DYNAMIC STREAM TEMPERATURE MODEL FOR UNSTEADY FLOW

Final report to

National Oceanic and Atmospheric Administration
National Weather Service
Office of Hydrology
Silver Spring
Maryland

David S. Bowles
Larry E. Comer
William J. Grenney

PRWG156
Utah Water Research Laboratory
College of Engineering
Utah State University
Logan, Utah 84322

December 1975

DYNAMIC STREAM TEMPERATURE MODEL FOR UNSTEADY FLOW

Final report to

National Oceanic and Atmospheric Administration
National Weather Service
Office of Hydrology
Silver Spring
Maryland

David S. Bowles
Larry E. Comer
William J. Grenney

PRWG156
Utah Water Research Laboratory
College of Engineering
Utah State University
Logan, Utah 84322

December 1975

ACKNOWLEDGMENTS

The development of the Dynamic Stream Temperature Model (DSTEMP) and its application to the Brazos-Little Rivers, Texas, were accomplished under contract to the Hydrologic Research Laboratory, National Weather Service, National Oceanic and Atmospheric Administration. Field investigations leading to the development of a mathematical submodel for heat transfer processes in the bed of a small stream were carried out under the same contract and are described in a separate report. Special thanks are extended to Dr. Danny L. Fread, who supervised the work for NOAA, and provided guidance throughout the contract period, especially with the adaptation and calibration of the Implicit Dynamic Routing Program (DNRT).

Gratitude is also expressed to those individuals and organizations who provided data for the Brazos-Little application of DNRT-DSTEMP. Particular mention is made of the following: R. J. Pickering, Chief, Quality of Water Branch, USGS, Reston, Virginia; Leon S. Hughes, Chief, Quality of Water Unit, USGS, Austin, Texas; John F. Griffiths, Texas State Climatologist, College Station, Texas; and the National Climatic Center, Asheville, North Carolina. In addition, thanks are estended to Carl Relyea, Hydrologic in Charge, Ohio River Forecast Center, NOAA, Cincinnati, Ohio, who provided data for application of DNRT-DSTEMP to the Ohio River. Although it was not practical to

apply DNRT-DSTEMP to the Ohio during the contract period it is hoped that a future application may make use of the excellent data made available by Mr. Relyea and his colleagues.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

Current interest in stream temperature prediction stems largely from concern for the possible deleterious environmental consequences of thermally polluted surface waters. Stream temperature is an important determinant of the solubility of dissolved gases, biological reaction kinetics, the distribution of fish and lower forms of aquatic life, and the efficiency of water treatment for domestic and industrial use. This report describes the Dynamic Stream Temperature Model (DSTEMP). The model is suitable for prediction of stream temperatures over a diurnal cycle or over extended periods of time. DSTEMP may be used for unsteady flow conditions by linkage with a dynamic streamflow routing model (DNRT). Alternatively steady flow conditions may be specified. Data requirements are realistic in terms of data types usually collected by the National Weather Service, NOAA, and the United States Geological Survey. A users manual for DSTEMP is included in Appendix A. In addition to describing the model an application of DSTEMP to the Brazos-Little Rivers, Texas, is included. The combined DNRT-DSTEMP models provide a powerful tool for streamflow-stream temperature forecasting in a wide variety of streams and river systems.

CHAPTER 1

INTRODUCTION

Temperature is perhaps the single most important parameter in stream water quality. Human activity generally raises natural stream-water temperatures due to impoundments, industrial uses, irrigation, and modifications of topographic features. As a result, higher temperatures reduce the solubility of dissolved oxygen, increase metabolism, respiration, and oxygen demand of aquatic life, intensify many types of toxicity, and promote "less desirable" fish species and aquatic organisms (McKee and Wolf, 1963).

Numerous mathematical models of the mechanisms of heat transfer in streams are now available. In contrast to most of the previous models, the stream temperature model described in this report is dynamic and can be used in conjunction with a dynamic streamflow model. The Dynamic Stream Temperature Model (DSTEMP) may be used for prediction of stream temperatures over a diurnal cycle or over extended periods of time. DSTEMP can be applied to small streams in which streambed heat exchange is important, or it can be applied to large river systems with first order tributaries, thermal discharges, and meteorologic conditions that vary spatially over the river basin. Data requirements are realistic in terms of data types usually collected by the National Weather Service, NOAA, and the United States Geological

Survey. A complete description of DSTEMP, its capabilities, and formulation is contained in Chapter 3. Appendix A includes a description and examples of the input requirements of DSTEMP.

In Chapter 4 an application of DSTEMP to the Brazos-Little River System, Texas, is presented. A 12 hour computational time interval is used for the simulation of a storm of 23 days duration. As part of the same research project DSTEMP was used to represent the diurnal variation of stream temperatures on a small mountain stream, Spawn Creek, Utah. Full details of this application are contained in Comer et al. (1975). An example of the DSTEMP input and output for the Spawn Creek study is contained in Appendix A. Another hypothetical example of a main river and tributary system is also included in Appendix A.

Chapter 3 contains a literature review of previous stream temperature models. Conclusions and suggestions for further work are presented in Chapter 5.

CHAPTER 2

REVIEW OF LITERATURE

Stream temperature models

The basis of most water quality modeling is the one-dimensional conservation of mass equation. This partial differential equation includes transport processes of advection and dispersion, and additional source-sink terms. A common form of the one-dimensional conservation equation is:

$$\underset{(a)}{\frac{\delta(AC)}{\delta t}} + \underset{(b)}{\frac{\delta(AUC)}{\delta x}} = \frac{\delta}{\delta x} \underset{(c)}{AE_L \frac{\delta C}{\delta x}} + \underset{(d)}{S} \quad . \; . \; . \; . \; . \; . \; . \qquad 2.1$$

in which

A = Cross-sectional area of channel

E_L = Longitudinal dispersion coefficient

U = Mean stream velocity at cross-section

x = Coordinate in downstream direction

t = Time

and where term (a) is rate of mass change, term (b) is advection, term (c) is dispersion, and (d) is a source-sink term(s) which is usually the distinguishing term among various simulation equations.

C represents the concentration of constituents and with regard to temperature modeling, can be replaced by T, water temperature.

Several assumptions are made with the use of the advection dispersion equation, one of which is one-dimensionality. One-dimensional simulations assume complete and total mixing so that temperature is uniform at any given cross-section. In a turbulent stream, total mixing is considered a reasonable assumption. The source-sink term for temperature is typically based on the thermal energy conservation or heat balance approach. Much of the thrust of past temperature modeling has been directed toward refinement or simplification of the thermal energy budget.

Further assumptions and simplifications are often made in model development to facilitate ease of use and solution, and to minimize the complexity of input data required. Additional variations are sometimes made to fit local situations or specific meteorologic conditions.

Summaries of several existing stream temperature models are presented in Table 2.1 with accompanying discussion focusing on the uniqueness of each model. The tabular format of the summary associates similarities in model components and reduces the erratic and conflicting notation found in literature into a common set of terms.

Table 2.1. Summary of stream water temperature models (notation explained on following pages).

Harper (1972)	
General Equation	$\frac{\partial T}{\partial t} + U \frac{\partial T}{\partial x} = \frac{\partial^2 T}{\partial x^2} + \frac{\phi_T}{C_p \gamma h}$
Energy Budget (Heat Balance)	$\phi_T = \phi_R - (\phi_B + \phi_E + \phi_H)$
Solar Radiation, ϕ_R	$\phi_R = f(\alpha, L, C)$ (Raphael, 1962) or Direct Observation
Evaporation, ϕ_E	$\phi_E = K_E U_a (e_s - e_a)$
Back Radiation, ϕ_B	$\phi_B = 0.79\sigma(T_w^4 - \beta T_a^4)$
Conduction, ϕ_H	$\phi_H = K_H UP(T - T_a)$
Streambed Heat Transfer, ϕ_{SB}	Assumed negligible
Other Terms	Tributaries--$T_B = \frac{QT + Q_{in} T_{in}}{Q + Q_{in}}$
	Steady flow, uniform cross-section, constant dispersion coefficient
Dailey and Harleman (1972)	
General Equation	$\frac{\partial}{\partial t}(A\ T) + \frac{\partial}{\partial x}(QT) = \frac{\partial}{\partial x}\left(AE_L \frac{\partial}{\partial x} T\right) - K_T A \Delta T_E + S$
	Nonuniform cross-sections, steady flow
Harleman et al. (1973)	
General Equation	$\frac{\partial}{\partial t}(AT) + \frac{\partial}{\partial x}(QT) = \frac{\partial}{\partial x}\left(AE_L \frac{\partial T}{\partial x}\right) + \frac{b\phi_T}{\rho C} + \frac{WHD + THD}{\rho\ C_p}$
Energy Budget (Heat Balance)	$\phi_T = \phi_{RI} - \phi_{RR} + \phi_a - \phi_{ar} - \phi_E - \phi_H$
	$\phi_T = \phi_R \{4 \times 10^8 (T_s + 460^4) + f(U)\{(e_s - e_a)\} + 0.255 (T_s - T_a)\}\}$

Table 2.1. Continued.

Harleman et al. (1973) Continued.	
Energy Budget (Heat Balance) (Continued)	$\phi_T \simeq -K\ (T_s - T_E)$
Solar Radiation, ϕ_R	$\phi_R = \phi_{RI} - \phi_{RR}$ (Same as Harper, 1973)
Evaporation, ϕ_E	$\phi_E = f(U)\ (e_s - e_a)$
Back Radiation, ϕ_B	$\phi_B = \phi_{bs} - \phi_a + \phi_{ar}$ WHERE $\phi_a = 1.2 \times 10^{-13}\ (T_a + 460)^6 (1 + kC^2)$ $\phi_{ar} = 0.03\ \phi_a,\ \phi_{bs} = 4.0 \times 10^{-8}\ (T_s + 460)^4$
Conduction, ϕ_H	$\phi_H = R\phi_E$ WHERE $R = 0.255 \left\lvert \frac{T_s - T_a}{e_s - e_a} \right\rvert$
Streambed Heat Transfer, ϕ_{SB}	Neglected due to generally low thermal conductivity of earth and limited temperature gradients
Other Terms	Heat Discharges-- $\frac{WHD + THD}{\rho C}$ Nonuniform cross-sections, unsteady flow
Novotny and Krenkel (1971)	
General Equation	$\frac{\partial T}{\partial t} + U \frac{\partial T}{\partial x} = E_L \frac{\partial^2 T}{\partial x^2} + \frac{K_a}{hC_p\rho} (\Delta T_E)$
Energy Budget (Heat Balance)	$\phi_T = \phi_{RI} - \phi_{RR} - \phi_a - \phi_{ar} - \phi_{bs} - \phi_E - \phi_H - \phi_W$
Streambed Heat Transfer, ϕ_{SB}	Assumes all thermal input at the air water interface
Other Terms	$K_a = 11.42 + h_v\ (0.0166e^{.0625T_a} + \rho_a\ C_{pa})$ WHERE $h_v = 392 \times {}^{-0.1}\ U_s$ Uniform cross-sections, steady flow, surface temperature differs from bulk

Table 2.1. Continued.

Pailey et al. (1974)	
General Equation	$\frac{\partial T}{\partial t} + U\frac{\partial T}{\partial x} = E_L \frac{\partial^2 T}{\partial x^2} + \frac{f(T)}{h\rho C_p}$
Energy Budget (Heat Balance)	$\phi_T = \phi_R - (\phi_B + \phi_E + \phi_H + \phi_S)$
	$\phi_T = -(\varepsilon T + \eta)$
Solar Radiation, ϕ_R	$\phi_R = \phi_{RI} - \phi_{RR}$ WHERE
	$\phi_{RI} = \phi_{CL}\{.35 + 0.61(10 - C)\}$
	$\phi_{RR} = 0.108\ \phi_{RI} - 6.766/10^{-5}\phi_{RI}{}^2$
Evaporation, ϕ_E	$\phi_E = \frac{\phi_H}{R}$ WHERE $R = 6.1 \times 10^{-4}\ \rho\left(\frac{T_w - T_a}{e_s - e_a}\right)$
Back Radiation, ϕ_B	$\phi_B = \phi_{bs} - \phi_a + \phi_{ar}$ WHERE $\phi_{bs} = .97\phi T_w{}^4$
	$\phi_a = (a + b\ e_a)\ \phi\ T_a{}^4$, $\phi_{ar} = 0.03\phi_a$
Conduction, ϕ_H	$\phi_H = \{8 + 0.35(T_w - T_a) + 3.9U_a\}\ (T_w - T_a)$
Streambed Heat Transfer, ϕ_{SB}	Not mentioned
Other Terms	$\phi_{sm} = 7.85v^{2.375}\ \{L + C_i\ (T_w - T_a)\}$
	Complete mixing, uniform cross-sections, steady flow
Brown (1965)	
General Equation	$\Delta T_{PR} = \frac{A_s \times \phi_T}{Q}\ (0.000267)$
Energy Budget (Heat Balance)	$\phi_T = \phi_{NR} \pm \phi_E \pm \phi_C \pm \phi_H \pm \phi_A$
Solar Radiation, ϕ_R	Net Radiation: $\phi_{NR} = \phi_R - \phi_B$ (Measured directly)
Evaporation, ϕ_E	$\phi_E = K_E L\ U_a\ (e_s - e_a)$
Back Radiation, ϕ_B	Accounted for in ϕ_{NR}

Table 2.1. Continued.

