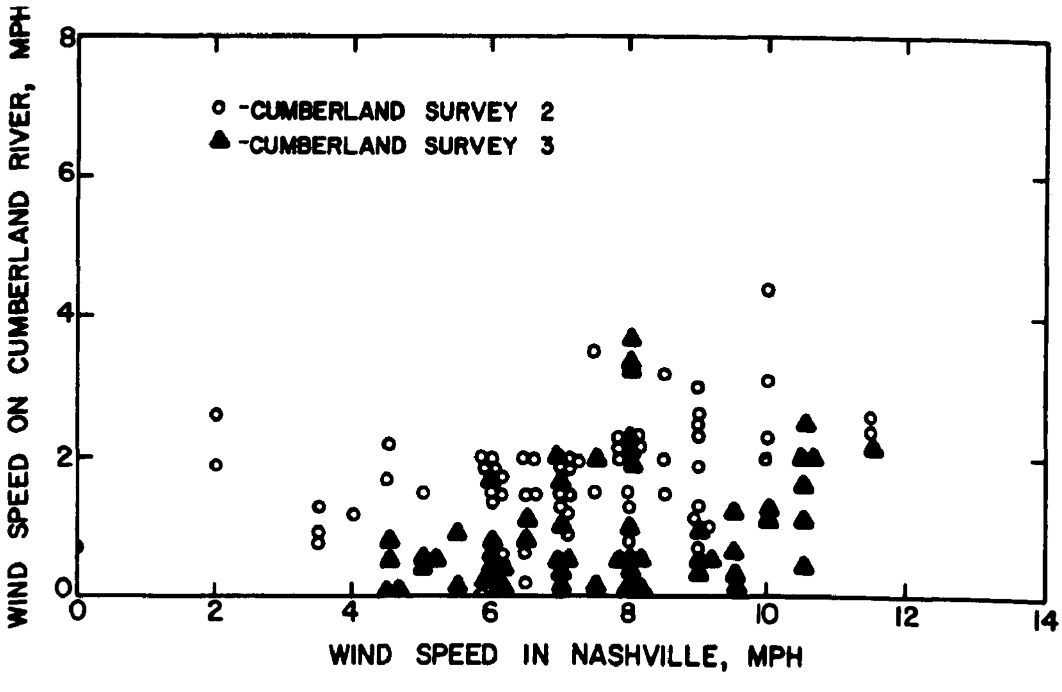

FIGURE 4 - WIND SPEED ON CUMBERLAND RIVER VS. WIND SPEED AT NASHVILLE

RESULTS OF THE STUDY

The computed rates of energy transfer are presented in graphical form in Figures 5 through 15. From the figures, several statements can be made.

1. Atmospheric radiation and back radiation almost balance each other, at the water temperatures found.

2. Evaporative and conduction energy transfers are of minor importance with the low wind speeds encountered, according to the equation used, Equation 15. The median wind speed encountered near the water was about one mile per hour.

3. Because of the facts noted above, solar radiation accounted for almost all of the energy transfer.

Should the river be above rather than below equilibrium temperature, the following would be true.

1. Back radiation would be considerably greater because of higher water temperatures.

2. Evaporative and conductive heat transfers would, of course, be negative rather than positive.

3. The total energy transfer would be negative.

The only component of the energy budget which could easily be recorded on the field surveys was solar radiation. It was measured with an Eppley pyroheliometer located at the bankside weather station. Results from only three of the five surveys are presented in Table 3 because the instrument was out of service when the studies were made on the Caney Fork and Holston rivers.

Agreement between the measured and calculated solar radiation was reasonably good. An analysis of variance test at the 95 percent confidence level showed that there was no significant difference in the three different methods of obtaining solar radiation data listed in Table 3. The computed values of solar radiation from the boat data of July 29, July 30, and August 30 of 1970 were

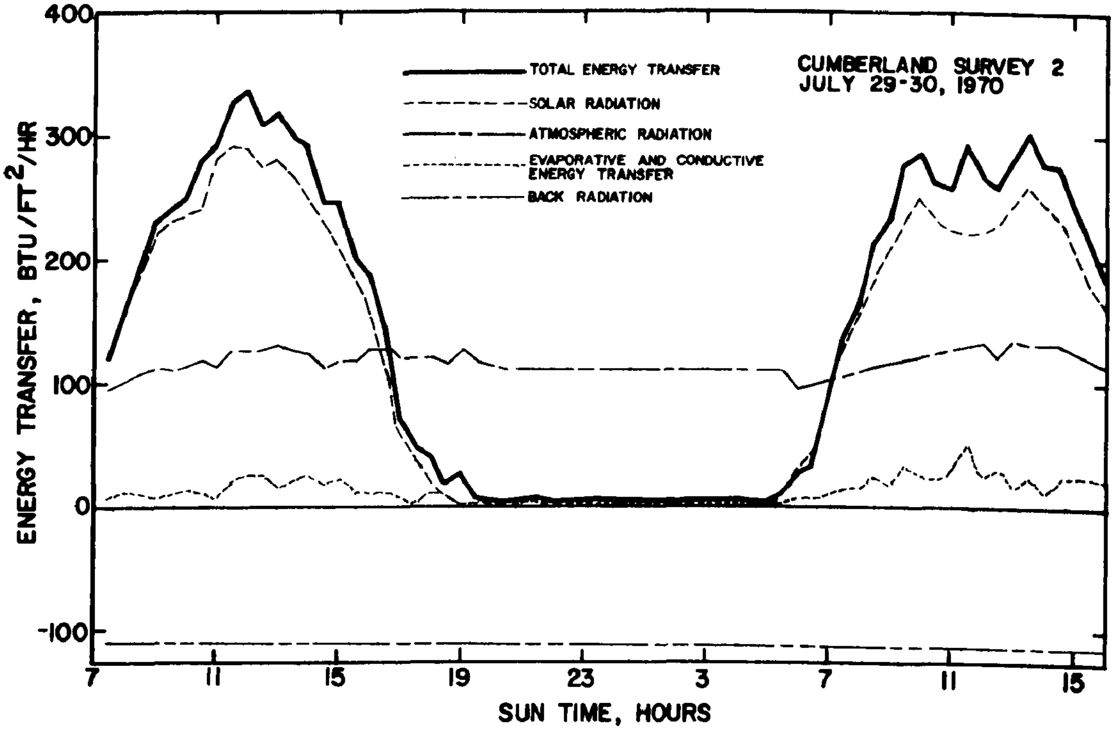

FIGURE 5 - ENERGY BUDGET COMPONENTS DURING CUMBERLAND RIVER SURVEY 2

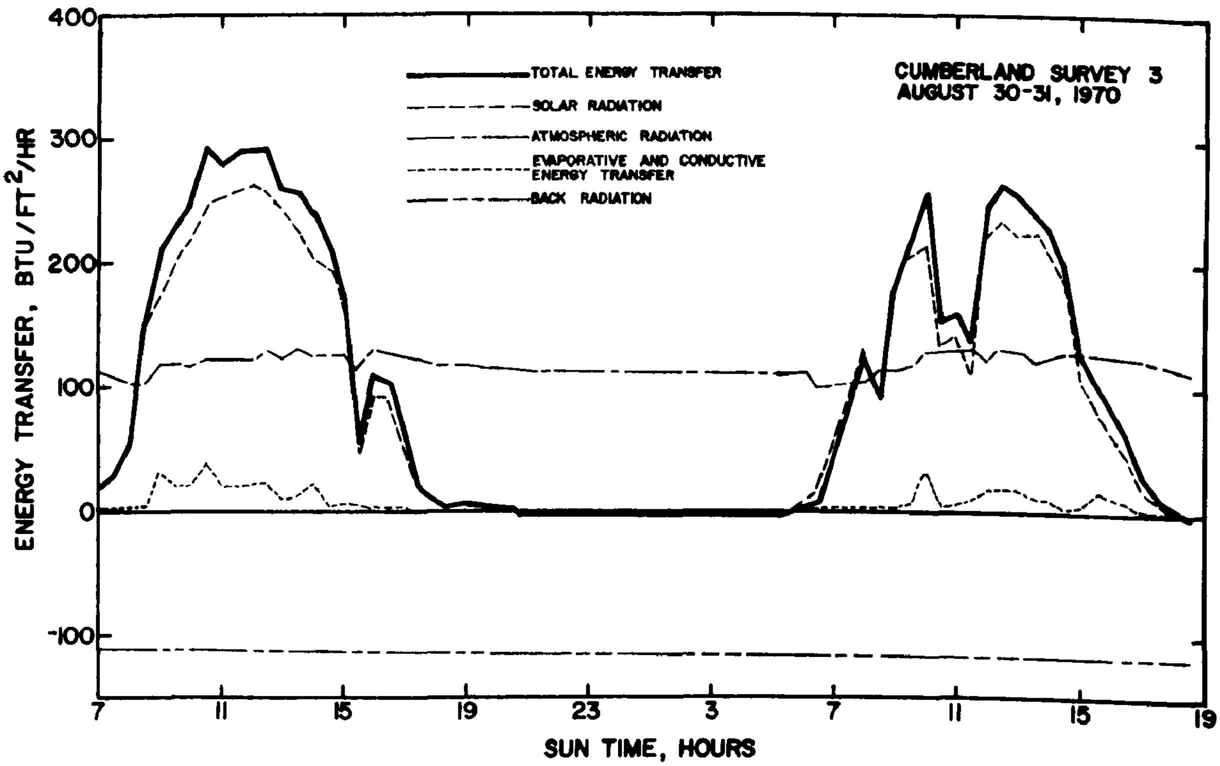

FIGURE 6 - ENERGY BUDGET COMPONENTS DURING CUMBERLAND RIVER SURVEY 3

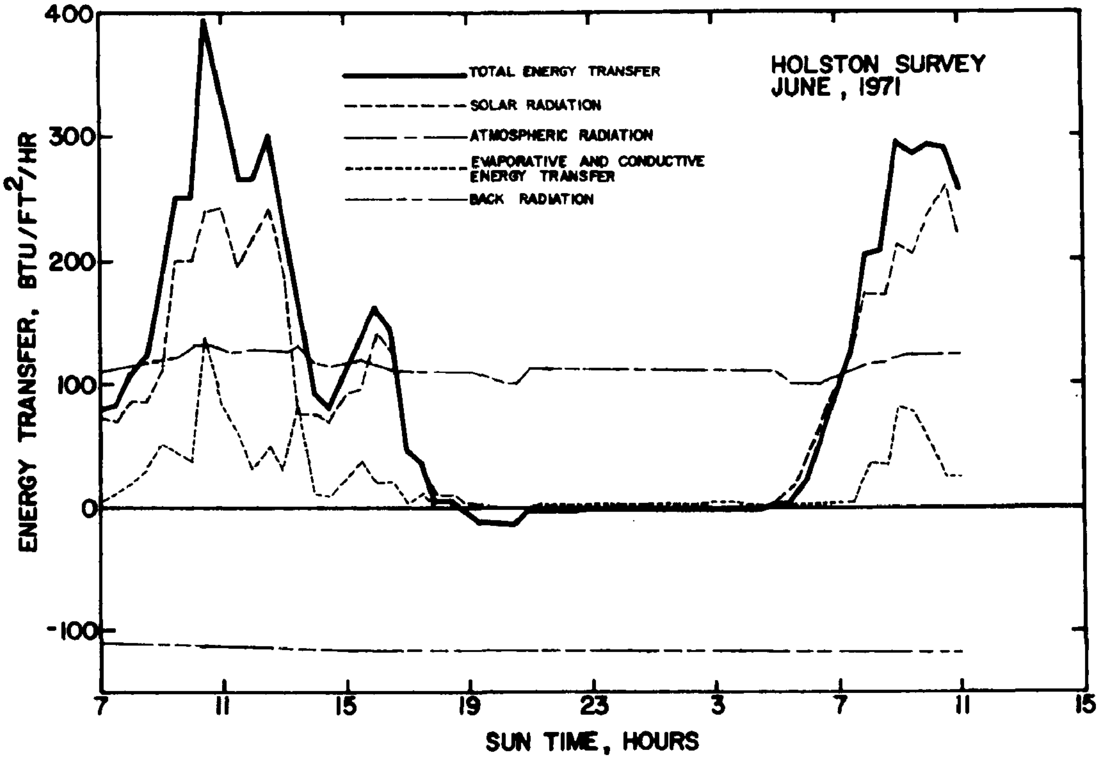

FIGURE 7 - ENERGY BUDGET COMPONENTS DURING HOLSTON RIVER SURVEY

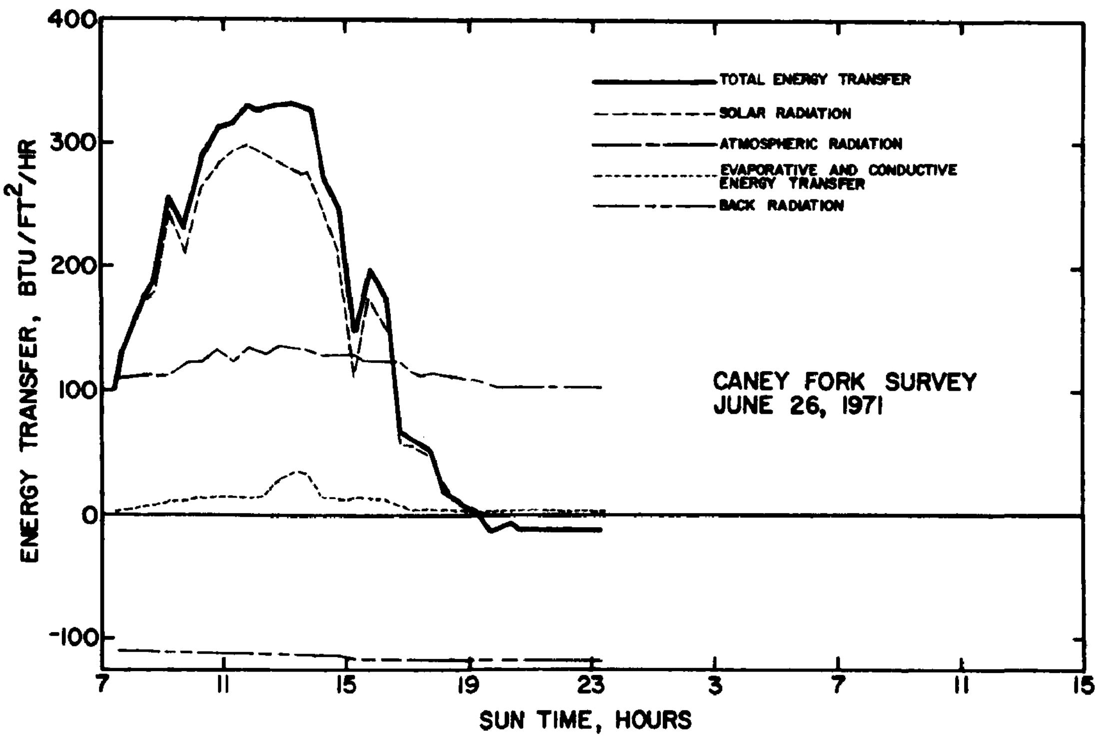

FIGURE 8 - ENERGY BUDGET COMPONENTS DURING CANEY FORK RIVER SURVEY

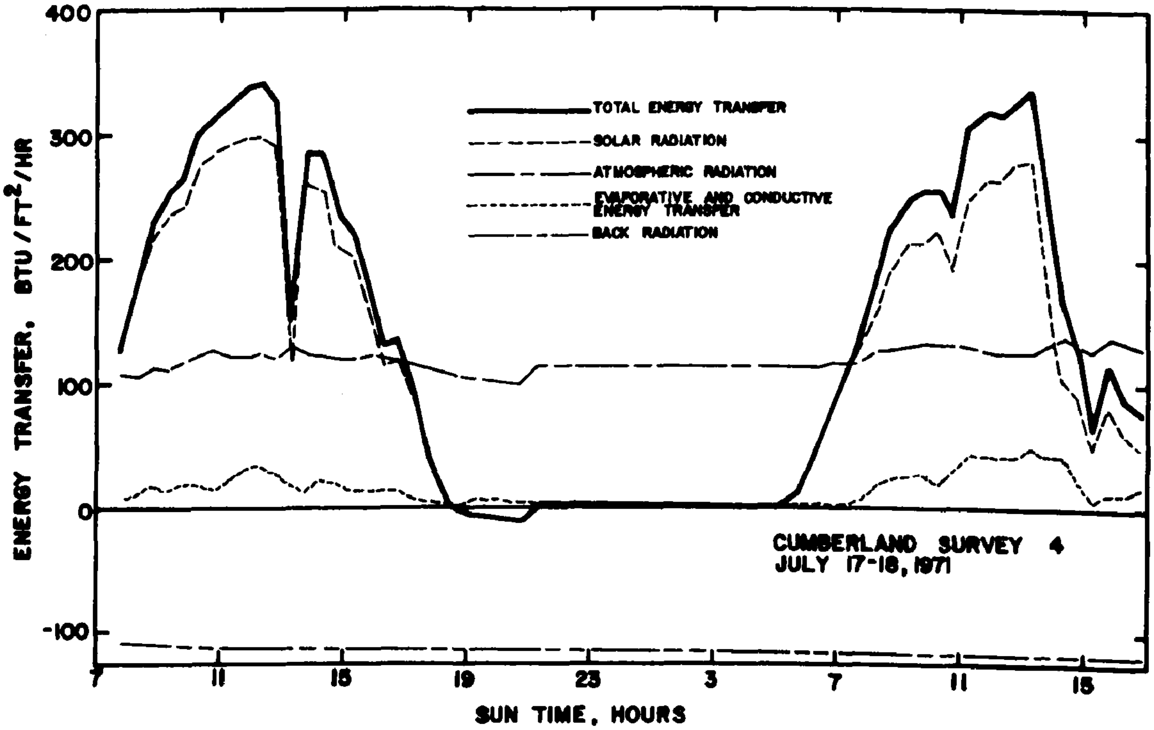

FIGURE 9 - ENERGY BUDGET COMPONENTS DURING CUMBERLAND RIVER SURVEY 4

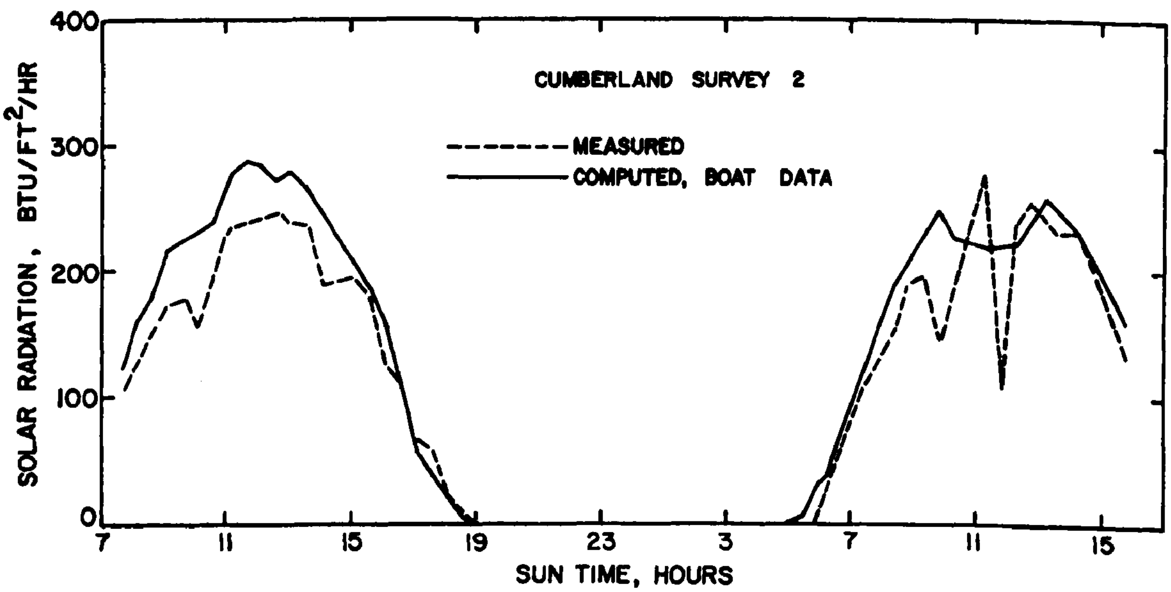

FIGURE 10 - MEASURED AND COMPUTED (FROM BOAT DATA) SOLAR RADIATION - CUMBERLAND RIVER SURVEY 2

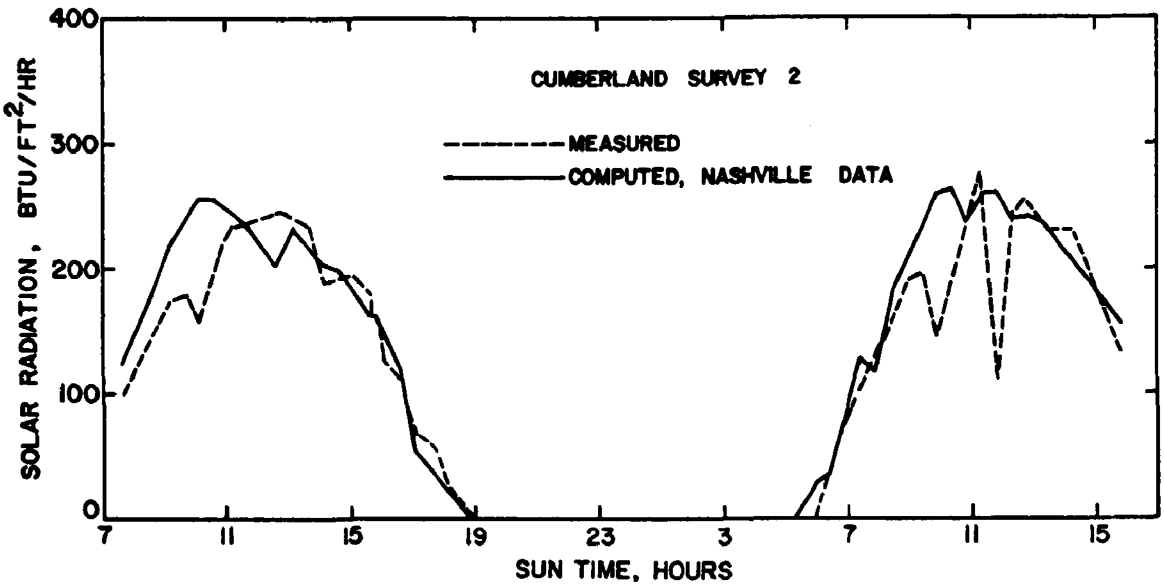

FIGURE 11 - MEASURED AND COMPUTED (FROM NASHVILLE DATA)
SOLAR RADIATION - CUMBERLAND RIVER SURVEY 2

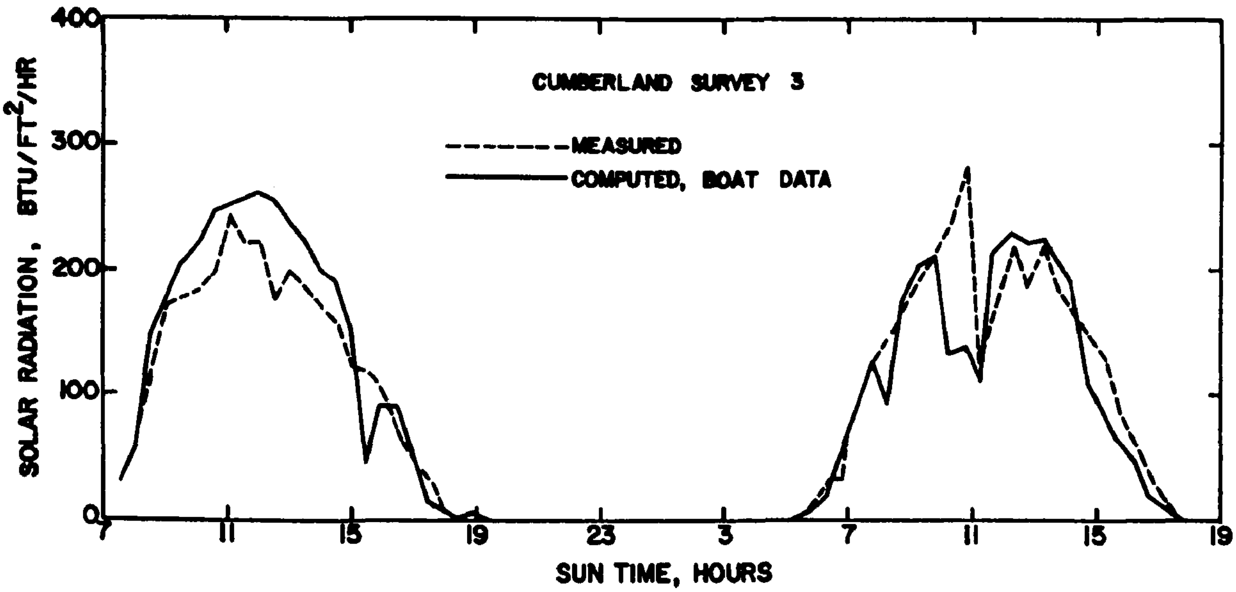

FIGURE 12 - MEASURED AND COMPUTED (FROM BOAT DATA)
SOLAR RADIATION - CUMBERLAND RIVER
SURVEY 3

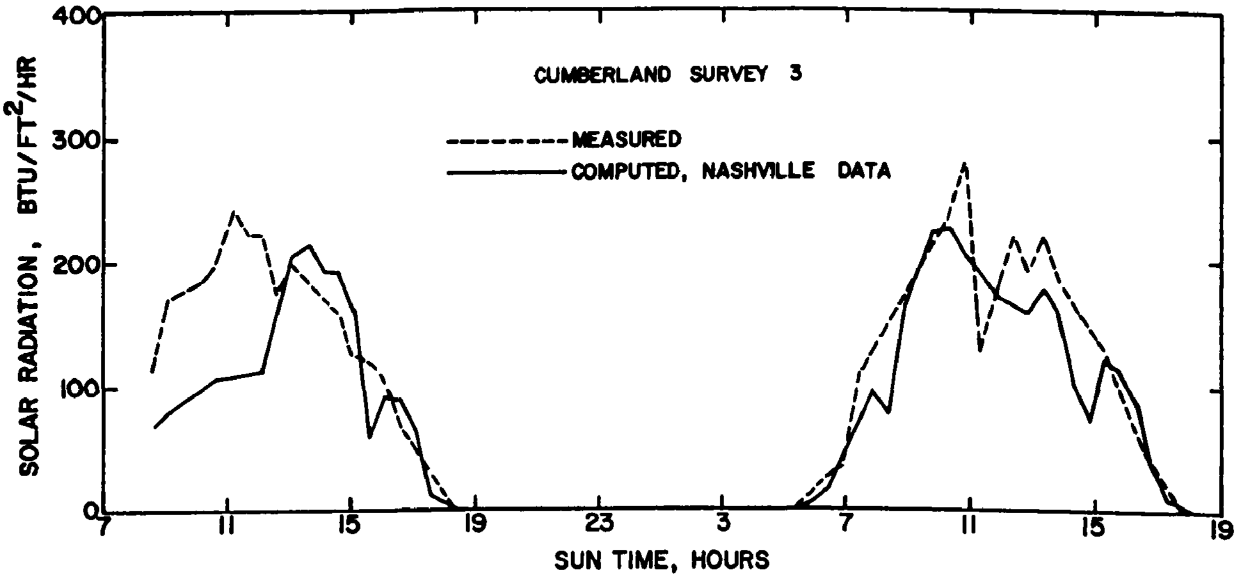

FIGURE 13 - MEASURED AND COMPUTED (FROM NASHVILLE DATA) SOLAR RADIATION - CUMBERLAND RIVER SURVEY 3

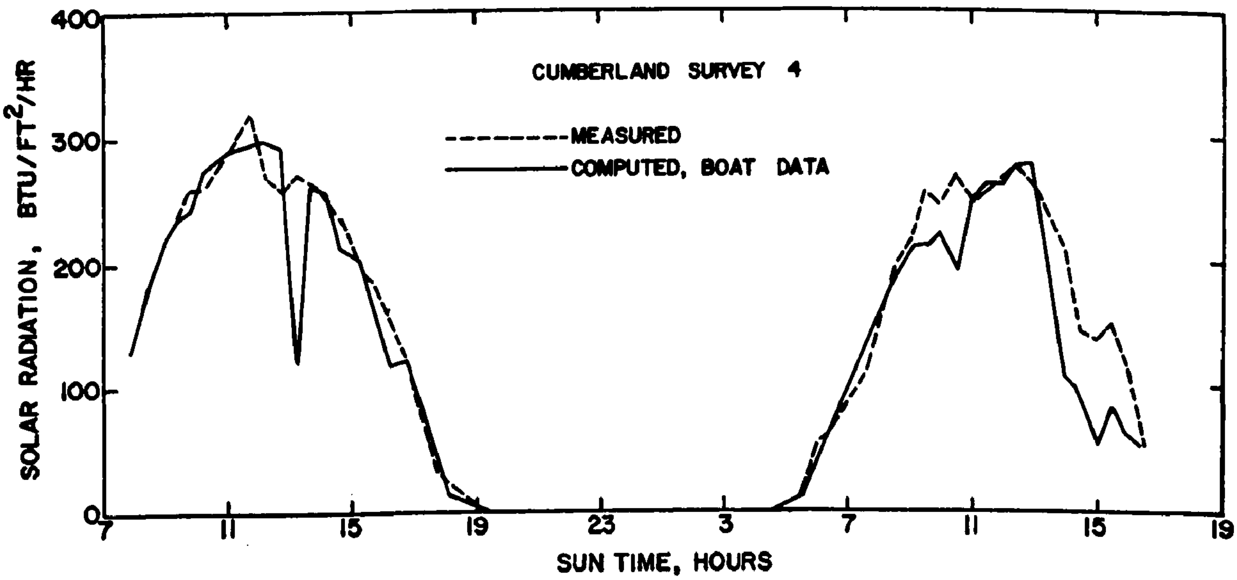

FIGURE 14 - MEASURED AND COMPUTED (FROM BOAT DATA) SOLAR RADIATION - CUMBERLAND RIVER SURVEY 4

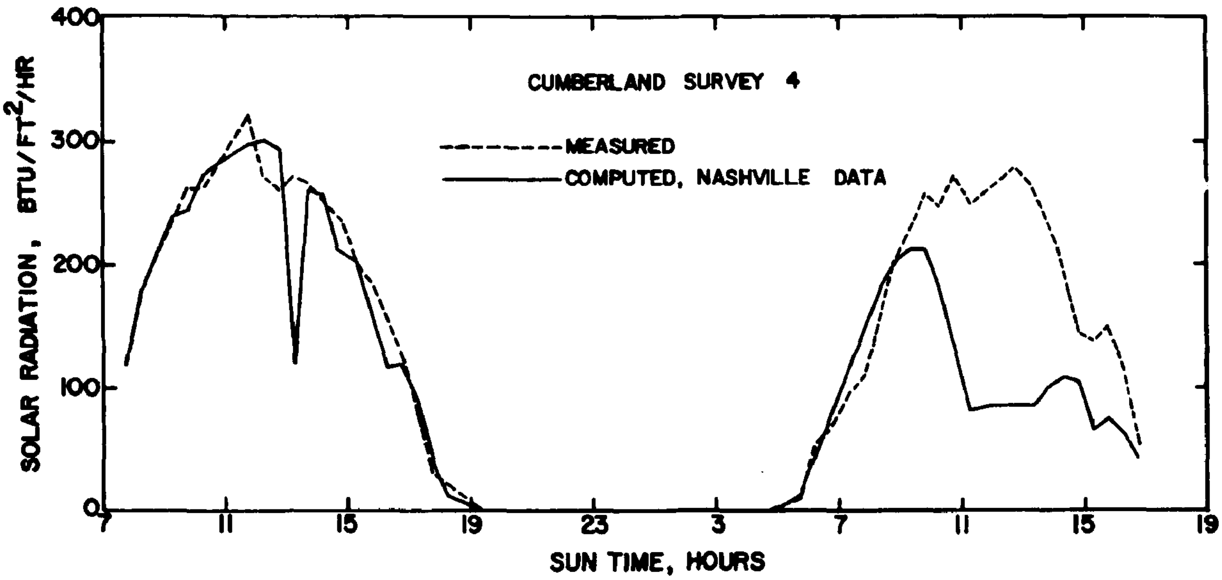

FIGURE 15 - MEASURED AND COMPUTED (FROM NASHVILLE DATA) SOLAR RADIATION - CUMBERLAND RIVER SURVEY 4

TABLE 3.- MEASURED AND COMPUTED SOLAR RADIATION

Survey	Day	Btu/ft^2 - day		
		Measured Near Survey Site	Computed From Boat Data	Computed From Nashville Data
Cumberland #2	July 29 1970	1843	2189*	2003
	July 30 1970	1768	1987*	2005
Cumberland #3	Aug. 30 1970	1463	1676*	1110**
	Aug. 31 1970	1661	1508	1477
Cumberland #4	July 17 1971	2253	2152	2159
	July 18 1971	1991	1756	1229

* Probably high because of low estimates of cloud cover.