Brown (1965)	
Conduction, ϕ_H	$\phi_H = 0.0002\ U\ P(T - T_a)$
Streambed Heat Transfer, ϕ_{SB}	$\phi_{SB} = K_{SB}\ (dT/dz)$ Up to 25% ϕ_{NR} absorbed
	Steady flow, no tributary sources, no groundwater
Brown (1972)	
General Equation	$\Delta T_{PR} = \frac{A_s \times \phi_{NR}}{Q}\ (0.000267)$
Energy Budget (Heat Balance)	$\phi_T \approx \phi_{NR}$
Solar Radiation, ϕ_R	ϕ_{NR} Measured directly or obtained graphically
Streambed Heat Transfer, ϕ_{SB}	About 20% ϕ_{NR} transferred to streambed (bedrock)
Other Terms	Non-flowing water not included in A_s
Assumptions	Steady flow, no tributaries, no groundwater $\phi_{NR} \approx 0.95\ \phi_T$
Morse (1972a)	
General Equation	$\frac{\partial T}{\partial t} + U \frac{\partial T}{\partial x} = \frac{\phi_T}{C_p \rho h}$
Energy Budget (Heat Balance)	$\phi_T = A''T^2 + B''T + C''$ A'', B'', and C'' from monthly averaged meterologic data
Streambed Heat Transfer, ϕ_{SB}	Neglected
Other Terms	ϕ_T found as a function of statistical constants A'', B'', and C''.
	Dispersion neglected, variable cross-sections, meteorological records "typical"

Table 2.1. Continued.

QUAL-1 (Texas Water Development Board) (1971)	
General Equation	$A \frac{\partial T}{\partial t} = \frac{\partial \left(A\ E_L \frac{\partial T}{\partial x}\right)}{\partial x} - \frac{\partial (A\ U\ T)}{\partial x} \pm \frac{A\phi_T}{\gamma C_p h}$
Energy Budget (Heat Balance)	$\phi_T = \phi_R + \phi_a - (\phi_B \pm \phi_H + \phi_E)$
Solar Radiation, ϕ_R	$\phi_R = \phi_{RI}\ a_t (1 - R)\ (1 - 0.65\ C^2)$
Evaporation, ϕ_E	$\phi_E = \gamma L\ (a + bU)\ (e_s - e_a)$
Back Radiation, ϕ_B	$\phi_B = \sigma(T_s + 460)^4$
Conduction, ϕ_H	$\phi_C = \phi_E(0.01\ R)$ WHERE $R = \frac{P}{29.92}\ \frac{(T_s - T_a)}{(e_s - e_a)}$
Streambed Heat Transfer, ϕ_{SB}	Considered groundwater heat input but conduction relatively insignificant compared to ϕ_T
Other Terms	$\phi_a = (2.89 \times 10^{-6})\ \sigma\ (T_a + 460)^6\ (1 + 0.17C^2)$ $(1 - .03)$
	Complete mixing, variable cross-section, variable dispersion coefficient
Bowles et al. (DSTEMP)	
General Equation	$\frac{\partial}{\partial t}(AT) + \frac{\partial}{\partial x}(QT) = \frac{\phi_{TS}\ w}{\rho c_p} + \frac{\phi_{SB}\ W}{\rho c_p} + Q_\ell T_\ell + q_g T_g W + q_r T_r w - q_e T_w$
	$\phi_{TS} = C_1 + C_2\ T$
	$\phi_{SB} = C_3 + C_4\ T$
Energy Budget (Heat Balance)	$\phi_{TS} = (\phi_{RI} - \phi_{RR}) + (\phi_v - \phi_{rr})\ (\phi_a - \phi_{ar}) - \phi_{bs} - \phi_E + \phi_H - \phi_s - \phi_W$
	$\phi_{SB} = \phi_{sb} + \phi_{bb} + \phi_{cb}$

Table 2.1. Continued.

Bowles et al. (DSTEMP) (Continued)	
Solar Radiation, ϕ_R	$\phi_R = f(\alpha, R_g, R, d_p, C)$ (Wunderlich, 1972) or by parabolic distribution of observed solar radiation between sunrise and sunset or by direct use of observed solar radiation
Vegetative Radiation, ϕ_v	$\phi_v = \sigma(T_a + 460)^4$ (Pluhowski (1970) $\phi_{vr} = R_\ell \phi_v$
Atmospheric Radiation, ϕ_a	$\phi_a = \beta\, \sigma(T_a + 460)^4$ (Raphael (1962) $\phi_{ar} = R_\ell \phi_a$
Back Radiation, ϕ_{bs}	$\phi_{bs} = 0.97\, \sigma(T + 460)^4$ (Anderson (1954)
Evaporation, ϕ_E	$\phi_E = \rho\, L\, K_E\, U_a\, (e_s - e_a)$ (Wunderlich (1972)
Conduction, ϕ_H	$\phi_H = 0.217\, (T - T_a)\, P\, \rho\, L\, K_H\, U_a$ (Bowen (1926)
Melting Snow, ϕ_s	$\phi_s = q_r\, \rho[L_f + c_s\, (T - T_r)]$
Surface Layout Renewal, ϕ_w	$\phi_w = 3.96 \times 10^4\, K_w \left(\frac{U}{h}\right)^{0.33} (T_s - T)$ (Novotny and Krenkel (1971)
Streambed Solar Radiation, ϕ_{sb}	$\phi_{sb} = 0.4\, (1 - R_b)\, \phi_R \exp(-zh)$
Streambed Back Radiation, ϕ_{bb}	$\phi_{bb} = \varepsilon\, \sigma\, (T_b + 460)^4$
Streambed Conduction, ϕ_{cb}	$\phi_{cb} = \alpha_1 + \alpha_2\, \phi_{sb} + \alpha_3\, T_g + \alpha_4\, T$ (Comer et al. (1975)
Other Terms	Point Loads $T_B = \dfrac{Q\, T + Q_{in}\, T_{in}}{Q + Q_{in}}$ Unsteady flow from Implicit Dynamic Routing Program (Fread, 1973), variable cross-sections, tributaries, point and diffuse thermal loads, variable meteorologic data across stream system, dynamic representation of temperature, dispersion neglected

NOTATION FOR TABLE 2.1.

(Units: H = heat, ℓ = length, m = mass, T = temperature, t = time)

A	=	Cross-sectional area of channel	ℓ^2
A''	=	Quadratic coefficient (Morse, 1972a)	
A_s	=	Surface area	ℓ^2
a, b	=	Long-wave radiation constants, a function of cloud height	
a_t	=	Atmospheric transmission	
B''	=	Linear coefficient (Morse, 1972a) . . .	
C	=	Cloud cover in tenths	
C''	=	Constant (Morse, 1972a)	
$C_{1,2,3,4}$	=	Coefficients (DSTEMP)	
c_i	=	Specific heat of ice	$Hm^{-1}T^{-1}$
c_p	=	Specific heat of water	$Hm^{-1}T^{-1}$
c_s	=	Specific heat of ice	$Hm^{-1}T^{-1}$
d_p	=	Total dust depletion coefficient of atmosphere	
$\frac{dT}{dz}$	=	Streambed temperature gradient	$T\ell^{-1}$
F_L	=	Longitudinal dispersion coefficient . . .	

e_a	=	Vapor pressure of ambient air	
e_s	=	Saturation vapor pressure of air . . .	
$f(U)$	=	Wind speed function for heat flux (energy/ area·time·time·p)	
g_r	=	Precipitation	ℓ
h	=	Mean depth of flow	ℓ
k	=	Coefficient of thermal diffusion . . .	
K	=	Overall heat transfer coefficient . . .	ℓt^{-1}
K_a	=	Vapor-transfer coefficient in boundary layer	ℓt^{-1}
K_E	=	Evaporation heat-transfer coefficient .	ℓt^{-1}
K_H	=	Convection heat-transfer coefficient . .	
K_{SB}	=	Thermal conductivity of streambed material	
K_w	=	Coefficient of thermal conductivity of water	$H\ell^{-1}t^{-1}T^{-1}$
L	=	Latent heat of vaporization	
L_f	=	Latent heat of fusion	Hm^{-1}
P	=	Atmospheric pressure	$m\ell^{-2}$
Q	=	Mean stream discharge	$\ell^3 t^{-1}$
Q_{in}	=	Discharge of tributary or point load . .	$\ell^3 t^{-1}$
Q_ℓ	=	Rate of surface lateral inflow	$\ell^2 t^{-1}$

q_e	=	Evaporation	ℓ
q_g	=	Rate of groundwater lateral inflow . . .	ℓt^{-1}
R	=	Albedo of the water surface to short-wave radiation	
R_b	=	Albedo of streambed to solar radiation . .	
R_g	=	Albedo of ground adjacent to stream to short-wave radiation	
R_ℓ	=	Albedo of water surface to long-wave radiation	
S	=	Thermal energy source-sink term . . .	
T	=	Water bulk temperature	T
T_a	=	Air temperature	T
T_b	=	Temperature of streambed interface . . .	T
T_B	=	Boundary temperature found by mass balance	T
T_E	=	Equilibrium	T
ΔT_E	=	$(T - T_E)$	T
T_g	=	Temperature of groundwater lateral inflow	T
T_ℓ	=	Temperature of surface lateral inflow . .	T
ΔT_{PR}	=	Predicted temperature	T
T_r	=	Wet-bulb temperature	T

T_s	=	Water surface temperature	T
T_w	=	Water temperature	T
THD	=	Tributary heat discharge	
U	=	Mean stream velocity	ℓt^{-1}
U_a	=	Wind velocity	ℓt^{-1}
v	=	Visibility	ℓ
w	=	Top width of stream	ℓ
W	=	Wetted perimeter of stream	ℓ
WHD	=	Waste heat discharge	
X	=	Distance downstream	ℓ
Z	=	Bulk extinction coefficient	ℓ^{-1}
α	=	Solar altitude	
$\alpha_{1,2,3,4}$	=	Regression coefficient (Comer et al., 1975) .	
β	=	Raphael's coefficient for long-wave radiation computation	
γ	=	Specific weight of water	
ρ	=	Density of water	$m\ell^{-3}$
ϵ	=	Heat exchange coefficient	
η	=	Base heat exchange rate	
σ	=	Stefan-Boltzman constant	
ϕ_a	=	Incoming long-wave radiation	$H\ell^{-2}t^{-1}$
ϕ_{ar}	=	Reflected long-wave radiation	$H\ell^{-2}t^{-1}$

ϕ_B	=	Back radiation heat flux	$H\ell^{-2}t^{-1}$
ϕ_{bb}	=	Back radiation heat flux emitted by streambed	$H\ell^{-2}t^{-1}$
ϕ_{bs}	=	Long-wave radiation for water surface . .	$H\ell^{-2}t^{-1}$
ϕ_{cb}	=	Conductive heat flux across streambed . .	$H\ell^{-2}t^{-1}$
ϕ_E	=	Evaporation heat flux	$H\ell^{-2}t^{-1}$
ϕ_H	=	Conductive heat flux	$H\ell^{-2}t^{-1}$
ϕ_r	=	Heat flux by surface layout renewal . . .	$H\ell^{-2}t^{-1}$
ϕ_R	=	Short-wave radiation heat flux	$H\ell^{-2}t^{-1}$
ϕ_{RI}	=	Incident short-wave radiation	$H\ell^{-2}t^{-1}$
ϕ_{RR}	=	Reflected short-wave radiation.	$H\ell^{-2}t^{-1}$
ϕ_s	=	Heat transfer during melting snow . . .	$H\ell^{-2}t^{-1}$
ϕ_{sb}	=	Short-wave radiation heat flux absorbed by streambed	$H\ell^{-2}t^{-1}$
ϕ_{SB}	=	Streambed heat transfer	$H\ell^{-2}t^{-1}$
ϕ_T	=	Total heat flux	$H\ell^{-2}t^{-1}$
ϕ_{TS}	=	Total surface heat transfer	$H\ell^{-2}t^{-1}$
ν	=	Vapor-transfer coefficient in air boundary layer	ℓt^{-1}

A Multi-Parametric Mathematical Model of Water Quality by Harper (1972) was based on the basic advection-dispersion equation with the addition of a source-sink term, S(x, t), which varied for each water quality parameter considered (see Table 2.1).

For stream temperature, the source-sink term was:

$$S_t = \frac{\phi_T}{c_p \gamma h} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad 2.2$$

in which

S_t = Rate of change in temperature

ϕ_T = Net heat transfer, positive if net flow of heat is to the water

h = Mean depth of flow at cross-section

c_p = Isobaric specific heat of water

γ = Unit weight of water

Net heat transfer components considered were incident solar radiation (ϕ_R), conducive heat transfer (ϕ_H), effective back radiation (ϕ_B), and evaporative heat transfer (ϕ_E). Equations for estimation of these components were provided, except for incident solar radiation. Harper suggested that solar radiation should be measured directly or calculated as a function of solar altitude, site latitude, and cloud cover, as reported by Raphael (1962).