** Heavy cloud cover over Nashville.

probably too high because the estimates of cloud cover were too low. Solar radiation computed from the Nashville data was close to the measured values when values of cloud cover were approximately the same at Nashville and the survey site. The large difference of August 30, 1970, was due to a heavy cloud over Nashville which was not present at Burksville, Kentucky. (See Table 2.) It should be noted that errors in river temperature predictions using boat data for Cumberland River surveys 2 and 3 correspond to errors in computed solar radiation. For reasons yet unknown, the temperature predictions for Cumberland River survey 4 were too high even though computed values of solar radiation were low.

Difficulties with the energy budget due to the unusual microclimatology were encountered, especially the confusing effects of the dense fog at night. Back radiation from the surface of the water is a function of water temperature alone, but there is a possibility that some of the back radiation might have been reflected back to the water surface by the fog.

Effects of the fog upon the incoming atmospheric radiation were also unknown. Atmospheric radiation is a function of cloud cover, air temperature, and relative humidity. The fog was, in effect, a low-lying cloud, covering the entire water surface for the entire night, and partially during the day. However, the thickness of the fog blanket was only about 20 to 40 feet. Therefore, there was a question as to whether or not the fog should be treated as complete cloud cover. The fog certainly covered the water, and undoubtedly contributed longwave radiation to the water surface, but whether or not the radiation was more or less than would have been received from a complete cover of normal clouds was not known.

Another problem was associated with the air temperature reading used in the longwave radiation calculation. Actually. the entire vertical air column radiates to the water surface. The air temperature measured 18 inches above the water surface is not necessarily representative of the entire air column, especially in light of the data shown in Figure 1. However, if it is assumed that, because of the presence of the dense fog and the generally clear skies above the fog, the major contribution of longwave radiation is from the fog, then the air temperature measured in the boat would be the correct one.

The above questions have not yet been satisfactorily answered during this study. Another project, using better instrumentation, could perhaps provide answers. However, a least squares method of curve fitting was used in an attempt to resolve the problem with the fog for the purpose of this project. Since 4 of the 5 surveys gave temperature prediction curves which closely matched the curves of observed temperature, data from these 4 surveys was used in an attempt to obtain the best fit. The data from the Cumberland River surveys 2 and 3 were used in its entirety.

During the Holston River survey, approximately 0.8 inches of rain fell in the area of the survey during a heavy afternoon thunderstorm. Because the amount of local inflow to the Holston River could not be determined, and the temperature of this inflow was unknown, the predictive model was unable to accurately determine temperature changes after the storm runoff entered the river. Thus, the portion of the Holston survey that was used in fitting the curve was that part unaffected by the storm runoff. An arbitrary cutoff was established at 19.0 hours on June 12.

Data from the Caney Fork survey was used up to 20.75 hours. The fluorometer ceased to function at about this time and the peak of the dye curve was lost.

The formula

$$T = \frac{(O_i - P_i)^2}{n-k}$$

was used for determining best fit, with O_i being the observed temperature at a particular time, P_i the predicted temperature at that time, n the total number of observations, and k the number of independent variables being manipulated to obtain a fit. The values of T for the four surveys were added to give a quantity which was an indicator of goodness of fit.

The above procedure was used in an attempt to determine the effect of various methods of handling the fog problem in the predictive model. The first method was to set the β term in the equation for longwave radiation equal to .95. The value of β is rarely this high under normal conditions in Raphaels (1) equations, but Anderson's (5) original data showed low-lying dense clouds to give a value of β equal to 0.95. Therefore, it was felt that the dense fog might radiate more energy to the surface of the water than would be normally received from complete cloud cover. The second method was to make no corrections for the fog, and simply to use the value of cloud cover observed in the upper atmosphere.

Thirdly, the value of cloud cover was set to 10 whenever fog was present. As Table 4 shows, the results were inconclusive. The summations of the values of T were not significantly different for the three methods.

Figures 16 through 20 illustrate the curves of observed and predicted temperature using the boat data with β set equal to .95 when fog was present. As has previously been stated, the errors in the predictions for the Holston River survey are largely due to local inflow, and the dye cloud was lost on the Caney Fork due to the failure of the fluorometer. The errors in the predictions for the Cumberland River survey of 1971 have not been satisfactorily explained. Errors in depth measurements would have resulted in a proportional error in temperature change, but that all of the error was due to incorrect depth measurements seems unlikely.

Weather data from the airport at Nashville, Tennessee, was also used to predict the temperature changes in the rivers. Nashville is approximately 100 miles west of the Cumberland and Caney Fork Rivers, and 200 miles west of the Holston River.

It is obvious that the temperature prediction model developed in this project would be worthless if the weather data to be used as input had to be gathered by a boat on the river itself. If this had to be done, it would be just as easy to measure the water temperature itself. The model could not then be used for predictive purposes.

One of the objectives of this research was to see how easily data from "nearby" weather stations could be used to predict the temperature changes in a stream. Comparison of the boat data with that from Nashville showed that there were consistent differences of the type discussed earlier in the section on "Characteristics of Streams Below Hydroelectric Installations." If data from Nashville or some similar station is to be used to predict changes in the water temperature of streams similar to the ones studied in this project, the air temperature and wind speed will have to be modified (reduced) to correspond to conditions at the water surface. Also, the relative humidity may need to be raised.

Comparison of the boat data with Nashville data showed that the Nashville air temperature was usually 2° to 3° higher than the air temperature measured on the boat during the

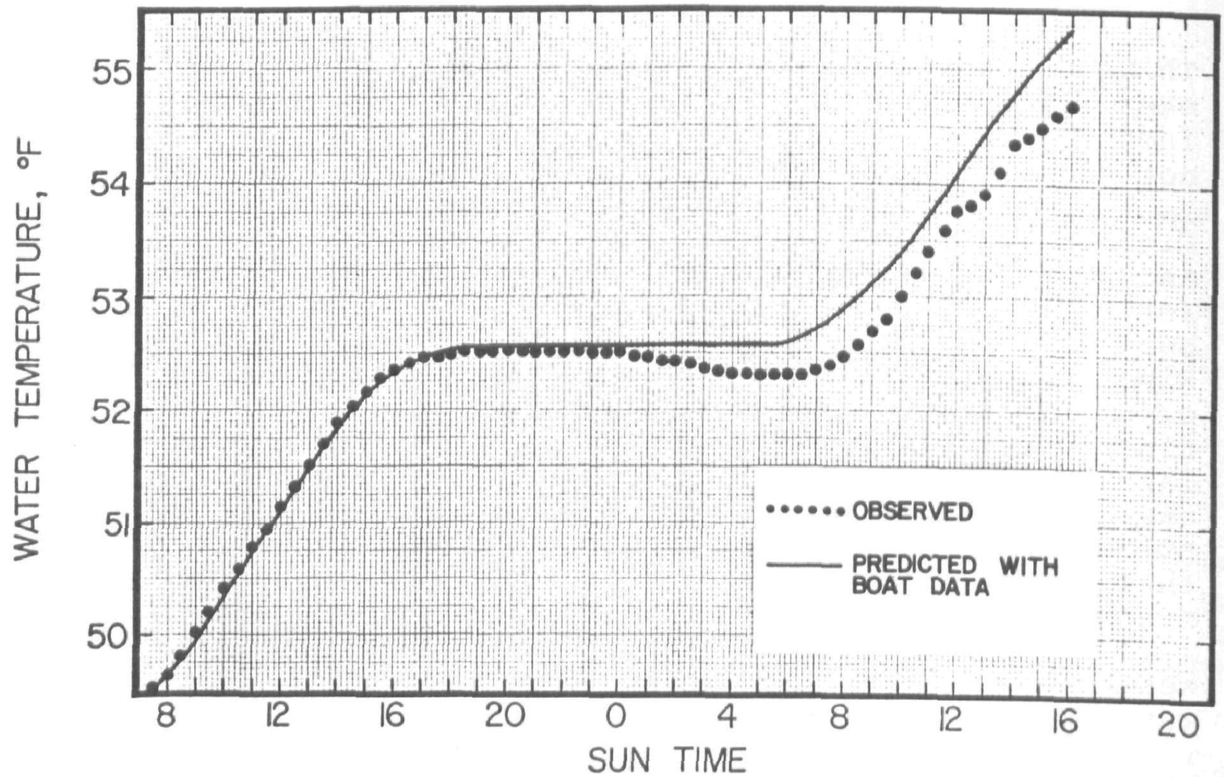

FIGURE 16 - OBSERVED AND PREDICTED (FROM BOAT DATA) TEMPERATURES, CUMBERLAND RIVER SURVEY 2

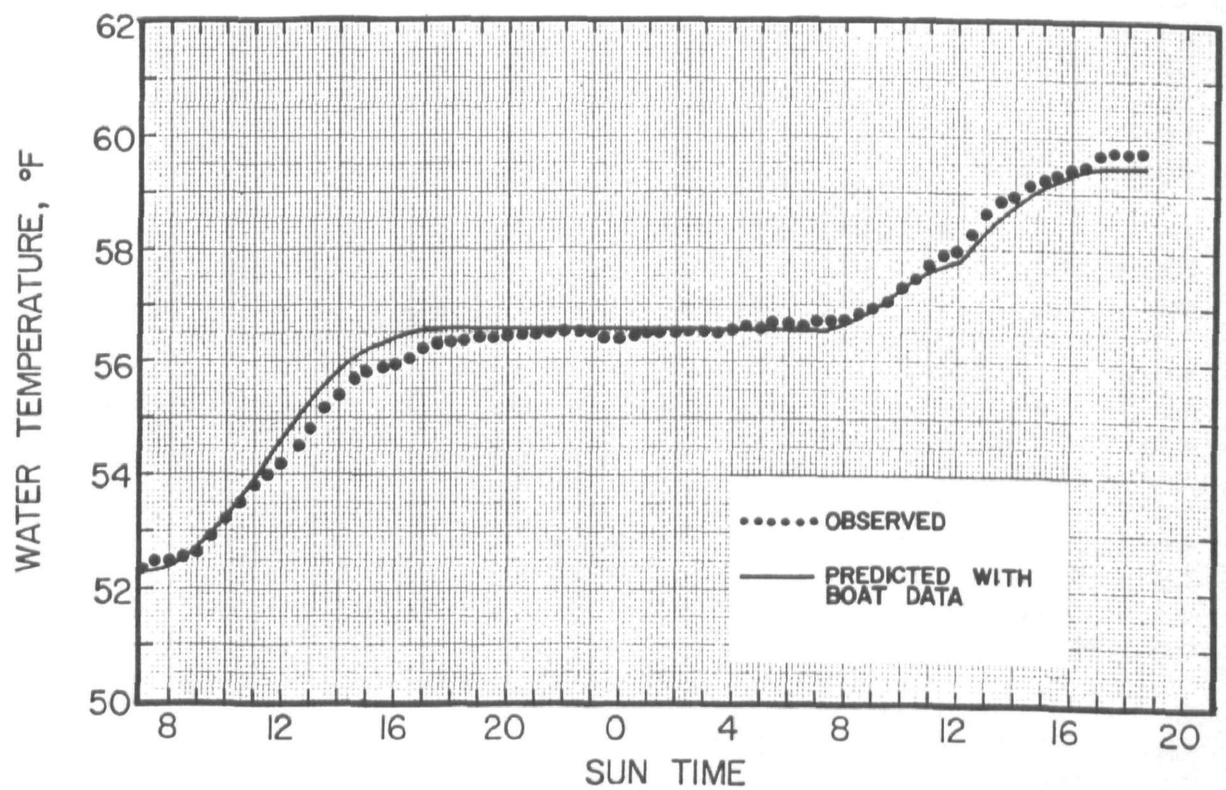

FIGURE 17 - OBSERVED AND PREDICTED (FROM BOAT DATA) TEMPERATURES, CUMBERLAND RIVER SURVEY 3

TABLE 4-LEAST SQUARES FIT OF BOAT DATA WITH VARIOUS CORRECTIONS FOR FOG

Survey	$\frac{\Sigma(O_i - P_i)^2}{n - k}$		
	β = .95 When Fog Present	No Corrections For Fog	Cloud Cover =10 When Fog Present
Cumberland #2	0.09232	0.03352	0.04719
Cumberland #3	0.07046	0.11828	0.07785
Holston	0.20695	0.20965	0.25019
Caney Fork	0.36281	0.36281	0.36252
	Σ = .73254	Σ = .72246	Σ = .73775