An additional source-sink term for advective sources includes point loads, tributaries, and groundwater inflow. A simple mass balance ratio was used to define a new boundary temperature and discharge. By dividing the modeled stream into reaches of constant physical and dynamic characteristics, such as cross-sectional area, discharge, and dispersion coefficients, and using these variables as new boundary conditions, the simulation equation may be further simplified. Harper assumed steady flow, uniform cross-sectional area, and a constant dispersion coefficient while employing these boundary condition techniques.

Other possible sources and sinks which are assumed negligible are heat transfer to the ground, internal heat generated by chemical and biological reactions, and friction losses.

A model developed by Dailey and Harleman (1972) is divided into two parts: a hydraulic submodel, and a water quality submodel which includes a temperature component (see Table 2. 1). Due to several shortcomings, this model was later modified (Harleman et al., 1973). Apart from a deficient derivation of terms in the temperature equation, the 1972 model failed to allow for variations in flow characteristics and variability of meteorological conditions. Harleman et al. (1973) stated that the earlier model was valid for temperature only when lateral inflow was zero.

In terms of the developed equation, the new model of Harleman et al. differs from the Dailey and Harleman (1972) model by only a flux term ϕ_T. Rather than using the linearized simplification of the surface heat flux, ϕ_T was calculated at each mesh point and time step by the following equation:

$$\phi_T = \phi_R - \{4x10^8 \, T_s + 460)^4 + f(U_a)\,[(e_s - e_a) + .255\,(T_s - T_a)]\} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; 1.3$$

Harleman et al. (1973) also used the equilibrium temperature concept, developed by Edinger and Geyer (1965). They defined the equilibrium temperature T_E as the temperature at which, under a given set of meteorological conditions, the net surface heat flux is equal to zero. Equilibrium temperature may be found by substituting T_E for T_S in Equation 2.3 and $\phi_T = 0$. Jobson and Yotsukura (1972) concluded that the introduction of the equilibrium temperature concept has been unnecessary and inconvenient due to its dependence on trial-and-error solution, error from the linearization effect of T_E, and inadequacy in predicting diurnal fluctuations.

Also included in this model are source terms allowing for waste heat discharge (WHD) and tributary heat discharges (THD). Development of net surface heat flux (Equation 2.3) was made under the assumption that radiation, convection, and evaporation are several orders of magnitude higher than other possible sources or sinks, such as heat fluxes via evaporated water and direct rainfall. Of particular interest is the rationale used for neglecting stream bed heat transfer:

> Heat transfer between a body of water and the environment can occur through the free surface and through the bottom and sides. In the latter case, the heat flux is limited by conduction in the adjacent soil and remains very small because of generally low thermal conductivity of earth and because the temperature gradients are limited. (Harleman et al., 1973, p. 89)

A model by Novotny and Krenkel (1973) describes the dynamic nature of the air-water interface of a turbulent river (see Table 2.1). It is assumed that the primary mechanism of heat transfer is turbulent motion of the water surface. Also, it is stressed that the water surface temperature is different from the bulk temperature. Timofeyev and Malevskiy-Malevich (1967) report that the difference may be as great as several tenths of a degree Celsius.

Novotny and Krenkel (1973) develop a thermal energy budget under the assumption that all thermal energy acts on the air-water interface. Heat transfer across the stream bed-water interface is not considered. Pailey et al. (1974) developed a closed-form solution of the unsteady one-dimensional advection-diffusion equation for temperature distributions downstream from a thermal load input (see Table 2.1). Rigorous solution of the conservation of thermal energy equation was made by assuming complete mixing, uniformity of stream cross-section, discharge, and diffusion coefficient, and linearity of surface heat exchanges. Pailey et al. (1974) state that the surface heat exchange term ϕ_T can be expressed as a linear function of the mixed temperature of the stream, without significant loss of accuracy. The linear relation is given as

$$\phi_T = -(\epsilon T + \eta) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad 2.4$$

where η = the base heat exchange rate corresponding to a stream temperature of $0^{\circ}C$; T = stream temperature in $^{\circ}C$; and ϵ = a heat exchange coefficient. Values for ϵ and η for various wind velocities, relative humidities, and air and stream temperatures are determined by approximate relations given by Dingman and Assur (1967). Correlation coefficients of at least 0.999 were found between the derived linear relation and the more involved energy budget.

Also presented are the linear relations of the equilibrium temperature model by Edinger and Geyer (1965) and an excess temperature model by Jobson and Yotsukura (1972).

Pailey et al. (1974) state that heat dispersed in a receiving water is eventually transferred to the atmosphere by evaporation, radiation, or by conduction as sensible heat. "There may be some transfer of heat at the soil-water interface due to infiltration of river water into the ground. The amount of heat transferred by diffusion and dispersion in the porous media, however, is generally very small and may be neglected." (p. 531)

The stream temperature submodel of QUAL-1 (Texas Water Development Board, 1971) is also based on the general heat budget equation (see Table 2.1). Net solar and atmospheric radiation are found analytically from basic input such as cloud cover, latitude, sun declination, air temperature, wind speed, and relative humidity. Minimal input requirements make QUAL-1 a valuable management tool.

The dynamic character of QUAL-1 is evidenced by the fact that it allows stream cross-section and longitudinal dispersion coefficients to vary with distance downstream. This permits the stream to be broken into discrete reaches of similar characteristics, allowing varying degrees of resolution. Subdivision of the stream into reaches allows more accurate handling of tributaries and inflows by redefining reach boundary conditions.

The authors of QUAL-1 state that the model considers "all heat transferred across the mud-water interface. In the absence of groundwater flow, heat is transported across the mud-water interface only by molecular conduction which is relatively insignificant in comparison to surface heat exchange." (Texas Water Development Board, 1971, p. 14)

A model by Morse (1970) ignores the second order dispersion term in the traditional conservation of energy equation and thus provides for an exact solution to the following equation:

$$\frac{\partial T}{\partial t} + U\frac{\partial T}{\partial x} = \frac{\phi_T}{C_p \rho h} \quad \ldots\ldots\ldots\ldots\ 2.5$$

The energy budget term ϕ_T is found by a statistical technique applied to local meteorological data. Solution of this model requires a minimal amount of data input: backwater profiles, discharge, and cross-sectional areas and widths. Heat exchange with the bottom and sides of the river is neglected.

In his stream temperature models Brown (1969, 1972) considers streambed heat transfer (see Table 2.1). Brown (1969, p. 74) states that "the phenomenon of bottom conduction, such as that measured on the rock-bottomed stream of the H. J. Experimental Forest, has not been considered elsewhere."

Brown's prediction equation is not dynamic, but is concerned with the temperature change in a small stream when exposed to sunlight as a result of clear-cutting of trees which formerly provided shading to the stream. The 1969 model has the form:

$$\Delta T_{PR} = \frac{A_s \ \phi_T}{Q} (0.000267) \quad \ldots \quad 2.6$$

where ΔT_{PR} is predicted temperature change after traveling through a given stream reach, A_s is surface area of the study section, Q is discharge, ϕ_T is change in the thermal energy budget, and the 0.000267 term is a proportionality constant which converts cfs to lb.water/min. so that Btu's may be expressed as change in ^oF. The energy budget ϕ_T is comprised of source and sink equations found throughout literature, but in addition, includes the streambed heat transfer term:

$$\phi_{SB} = K_{SB} \frac{dT}{dz} \quad \ldots \quad 2.7$$

where ϕ_{SB}, the heat transfer through the streambed is equal to the product of K_{SB}, the streambed material thermal conductivity, and dT/dz, the streambed temperature gradient. The bed transfer term is a function of conduction only and did not consider heat transport due to groundwater inflow.

Brown (1969) measured temperature gradients in streambeds of gravel and bedrock materials by the use of copper-constantan thermocouples placed at 1 cm intervals but at an unspecified depth. Thermocouples were simply inserted into the streambed of two gravel streams. The temperature gradient in bedrock material was found by removing boulders similar to the streambed, fitting them with thermocouples, and then placing them in water baths which simulate stream temperatures. Although the bedrock measurements were not *in situ*, Brown concluded that up to 25 percent of the energy absorbed by a bedrock bottom stream may be transferred to the bed. No consideration was given to the fate of this thermal energy. Brown (1969, p. 74) concluded that:

> Consideration of this energy budget component was essential for accurate temperature prediction. The rock acted as an energy sink during midday hours and as an energy source later in the day. In contrast, gravel bottoms seem to be insignificant energy sinks. Although temperature gradients were measured in the gravel-bottomed stream, thermal conductivities of the water-gravel mixture, approximately 0.05 Btu/ft^2-inch-min ^{o}F, were too low to provide any heat exchange that noticeably affected the predictions.

In later work, Brown (1970) simplified the temperature change equation by reducing the energy budget ϕ_T to net radiation, ϕ_{NR}. Rationale for this simplification was the observation that, for the stream studied, 95 percent of the heat input during the midday period of midsummer was accounted for by solar radiation. Streambed conduction was not included in this less sophisticated model.

The simplified model was the forerunner to an improved temperature prediction model for small streams (Brown, 1972). This study included further observations of streambed conduction. Thermocouples were placed at 1 cm vertical intervals and at an unspecified depth in gravel bottomed streams and in a bedrock boulder, but on this occasion the boulder was returned to the stream.

Results of this study showed gravel-bottomed streams to be effectively isothermal in the upper 20 cm layer. Gradients of $0.05^{\circ}C/cm$ or less were observed between the 5 cm layer and the surface. A maximum gradient of $1.1^{\circ}C$ was observed between the 20 cm layer and the surface. Midday temperature gradients of $0.45\ ^{\circ}C/cm$ were observed in the upper layers of the bedrock. This was about 18 percent of the incoming heat load. Preliminary results from a probe in the gravel bed of Spawn Creek also show isothermal conditions in the upper zone. However, below this zone a significant temperature gradient was observed.

Brown (1972) considered that the isothermal conditions in the top 20 cm of the gravel streambed was due to the free circulation of surface water within this layer because of its open porous nature. He concluded that conductive heat transfer is restricted by point-to-point contact between gravel particles together with the efficient heat transfer between particles and the circulating intergravel water.

Brown (1972) concluded that in bedrock bottom streams, 15 to 20 percent of the net all-wave radiation absorbed by the stream may be lost to the bed. On this basis the magnitude of predicted temperature was reduced by 15 to 20 percent.

Meteorologic considerations

Past models of stream temperature have considered solar radiation to be the major component of the energy budget. In addition, it is often assumed that radiation is completely absorbed at the air-water interface (Edinger et al., 1968; Edinger and Geyer, 1965; Parker and Krenkel, 1969). This may be valid for deep, turbid rivers, but this assumption is false for clear, shallow streams (Pivovarov, 1973; Viskanta and Toor, 1972). Some investigators recognized transmission of solar energy through water, but considered its effect equilibrated over depth by turbulence (Novotny and Krenkel, 1973).

This is a sound assumption in turbulent streams, but it ignores the fate of radiation which is transmitted to and absorbed by the stream bottom.

The amount of radiant energy which penetrates the water surface depends on surface albedo, as well as water clarity. Primary factors determining albedo are sun elevation, cloud cover, and physical character of the surface. Water has a relatively low albedo which varies from 3 percent to 10 percent (Dake and Harleman, 1969). The net solar radiation reaching the water surface is:

$$\phi_o = (1 - \text{albedo})\,\phi_s \quad . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \quad 2.8$$

where ϕ_s is the total solar radiation reaching the surface.

Pivovarov (1973) gives a simplified formula for calculating albedo under clear skies and medium surface turbulence as

$$\text{Albedo} = \frac{a}{\sin h_o + a} \quad . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \quad 2.9$$

where a = 0.04 is an empirical parameter and h_o is sun elevation in degrees. This equation, however, is not valid for low solar angles. Absorption and scattering of radiant energy water varies with wavelength, and the attenuating properties vary with depth. Pivovarov notes that the attenuation factor η, varies greatly in the top water layers where the majority of red and infrared radiation is absorbed, and gives a table of values for η for various depths and water bodies. The bulk of the radiant energy which penetrates the surface is attenuated within the first meter depth and is therefore very important in shallow streams. Below this depth, water is penetrated mostly by the visible spectrum.

A function which is commonly given to estimate radiation adsorption with water depth is the exponential

$$\phi_{(z)} = (1-\beta)\,\phi_o\, e^{-\eta z}, \text{ for } z > 0 \quad . \; . \; . \; . \; . \; . \; . \; . \quad 2.10$$

in which

$\phi_{(z)}$ = Absorbed radiation

z = Depth below water surface

β = Proportion absorbed at water surface (≈ 0.60)

ϕ_o = Net solar radiation reaching surface

η = Attenuation factor (Dake and Harleman, 1969).