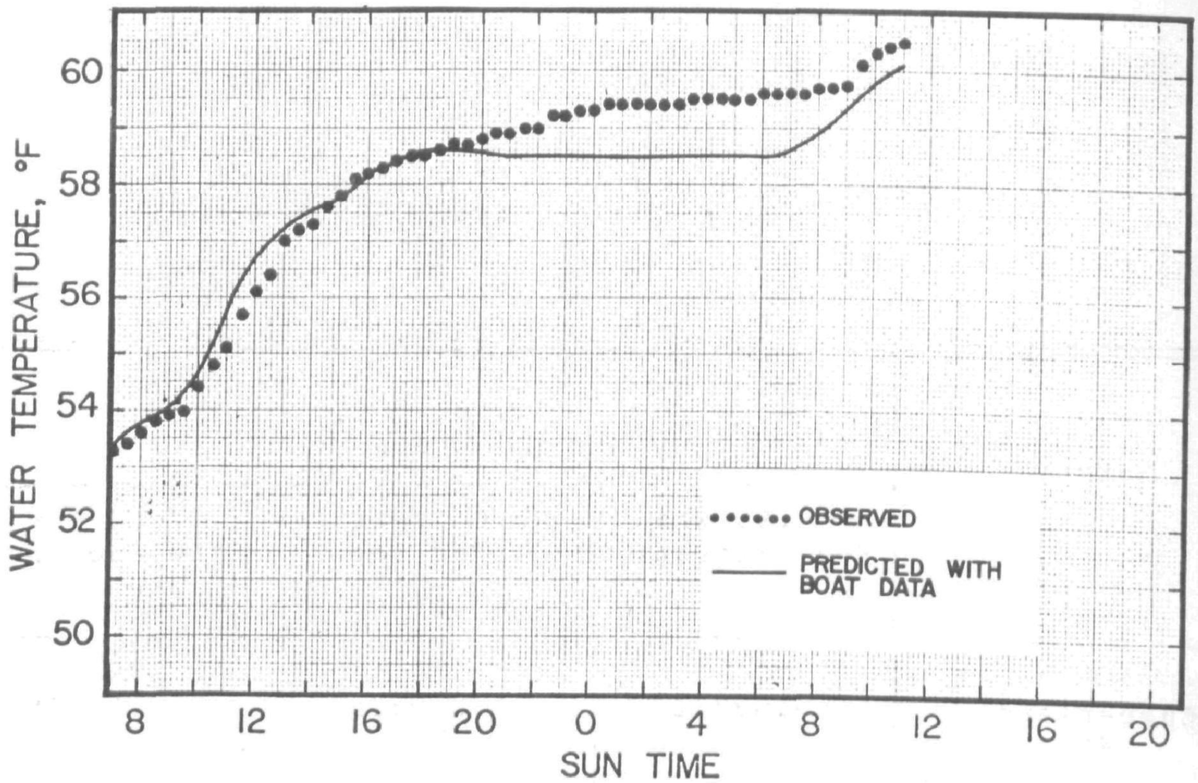

FIGURE 18 - OBSERVED AND PREDICTED (FROM BOAT DATA) TEMPERATURES, HOLSTON RIVER SURVEY

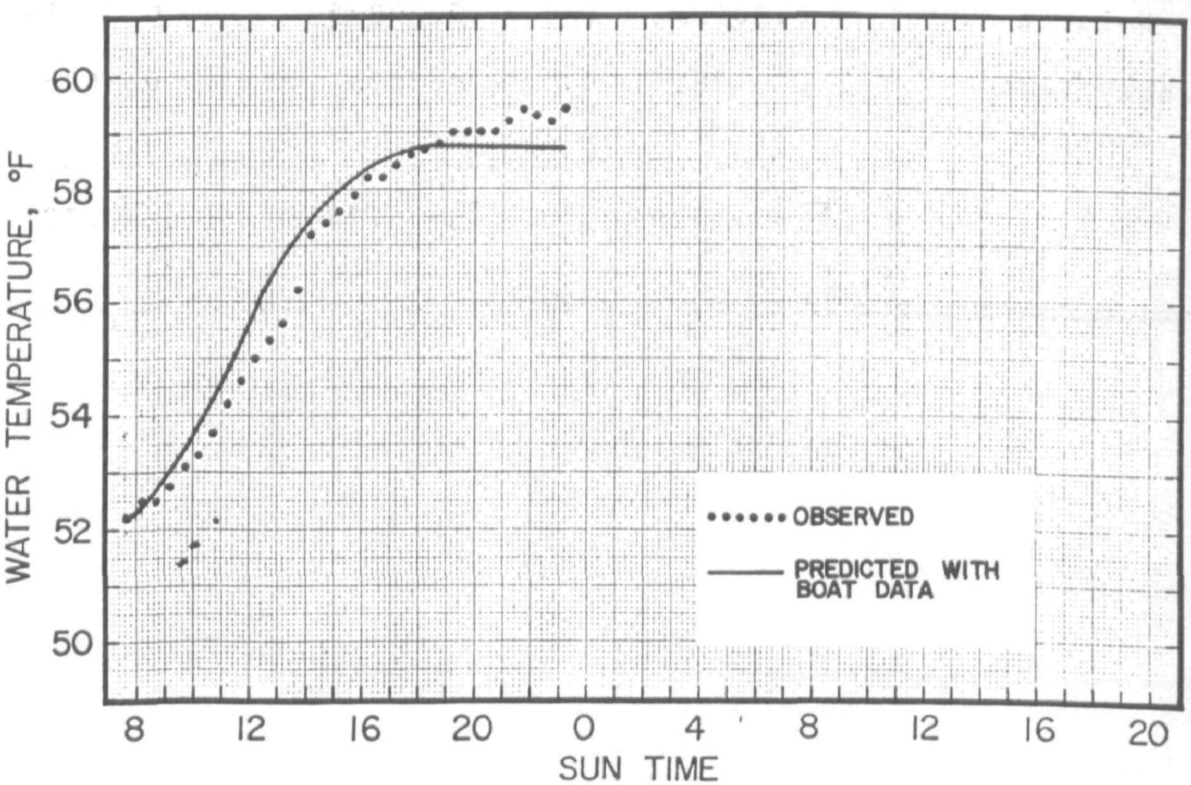

FIGURE 19 - OBSERVED AND PREDICTED (WITH BOAT DATA) TEMPERATURES, CANEY FORK RIVER SURVEY

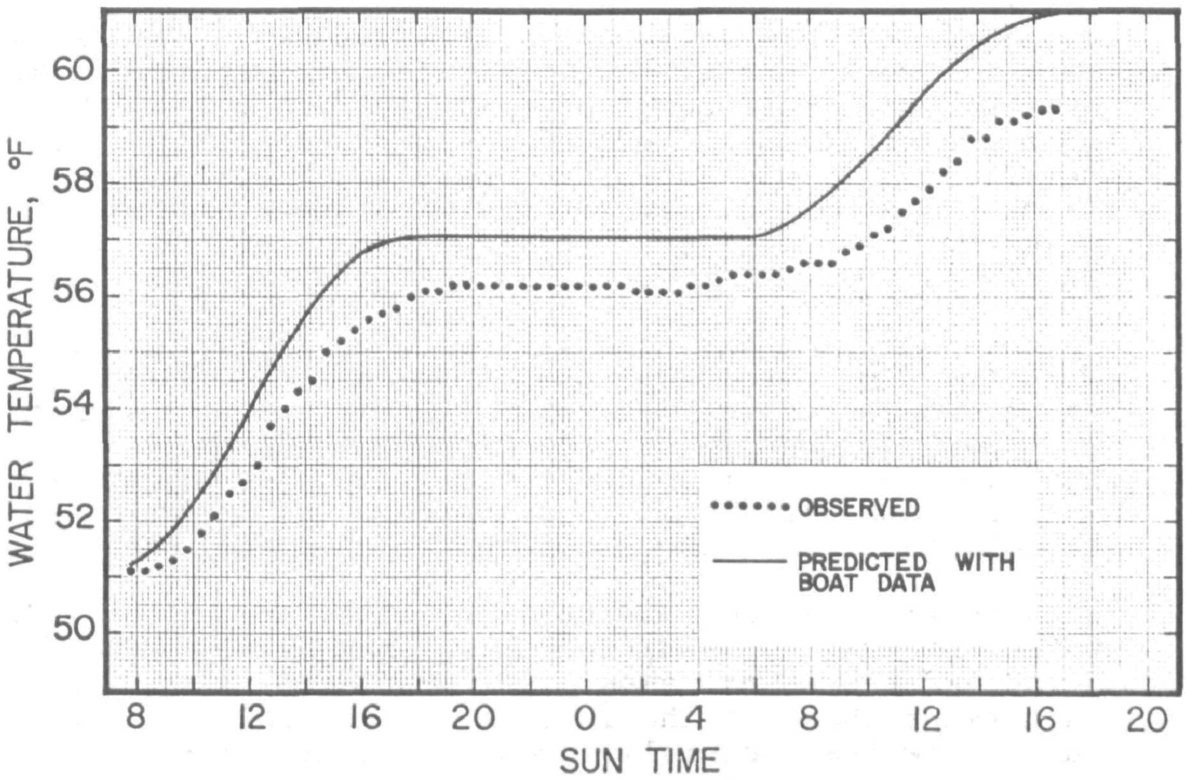

FIGURE 20 - OBSERVED AND PREDICTED (WITH BOAT DATA) TEMPERATURES, CUMBERLAND RIVER SURVEY 4

daytime, and 5^{o} - $10^{o}F$ higher than the boat-measured air temperature at night. The Nashville wind speed was also determined to have been consistently higher than that measured on the boat, but no clear relationship could be determined, as was shown by Figure 4. Therefore, the final adjustment simply set the wind speed at 1.5 mph, which was the approximate average wind speed actually observed.

Various combinations of adjustments to Nashville data were tried before it was used to predict temperatures in the streams studied. The same least squares procedure that was used to try to determine the best method of handling fog was also used to determine the effect of the various combinations of adjustments. The results from 4 such adjustments are shown in Table 5.

Figures 21 - 24 show the observed water temperature, the water temperature predicted using unadjusted Nashville data, and the water temperature predicted using the adjustment shown in the last column of Table 5. The results show that generally good agreement between observed and predicted temperatures can be realized if appropriate adjustments to the Weather Bureau data can be made. On the other hand, unadjusted data from even nearly weather stations is not likely to give good results because of the great differences between the microclimates of airport weather stations and river valleys. Even bankside weather stations must be checked carefully.

Obviously, the particular adjustments found to be appropriate in this case are not necessarily typical. In particular, rivers used for power plant discharges are likely to be wider, flatter, and more exposed, with a wider flood plain terrace than the ones studied, so that their microclimate would likely be more similar to nearby weather stations than the deep, narrow, sheltered valleys encountered in this study. Thus, the necessary adjustments might not be as great as the ones found necessary in this case. The important point is that there are differences that must be taken into account, but that, when these differences are accounted for, reasonable predictions can be made.

In each case, a preliminary study of the weather in the vicinity of the stream, as compared with that of the weather station to be used, must be made. The approximate depth of the stream for various flows and the influence of

TABLE 5 - LEAST SQUARES FIT OF NASHVILLE DATA USING VARIOUS CORRECTIONS

Survey	$\frac{(O_i - P_i)^2}{n - k}$			
	No Correction	Air Temp. $-2^{o}F$	Air Temp. $-4^{o}F$	Air Temp. $-4^{o}F$ Wind Speed = 1.5 mph
Cumberland #2	1.89664	1.44248	1.06291	0.05161
Cumberland #3	1.91275	1.09745	0.52697	0.91710
Caney Fork	14.87599	12.20794	9.88349	0.4415
Total	18.68538	14.74787	11.47337	1.41021

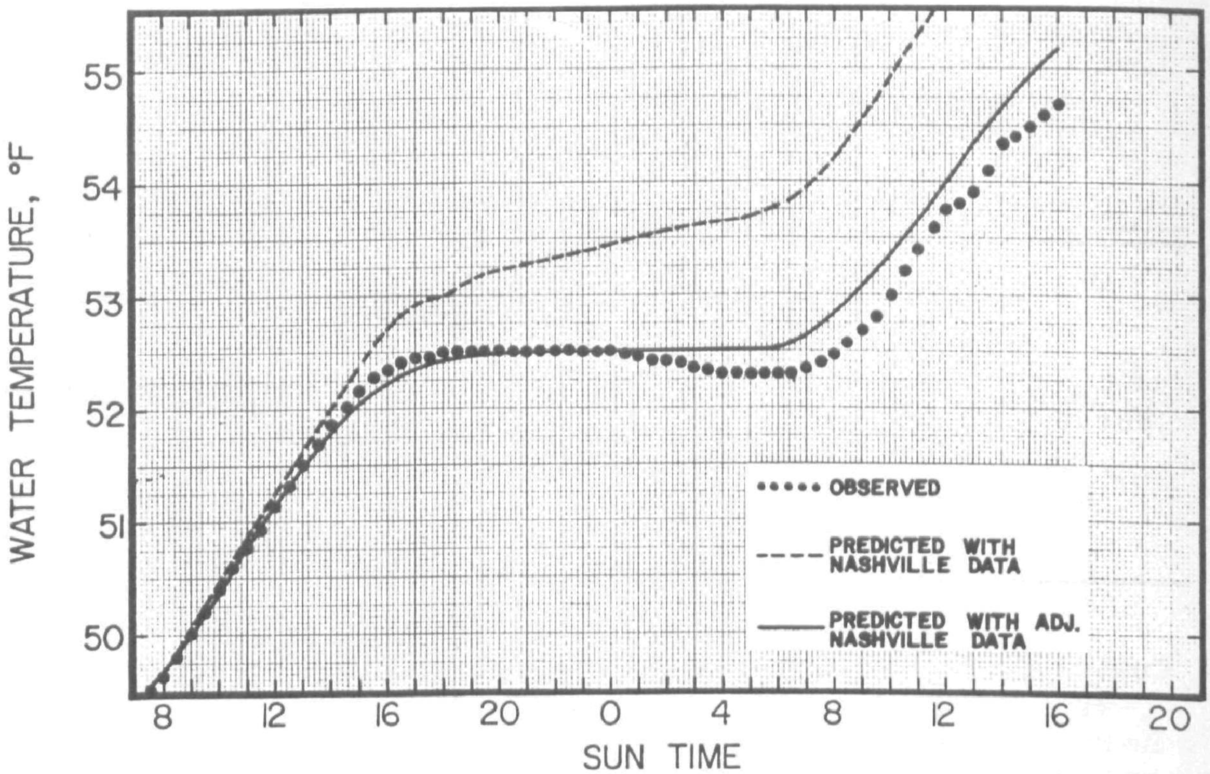

FIGURE 21 - OBSERVED AND PREDICTED (WITH NASHVILLE DATA) TEMPERATURES, CUMBERLAND RIVER SURVEY 2

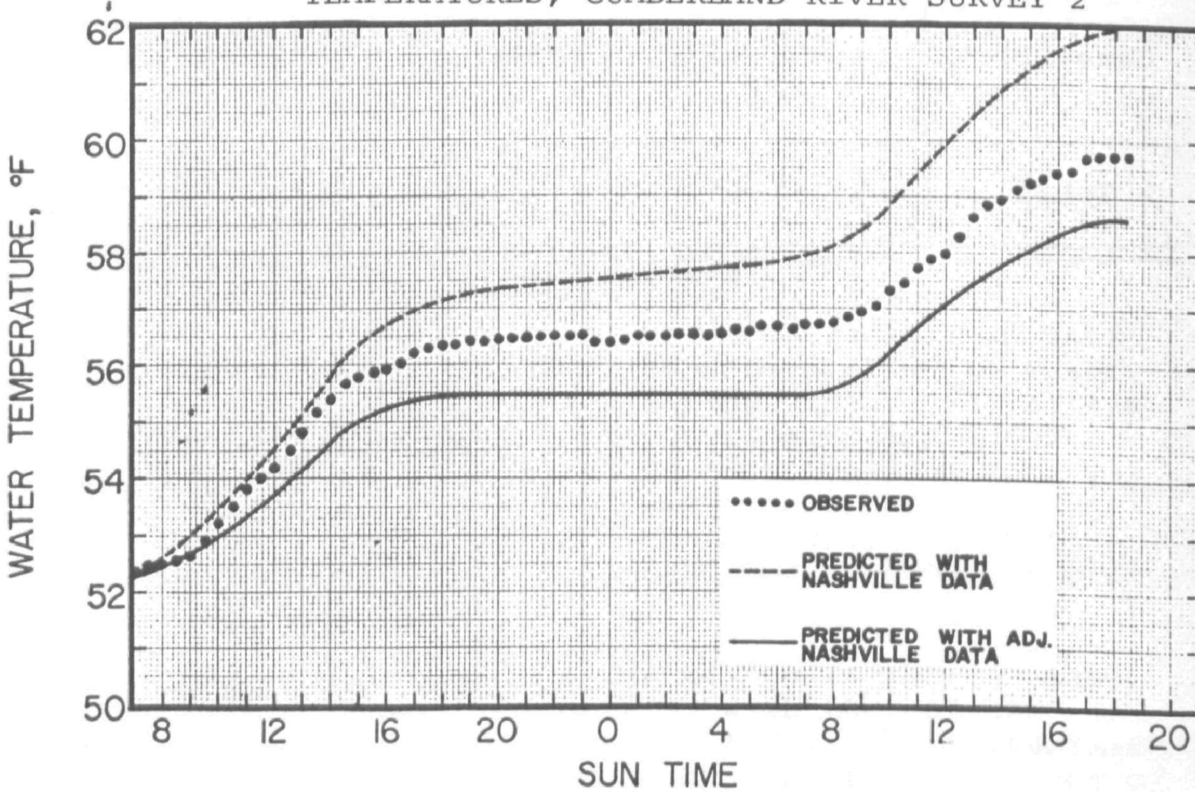

FIGURE 22 - OBSERVED AND PREDICTED (WITH NASHVILLE DATA) TEMPERATURES, CUMBERLAND RIVER SURVEY 3

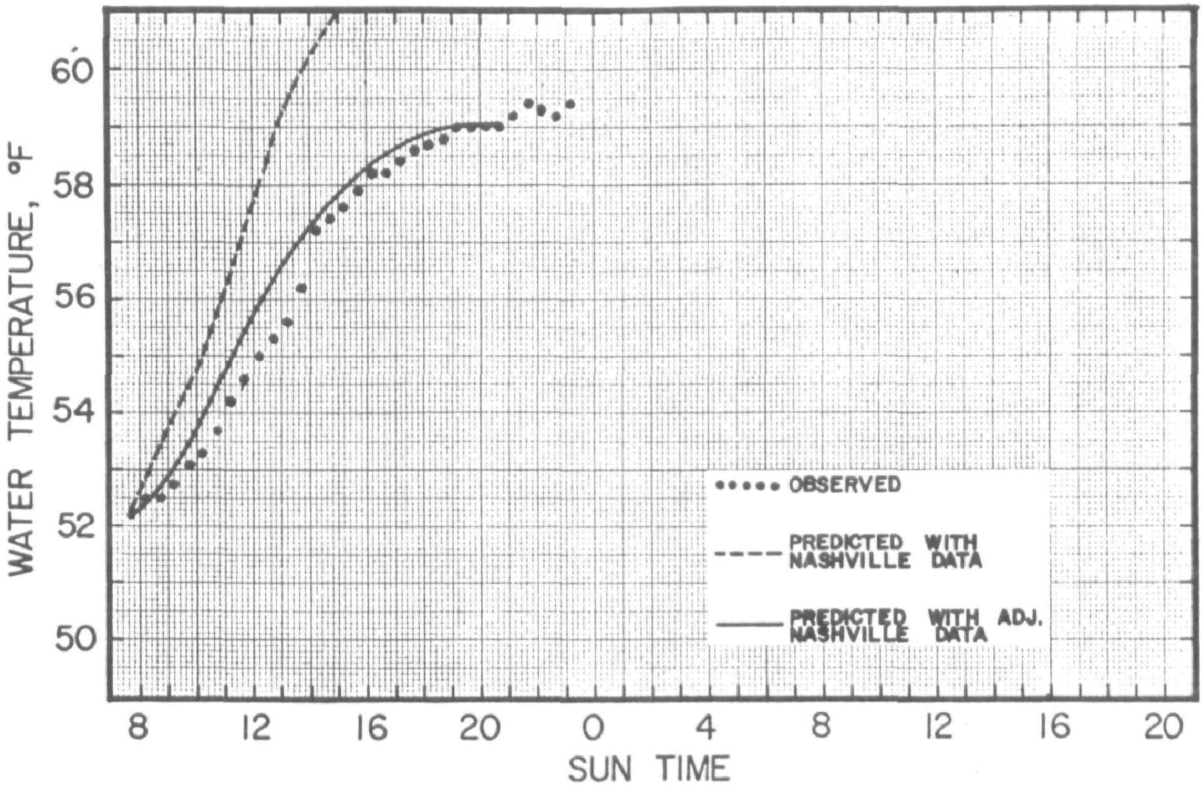

FIGURE 23 - OBSERVED AND PREDICTED (WITH NASHVILLE DATA) TEMPERATURES, CANEY FORK RIVER SURVEY

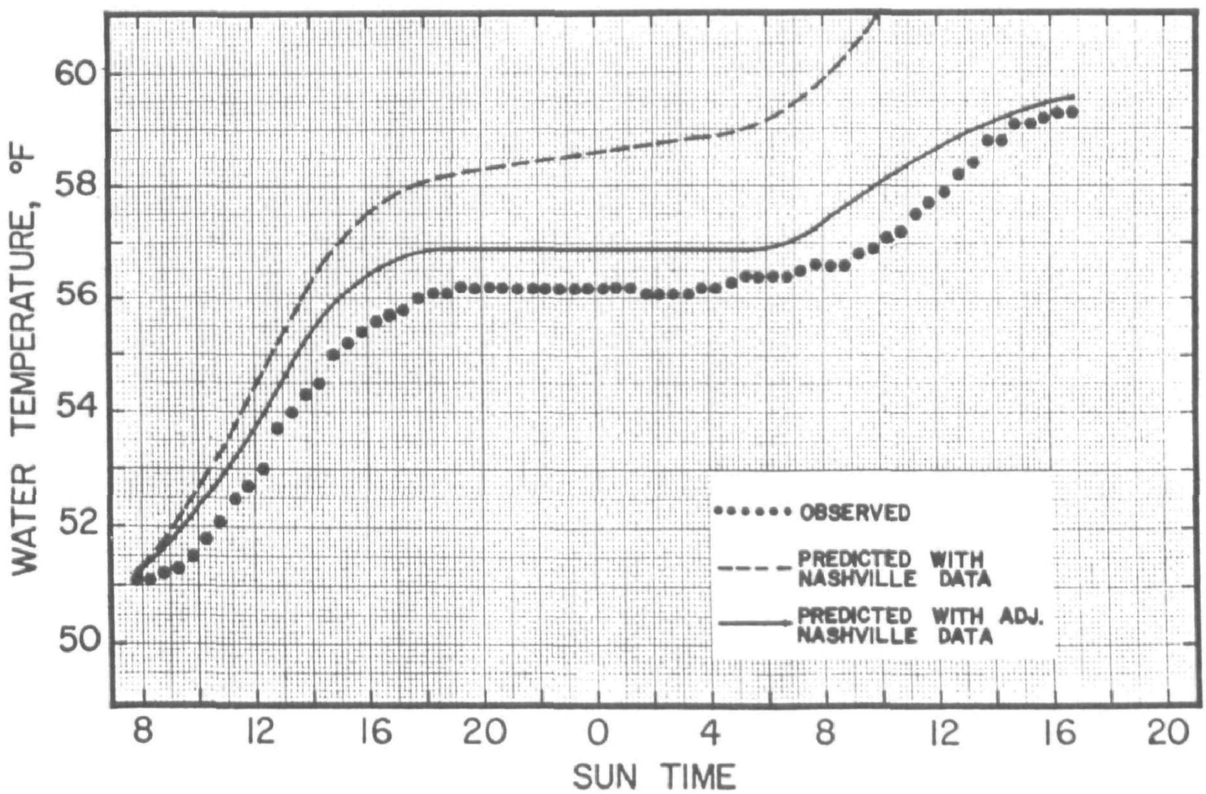

FIGURE 24 - OBSERVED AND PREDICTED (FROM NASHVILLE DATA) TEMPERATURE, CUMBERLAND RIVER SURVEY 4

bank shading and blockage of the sky must also be determined. After this data is accumulated, then present, historical, derived, or predicted weather data, with the appropriate adjustments, should be usable in the model presented herein for prediction of the downstream water temperature for various water conditions and power plant loadings. The model should thus be a valuable management tool for managing the quality of our nation's waters.

CONCLUSIONS

This study has demonstrated that temperatures of flowing rivers can be rather accurately forecast if the river depth, river valley geometry, and weather variables are known. Solar radiation, which is primarily influenced by cloud cover, is by far the most important factor in the energy budget of flowing streams.

Although some difficulties were encountered in predicting stream temperatures with weather data from stations other than in the river valley, appropriate modifications can be made to account for the climatological differences between the two locations.

The problems encountered by studying rivers below equilibrium temperature appear to be considerably greater than studying those above equilibrium temperature. Air temperatures exhibit considerable lapse rates in river valleys below hydroelectric installations. These vertical temperature differentials are primarily due to the stratification resulting from density differences. In contrast, the air above heated rivers would tend to be unstable with low lapse rates. The temperature at weather stations in the area would tend to be much more indicative of air temperatures in valleys through which warm rivers flow.

Adjustments for wind speeds are necessary to use any data from local weather stations. This adjustment should be relatively easy to make, given the geometry of the river valley. Wind speeds measured in the river valleys were much lower than those recorded at nearby weather stations, and this pattern would probably be similar in most instances.

Average depths for use in the model could possibly be determined from relatively few cross-sections. Great care had to be used in determining river depths in the studies conducted because unsteady flow conditions were encountered. Releases from the dams were variable, often being almost constant during the daytime and completely shut off during the late evening and early morning hours. Unsteady flow conditions presented no problem to the weather boat, because it followed a tagged slug of water, but the dye boat (which measured depth) had to be careful to measure depths at a particular river mile near the time when the weather boat passed, because the depth at a particular river mile changed with time.

The temperature predictions determined by the model can only be as accurate as the weather data used for input. Highly accurate weather predictions are difficult to obtain. However, the model studied appears to be a useful tool. It should be of value in defining the consequences of critical weather conditions, as well as temperature changes during ordinary circumstances.

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APPENDIX 1

Equipment Used For Measuring Variables In Model

	Variable	Description
1.	Depth	Fathometer, Raytheon Model DE-719. Uses sonar principle. Four ranges: 0-55, 50-105, 100-155, 150-205 feet. Built-in power supply. Recorder chart speed ranges from 1 - 4 inch/ min.
2.	Air Temperature and Wet Bulb Temperature	Bendix aspirated psychrometer. Contains matched wet and dry bulb mercury thermometers and a minature electric fan powered by 3 standard D-cell flashlight batteries. Air velocity of greater than 15 ft/sec created by fan. Thermometers graduated from 10^{o} to 110^{o} and accurate to .7^{o}F.
3.	Cloud Cover	Estimated by eye and reported as tenths of sky covered by clouds.
4.	Wind Velocity	Stewart Electronic Odometer. Five digit non-reset electromagnetic counter designed for remote wire connection to a contacting anemometer.
5.	Shaded Fraction of Water Surface	Estimated by eye.
6.	Blocked Fraction of Solar Hemisphere	Average angle of the sky blocked by hills and bluffs determined by measuring in four directions with a Navy sextant. Blocked fraction of sky is sine of average angle.
7.	Water Temperature	Whitney model TF-20 portable underwater thermometer. Range of 30^{o}-110^{o}F in four increments. Accuracy of $\pm$.2^{o}F. Resolution of .1^{o}F. Powered by 8 standard D cell flashlight batteries.

APPENDIX 2

Computer Program and User's Manual

The computer program uses the energy budget approach to calculate water temperatures in non-stratified water bodies. The equations discussed in Chapter I are utilized with the general procedure being that described on page 7.

The program is written in Fortran IV and was run on the Vanderbilt University XDS Sigma 7 computer.

Line Number	See Page	Equation Number	Comment
1			Common statement allows certain variables to be used in both the main program and a subroutine.
2-4			Dimension statement for other variables used.
5			Real statement allows variables lat, long, netsum, netsky to be used as real variables.
6-8			Variables initially set equal to zero.
9-20			Read statements to get general information about survey into the program.
21-23			Initial water temperature is fifth card in data deck.
25-29			Latitude, longitude, elevation, number of data points, and general location specified.
31-39			Comment cards defining variables.
40-44			Routine to read all meteorological information.
45-47			Routine to read all water temperatures
48-65			Information on first six data cards printed.
66-67			Latitude set to an integer value.
69-76			Routine to handle time when changing days.
77-225			Routine to compute water temperature changes.
77-81			Variables for particular time interval printed.

Line Number	See Page	Equation Number	Comment
82	3	5	Declination of the sun calculated.
83-86	3	4	Sine of solar altitude calculated.
87-88	3	6	Solar altitude calculated.
92-96	2	2	Direct solar radiation uncorrected for clouds or shaded fraction calculated.
97	3	7	Correction for part of river shaded applied to direct solar radiation.
98-100	2	3	Diffuse solar radiation calculated.
101	3	8	Correction for part of the sky blocked applied to diffuse solar radiation.
103	4	9	Total solar radiation calculated by applying correction for cloud cover.
105-147			Routine to calculate atmospheric radiation.
106-108	5	12	Wet bulb temperature calculated from relative humidity and air temperature.
109			Air vapor pressure calculated.
110	6	16	Vapor pressure air would have at water temperature calculated.
112-139	4	10	Routine to pick equation for β for each value of cloud cover.
141-147	4	10	Atmospheric radiation calculated.
149-153	5	14	Back radiation from water calculated.
155-158	6	15	Energy transfer by evaporation or condensation calculated.