It is easily seen that using this equation, significant portions of the incident solar radiation could penetrate to the stream bottom, especially in shallow streams ($z \leq 1.0$ m).

A model developed by Viskanta and Toor (1972) predicts the internal absorption of solar radiation in natural waters using exact radiative transfer theory. The development considers absorption, scattering, and transmission to and reflection from the bottom.

The streambed is considered to be a diffuse reflector of radiation. Reflectance of the bottom material is assumed to be gray (independent of wavelength) and equal to $0 < \rho < 1$ where $\rho = 1$ is a perfectly reflecting bottom and $\rho = 0$ is a perfectly absorbing bottom.

In the case of a perfectly reflecting bottom ($\rho = 1$), the rate of internal absorption of water is increased, but in cases when $\rho < 1$, which is most often the case in natural waters, the portion which is absorbed by the bed (not reflected) is neglected in this model. However, through interpretation of their graphic results, nearly 50 percent of the total flux incident on the water surface is absorbed by the bottom when $\rho = 0$ and depth is 1 meter, and 25 percent of the total flux is absorbed by the bottom when $\rho = 0.5$.

CHAPTER 3

DYNAMIC STREAM TEMPERATURE MODEL DESCRIPTION

Introduction

The Dynamic Stream Temperature Model (DSTEMP) described in this chapter is designed to be used in conjunction with a flood routing technique (DNRT) developed by the Hydrologic Research Laboratory of the National Weather Service, National Oceanic and Atmospheric Administration. Stream geometry and streamflow data generated by the Implicit Dynamic Routing Program (DNRT) (Fread, 1973; Fread, 1974) are used in the temperature model, DSTEMP. Alternatively, these stream geometry and streamflow data may be input directly to DSTEMP without using DNRT. Program capabilities, model formulation, and numerical solution are described below. The various heat exchange processes acting over the air-water and soil-water interfaces are represented by mathematical submodels described in this chapter. A flowchart, input data and decision parameters description, program listing, and two examples of input and output are contained in the DSTEMP Users Manual (Appendix A).

Program Capabilities

DSTEMP can be applied to the prediction of mean daily stream temperatures or to the prediction of the diurnal variation of stream temperatures. Time and space steps in DNRT and DSTEMP are specified by the user. Successive time steps need not be of equal length. Also subreaches of different lengths can be specified. The program is structured in a flexible manner so that individual components of heat transfer across the stream boundaries can be omitted through user options. Lack of data may necessitate the use of this option for streambed conduction, for example. A choice between three alternative techniques of calculating incident and solar radiation flux at the stream surface is provided. These techniques range from the direct use of observed data, to the calculation of solar radiation flux from meteorologic and astronomical data. The calculation approach requires some coefficient estimation before it can be applied but in return it takes account of local factors affecting solar radiation. A separate subroutine is used to calculate each component of net heat transfer at the stream surface and streambed. Therefore, a technique currently used to estimate one of the heat transfer components may be readily replaced by another technique without changing the main program unless new data requirements are introduced.

Two important features of the meteorologic data requirements are the use of meteorologic data sets and meteorologic time intervals that differ from the computational time intervals. A meteorologic data set comprises a complete set of data for all the meteorologic variables required in DSTEMP. Several meteorologic data sets may be used for modeling a stream system. Each data set is applied to a different group of subreaches for which the observed meteorologic data in the data set are considered representative. Meteorologic data are often available on a daily basis whereas the computational time interval for a diurnal study may be 3 hours, for example. By specifying the ratio of the meteorologic time increment to the computational time increment (IMDT), the user may opt to reuse meteorologic data for several computational time intervals contained within the meteorologic time interval. Figure 3.1 illustrates this feature. In addition, several options to reduce the data preparation requirements were included in the input procedure.

Meteorologic data are assumed to be constant over each computational time interval in which they are used. Thus meteorologic data are treated as cumulated or averaged values over the computational time interval. Examples include dry-bulb temperature which is assumed to be averaged over the computational time interval, and observed solar radiation which is assumed to be the cumulated value in the same interval. In contrast, hydraulic and stream

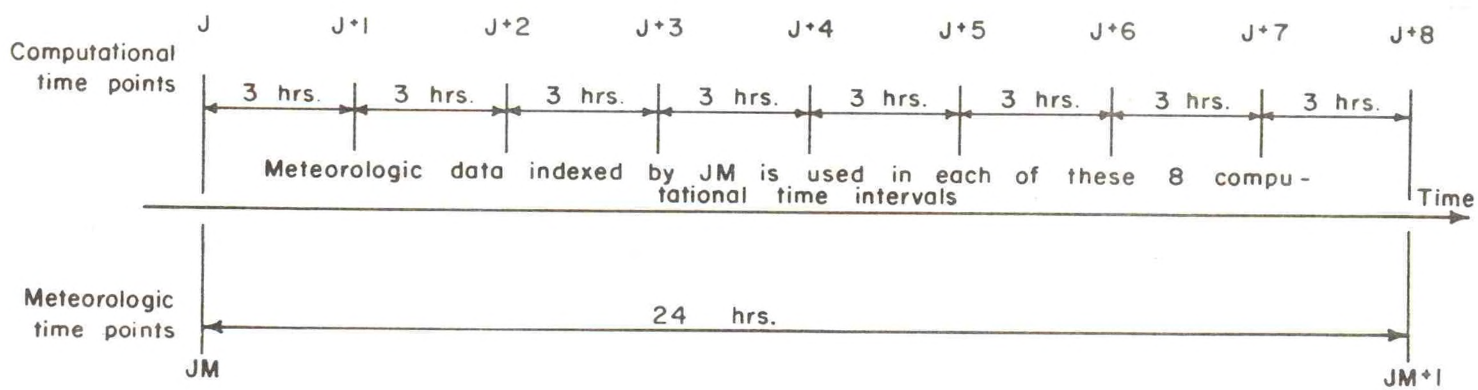


Figure 3.1. Relationship between computational time intervals and meteorologic time intervals for the case where IMDT = 8 and DT(JJ) = 3, JJ = J, (J + 8).

temperature data are treated as instantaneous values at each time point. These distinctions are made in the input description contained in the Users Manual (Appendix A), and in the development of the numerical solution in this chapter.

Units used in DNRT and DSTEMP are those used by the National Weather Service and United States Geological Survey in published data which are likely to be used in applications of the models. When programming DSTEMP, an attempt was made to facilitate a future program option in which S.I. or British units could be used. The S.I. option is not available in the current version of DSTEMP.

Provision has been made to treat surface and subsurface lateral inflows separately. A different temperature may be specified for each. In this way unmodeled tributaries, overland flow, interflow, return flows, etc., can be separated from baseflow originating in the groundwater body. Both surface and subsurface lateral inflows can be negative in which case they are outflows from the river and the temperature associated with them is the stream temperature.

Any number of first order tributaries to the main stream can be handled by DNRT and DSTEMP providing dimension statements are adjusted to the appropriate size. Following the technique used in DNRT, tributary flows are input to the main stream as surface lateral inflow uniformly distributed over a specified subreach. Therefore, stream temperatures for a time point are predicted along all the tributaries before predictions commence on the main stream (see flowchart in Appendix A). In this way the surface lateral inflow temperatures of tributary inflows are available when they are required for temperature predictions on the main stream.

Thermal loads located as point sources are handled by a simple heat balance procedure. Stream temperatures immediately upstream and downstream of the location at which the point load enters the stream are calculated and output.

All data input are printed at the beginning of the program output. Two types of output tables are used: a table of stream temperatures, advective heat sources, and hydraulic data for each computational point at each time point; and a table of components of heat exchange at stream surface and bed for each subreach at each time interval.

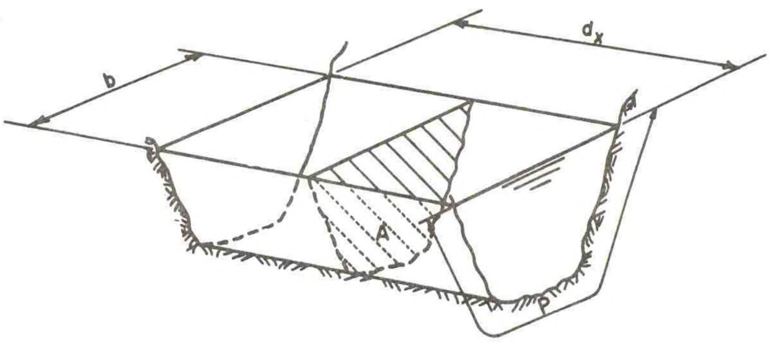
Implicit Dynamic Routing Program (DNRT)

DNRT is a technique for streamflow forecasting in which transient stages and discharges are computed for various forecast points along a river from a given stage or discharge hydrograph at the upstream boundary of a river reach in which a flood wave is propagating (Fread, 1974). The interaction of storage and dynamic effects between a river and its tributaries may be efficiently simulated using DNRT (Fread, 1973). Stages and discharges are computed by an implicit dynamic routing technique in which the complete one dimensional differential equations of unsteady flow are solved by an implicit four-point finite difference method which necessitates the solution of successive systems of nonlinear equations. A very efficient solution for the nonlinear systems is provided by the Newton-Raphson iterative method used in conjunction with an extrapolation technique and a special quad-diagonal Gaussian elimination procedure. DNRT has been verified on several floods and hurricane surges in the Lower Mississippi River.

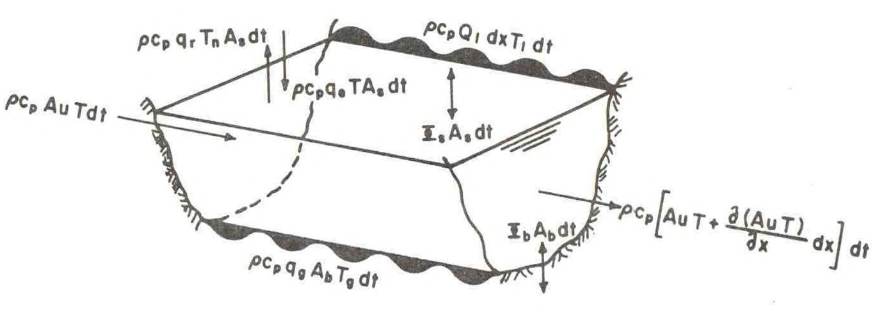
Hydraulic and stream geometry data transferred to DSTEMP from DNRT are described in detail by read statements 2 through 13 in the DSTEMP input description contained in Appendix A. These data include: computational time intervals, subreach lengths, cross-sectional areas, top widths of flow, wetted perimeters, streamflow rates, stream stages, and surface lateral inflow rates.

Model Formulation

The model for prediction of average and diurnal stream temperatures was formulated by performing a heat balance on a control volume in the stream (Figure 3.2). Two important assumptions were made: complete and instantaneous mixing over each stream cross-section; and negligible longitudinal diffusion. In addition, heat resulting from biological and chemical processes and from fluid friction was disregarded. Also no attempt was made to represent the situation in



(i) Stream geometry



(ii) Heat fluxes

Figure 3.2. Sub-reach control volume.

which ice formation occurs.

The assumption of complete and instantaneous mixing implies that transverse temperature gradients over a stream cross-section can be neglected. Usually only one stream temperature measurement is available at each water quality station and therefore transverse temperature gradients would be impossible to define except in a few well instrumented streams. The assumption permitted the use of a one-dimensional analysis instead of the more complex two- and three-dimensional approaches (Jobson and Yotsukura, 1973). Thus stream temperatures represented by the model were assumed to be average temperatures across the stream cross-section. It should be noted that the cross-section averaged predicted stream temperatures were compared with stream temperatures observed at a single location in the stream cross-section.

Fischer (1973) has stated that longitudinal diffusion, either molecular or turbulent, is relatively unimportant compared to the effect of velocity upon the longitudinal temperature distribution and is, therefore, usually ignored. By neglecting diffusion a first-order rather than a second-order analysis was required. This simplification permitted the use of the implicit four-point finite difference technique which is applicable only to first-order equations. By using the same numerical scheme in both the hydraulic and stream temperature models it is intended that space and time steps will be compatible in both models. The implicit four-point finite difference scheme allows for variable size space and time steps.

Although frictional heat added to the stream due to boundary roughness was neglected in the current version of DSTEMP, Vugts (1974) indicated that it may not be unimportant. According to Pluhowski (1970) friction heat flux, ϕ_f, can be calculated as follows:

$$\phi_f = \frac{Q \rho \, s \, dx}{J} \qquad (3.1)$$

in which

Q streamflow rate (cfs)

ρ density of water (62.32 lbs. ft^{-3})

s slope of subreach (ft. ft^{-1})

dx computational space interval on length of subreach (ft)

J a constant (778 ft. lbs. BTU^{-1})

Four types of heat flux were considered in the heat balance on the control volume (Figure 3.2):

1. Nonadvective heat exchange across the stream surface.
2. Nonadvective heat exchange across the streambed.
3. Advection of heat associated with stream velocity.
4. Other advective heat fluxes by lateral inflow, tributary inflow, groundwater infiltration and seepage, rainfall and snowfall, and evaporation.