Line Number	See Page	Equation Number	Comment
160-164	6	17	Energy transfer by conduction calculated.
166-179	2	1	Total energy transfer rate calculated.
180-183	7	20	Temperature change for time interval calculated.
185-189			New water temperature calculated.
77-225			If not at end of data, new rate of energy transfer computed for the next time interval.
240-279			Subroutine to plot observed and predicted water temperatures versus time.

```
      COMMON HOUR(150),TW(150),TWO(150),NO
      DIMENSION DEPTH(150),TAIR(150),R(150),CC(150),U(150),SHADE(150),DA
     1Y(150),TIME(150),BLOCK(150),TAIRA(150),RA(150),IFOG(150),UA(150),C
     2CA(150),QCI(150)
      REAL LAT,LONG,NETSUN,NETSKY
       ALPHA=0.
      H=0.
      DELTA=0.
      READ(5,30)R1,R2,R3,R4,R5,R6,R7,R8,R9,R10,R11,R12,R13,R14,R15,R16,R
     117,R18,R19,R20
   30 FORMAT(20A4)
       READ(5,32)A1,A2,A3,A4,A5,A6,A7,A8,A9,A10,A11,A12,A13,A14,A15,A16,
     1  A17,A18,A19,A20
   32 FORMAT(20A4)
       READ(5,33)B1,B2,B3,B4,B5,B6,B7,B8,B9,B10,B11,B12,B13,B14,B15,B16,
     1B17,B18,B19,B20
   33 FORMAT(20A4)
       READ(5,34)C1,C2,C3,C4,C5,C6,C7,C8,C9,C10,C11,C12,C13,C14,C15,C16,
     1  C17,C18,C19,C20
   34 FORMAT(20A4)
C     TWAT IS THE INITIAL WATER TEMPERATURE WHICH IS READ IN AT THIS PT.
      READ(5,46) TWAT
   46 FORMAT(F10.5)
  930 CONTINUE
C   NO IS THE TOTAL NUMBER OF OBSERVATIONS
      READ(5,25)  LAT,LONG,ELEV,NO,STA1,STA2,STA3,STA4,STA5,STA6,STA7,ST
     1A8,STA9,STA10
   25 FORMAT(3F10.2,I10,10A4)
      IF(LAT)17,17,940
  940 CONTINUE
C     TAIR=TEMPERATURE OF AIR IN DEGREES F
C     R=RELATIVE HUMIDITY AS FRACTION
C     U=WIND SPEED IN MILES PER HOUR
C     CC=CLOUD COVER IN TENTHS OF SKY
C     DAY IS THE DAY OF THE YEAR
C     HOUR IS THE HOUR OF DAY
```

```
C       THETA IS THE TIME INCREMENT
C       SHADE IS THE FRACTION OF THE RIVER WHICH IS SHADED
C      BLOCK IS THE FRACTION OF THE SKY WHICH IS BLOCKED FROM THE RIVER
        DO 10 J=1,NO
        READ(5,11)DAY(J),HOUR(J),DEPTH(J),TAIR(J),P(J),CC(J),U(J),SHADE(J)
       1,BLOCK(J),IFOG(J)
   11    FORMAT(2F5.2,6F10.2,F9.2,I1)
     10 CONTINUE
        DO 5200 J=1,NO
   5200 READ(5,5201)TWO(J)
   5201 FORMAT(F10.0)
        WRITE(6,55)
     55 FORMAT('1')
        WRITE(6,31)R1,R2,R3,R4,R5,R6,R7,R8,R9,R10,R11,R12,R13,R14,R15,R16,
       1R17,R18,R19,R20
     31 FORMAT(20A4)
        WRITE(6,42)A1,A2,A3,A4,A5,A6,A7,A8,A9,A10,A11,A12,A13,A14,A15,A16,
       1  A17,A18,A19,A20
    42  FORMAT(20A4)
        WRITE(6,43)B1,B2,B3,B4,B5,B6,B7,B8,B9,B10,B11,B12,B13,B14,B15,B16,
       1B17,B18,B19,B20
    43  FORMAT(20A4)
        WRITE(6,44)C1,C2,C3,C4,C5,C6,C7,C8,C9,C10,C11,C12,C13,C14,C15,C16,
       1  C17,C18,C19,C20
    44  FORMAT(20A4)
        WRITE(6,39)STA1,STA2,STA3,STA4,STA5,STA6,STA7,STA8,STA9,STA10,LAT,
       1LONG,ELEV
     39 FORMAT('LOCATION IS ',10A4,2X,'LATITUDE IS ',F6.2,2X,'LONGITUDE IS
       1 ',F6.2,2X,'ELEVATION IS ',F5.0)
        LAT=LAT+0.5
        LAT=INT(LAT)
      5 CONTINUE
        INDEX=0
        TIME(1)=HOUR(1)
        DO 41 J=2,NO
        IF(HOUR(J)-HOUR(J-1)) 40,41,41
```

```
   40 INDEX=INDEX+1
   41 TIME(J)=HOUR(J)+(INDEX*24.)
      DO 3 I=1,NO
      GO TO 4
   15 WRITE(6,12) DAY(I),HOUR(I),DEPTH(I),TAIR(I),R(I),CC(I),U(I),SHADE(
     1I),BLOCK(I)
   12 FORMAT('DAY= ',F5.0,2X,'HOUR= ',F6.3,2X,'DEPTH= ',F5.1,2X,'TAIR= '
     1,F5.1,2X,'REL HUM= ',F4.2,2X,'CC= ',F4.1,2X,'U= ',F5.1,'  SHAD. FR
     2.= ',F4.2,2X,'BLOCKED FR. = ',F4.2,/)
    4 DELTA=-23.28*COS(2.*3.14159*DAY(I)/365.+0.164)
C     H=HOUR ANGLE OF THE SUN
      H=360.*((12.-HOUR(I))/24.)
      SINAL=(SIN(LAT/57.296)*SIN(DELTA/57.296)+COS(LAT/57.296)*COS(DELTA
     1/57.296)*COS(H/57.296))
      ALPHA=(SINAL)+(SINAL**3)/6+(3*(SINAL**5))/40.+(15.*(SINAL**7))/336.
      ALPHA=ALPHA*57.296
      IF(ALPHA)107,107,130
  107 QI=0.0
      GO TO 109
C     SUN IS DIRECT SOLAR RADIATION UNCORRECTED FOR CLOUDS OR SHADED
C     FRACTION
  130 SUN=-0.1469996*ALPHA+0.3023495*ALPHA**2-0.00854603*ALPHA**3+(0.12
     1706045E-03)*ALPHA**4-(0.10125053E-05)*ALPHA**5+(0.32963452E-08)*AL
     2PHA**6
      NETSUN=SUN*(1.-SHADE(I))
C    SKY IS DIFFUSE SOLAR RADIATION UNCORRECTED FOR BLOCKED SKY FRACTION
      SKY=1.6802983*ALPHA-(0.31777075E-01)*ALPHA**2+(0.24141906E-03)*ALPH
     1A**3-(0.47294341E-06)*ALPHA**4-(0.58583716E-08)*ALPHA**5
      NETSKY=SKY*(1.-BLOCK(I))
C     QI IS ACTUAL SOLAR RADIATION
      QI=(NETSKY+NETSUN)*(1.-0.0071*CC(I)**2)
C     .................................................................
C     EW IS THE COMPUTED VAPOR PRESSURE OF THE WATER IN SATURATED
C         AIR AT TEMPERATURE OF THE WATER
  109 RATIO=0.655+0.36*R(I)
      WETT=RATIO*TAIR(I)
```

```
      EA=EXP(17.62302-9500.826/(WETT+460.))
      EW=EXP(17.62302-9500.826/(TWAT+460))
      EAS = EA
      K=CC(I)
      IF(IFOG(I).EQ.1)GO TO 120
      GO TO 190
  120 BETA=0.95
  121 GO TO 217
  190 IF(K)199,200,199
  199 GO TO (201,202,203,204,205,206,207,208,209,210),K
  200 BETA=(0.15)*EAS+0.74
      GO TO 217
  201 BETA=(0.15)*EAS+0.75
      GO TO 217
  202 BETA=(0.15)*EAS+0.76
      GO TO 217
  203 BETA=(0.143)*EAS+0.771
      GO TO 217
  204 BETA=(0.138)*EAS+0.783
      GO TO 217
  205 BETA=(0.137)*EAS+0.793
      GO TO 217
  206 BETA=(0.135)*EAS+0.8
      GO TO 217
  207 BETA=(0.13)*EAS+0.81
      GO TO 217
  208 BETA=(0.12)*EAS+0.825
      GO TO 217
  209 BETA=(0.105)*EAS+0.845
      GO TO 217
  210 BETA=(0.09)*EAS+0.866
C     ..........................................................................
C    QA IS LONG WAVE ATMOSPHERIC RADIATION
C     SIGMA IS THE STEFAN-BOLTZMANN RADIATION CONSTANT
  217 SIGMA=0.0000000166
      GO TO 218
```

```
 3001 OUTPUT BETA
  218 TA4=(TAIR(I)+459.67)**4
      QA=0.97*SIGMA*BETA*TA4
C     ..................................................................
C     QB IS THE EFFECTIVE BACK RADIATION
C     IT IS A FUNCTION OF SIGMA, BETA, AIR TEMPERATURE, AND WATER
C         TEMPERATURE.
  219 TW4=(TWAT+459.67)**4
  220 QB=-0.97*SIGMA*TW4
C     ..................................................................
C     QE IS THE EVAPORATED HEAT
C     IT IS A FUNCTION OF WIND VELOCITY AND THE DIFFERENCE BETWEEN
C        VAPOR PRESSURE OF SATURATED AIR AND ACTUAL AIR
  310 QE=-13.9*U(I)*(EW-EA)
C     ..................................................................
C     QH IS THE CONDUCTED HEAT BETWEEN WATER-AIR INTERFACE
C      IT IS A FUNCTION OF WIND VELOCITY, BAROMETRIC PRESSURE AND
C        DIFFERENCE BETWEEN TEMPERATURES OF WATER AND AIR
      P=29.92/EXP((32.15*ELEV)/(1545.*(TAIR(I)+460.)))
  400 QH=0.00543*U(I)*P*(TAIR(I)-TWAT)
C     ..................................................................
C     QT IS THE TOTAL SURFACE HEAT TRANSFER
  500 QT=QI+QB+QE+QH+QA
C     SUREN IS THE ENERGY CHANGE DUE TO SURFACE HEAT TRANSFER
      AREA=1.0
C     THETA IS THE TIME INCREMENT IN HOURS
      IF(I.EQ.1) GO TO 550
      GO TO 560
  550 THETA=(TIME(2)-TIME(1))/2.
      GO TO 600
  560 IF(I.EQ.ND) GO TO 570
      GO TO 580
 570      THETA=(TIME(ND)-TIME(ND-1))/2.
      GO TO 600
  580 THETA=(TIME(I+1)-TIME(I-1))/2.
  600 SUREN=QT*AREA*THETA/62.4
```

```
C         ..............................................................
C         TOTEN IS THE TOTAL ENERGY CHANGE
      800 TOTEN=SUREN
C         ..............................................................
C         TEMP IS THE TEMPERATURE CHANGE IN DEGREES FARENHEIT
          VOL=AREA*DEPTH(I)
      900 TEMP=TOTEN/VOL
C         TWAT IS THE CALCULATED WATER TEMPERATURE DURING THIS TIME INTERVAL
      950 TWAT=TWAT+TEMP
C         ..............................................................
          WRITE(6,1000)ALPHA,H,DELTA,EW,EA,WETT
     1000 FORMAT('ALPHA=',F10.5,2X,'H=',F10.5,2X,'DELTA=',F10.5,2X,'EW=',F10
         1.5,2X,'EA= ',F10.5,2X,'WET BULB= ',F8.3,//)
          WRITE(6,13)QI,QA,QB,QE,QH,QT
       13 FORMAT('SOLAR=',F7.1,2X,'ATM=',F7.1,2X,'BACK=',F8.1,2X,'EVAP=',F8.
         11,2X,'COND=',F7.1,2X,'TOTAL=',F8.1,2X,'BTU/SQ FT-HR',/)
          WRITE(6,18)TOTEN
       18 FORMAT('TOTAL ENERGY CHANGE=',F12.3,2X,'DEGREES FAHRENHEIT-FT**3',
         1/)
          WRITE (6,20)
       20 FORMAT('THE COMPUTED TEMPERATURE INCREMENT IN DEGREES FARENHEIT IS
         1')
          WRITE(6,21)TEMP
       21 FORMAT(F12.6,/)
          WRITE(6,22)
       22 FORMAT('THEREFORE THE CALCULATED WATER TEMPERATURE IN DEGREES FARE
         1NHEIT IS')
          WRITE(6,23)TWAT
       23 FORMAT(F12.6)
     2000  IF(I.EQ.1) GO TO 50
          GO TO 60
       50 TIME1=HOUR(1)
          TIME2=HOUR(1)+THETA
          GO TO 90
       60 IF(I.EQ.NO) GO TO 70
          GO TO 80
```

```
   70 TIME1=HOUR(NO)-THETA
      TIME2=HOUR(NO)
      GO TO 90
   80 TIME1=HOUR(I)-((HOUR(I)-HOUR(I-1))/2.)
      TIME2=HOUR(I)+((HOUR(I+1)-HOUR(I))/2.)
      GO TO 2001
   90 WRITE(6,24) TIME1,TIME2
   24 FORMAT('DURING THE TIME INTERVAL FROM ',F6.3,1X,'TO ',F6.3,////)
 2001 TW(I) = TWAT
    3 CONTINUE
      WRITE(6,64)
   64 FORMAT('1')
      WRITE(6,31)R1,R2,R3,R4,R5,R6,R7,R8,R9,R10,R11,R12,R13,R14,R15,R16,
     1R17,R18,R19,R20
      WRITE(6,42)A1,A2,A3,A4,A5,A6,A7,A8,A9,A10,A11,A12,A13,A14,A15,A16,
     1  A17,A18,A19,A20
      WRITE(6,43)B1,B2,B3,B4,B5,B6,B7,B8,B9,B10,B11,B12,B13,B14,B15,B16,
     1B17,B18,B19,B20
      WRITE(6,44)C1,C2,C3,C4,C5,C6,C7,C8,C9,C10,C11,C12,C13,C14,C15,C16,
     1  C17,C18,C19,C20
      CALL GRAPH
   17 CALL EXIT
      END
      SUBROUTINE GRAPH
      COMMON HOUR(150),TW(150),TWO(150),NO
      DIMENSION LINE(121),IA(13)
      DATA IP,IO,ID,IS,IB,IL/'P','O','.','*',' ','I'/
      MIN=TWO(1)
      DO 100 I=1,NO
      IF(I-1)15,15,30
C    AXIS LABELLING
   15 DO 16 K=1,13
   16 IA(K)=MIN+(K-1)
      WRITE(6,22)
   22 FORMAT(1H1)
      IF(I.EQ.1)WRITE(6,17)
```

```
   17 FORMAT(69X,'TEMP., DEG. F')
      WRITE(6,18)(IA(K),K=1,13)
   18 FORMAT(' TIME',5X,I2,12(8X,I2))
      DO 19 K=1,121
   19 LINE(K)=ID
      WRITE(6,20)LINE
   20 FORMAT(10X,121A1)
   30 CONTINUE
      DO 10 J=1,121
   10 LINE(J)=IB
      DO 40 K=1,121,10
   40 LINE(K)=IL
      PT1=(TW(I)-MIN)*10.+1.
      IP1=PT1
      S=PT1-IP1
      IF(S-0.5)50,55,55
   55 IPT1=IP1+1
      GO TO 57
   50 IPT1=IP1
   57 CONTINUE
      IPT2=(TWD(I)-MIN)*10+1
      LINE(IPT1)=IP
      LINE(IPT2)=ID
      IF(IPT1.EQ.IPT2)LINE(IPT1)=IS
  100 WRITE(6,35)HOUR(I),LINE
   35 FORMAT(1X,F4.1,5X,121A1,/)
      RETURN
      END
```

APPENDIX 3 - DATA

Two sets of data are necessary to execute the program. The first is the stream geometry and weather data. The second is the set of measured stream temperatures. The first water temperature measurement corresponds with the first stream geometry and weather variable measurement. The format for the data is at line 41 in the computer program.

CUMBERLAND RIVER SURVEY #2
JULY 29-30,1970
BOAT DATA

49.5
37.20 85.30 560. 66 BURKSVILLE,KY.

210.	7.5	13.5	61.0	.90	0.0	1.46	.04	.35	
210.	8.0	12.0	66.0	.86	0.0	1.73	.04	.1	
210.	8.5	10.0	70.5	.88	0.0	1.23	.05	.25	
210.	9.00	13.0	75.0	.71	1.0	.77	0.0	.15	
210.	9.5	10.5	71.0	.90	3.0	.87	0.0	.1	
210.	10.0	9.0	74.5	.65	4.0	1.33	0.0	.1	
210.	10.5	14.0	77.5	.76	4.0	2.6	0.0	.25	
210.	11.0	10.0	76.0	.70	0.0	.70	0.0	.35	
210.	11.5	13.5	82.0	.70	1.0	1.93	0.0	.15	
210.	12.0	12.5	86.5	.60	2.0	2.23	0.0	.1	
210.	12.5	14.5	82.0	.67	1.0	1.8	.05	.25	
210.	13.0	13.3	89.0	.52	2.0	1.27	0.0	.1	
210.	13.5	13.0	83.0	.58	1.0	2.0	.02	.25	
210.	14.0	16.2	83.0	.72	1.0	2.17	.05	.1	
210.	14.5	14.0	73.5	.81	0.0	2.0	.05	.25	
210.	15.0	12.2	80.0	.64	1.0	2.47	.05	.1	
210.	15.5	14.4	79.0	.73	1.0	1.27	.05	.25	
210.	16.0	14.1	76.0	.68	1.0	1.13	.05	.1	1
210.	16.5	15.6	76.0	.75	3.0	1.27	.10	.1	1
210.	17.0	14.0	70.0	.76	1.0	.85	.50	.25	1
210.	17.5	12.2	70.0	.84	3.0	.23	.50	.15	1
210.	18.0	11.7	71.0	.93	1.0	1.47	.60	.15	1
210.	18.5	15.0	64.5	.95	2.0	1.67	1.0	.15	1
210.	19.0	14.0	75.0	.93	2.0	1.40	1.0	.25	1
210.	19.5	15.0	65.0	1.00	1.0	.53	1.0	.15	1
210.	20.0	19.0	63.5	1.00	1.0	0.0	1.0	.15	1
210.	20.5	19.0	60.0	1.0	1.0	.57	1.0	.15	1
210.	21.0	23.9	60.5	1.0	0.0	1.27	1.0	.25	1
210.	21.5	20.0	62.0	1.0	0.0	.77	1.0	.25	1
210.	22.0	20.0	59.5	1.0	0.0	.7	1.0	.15	1

210.	22.5	20.0	58.5	1.0	0.0	1.5	1.0	.15	1
210.	23.0	20.0	58.0	1.0	0.0	1.5	1.0	.15	1
210.	23.5	20.1	60.0	.97	0.0	1.5	1.0	.15	1
211.	0.0	16.0	58.0	1.0	0.0	1.5	1.0	.15	1
211.	0.5	13.4	57.5	1.0	0.0	1.5	1.0	.35	1
211.	1.0	15.0	58.0	1.0	0.0	1.5	1.0	.25	1
211.	1.5	17.0	58.0	1.0	0.0	1.5	1.0	.25	1
211.	2.0	18.6	57.5	1.0	0.0	1.5	1.0	.25	1
211.	2.5	18.0	59.0	1.0	0.0	2.0	1.0	.15	1
211.	3.0	17.0	57.5	1.0	0.0	2.0	1.0	.35	1
211.	3.5	14.0	58.5	1.0	0.0	2.0	1.0	.15	1
211.	4.0	13.0	60.0	1.0	1.0	2.0	1.0	.15	1
211.	4.5	13.0	57.5	1.0	0.0	2.0	1.0	.15	1
211.	5.0	13.0	58.0	1.0	0.0	2.0	1.0	.15	1
211.	5.5	13.0	58.5	1.0	0.0	2.0	1.0	.15	1
211.	6.0	9.7	61.0	1.0	0.0	2.0	.25	.15	
211.	6.5	11.0	63.0	.89	0.0	2.0	.5	.35	
211.	7.0	11.0	68.0	.85	0.0	2.0	.15	.15	
211.	7.5	11.0	69.0	.95	0.0	2.33	.05	.25	
211.	8.0	13.0	71.0	.88	0.0	2.27	.05	.25	
211.	8.5	11.2	78.0	.74	0.0	2.63	.05	.15	
211.	9.0	20.0	79.0	.68	0.0	1.93	.05	.15	
211.	9.5	17.5	82.0	.70	1.0	3.23	.05	.1	
211.	10.0	17.1	83.0	.71	3.0	2.27	0.0	.1	
211.	10.5	12.0	81.5	.68	5.0	2.27	0.0	.15	
211.	11.0	16.7	85.0	.63	5.0	2.43	.05	.25	
211.	11.5	14.3	86.5	.64	6.0	4.43	0.0	.1	
211.	12.0	11.8	88.0	.58	6.0	2.07	0.0	.1	
211.	12.5	11.1	79.0	.75	5.0	3.47	.05	.35	
211.	13.0	13.8	91.0	.53	4.0	1.30	.05	.1	
211.	13.5	11.0	90.0	.53	2.0	2.1	.05	.15	
211.	14.0	16.0	90.5	.56	2.0	1.03	.05	.15	
211.	14.5	15.0	90.0	.53	1.0	2.03	.05	.1	
211.	15.0	10.9	84.0	.57	2.0	2.6	.05	.1	
211.	15.5	11.0	81.0	.59	3.0	3.13	.05	.1	
211.	16.0	10.0	77.0	.70	1.0	3.0	.05	.1	