For the purpose of developing the heat balance only the net quantities of nonadvective heat exchange across the stream surface and streambed are considered; these quantities are represented by Φ_s and Φ_b, respectively. Each of the components comprising these net terms are described in a later section.

A heat balance over the time interval dt for the subreach control volume shown in Figure 3.2 was obtained by equating the sum of the four types of heat flux to the net change in total heat contained in the control volume. The sign convention adopted was positive for heat fluxes associated with advection of mass into the stream. Heat exchange, such as radiation, which is not associated with mass transfer was treated as positive when the transfer of heat was into the stream.

1. surface heat exchange — 2. streambed heat exchange

$$\Phi_s A_s dt \quad + \quad \Phi_b A_b dt$$

3. stream velocity heat flux

$$+ \quad \rho c_p A u dt - \rho c_p [AuT + \frac{\partial}{\partial x} (AuT)\, dx]\, dt$$

4. other advective heat fluxes

$$+ \ \rho c_p Q_\ell dx\, T_\ell\, dt + \rho c_p q_g A_b T_g\, dt + \rho c_p q_r A_s T_r\, dt - \rho c_p q_e A_s T\, dt$$

change in total heat in control volume

$$= \rho c_p d(AT)dx \quad . \; . \; . \; . \; . \; . \; . \; . \quad (3.2)$$

in which

c_p specific heat of water at constant pressure (0.9988 BTU lbs^{-1} deg. F^{-1})

A cross-sectional area of stream (ft^2)

u stream velocity (ft. s^{-1})

dt computational time interval (s)

dx computational space interval or subreach length (ft)

T stream temperature (deg. F)

Φ_s net nonadvective heat exchange across water surface (BTU ft^{-2} s^{-1})

A_s stream surface area (ft^2)

Φ_b net nonadvective heat exchange across streambed (BTU ft^{-2} s^{-1})

A_b streambed area (ft^2)

Q_ℓ rate of surface lateral inflow (overland flow plus interflow) per unit length of subreach (cfs ft^{-1})

T_ℓ temperature of surface lateral inflow (deg. F)

q_g rate of groundwater lateral inflow per unit area of streambed (cfs ft^{-2})

T_g groundwater temperature (deg. F)

q_r precipitation (ft. s^{-1})

T_r wet-bulb temperature (deg. F)

q_e evaporation (ft. s^{-1})

Equation 3.2 was rearranged and combined with the following substitutions:

$$Q = Au \quad \quad (3.3)$$

$$A_s = b\,dx \quad \quad (3.4)$$

$$A_b = P\,dx \quad \quad (3.5)$$

in which

b top breadth of stream (ft)

P wetted perimeter of stream (ft)

When water leaves the stream by overbank spill, diversions, or seepage the rates of surface (Q_ℓ) or groundwater (q_g) lateral inflow are negative. In these cases the temperature of water leaving the stream is the stream temperature, T. Therefore, the advective terms in Equation 3.2 associated with Q_ℓ and q_g are each separated into two terms according to the signs of Q_ℓ and q_g. If Q_ℓ and q_g are positive (Q_ℓ^+, q_g^+) then the temperatures T_ℓ and T_g are used respectively. When Q_ℓ and q_g are negative (Q_ℓ^-, q_g^-) then T is used instead of T_ℓ and T_g.

Net surface and streambed exchange, Φ_s and Φ_b, are each calculated from the summation of a number of component heat transfers which are described in a later section. Some of these components are nonlinear in T and to simplify the numerical solution procedures most stream temperature models employ a linearized approximation for Φ_s and Φ_b. Two notable exceptions to this are the parabolic approximations used by Wunderlich (1968) and Morse (1970, 1972a, 1972b). Wunderlich proposed that, depending on the required accuracy and the temperature range of interest, Φ_s may be determined from either

$$\Phi_s = C'' + B''T + A''T^2 \quad . \; . \; . \; . \; . \; . \; . \qquad (3.6)$$

or

$$\Phi_s = C' + B'T \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \qquad (3.7)$$

in which C'', B'', A'', C' and B' are determined by least square regression of Φ_s against T. Values of Φ_s were calculated for a range of values of T and using monthly averages of daily meteorologic data. Morse refined Wunderlich's work to 3 hour time intervals and used least squares to estimate a set of values of C'', B'', A'', C', and B' for each of the eight 3 hour time intervals in a day. Meteorologic data for calculating Φ_s was obtained for each of the eight 3 hour time intervals in a day by averaging over the same 3 hour periods in several successive days. Morse (1970) reported that the parabolic relationship provided a statistically better fit than the linear relationship when applied to calculated surface heat exchange for the Columbia River over a 10 day period in July, 1966. By averaging meteorologic data over a period of several days, it is assumed that these data are essentially constant over the averaging period. A cooling trend during one study period led Morse (1972a) to the observation that more representative results can be obtained from shorter averaging periods. However, as fewer days are used to estimate the least square coefficients statistical confidence in the estimated values decreases.

The approach of Wunderlich and Morse to developing a parabolic approximation for the net surface exchange by least squares can be applied to development of the linear relationship in Equation 3.7. Other linearization procedures include the concept of an equilibrium temperature, the use of a truncated Taylor series expansion of the nonlinear terms in Φ_s and Φ_b, and the use of empirical linear approximations to the nonlinear terms in Φ_s and Φ_b.

Equilibrium temperature, T_E, is the stream temperature at which Φ_s is zero. Edinger and Geyer (1965) first proposed the use of equilibrium temperature for linearizing the net surface exchange as follows:

$$\Phi_s = -K(T - T_E) \quad . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \quad (3.8)$$

in which K is the surface heat transfer coefficient (BTU ft^{-2} s^{-1} deg. F^{-1}). T_E must be obtained by a cumbersome trial and error procedure and its value can vary by up to 90 deg. F on a diurnal basis (Edinger et al., 1968). Therefore in their discussion of linearization techniques for Φ_s Jobson and Yotsukura (1973) describe the equilibrium temperature concept as "inadequate for predicting diurnal fluctuations in water temperature." They concluded that "the introduction of the equilibrium temperature concept has been both unnecessary and inconvenient."

Another approach to linearizing nonlinear terms in Φ_s is by using the first two terms in the Taylor series expansion about an arbitrary reference temperature, T_R. By careful selection of T_R linearization errors may be minimized (Jobson and Yotsukura, 1973).

In DSTEMP empirical linear approximations, piecewise-linear approximations, and least squares linear approximations to nonlinear components of Φ_s and Φ_b are employed. Thus Φ_s and Φ_b are expressed in the linear forms:

$$\Phi_s = C_1 + C_2 T = \sum_{i=1}^{n} (c_1^i + c_2^i T) \quad . \quad . \quad . \quad . \quad . \qquad (3.9)$$

$$\Phi_b = C_3 + C_4 T = \sum_{i=1}^{m} (c_3^i + c_4^i T) \quad . \quad . \quad . \quad . \quad . \qquad (3.10)$$

in which each of the n components of Φ_s are expressed in the linear form $c_1^i + c_2^i T$ and each of the m components of Φ_b are expressed in the linear form $c_3^i + c_4^i T$. Calculation of c_1^i, c_2^i, c_3^i, and c_4^i is discussed in a later section in which estimation of the surface and streambed heat exchange components are described. Coefficients C_1, C_2, C_3, and C_4 were obtained as follows:

$$C_1 = \sum_{i=1}^{n} c_1^i \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (3.11)$$

$$C_2 = \sum_{i=1}^{n} c_2^i \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (3.12)$$

$$C_3 = \sum_{i=1}^{m} c_3^i \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (3.13)$$

$$C_4 = \sum_{i=1}^{m} c_4^i \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (3.14)$$

The rearranged form of Equation 3.2, including the substitution of Equations 3.3, 3.4, 3.5, 3.9, and 3.10, and the addition of the extra terms associated with negative surface and groundwater lateral inflows is as follows:

$$\frac{\partial(AT)}{\partial t} + \frac{\partial(QT)}{\partial x} - \left[\frac{bC_1 + PC_3}{\rho c_p} + Q_\ell^+ T_\ell + q_g^+ PT_g + q_r bT_r\right]$$

$$- \left[\frac{bC_2 + PC_4}{\rho c_p} + Q_\ell^- + q_g^- P - q_e b\right] T = 0 \quad . \quad . \quad (3.15)$$

Numerical Solution

Implicit four-point finite difference scheme

Explicit finite difference techniques applied to the solution of the unsteady flow equations are restricted by numerical stability considerations to very small computational time steps of the order of minutes or seconds. Therefore, the explicit method is very inefficient for stream simulations lasting several days or weeks. In contrast implicit finite difference techniques have no restrictions on the size of the specified time interval due to computational stability; however, accuracy constraints may limit its size.

The generalized implicit four-point finite difference scheme utilized by Fread in DNRT allows for variable size space intervals Δx and time intervals Δt. Figure 3.3 contains a four-point grid identified by the intersections of the vertical lines x_i and x_{i+1} with the horizontal lines t^j and t^{j+1}. Finite differencing is carried out for a point M within the four-point grid. At the point M the

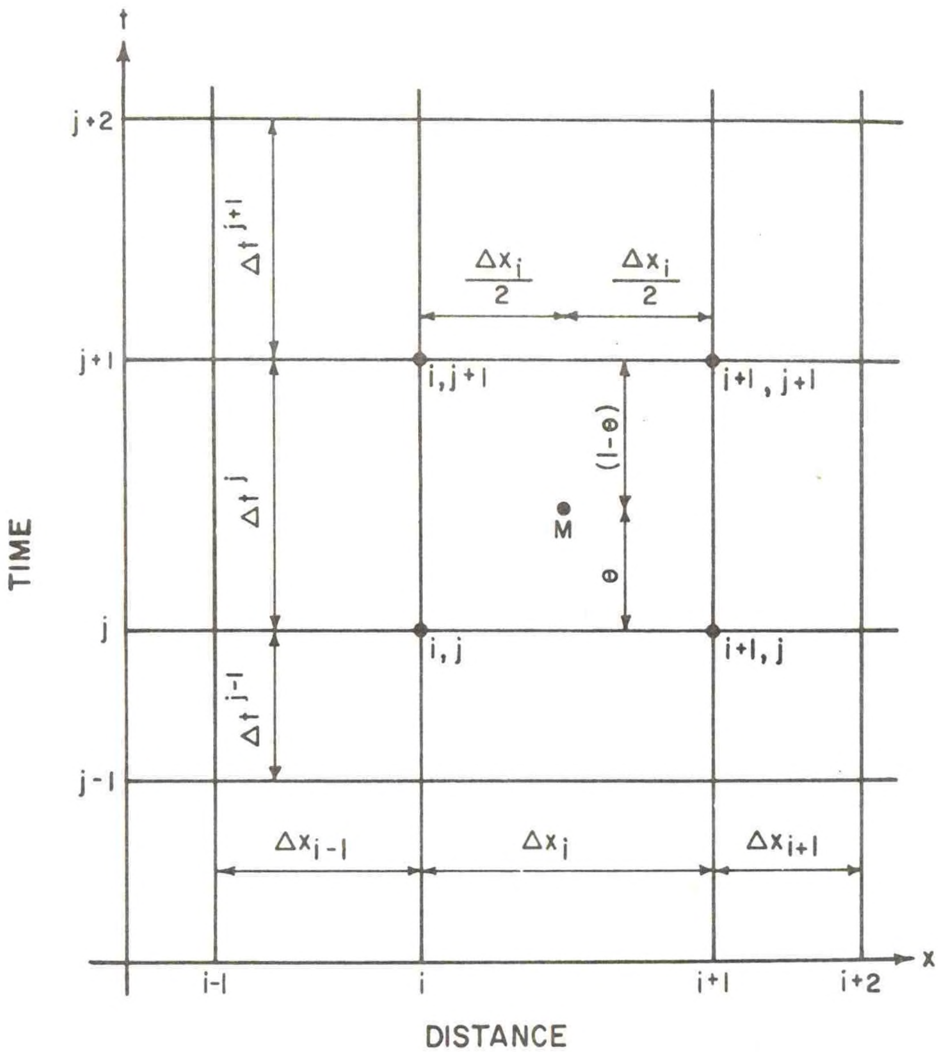


Figure 3.3 Network of points on (x, t) plane for the generalized implicit four-point finite difference method (adapted from Amein and Fang, 1970).

value of a function K(M) is represented by:

$$K(M) \simeq \theta \left(\frac{K_i^{j+1} + K_{i+1}^{j+1}}{2} \right) + (1 - \theta) \left(\frac{K_i^j + K_{i+1}^j}{2} \right) \quad . \quad (3.16)$$

in which θ is a weighting factor determining the location of M between the two adjacent time lines t^j and t^{j+1}. Space and time partial derivatives of K(M) are approximated by:

$$\frac{\partial K(M)}{\partial x} \simeq \theta \left(\frac{K_{i+1}^{j+1} - K_i^{j+1}}{\Delta x_i} \right) + (1 - \theta) \left(\frac{K_{i+1}^j - K_i^j}{\Delta x_i} \right) \quad . \quad (3.17)$$

$$\frac{\partial K(M)}{\partial t} \simeq \frac{K_i^{j+1} + K_{i+1}^{j+1} - K_i^j - K_{i+1}^j}{2 \Delta t^j} \quad . \; . \; . \; . \quad (3.18)$$

Fread (1974) found that for slowly varying transients in large rivers $\theta = 0.55$ minimizes the loss of accuracy associated with greater values while avoiding the possibility of a weak or pseudo-instability.

Numerical solution of advection equations

The generalized implicit four-point finite difference scheme used in the routing model DNRT (Fread, 1973; Fread, 1974) was also applied in DSTEMP. Substituting Equations 3.16, 3.17, and 3.18 into the advection equation (Equation 3.15) yields the following:

$$\frac{1}{2\Delta t^j}\left[(AT)_i^{j+1} + (AT)_{i+1}^{j+1} - (AT)_i^j - (AT)_{i+1}^j\right]$$

$$+ \frac{\theta}{\Delta x_i}\left[(QT)_{i+1}^{j+1} - (QT)_i^{j+1}\right] + \frac{(1-\theta)}{\Delta x_i}\left[(QT)_{i+1}^j - (QT)_i^j\right]$$

$$- \frac{\theta}{2}\left\{\frac{C_1}{\rho c_p}\left[b_i^{j+1} + b_{i+1}^{j+1}\right] + \frac{C_3}{\rho c_p}\left[P_i^{j+1} + P_{i+1}^{j+1}\right]\right.$$

$$+ \left[(Q_\ell^+ T_\ell)_i^{j+1} + (Q_\ell^+ T_\ell)_{i+1}^{j+1}\right] + \left[(q_g^+ PT_g)_i^{j+1} + (q_g^+ PT_g)_{i+1}^{j+1}\right]$$

$$\left. + \left[(q_r bT_r)_i^{j+1} + (q_r bT_r)_{i+1}^{j+1}\right]\right\}$$

$$- \frac{(1-\theta)}{2}\left\{\frac{C_1}{\rho c_p}\left[b_i^j + b_{i+1}^j\right] + \frac{C_3}{\rho c_p}\left[P_i^j + P_{i+1}^j\right]\right.$$

$$+ \left[(Q_\ell^+ T_\ell)_i^j + (Q_\ell^+ T_\ell)_{i+1}^j\right] + \left[(q_g^+ PT_g)_i^j + (q_g^+ PT_g)_{i+1}^j\right]$$

$$\left. + \left[(q_r bT_r)_i^j + (q_r bT_r)_{i+1}^j\right]\right\}$$

$$- \frac{\theta}{2}\left\{\frac{C_2}{\rho c_p}\left[(bT)_i^{j+1} + (bT)_{i+1}^{j+1}\right] + \frac{C_4}{\rho c_p}\left[(PT)_i^{j+1} + (PT)_{i+1}^{j+1}\right]\right.$$

$$+ \left[(Q_\ell^- T)_i^{j+1} + (Q_\ell^- T)_{i+1}^{j+1}\right] + \left[(q_g^- PT)_i^{j+1} + (q_g^- PT)_{i+1}^{j+1}\right]$$

$$\left. - \left[(q_e bT)_i^{j+1} + (q_e bT)_{i+1}^{j+1}\right]\right\}$$

$$- \frac{(1-\theta)}{2} \left\{ \frac{C_2}{\rho c_p} \left[(b\,T)_i^j + (b\,T)_{i+1}^j \right] + \frac{C_4}{\rho c_p} \left[(P\,T)_i^j + (P\,T)_{i+1}^j \right] \right.$$

$$+ \left[(Q_\ell^- \,T)_i^j + (Q_\ell^- \,T)_{i+1}^j \right] + \left[(q_g^- \,P\,T)_i^j + (q_g^- \,P\,T)_{i+1}^j \right]$$

$$\left. - \left[(q_e \,b\,T)_i^j + (q_e \,b\,T)_{i+1}^j \right] \right\} = 0 \quad \ldots\ldots\ldots \quad (3.19)$$

In DSTEMP Q_ℓ^+, Q_ℓ^-, and T_ℓ were assumed invariant over a subreach Δx_i. In the general nomenclature of Equations 3.16, 3.17, and 3.18 this invariance can be expressed as:

$$K_i^j = K_{i+1}^j \quad \ldots\ldots\ldots\ldots \quad (3.20)$$

and

$$K_i^{j+1} = K_{i+1}^{j+1} \quad \ldots\ldots\ldots\ldots \quad (3.21)$$

Also q_g^+, q_g^-, T_g, q_r, T_r, and q_e were assumed invariant over a subreach Δx_i and a time interval Δt^j. In the case of invariance of T_r over Δt^j, for example, it was assumed that the value of wet-bulb temperature was the average value over the time interval Δt^j. Invariance of q_r over Δt^j implies that q_r is the depth of precipitation cumulated over the time interval Δt^j. In the general nomenclature of Equations 3.16, 3.17, and 3.18 the invariance over Δx_i and Δt^j can be expressed as:

$$K_i^j = K_{i+1}^j = K_i^{j+1} = K_{i+1}^{j+1} \quad \ldots\ldots\ldots\ldots \quad (3.22)$$

Equation 3.19 was rearranged into the following general form after substitution of Equations 3.20, 3.21, and 3.22 applied to the appropriate variables:

$$A_i T_i^{j+1} + B_i T_{i+1}^{j+1} = C_i T_i^j + D_i T_{i+1}^j + E_i \quad \ldots\ldots \quad (3.23)$$

in which A_i, B_i, C_i, D_i, and E_i are coefficients that are independent of T. Equation 3.23 was then solved for T_{i+1}^{j+1}:

$$T_{i+1}^{j+1} = \frac{C_i T_i^j + D_i T_{i+1}^j + E_i - A_i T_i^{j+1}}{B_i} \quad \ldots\ldots \quad (3.24)$$

To improve the program efficiency "array look-ups" and repeated identical calculations were minimized by the introduction of dummy variables defined in Table 3.1. In terms of these dummy variables, the coefficients in Equations 3.23 and 3.24 are defined as follows:

$$A_i = D5*D27 - D6*(Q)_i^{j+1} - D2*(D14*D17 + D13*D21 + D15) \quad \ldots\ldots \quad (3.25)$$

$$B_i = D5*D28 - D6*D25 - D2*(D14*D18 + D13*D22 + D15) \quad \ldots\ldots \quad (3.26)$$

$$C_i = D5*D29 + D7*(Q)_i^j + D3*(D14*D19 + D13*D23 + D16) \quad \ldots\ldots \quad (3.27)$$

$$D_i = D5*D30 - D7*(Q)_{i+1}^j + D3*(D14*D20 + D13*D24 + D16) \quad \ldots\ldots \quad (3.28)$$

Table 3.1 Definition of dummy variables used in DSTEMP and in Equations 3.25 through 3.29.

Dummy variable	Equation form	Program form
D1	$(1 - \theta)$	1 - THETA
D2	$\theta/2$	THETA/2
D3	$(1 - \theta)/2$	D1/2
D4	$1/\rho c_p$	1/(RHO*CP)
D5	$1/2\Delta t^j$	1/(2*DT(J))
D5A	$1/\Delta t^j$	2*D5
D6	$\theta/\Delta x_i$	THETA/DX
D7	$(1 - \theta)/\Delta x_i$	D1/DX
D8	$C_1/\rho c_p$	D4*C1
D9	$C_2/\rho c_p$	D4*C2
D10	$C_3/\rho c_p$	D4*C3
D11	$C_4/\rho c_p$	D4*C4
D12	$\frac{C_3}{c_p} + (q_g^+ T_g)_i$	D10+QGP*D31
D13	$\frac{C_4}{c_p} + (q_g^-)_i$	D11+QGM
D14	$\frac{C_2}{c_p} - (q_e)_i^j$	D9-QEE
D15	$(Q_\ell^-)_i^{j+1}$	QLM(2)
D16	$(Q_\ell^-)_i^j$	QLM(1)

Table 3.1 Continued.

Dummy variable	Equation form	Program form
D17	$(b)_i^{j+1}$	BD(I, J1, K)
D18	$(b)_{i+1}^{j+1}$	BD(I1, J1, K)
D19	$(b)_i^j$	BD(I, J, K)
D20	$(b)_{i+1}^j$	BD(I1, J, K)
D21	$(P)_i^{j+1}$	PM(I, J1, K)
D22	$(P)_{i+1}^{j+1}$	PM(I1, J1, K)
D23	$(P)_i^j$	PM(I, J, K)
D24	$(P)_{i+1}^j$	PM(I1, J, K)
D25	$(Q)_{i+1}^{j+1}$	QS(I1, J1, K)
D26	$\frac{C_1}{c_p} + (q_r T_r)_i^j$	D8+QRR*TRR
D27	$(A)_i^{j+1}$	CSA(I, J1, K)
D28	$(A)_{i+1}^{j+1}$	CSA(I1, J1, K)
D29	$(A)_i^j$	CSA(I, J, K)
D30	$(A)_{i+1}^j$	CSA(I1, J, K)
D31	$(T_g)_i$	TG(I, K)

$$E_i = D2*[D26*(D17+D18) + D12*(D21+D22) + 2*(Q_\ell^+ T_\ell)_i^{j+1}]$$
$$+ D3*[D26*(D19+D20) + D12*(D23+D24) + 2*(Q_\ell^+ T_\ell)_i^{j}]$$
$$. \quad . \quad . \quad . \quad . \quad . \quad . \qquad (3.29)$$

Point loads

Thermal loads associated with a point inflow to the stream can also be handled by DSTEMP. Point sources must be located inbetween subreaches at computational points. Therefore, it follows from the assumption of instantaneous and complete mixing, that point loads do not enter into the heat balance on the subreach control volume. If point loads are modeled when DSTEMP is used in conjunction with DNRT some care must be exercised. This is because the current version of DNRT does not allow for point loads to be input at a single point. Instead they are represented as lateral inflow over a short subreach. This may not be a realistic means of representing return flows from a cooling process for example, that are small in quantity in comparison to the streamflow rate but significant in their impact on stream temperature. Such a point load could probably be neglected in DNRT, but should be included in DSTEMP when seeking to provide a good representation of the stream temperature regime. If a point load is handled as a lateral inflow in DNRT it must be handled in the same manner in DSTEMP and thus its temperature must be specified as a surface lateral inflow temperature. If a point load is neglected in DNRT because it is small in flowrate but it is thermally significant, then it should be treated as a point load in DSTEMP.

Continuing the assumption of complete and instantaneous mixing point loads are handled by a simple heat balance at the point of entry to the stream:

$$(T')_{i+1}^{j+1} = \frac{(QT)_{i+1}^{j+1} + Q_p T_p}{(Q)_{i+1}^{j+1} + Q_p} \quad \ldots\ldots\ldots \quad (3.30)$$

in which

$(T')_{i+1}^{j+1}$ stream temperature immediately downstream of point load (indexed by L = 1 in program) (deg. F)

Q_p flowrate of point load (cfs)

T_p temperature of point load (deg. F)

Both the values of stream temperature immediately upstream and immediately downstream of the point load are stored in the computer program and printed in the DSTEMP output.

Heat Exchange Components

General

The general linear forms of heat exchange components of net nonadvective heat exchange across the surface and streambed are:

$$\phi_{\text{ith surface component}} = c_1^i + c_2^i T \quad . \; . \; . \; . \; . \; . \; . \quad (3.31)$$

$$\phi_{\text{ith bed component}} = c_3^i + c_4^i T \quad . \; . \; . \; . \; . \; . \; . \quad (3.32)$$

In this section the physical constants, empirical coefficients, and meteorologic, astronomical, and other data required to estimate each component of nonadvective heat exchange as a function of stream temperature are described.

Components of net nonadvective heat exchange across the stream surface are:

$$\Phi_s = (\phi_s - \phi_{sr}) + (\phi_v - \phi_{vr}) + (\phi_a - \phi_{ar}) - \phi_b - \phi_e + \phi_c - \phi_{sn} - \phi_w \quad . \; . \; . \; . \; . \; . \quad (3.33)$$

in which

ϕ_s solar radiation flux incident at stream surface

ϕ_{sr} solar radiation flux reflected from stream surface

ϕ_v vegetative radiation flux incident at stream surface

ϕ_{vr} vegetative radiation flux reflected from stream surface

ϕ_a atmospheric radiation flux incident at stream surface

ϕ_{ar} atmospheric radiation flux reflected from stream surface

ϕ_b back radiation flux emitted by stream surface

ϕ_e heat flux due to latent heat of vaporization associated with evaporation from stream

ϕ_c conductive flux across stream surface

ϕ_{sn} heat flux due to latent heat of fusion associated with melting of snow falling into the stream

ϕ_w heat flux by surface layer renewal

Components of net nonadvective heat exchange across the streambed are:

$$\Phi_b = \phi_{bs} + \phi_{bb} + \phi_{bc} \quad \ldots\ldots\ldots \quad (3.34)$$

in which

ϕ_{bs} solar radiation flux absorbed by streambed

ϕ_{bb} back radiation flux emitted by streambed

ϕ_{bc} conductive flux across streambed

The units of each component are BTU $ft^{-2}hr^{-1}$. User options have been included in DSTEMP to permit inclusion or exclusion of individual components. In this way studies of the sensitivity of stream temperatures to individual components are facilitated. Also components for which adequate data is unavailable can be omitted. However, care must be exercised when excluding components from predictive runs; for example, it is difficult to conceive of a situation in which solar radiation could justifiably be omitted.