CUMBERLAND RIVER SURVEY #2
JULY 29-30,1970
WEATHER DATA FROM NASHVILLE

49.5
37.20 85.30 560. 66BURKESVILLE KENTUCKY

210.	7.5	13.5	78.	.70	0.	5.0	.04	.35	
210.	8.0	12.0	81.	.65	0.	4.5	.04	.1	
210.	8.5	10.0	82.5	.59	0.	4.0	.05	.25	
210.	9.0	13.0	84.	.55	0.	3.5	0.0	.15	
210.	9.5	10.5	85.5	.52	1.	3.5	0.0	.1	
210.	10.0	9.0	87.	.52	2.	3.5	0.0	.1	
210.	10.5	14.0	88.	.50	3.	2.	0.0	.25	
210.	11.0	10.	89.	47	4.	0.	0.0	.35	
210.	11.5	13.5	89.5	.43	5.	2.	0.0	.15	
210.	12.0	12.5	90.	.39	6.	4.5	0.0	.1	
210.	12.5	14.5	91.	.37	6.	5.	.05	.25	
210.	13.0	13.3	92.	.35	5.	6.	0.0	.1	
210.	13.5	13.0	91.	.36	5.	7.	.02	.25	
210.	14.0	16.2	90.0	.37	5.	8.	.05	.1	
210.	14.5	14.0	91.5	.32	4.	8.5	.05	.25	
210.	15.0	12.2	93.	.27	4.	9.	.05	.1	
210.	15.5	14.4	92.5	.28	4.	9.	.05	.25	
210.	16.0	14.1	92.	.28	3.	9.	.05	.1	
210.	16.5	15.6	91.	.30	2.	8.	.10	.1	
210.	17.0	14.0	90.	.32	2.	7.	.50	.25	
210.	17.5	12.2	89.5	.34	1.	6.5	.50	.15	
210.	18.0	11.7	89.	.36	0.	6.	.60	.15	
210.	18.5	15.0	87.5	.40	1.	6.	1.0	.15	
210.	19.0	14.0	86.	.45	2.	6.	1.0	.25	
210.	19.5	15.0	85.5	.46	2.	6.	1.0	.15	
210.	20.0	19.0	85.	.48	.2	6.	1.0	.15	1
210.	20.5	19.0	83.	.60	1.	6.5	1.0	.15	1
210.	21.0	23.9	79.	.72	0.	7.	1.0	.25	1
210.	21.5	20.0	79.5	.66	0.	8.	1.0	.25	1
210.	22.0	20.0	80.	.61	0.	9.	1.0	.15	1

210.	22.5	20.0	79.	.60	0.	8.5	1.0	.15	1
210.	23.0	20.0	78.	.60	0.	8.	1.0	.15	1
210.	23.5	20.1	77.5	.62	0.	7.5	1.0	.15	1
211.	0.0	16.0	77.	.63	0.	7.	1.0	.15	1
211.	0.5	13.4	77.	.63	0.	6.5	1.0	.35	1
211.	1.0	15.0	77.	.63	0.	6.	1.0	.25	1
211.	1.5	17.0	76.	.67	0.	6.5	1.0	.25	1
211.	2.0	18.6	75.	.70	0.	7.	1.0	.25	1
211.	2.5	18.0	74.5	.70	0.	6.5	1.0	.15	1
211.	3.0	17.0	74.	.70	0.	6.	1.0	.35	1
211.	3.5	14.0	73.5	.72	0.	6.0	1.0	.15	1
211.	4.	13.	73.	.74	0.	6.	1.	.15	1
211.	4.5	13.	72.5	.76	0.	6.5	1.	.15	1
211.	5.	13.	72.	.76	0.	7.	1.	.15	1
211.	5.5	13.	73.	.76	0.	7.	1.	.15	1
211.	6.	9.7	74.	.74	0.	7.	.25	.15	1
211.	6.5	11.	76.	.71	0.	7.	.5	.35	1
211.	7.	11.	78.	.68	0.	7.	.15	.15	1
211.	7.5	11.	80.	.63	0.	8.	.05	.25	
211.	8.	13.6	82.	.58	6.	9.	.05	.25	
211.	8.5	11.2	84.	.55	3.	9.	.05	.15	
211.	9.	20.	86.	.54	0.	9.	.05	.15	
211.	9.5	17.5	87.	.52	0.	8.5	.05	.1	
211.	10.	17.1	88.	.49	0.	8.	0.	.1	
211.	10.5	12.	88.5	.46	2.	10.	0.	.15	
211.	11.	16.7	89.	.44	4.	11.5	.05	.25	
211.	11.5	14.3	90.	.39	4.	10.	0.	.1	
211.	12.	11.8	91.	.38	4.	8.	0.	.1	
211.	12.5	11.1	91.5	.36	4.	7.5	.05	.35	
211.	13.	13.8	92.	.33	4.	7.	.05	.1	
211.	13.5	11.	92.	.34	4.	8.	.05	.15	
211.	14.	16.	92.	.36	4.	9.	.05	.15	
211.	14.5	15.	91.5	.37	4.	10.	.05	.1	
211.	15.	10.9	91.	.38	4.	11.5	.05	.1	
211.	15.5	11.	91.5	.35	3.	10.	.05	.1	
211.	16.	10.	92.	.32	2.	9.	.05	.1	

WATER TEMPERATURE CUMBERLAND RIVER SURVEY #2

49.5
49.6
49.6
50.0
50.2
50.4
50.5
50.7
50.9
51.15
51.40
51.5
51.65
51.8
52.0
52.2
52.3
52.35
52.40
52.45
52.45
52.50
52.5
52.5
52.5
52.5
52.5
52.5
52.6
52.7
52.5
52.5
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52.5
52.4
52.4
52.4
52.2
52.3
52.3
52.3
52.3
52.3
52.3
52.3
52.5
52.5
52.55
52.6
52.7
52.85
53.0
53.2
53.4
53.6
53.75
53.8
53.9
54.1
54.35
54.4
54.5
54.6
54.7

CUMBERLAND RIVER SURVEY #3
AUGUST 30-31,1970
BOAT DATA

52.3
37.20 85.30 560. 72 BURKSVILLE,KY.

242.	7.	7.6	65.	.94	10.	.1	0.	.33	
242.	7.5	7.6	61.5	.94	10.	.40	.05	.23	
242.	8.0	6.5	61.5	.97	3.	1.2	.05	.26	
242.	8.5	6.7	64.0	.89	3.	1.0	.05	.23	
242.	9.0	8.1	76.0	.86	2.	3.2	.05	.33	
242.	9.5	5.6	78.	.78	1.	2.2	.05	.31	
242.	10.	12.2	77.	.74	1.	2.3	.05	.26	
242.	10.5	10.7	81.0	.72	1.	3.7	.03	.17	
242.	11.	4.2	79.	.76	2.	2.1	.03	.16	
242.	11.5	5.7	81.5	.74	1.	2.0	.03	.26	
242.	12.0	7.6	81.	.68	1.	2.3	.03	.23	
242.	12.5	7.6	86.	.61	2.	2.	.03	.21	
242.	13.	6.8	81.	.66	2.	1.	.05	.28	
242.	13.5	6.8	87.5	.59	3.	1.1	.05	.19	
242.	14.	8.6	85.	.69	3.	2.2	.05	.24	
242.	14.5	6.5	84.	.68	3.	.4	.05	.24	
242.	15.	10.5	83.	.71	3.	.6	.15	.26	
242.	15.5	8.5	73.5	.86	5.	.5	.75	.26	
242.	16.	7.5	78.	.6	1.	.5	.35	.29	1
242.	16.5	12.9	73.	.68	1.	.5	.1	.33	1
242.	17.	11.	71.	.97	1.	.2	.10	.29	1
242.	17.5	9.4	70.5	.68	1.	.2	1.	.26	1
242.	18.	12.1	66.	1.	1.	.1	1.	.24	1
242.	18.5	12.1	65.	.97	0.	.4	1.	.31	1
242.	19.	12.1	67.	.95	0.	.8	1.	.09	1
242.	19.5	14.4	62.5	1.	0.	.4	1.	.17	1
242.	20.	7.3	64.	1.	0.	.5	1.	.17	1
242.	20.5	5.5	62.	1.	0.	.5	1.	.26	1
242.	21.	7.7	61.	1.	0.	0.	1.	.17	1

242.	21.5	7.7	62.	1.	0.	.4	1.	.21	1
242.	22.	10.2	61.	1.	0.	0.	1.	.17	1
242.	22.5	6.9	61.	1.	0.	.15	1.	.14	1
242.	23.	6.9	60.	1.	0.	.9	1.	.26	1
242.	23.5	7.4	61.	1.	0.	.1	1.	.17	1
242.	24.	9.7	60.	1.	2.	.4	1.	.21	1
243.	24.5	9.7	60.5	.97	3.	.02	1.	.26	1
243.	1.	11.4	50.	.93	0.	0.	1.	.26	1
243.	1.5	11.4	50.	1.	0.	.07	1.	.26	1
243.	2.	9.1	56.5	1.	0.	.5	1.	.17	1
243.	2.5	10.9	59.5	1.	2.	.8	1.	.34	1
243.	3.	12.4	56.5	1.	0.	.5	1.	.21	1
243.	3.5	11.2	58.	1.	0.	.4	1.	.17	1
243.	4.	12.3	56.	1.	0.	.15	1.	.34	1
243.	4.5	12.3	58.	1.	0.	.15	1.	.26	1
243.	5.	9.	58.	1.	1.	.1	1.	.14	1
243.	5.5	13.8	61.5	.9	1.	.2	1.	.17	1
243.	6.	10.5	62.5	.88	2.	.2	.95	.16	1
243.	6.5	12.	60.5	.96	2.	.05	.5	.31	
243.	7.	10.1	63.	.9	1.	.8	.1	.23	
243.	7.5	12.7	67.5	.9	0.	.6	.05	.23	
243.	8.	12.9	68.	1.	0.	.6	.05	.19	
243.	8.5	13.9	74.5	.65	0.	.6	.5	.39	
243.	9.	7.9	76.0	.76	0.	.4	.05	.36	
243.	9.5	9.2	78.5	.71	1.	1.1	.03	.28	
243.	10.	11.1	86.	.6	3.	3.3	.02	.33	
243.	10.5	5.4	83.	.58	8.	.5	.02	.24	
243.	11.	13.	84.	.63	8.	.3	.02	.21	
243.	11.5	7.	83.5	.58	9.	1.2	.02	.19	
243.	12.	10.8	76.	.7	5.	2.5	.02	.21	
243.	12.5	12.3	85.	.6	4.	2.	.02	.23	
243.	13.	8.5	85.	.6	4.	2.	.02	.33	
243.	13.5	7.2	81.5	.59	3.	1.6	.03	.28	
243.	14.	14.1	83.	.72	3.	1.1	.05	.33	
243.	14.5	5.6	84.	.71	2.	.4	.1	.33	
243.	15.	10.2	81.	.76	7.	.5	.1	.31	

243.	15.5	6.8	81.5	.69	8.	1.7	.1	.19
243.	16.	7.7	80.	.68	8.	1.7	.15	.26
243.	16.5	6.9	78.5	.68	8.	1.1	.15	.33
243.	17.	6.1	76.	.8	9.	.5	.5	.29
243.	17.5	8.9	74.	.81	8.	.07	1.	.36
243.	18.	8.2	68.5	1.	9.	.02	1.	.33
243.	18.5	8.2	67.5	.92	8.	.02	1.	.26

WATER TEMPERATURE CUMBERLAND RIVER SURVEY #3

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HOLSTON RIVER SURVEY
JUNE 12-13,1971
BOAT DATA

55.3								
36.1		33.7	860.		26	JEFFERSON CITY TENNESSEE		
1								
163.	6.5	8.	65.	.73	6.	.7	.05	.17
163.	7.	5.5	66.5	.72	7.	.7	0.	.26
163.	7.5	4.7	70.	.72	8.	.6	.1	.37
163.	8.	4.5	71.	.73	8.	1.4	.1	.37
163.	8.5	5.6	74.5	.66	9.	2.1	0.	.41
163.	9.	8.5	76.5	.57	8.	2.8	.1	.24
163.	9.5	7.5	81.5	.55	8.	2.9	.05	.21
163.	10.	5.5	86.5	.53	5.	4.4	.1	.31
163.	10.5	7.3	90.	.45	4.	4.	.05	.24
163.	11.	7.8	84.	.55	5.	5.3	0.	.21
163.	11.5	7.7	82.	.51	7.	3.9	0.	.21
163.	12.	7.5	83.5	.53	6.	2.6	0.	.31
163.	12.5	7.7	84.5	.56	4.	2.7	.10	.23
163.	13.	8.4	83.	.55	6.	2.2	.15	.36
163.	13.5	7.8	81.5	.69	10.	3.2	.10	.14
163.	14.	5.0	70.	.85	10.	3.0	.05	.17
163.	14.5	4.0	67.	.95	10.	1.2	.05	.12
163.	15.	5.	70.5	.64	9.	1.8	.1	.14
163.	15.5	4.	74.	.73	8.	3.	.15	.17
163.	16.	2.6	73.	.78	4.	2.8	.10	.19
163.	16.5	7.	75.5	.77	.5	1.8	.15	.22
163.	17.	7.	74.	.78	.5	1.2	.7	.33
163.	17.5	5.9	74.	.78	0.	1.2	.40	.31
163.	18.	4.	71.	.66	0.	1.2	.5	.22
163.	18.5	4.9	72.	.8	1.	.8	.7	.17
163.	19.	6.4	70.	.81	1.	.1	.7	.21
163.	19.5	7.5	66.	.9	1.	.1	1.	.14
163.	20.	6.	65.	.95	1.	.2	1.	.34
163.	20.5	4.4	63.5	.89	1.	.2	1.	.26

163.	21.	3.2	62.5	.94	1.	1.	1.	.14	1
163.	21.5	7.5	61.5	1.	2.	.5	1.	.17	1
163.	22.	13.6	61.	1.	2.	.4	1.	.14	1
163.	22.5	13.2	61.5	1.	3.	.4	1.	.17	1
163.	23.	11.2	61.5	1.	5.	.8	1.	.17	1
163.	23.5	8.2	61.	1.	9.	1.2	1.	.17	1
163.	24.	7.2	61.5	1.	9.	.8	1.	.09	1
164.	.05	7.1	61.	1.	9.	.4	1.	.09	1
164.	1.	6.8	60.5	1.	9.	.8	1.	.09	1
164.	1.5	6.4	61.	1.	9.	1.2	1.	.09	1
164.	2.	6.3	60.5	1.	9.	.9	1.	.09	1
164.	2.5	6.1	61.	1.	10.	1.2	1.	.09	1
164.	3.	10.5	60.5	1.	10.	1.3	1.0	.09	1
164.	3.5	10.7	60.5	1.	2.	1.5	1.	.17	1
164.	4.	10.9	60.5	1.	5.	1.4	1.	.26	1
164.	4.5	10.5	60.5	1.	3.	.8	1.	.14	1
164.	5.	9.2	60.5	1.	3.	1.	1.	.14	1
164.	5.5	8.5	60.5	1.	3.	1.3	.5	.17	
164.	6.	10.	61.5	1.	2.	1.1	.3	.26	
164.	6.5	12.1	64.	.94	1.	1.	.1	.26	
164.	7.	13.	68.	.88	3.	1.3	.1	.23	
164.	7.5	13.6	72.5	.81	2.	1.8	.1	.31	
164.	8.	12.8	76.	.72	2.	3.4	0.	.17	
164.	8.5	10.	77.	.69	2.	6.0	.15	.24	
164.	9.	8.5	80.	.67	3.	8.6	.05	.05	
164.	9.5	9.5	81.5	.63	4.	10.8	.1	.17	
164.	10.	10.3	82.	.61	4.	8.8	.05	.05	
164.	10.5	10.2	82.	.61	4.	5.6	0.	0.	
164.	11.	10.1	80.5	.68	6.	3.7	0.	0.	