Several components are not modeled in the current version of DSTEMP. For these components methods of estimation are proposed in this section. Users could readily introduce these methods into the empty subroutine shells of the present program if desired.

Equation 3.2 in the model formulation section shows that Φ_s and Φ_b were considered to act over the areas A_s and A_b, respectively. ϕ_{bs} was considered to act on an area equal to A_s projected onto the streambed. Therefore, the ϕ_{bs} component was included in Φ_s instead of Φ_b in the program form of the numerical solution but appears as a component of Φ_b in all output tables.

Solar radiation

Three techniques for estimating incident and reflected solar radiation flux are included in the current version of DSTEMP:

1. Solar radiation flux calculated.
2. Total daily observed solar radiation flux distributed in parabolic manner between sunrise and sunset.
3. Observed solar radiation flux in computational time interval used directly.

Results from these techniques will be compared and factors to be considered when selecting one of the techniques will be discussed. Firstly, each of the techniques will be described.

Technique 1 - calculated solar radiation. A method of calculating solar radiation flux described in detail by Wunderlich (1972) was adapted to DSTEMP. The method is divided into three steps:

1. Solar radiation flux received at the top of the atmosphere.

2. Solar radiation flux received at the ground under a clear sky.

3. Solar radiation flux received at the ground under a cloudy sky.

The computation of solar radiation flux received at the top of the earth's atmosphere, the extraterrestrial solar radiation flux, is based on measured values of radiation emitted by the sun and the trigonometric relationship to express the direct solar beam intensity on a horizontal (tangential) plane (List, 1963). With extraterrestrial radiation flux known, the clear sky solar radiation flux received at the ground is principally a function of atmospheric transmittance. The method used for computation was selected by Wunderlich (1972) as the method that accounts for the maximum effect of local factors (Bolsenga, 1964). Attenuation of solar radiation by clouds is difficult to predict because of the great variety of types, distributions, and albedos of clouds, and the lack of analytical parameters to satisfactorily express this combined effect on solar radiation (Wunderlich, 1972).

Only a summary of the computational technique is presented below. For further details the reader is referred to Wunderlich (1972).

Declination of sun

$$\sin \delta = \sin \left(\frac{23.445\ \pi}{180}\right) \sin \left[\frac{2\ \pi}{360} \left(279.9348 + \frac{360}{2\ \pi}\ d\right.\right.$$

$$+ 1.914827 \sin d - 0.079525 \cos d$$

$$\left.\left. + 0.019938 \sin 2d - 0.001620 \cos 2d\right)\right] \quad . \quad . \quad . \quad . \quad (3.35)$$

in which

δ declination of sun (radians)

$$d = \frac{2\ \pi}{365.242}\ (D-1) \quad (\text{radians}) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3.36)$$

D day number in the year

Relative distance of earth-sun

$$r = 1 + 0.017 \cos\left[\frac{2\ \pi}{365}\ (186-D)\right] \quad . \quad . \quad . \quad . \quad . \quad . \quad (3.37)$$

in which

r relative distance of earth-sun (dimensionless)

Hour angle of sunrise

$$\cos h_{sr} = \frac{\sin \alpha_{sr} - \sin \phi \sin \delta}{\cos \phi \cos \delta} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3.38)$$

in which

h_{sr} hour angle of sunrise (radians)

α_{sr} solar altitude at sunrise (radians)

ϕ latitude of the location (radians)

Hour angle of sunset

$$\cos h_{ss} = \frac{\sin \alpha_{ss} - \sin \phi \sin \delta}{\cos \phi \cos \delta} \quad . \; . \; . \; . \; . \qquad (3.39)$$

in which

h_{ss} hour angle of sunset (radians)

α_{ss} solar altitude at sunset (radians)

Standard time of sunrise and sunset

$$STR = \frac{12}{\pi} h_{sr} - 12 + DTSL - ET \quad . \; . \; . \; . \; . \qquad (3.40)$$

$$STS = \frac{12}{\pi} h_{ss} + 12 + DTSL - ET \quad . \; . \; . \; . \; . \qquad (3.41)$$

in which

STR standard time of sunrise (hours)

STS standard time of sunset (hours)

DTSL time difference between local and standard meridian (hours). DTSL is a constant for the location and is computed by:

$$DTSL = \frac{e}{15} (LSM - LLM) \quad . \; . \; . \qquad (3.42)$$

LSM longitude of standard meridian (degrees from Greenwich)

LLM longitude of local meridian (degrees from Greenwich)

$e = -1$ for west longitude

$e = +1$ for east longitude

ET equation of time (hours) given by:

$$ET = -60\,(0.123570 \sin d - 0.004289 \cos d + 0.153809 \sin 2d + 0.060783 \cos 2d) \quad . \; . \; . \; . \; . \; . \quad (3.43)$$

Hour angle-time relationships

$$h_B = \frac{\pi}{12}\,(ST_B - DTSL + ET + \epsilon) \quad . \; . \; . \; . \; . \; . \quad (3.44)$$

$$h_E = \frac{\pi}{12}\,(ST_E - DTSL + ET + \epsilon) \quad . \; . \; . \; . \; . \; . \quad (3.45)$$

in which

h_B hour angle of the beginning of computational time interval (radians)

h_E hour angle of the end of computational time interval (radians)

ST_B standard time of the beginning of computational time interval (hours)

ST_E standard time of the end of computational time interval (hours)

$\epsilon = +12$ for standard time before noon

$\epsilon = -12$ for standard time after noon

Solar altitude

$$\sin \alpha = \sin \phi \sin \delta + \cos \phi \cos \delta \cos h \quad . \; . \; . \; . \; . \; . \quad (3.46)$$

in which

α solar altitude, $\phi \leq \alpha \leq \frac{\pi}{2}$ (radians)

Extraterrestrial solar radiation integrated over computational time interval

$$q_o = \frac{12}{\pi} \frac{I_o}{r^2} [\sin \phi \sin \delta (h_E - h_B) + \cos \phi \cos \delta (\sin h_E - \sin h_B)] \quad . \; . \; . \; . \; . \quad (3.47)$$

in which

q_o extraterrestrial solar radiation flux for period $(h_E - h_B)$ (BTU ft^{-2} hr^{-1})

I_o solar constant (429 BTU ft^{-2} hrs^{-1})

Precipitable water content of the atmosphere

$$w = \exp (0.0341 T_d - 2.0762) \quad . \; . \; . \; . \; . \; . \; . \; . \quad (3.48)$$

in which

w precipitable water content of the atmosphere (ins.)

T_d dew point temperature (deg. F)

Optical air mass

$$m_p = \frac{(1 - 0.000006879Z)^{5.256}}{\sin \alpha + 0.15 (\frac{180}{\pi} \alpha + 3.885)^{-1.253}} \quad . \; . \; . \; . \quad (3.49)$$

in which

m_p optical air mass adjusted to local altitude (dimensionless)

Z elevation of subreach above mean sea level (ft)

Mean atmospheric transmission coefficients

$$a' = \exp\left\{-(0.465 + 0.134\,w)\left[0.129 + 0.171\exp(-0.880\,m_p)\right]m_p\right\} \quad \ldots\ldots\ldots \quad (3.50)$$

$$a'' = \exp\left\{-(0.465 + 0.134\,w)\left[0.179 + 0.421\exp(-0.721\,m_p)\right]m_p\right\} \quad \ldots\ldots\ldots \quad (3.51)$$

in which

a' mean atmospheric transmission coefficients after scattering (cm)

a'' mean atmospheric transmission coefficient after scattering and absorption (cm)

Solar short wave radiation flux incident at stream surface

$$q_i = q_o \frac{[a'' + 0.5(1 - a' - d_p)]}{[1 - 0.5R_g(1 - a' - d_p)]}(1 - 0.0065\,C^2)(1 - S)\,. \quad (3.52)$$

in which

q_i incident solar radiation flux at stream surface (BTU ft^{-2} hr^{-1})

R_g albedo of ground adjacent to stream (Table 3.2) (dimensionless)

Table 3.2. Total dust depletion coefficient, d_p. (Summarized by Bolsenga (1964) based on data by Kimball (1927, 1928, 1930).)

Season	Washington, D.C.		Madison, Wisc.		Lincoln, Nebr.	
	$m^a = 1$	$m = 2$	$m = 1$	$m = 2$	$m = 1$	$m = 2$
Winter	-	0.13	-	0.08	-	0.06
Spring	0.09	0.13	0.06	0.10	0.05	0.08
Summer	0.08	0.10	0.05	0.07	0.03	0.04
Fall	0.06	0.11	0.07	0.08	0.04	0.06

[a] Optical air mass $m = 1/[\sin \alpha + 0.15\ (\alpha + 3.885)^{-1.253}]$.

d_p total dust depletion coefficient of the atmosphere (Table 3.3) (dimensionless)

C cloud cover in an integer number of tenths of cover

S fraction of sky shaded from the stream surface by vegetation or other obstructions excluding cloud cover (dimensionless)

Solar short wave radiation flux reflected at stream surface

$$q_r = q_i R_t \quad \ldots \ldots \ldots \ldots \quad (3.53)$$

in which

q_i reflected solar radiation flux at stream surface (BTU ft^{-2} hr^{-1})

R_t reflectivity of water surface given by:

$$R_t = 1.18 \left(\frac{180}{\pi} \alpha \right)^{-0.77} \quad \ldots \ldots \quad (3.54)$$

Technique 2 - distributed observed solar radiation. A method of distributing solar radiation flux in a parabolic manner between sunrise and sunset was adapted from Albertson et al. (1974). The choice of a parabolic distribution was made on the basis of radiation data collected by Raphael (1962). Solar radiation flux incident at the stream surface during the time period (h_E - h_B) was computed as follows (Figure 3.4):

$$q_i = \frac{12\, I_{obs}}{L^3} \left[\frac{L}{4} (X_2^2 - X_1^2) - \frac{1}{6} (X_2^3 - X_1^3)\, (1 - S) \right] \quad \ldots \quad (3.55)$$

Table 3.3. Albedo of ground surface, R_g. (After Buttner (1953) and Sutton (1953).)

Ground Condition	R_g
Meadows and Fields	0.14[a]
Leave and Needle Forest	0.07 - 0.09[a]
Dark, Extended Mixed Forest	0.045[a]
Heath	0.10[a]
Flat Ground, Grass Covered	0.25 - 0.33
Flat Ground, Rock	0.12 - 0.15
Sand	0.18
Vegetation Early Summer, Leaves with High Water Content	0.19
Vegetation Late Summer, Leaves with Low Water Content	0.29
Fresh Snow	0.83
Old Snow	0.42 - 0.70

[a]May be too low.