WATER TEMPERATURE HOLSTON RIVER SURVEY

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CANEY FORK RIVER SURVEY
JUNE 26,1971
BOAT DATA

52.1
36.2 85.9 460. 26 CARTHAGE,TENNESSEE
1

177	7.5 4.9	70.	.72	8.	.3	.3	.35	
177.	7.75 4.7	71.	.73	6.	.3	.2	.21	
177.	8.25 8.9	74.5	.73	4.	.6	.1	.45	
177.	8.75 7.6	76.	.75	2.	.9	.2	.28	
177.	9.25 4.8	76.	.75	0.	1.2	0.	.12	
177.	9.75 5.7	84.	.58	0.	1.	.2	.29	
177.	10.254.7	86.	.61	0.	1.	.05	.29	
177.	10.755.	94.	.44	0.	1.	.05	.16	
177.	11.254.7	85.	.69	0.	1.	0.	.31	
177.	11.755.3	93.	.5	0.	1.	0.	.31	
177.	12.255.1	90.	.5	0.	1.4	0.	.39	
177.	12.754.6	95.	.47	.5	2.	.05	.21	
177.	13.257.4	96.	.43	0.	2.7	.05	.21	
177.	13.7510.5	92.	.59	0.	2.5	0.	.26	
177.	14.256.6	89.	.55	0.	1.2	.05	.29	
177.	14.756.1	90.	.56	0.	1.1	.1	.41	
177.	15.255.6	87.	.64	.5	1.7	.5	.34	
177.	15.756.4	86.5	.59	.5	1.7	.1	.225	
177.	16.256.	86.	.61	0.	1.4	.05	.29	
177.	16.755.3	83.	.61	0.	.8	.6	.47	
177.	17.254.5	76.5	.77	0.	.7	.5	.24	
177.	17.754.3	77.	.75	0.	.7	.3	.29	
177.	18.255.3	74.	.82	0.	.4	.6	.19	
177.	18.754.8	73.	.78	1.	.6	.4	.24	
177.	19.254.8	71.5	.64	0.	.7	1.	.31	
177.	19.754.4	67.	.9	0.	.5	1.	.24	1
177.	20.257.8	68.5	.98	0.	.9	1.	.42	1
177.	20.757.9	67.	.9	0.	.8	1.	.42	1

CANEY FORK RIVER SURVEY
JUNE 26,1971
AIR TEMPERATURE, CLOUD COVER, & RELATIVE HUMIDITY FROM NASHVILLE, TENNESSEE

52.1								
36.2		85.9	460.		33	CARTHAGE,TENNESSEE		
177.	7.5	4.9	79.	.85	3.	.3	.30	.35
177.	7.75	4.7	81.	.81	2.	.3	.20	.21
177.	8.25	8.9	83.	.77	2.	.6	.10	.45
177.	8.75	7.6	85.	.72	2.	.9	.20	.28
177.	9.25	4.8	87.	.68	2.	1.2	.0	.12
177.	9.75	5.7	88.5	.63	2.	1.0	.20	.29
177.	10.25	4.7	90.	.57	1.	1.0	.05	.29
177.	10.75	5.0	91.5	.52	1.	1.0	.05	.16
177.	11.25	4.7	93.	.47	1.	1.0	.0	.31
177.	11.75	5.3	94.5	.42	0.	1.0	.0	.31
177.	12.25	5.1	96.	.37	0.	1.4	.0	.39
177.	12.75	4.6	96.	.38	0.	2.0	.05	.21
177.	13.25	7.4	96.	.38	1.	2.7	.05	.21
177.	13.75	10.5	96.	.39	1.	2.5	.0	.26
177.	14.25	6.6	95.	.39	1.	1.2	.05	.29
177.	14.75	6.1	95.	.40	2.	1.1	.10	.41
177.	15.25	5.6	95.	.41	2.	1.7	.50	.34
177.	15.75	6.4	95.	.42	2.	1.7	.10	.225
177.	16.25	6.0	94.	.43	1.	1.4	.05	.29
177.	16.75	5.3	94.	.43	1.	.6	.60	.47
177.	17.25	4.5	94.	.44	1.	.7	.50	.24
177.	17.75	4.3	93.	.45	0.	.7	.30	.29
177.	18.25	5.3	93.	.46	0.	.4	.60	.19
177.	18.75	4.8	91.5	.49	0.	.6	.4	.24
177.	19.25	4.8	90.	.52	0.	.7	1.0	.31
177.	19.75	4.4	88.	.55	0.	.5	1.0	.24
177.	20.25	7.8	87.	.59	0.	.9	1.0	.42
177.	20.75	7.9	85.	.62	0.	.8	1.0	.42

WATER TEMPERATURE CANEY FORK RIVER SURVEY

52.1
52.2
52.5
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CUMBERLAND RIVER SURVEY #4
JULY 17-18,1971
BOAT DATA

51.1
36.79 85.37 560. 67 BURKSVILLE,KY.

198.	7.75 5.9	77.	.69	0.	4.5	.20	.375	
198.	8.25 8.4	79.	.65	0.	4.5	.05	.26	
198.	8.75 8.8	80.5	.59	0.5	5.75	0.	.28	
198.	9.25 7.8	82.	.56	1.0	7.0	0.	.17	
198.	9.75 8.8	83.	.46	.5	7.5	.05	.34	
198.	10.256.	84.	.38	0.	8.0	0.	.26	
198.	10.756.1	84.5	.35	0.	9.75	0.	.26	
198.	11.256.6	85.	.28	0.	11.5	0.	.26	
198.	11.757.	86.5	.25	0.	9.25	0.	.21	
198.	12.255.5	88.	.22	0.	7.0	0.	.14	
198.	12.754.35	88.5	.25	0.	5.25	0.	.14	
198.	13.257.2	89.	.29	0.	3.5	.0	.32	
198.	13.754.7	89.5	.27	0.	6.5	.05	.25	
198.	14.255.1	90.	.25	0.	9.5	.02	.19	
198.	14.757.1	89.5	.26	0.	8.75	.1	.34	
198.	15.258.2	89.	.26	0.	8.0	.05	.32	
198.	15.754.9	88.5	.30	0.	5.25	.15	.32	
198.	16.256.3	88.	.33	0.	4.5	.3	.24	
198.	16.757.6	87.5	.34	0.	5.25	.05	.24	
198.	17.256.1	87.	.35	0.	6.0	.05	.26	
198.	17.757.75	86.	.36	0.	4.75	.5	.22	
198.	18.258.2	85.	.36	0.	3.5	1.	.26	
198.	18.757.6	82.5	.44	0.	4.0	1.	.28	
198.	19.256.9	80.	.54	0.	4.5	1.	.28	
198.	19.756.05	78.	.64	0.	5.7	1.	.42	
198.	20.255.9	76.	.75	0.	7.0	1.	.39	
198.	20.756.3	74.5	.80	0.	7.0	1.	.44	
198.	21.256.7	73.	.87	0.	7.0	1.	.31	1
198.	21.757.1	72.5	.87	0.	7.0	1.	.34	1
198.	22.257.4	72.	.86	0.	7.0	1.	.34	1

198.	22.757.2	72.	.85	0.	7.5	1.	.26	1
198.	23.256.9	72.	.81	0.	8.0	1.	.24	1
198.	23.757.8	72.	.85	0.	8.0	1.	.41	1
199.	.25 9.6	72.	.86	0.	8.0	1.	.28	1
199.	.75 7.9	72.	.87	0.	8.7	1.	.17	1
199.	1.25 8.7	72.	.90	0.	9.5	1.	.17	1
199.	1.75 10.8	72.	.90	0.	8.2	1.	.17	1
199.	2.25 11.4	72.	.90	0.	7.0	1.	.26	1
199.	2.75 10.	72.	.90	0.	6.5	1.	.26	1
199.	3.25 8.4	72.	.90	0.	6.0	1.	.12	1
199.	3.75 7.9	71.	.94	0.	6.0	1.	.12	1
199.	4.25 7.75	70.	.95	0.	6.0	1.	.17	1
199.	4.75 8.9	71.5	.96	0.	7.0	1.	.21	1
199.	5.25 10.	73.	.96	0.	8.0	1.	.42	1
199.	5.75 11.1	75.	.90	1.	7.5	.7	.34	1
199.	6.25 9.85	77.	.83	2.	7.0	.30	.26	1
199.	6.75 6.75	79.	.76	1.	8.75	.2	.17	1
199.	7.25 7.2	81.	.69	0.	10.5	.15	.17	1
199.	7.75 9.	82.5	.64	0.	12.25	.1	.34	1
199.	8.25 9.25	84.	.57	0.	14.0	.05	.23	1
199.	8.75 9.5	85.	.52	1.5	14.5	.05	.22	
199.	9.25 8.3	86.	.49	3.	15.0	.05	.22	
199.	9.75 6.2	87.	.48	5.	14.5	0.	.22	
199.	10.258.8	88.	.47	7.	14.0	0.	.28	
199.	10.759.	88.5	.46	8.5	12.25	.1	.33	
199.	11.259.2	89.	.44	10.	10.5	.1	.24	
199.	11.756.5	89.5	.45	10.	12.75	0.	.19	
199.	12.258.3	90.	.45	10.	15.0	0.	.17	
199.	12.759.2	90.	.45	10.	14.0	0.	.17	
199.	13.2510.3	90.	.45	10.	13.0	0.	.15	
199.	13.759.4	90.5	.43	9.5	13.5	0.	.17	
199.	14.257.1	91.	.38	9.	14.0	.05	.17	
199.	14.758.5	89.5	.44	8.5	12.25	.1	.16	
199.	15.259.7	88.	.47	8.	10.5	.5	.26	
199.	15.7510.6	88.	.47	8.5	10.5	.2	.22	
199.	16.2511.8	88.	.47	9.	10.5	.1	.25	
199.	16.7511.	86.5	.50	9.	8.75	.3	.14	

CUMBERLAND RIVER SURVEY #4
JULY 17-18, 1971
WEATHER DATA FROM NASHVILLE

51.1								
37.20	85.30	560.		66	BURKSVILLE, KY.			
198.	7.75 5.9	69.5	.83	0.	.94	.40	.375	
198.	8.25 8.4	68.	.78	0.	1.44	.05	.26	
198.	8.75 8.8	74.5	.82	0.	1.79	0.	.28	
198.	9.25 7.8	74.5	.74	0.	1.79	0.	.17	
198.	9.75 8.8	79.	.79	0.	1.72	.05	.34	
198.	10.256.	85.	.6	0.	1.35	0.	.26	
198.	10.756.1	87.5	.53	0.	1.1	0.	.26	
198.	11.256.6	85.	.51	0.	2.22	0.	.26	
198.	11.757.	83.	.59	1.	3.22	0.	.21	
198.	12.255.5	85.	.55	1.	3.19	0.	.14	
198.	12.754.35	83.	.56	1.	2.74	0.	.14	
198.	13.257.2	85.	.69	3.	1.47	.6	.33	
198.	13.754.7	84.	.72	0.	1.18	.05	.25	
198.	14.255.1	85.	.57	0.	2.23	.02	.19	
198.	14.757.1	82.	.62	1.	2.2	.1	.34	
198.	15.258.2	81.	.74	.5	1.43	.05	.32	
198.	15.754.9	84.	.63	.5	1.43	.15	.32	
198.	16.256.3	79.5	.67	0.	1.82	.3	.24	
198.	16.757.6	82.5	.6	0.	1.48	.05	.24	
198.	17.256.1	78.	.79	0.	.6	.05	.26	
198.	17.757.75	73.5	.85	0.	.4	.5	.22	
198.	18.258.2	70.	.95	0.	.35	1.	.26	
198.	18.757.6	69.	.9	0.	.6	1.	.28	
198.	19.256.9	67.	.95	0.	1.26	1.	.28	
198.	19.756.05	65.5	.95	0.	1.51	1.	.42	
198.	20.255.9	65.	.95	0.	1.4	1.	.39	
198.	20.756.3	63.5	.95	0.	1.4	1.	.44	
198.	21.256.7	62.5	.95	1.	1.4	1.	.31	1
198.	21.757.1	62.5	.95	0.	1.4	1.	.34	1
198.	22.257.4	61.5	.95	0.	1.4	1.	.34	1

198.	22.757.2	62.	1.0	0.	1.33	1.	.26	1
198.	23.256.9	60.	.94	0.	.75	1.	.24	1
198.	23.757.8	60.	1.	0.	.14	1.	.41	1
199.	.25 8.6	60.	1.	0.	.25	1.	.28	1
199.	.75 7.9	60.	1.	0.	.76	1.	.17	1
199.	1.25 8.7	60.	1.	0.	1.	1.	.17	1
199.	1.75 10.6	60.	1.	0.	.48	1.	.17	1
199.	2.25 11.4	60.	1.	0.	.2	1.	.26	1
199.	2.75 10.	60.	1.	0.	.16	1.	.26	1
199.	3.25 8.4	60.	1.	0.	.21	1.	.12	1
199.	3.75 7.9	60.	1.	0.	.45	1.	.12	1
199.	4.25 7.75	60.	1.	1.	.37	1.	.17	1
199.	4.75 8.9	61.5	.95	3.	.45	1.	.21	1
199.	5.25 10.	60.5	.98	1.	.83	1.	.42	1
199.	5.75 11.1	60.0	.98	0.	.65	.7	.34	1
199.	6.25 9.85	62.5	.92	0.	.57	.30	.26	1
199.	6.75 6.75	65.	.88	1.	.38	.2	.17	1
199.	7.25 7.2	66.	.83	3.	.24	.15	.17	1
199.	7.75 9.	68.	.86	3.	1.06	.1	.34	1
199.	8.23 9.25	77.	.81	4.	2.2	.05	.23	1
199.	8.75 9.5	83.5	.68	3.	2.43	.05	.22	
199.	9.25 8.3	84.5	.68	3.	2.4	.05	.22	
199.	9.75 6.2	88.	.62	5.	2.36	0.	.22	
199.	10.258.8	86.	.67	5.	1.7	0.	.28	
199.	10.759.	88.	.6	6.	2.71	.1	.33	
199.	11.259.2	87.5	.59	3.	4.36	.1	.24	
199.	11.756.5	83.5	.68	4.	4.72	0.	.19	
199.	12.258.3	83.	.65	4.	5.06	0.	.17	
199.	12.759.2	84.	.62	3.	5.28	0.	.17	
199.	13.2510.3	84.5	.62	2.	5.75	0.	.15	
199.	13.759.4	84.5	.62	7.	5.2	0.	.17	
199.	14.257.1	90.	.53	9.	4.28	.05	.17	
199.	14.758.5	85.	.66	9.	2.56	.1	.16	
199.	15.259.7	81.	.76	9.	.65	.5	.26	
199.	15.7510.6	89.	.64	8.	1.05	.2	.22	
199.	16.2511.8	87.	.48	9.	1.76	.1	.25	
199.	16.7511.	83.	.72	8.	1.9	.3	.14	

WATER TEMPERATURE CUMBERLAND RIVER SURVEY #4

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7. AUTHOR(S) Robert W. Troxler, Jr.and Edward L. Thackston		8. PERFORMING ORGANIZATION REPORT NO.
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15. SUPPLEMENTARY NOTES

16. ABSTRACT

A mathematical model for predicting the change in water temperature in a flowing stream as a function of stream geometry and standard weather information was developed and tested. Five field tests were conducted on cold water released from hydro-power stations as it warmed up moving downstream over periods up to 38 hours.

Predictions of temperature changes were made based on (a) weather data from a boat floating with the water, (b) data from a station on the bank, and (c) data from a remote weather station 100 miles away. Agreement between predicted and observed temperature changes was good, even with remote data, when adjustments to compensate for the local micro-climate were made. Computer programs and all data are included. This report was submitted in fulfillment of Project Number 16130 FDQ, Grant Number R-800613, by Vanderbilt University, Department of Environmental and Water Resources Engineering under the sponsorship of the Environmental Protection Agency. Work was completed as of November 1974.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Water temperature, heat budget, mathematical models, climatology	River temperature prediction	13/13B

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