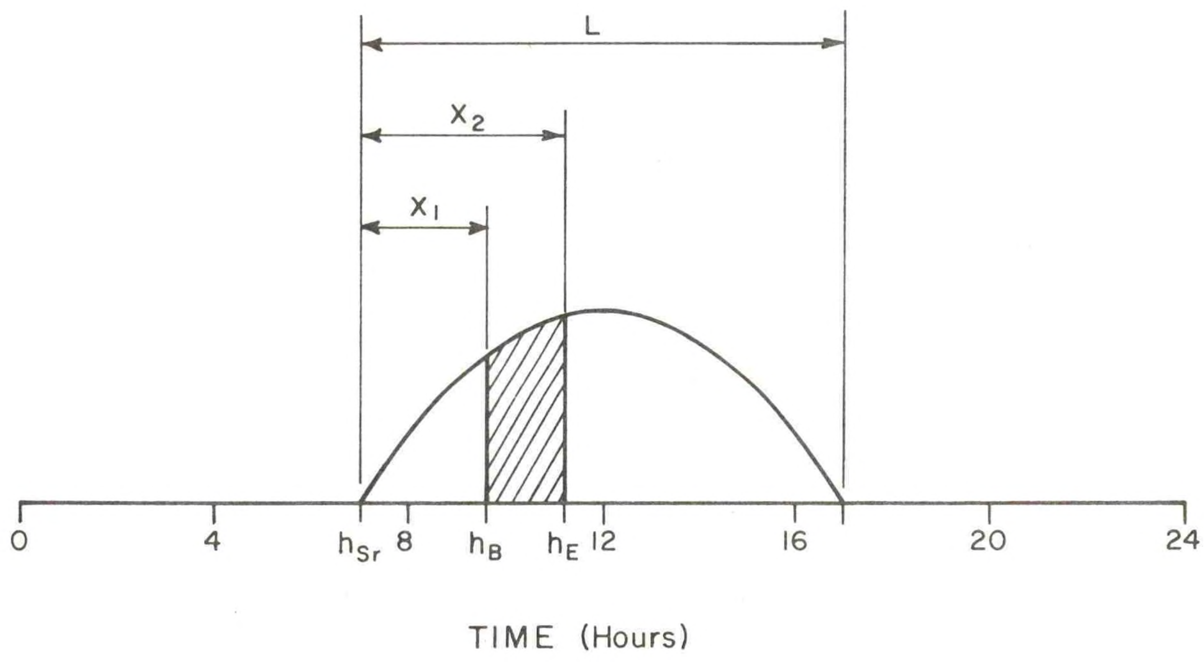


Figure 3.4. Parabolic distribution of daily solar radiation flux by technique 2 (adapted from Albertson et al., 1974).

in which

q_i	solar radiation flux incident at the stream surface during the time period $(h_E - h_B)$ (BTU ft^{-2} hr^{-1})
I_{obs}	observed total daily solar radiation flux (BTU ft^{-2} hr^{-1})
$L = h_{ss} - h_{sr}$	sunrise - sunset period (hours)
$X_1 = h_B - h_{sr}$	time from sunrise to beginning of computational time interval, h_B (hours)
$X_2 = h_E - h_{sr}$	time from sunrise to end of computational time interval, h_E (hours)
S	fraction of sky shaded from the stream surface by vegetation or other obstructions excluding cloud cover (dimensionless)

Solar radiation flux reflected at the stream surface during the time period $(h_E - h_B)$ was computed in the following way:

$$q_r = q_i R_t \qquad (3.56)$$

in which

R_t	reflectivity of water surface as input by the user (dimensionless)

Technique 3 - observed solar radiation. In this approach solar radiation flux incident at the stream surface was equated to the observed solar radiation in each computational time interval modified only by a shading factor:

$$q_i = I_{obs} (1 - S) \qquad (3.57)$$

and reflected solar radiation at stream surface was estimated by:

$$q_r = q_i R_t \qquad (3.58)$$

In the general form of Equation 3.31 incident and reflected solar radiation flux at the stream surface are given by:

$$\phi_s = q_i \qquad (3.59)$$

$$\phi_{sr} = q_r \qquad (3.60)$$

Techniques compared. The principal source of error in predicting incident solar radiation lies in handling the effects of cloud cover (Wunderlich, 1972). When observed solar radiation data at one location are used for stream temperature predictions at another location the differences in cloud cover at the two locations can introduce considerable error to surface heat exchange calculations. Times of sunrise and sunset vary for different subreaches in a stream because of the effects of channel orientation and topographic features above which the sun must rise before the solar beam is incident on the water surface. Other factors influencing the amount of solar radiation flux incident on the stream surface include the albedo of the ground surface adjacent to the stream, R_g, and the atmospheric transmittance depending in part on the dust depletion coefficient d_p.

Technique 1 has the advantages of accounting for the variation in local factors such as orientation and topographic effects (described by α_{sr} and α_{ss}) and the ground surface albedo, R_g. It has the disadvantage of depending heavily on good cloud cover data. However, unless observed solar radiation data are available close to the study subreaches techniques 2 and 3 also may provide unrealistic estimates of incident and reflected solar radiation. When diurnal predictions are made using daily data technique 2 gives the solar radiation data a distribution which approximates the distribution expected under constant cloud cover conditions. If observed solar radiation data are available at less than a daily frequency then technique 3 should be used if it is considered that these observed data provide a more realistic distribution of solar radiation throughout the day than the parabolic approximation in technique 2. Another approach is to calibrate technique 1 to the site at which solar radiation data were observed. Calibration is achieved by estimating α_{sr}, α_{ss}, R_g, and d_p for the site and then adjusting these coefficients within a reasonable range of values until the observed solar radiation is closely matched. Both the times of sunset and sunrise and also the total amount of observed daily solar radiation should be closely matched. Technique 1 could then be used on each subreach by giving α_{sr}, α_{ss}, and R_g values appropriate to each subreach. The calculation approach requires some coefficient estimation before it can be applied but in return it takes account of local factors affecting solar radiation.

Figures 3.5 and 3.6 contain the results of sensitivity studies on two coefficients (R_g and d_p) in the computational method of estimating incident and reflected solar radiation flux at the stream surface (technique 1). By raising R_g from its lower limit for without-snow conditions (0.05 from Table 3.3) to its upper limit for without-snow conditions (0.45) the cumulative incident solar radiation in a 24 hour period was increased by 27 percent. When R_g was further increased to the upper limit for fresh snow conditions (0.85) the increase in cumulative incident solar radiation over the case where $R_g = 0.05$ was 72 percent.

Albedo of snow decreases with age over the range 0.85 to 0.4. Because of the importance of R_g in determining the incident solar radiation flux it appears that a snowpack simulation to determine the presence of snow and the albedo of the snow surface should be developed. The relative importance of solar radiation to the total heat budget in times of snow should be evaluated before proceeding with the snowpack simulation. A snowpack routine applied by Bowles et al. (1975) in a watershed simulation model could be adapted for this purpose.

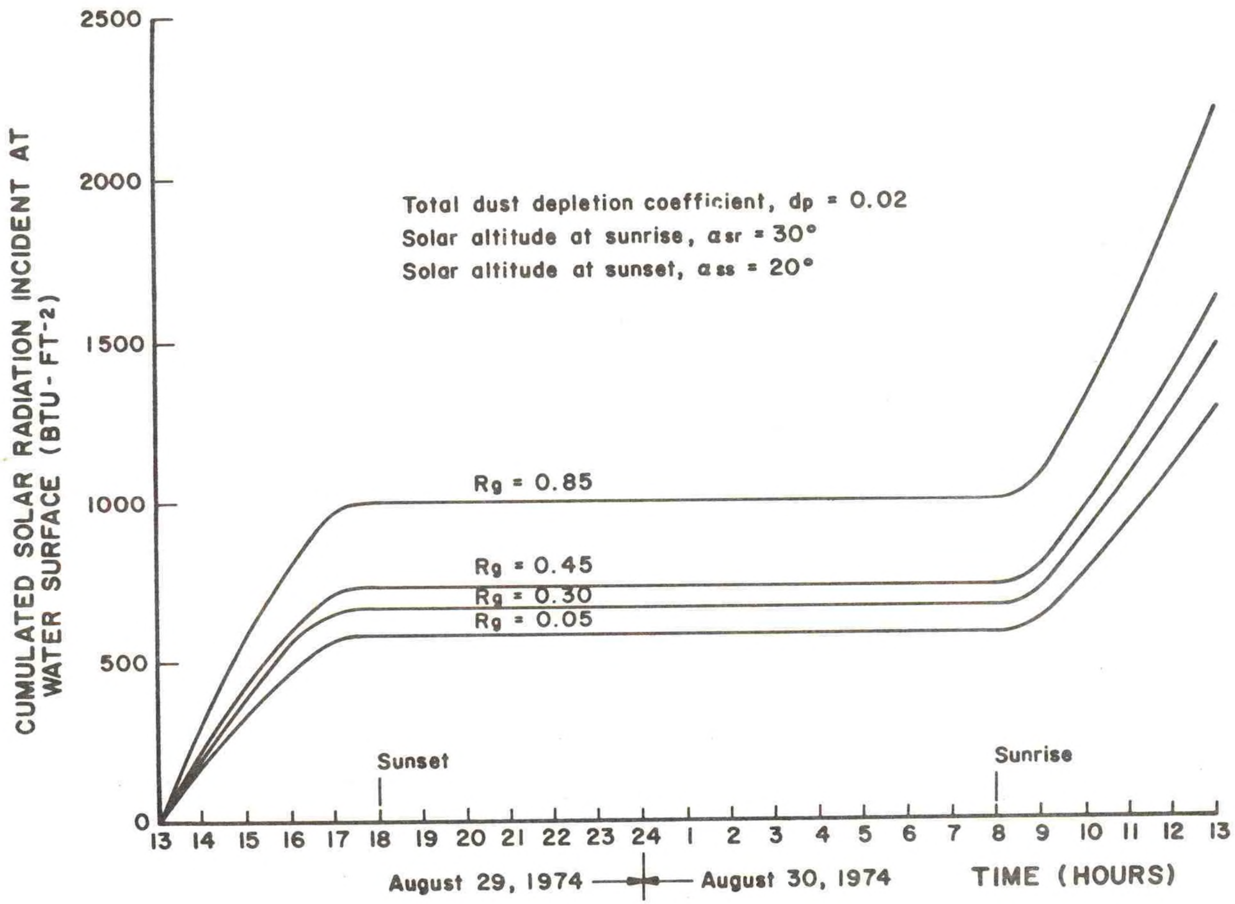


Figure 3.5. Sensitivity of incident solar radiation to reflectivity of ground adjacent to stream (R_g).

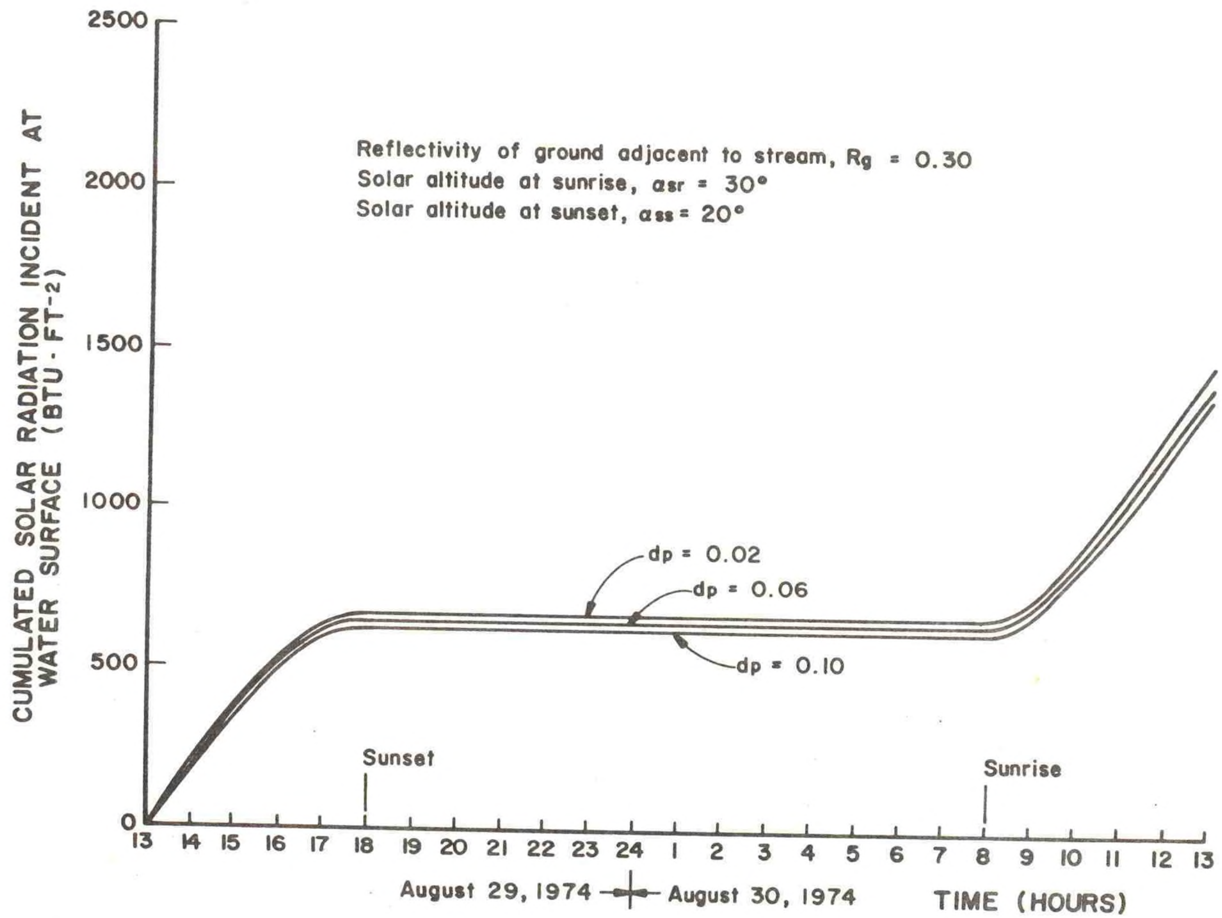


Figure 3.6. Sensitivity of incident solar radiation to total dust depletion coefficient (d_p).

Incident solar radiation flux was shown to be fairly insensitive to the dust depletion coefficient, d_p (Figure 3.6). By varying d_p over its range for the summer season, 0.02 to 0.10 (Table 3.2) cumulative incident solar radiation decreased by less than 4 percent.

Figure 3.7 is a comparison of cumulated incident solar radiation calculated by the three techniques available in DSTEMP. Observed data were recorded at Utah State University (USU) which is located 15 miles (24 km) southwest of the study stream, Spawn Creek. The discrepancy between the calculated (ITECH = 1) and observed (ITECH = 3) lines can be attributed to several factors: topographic differences between the measurement site and study stream (different α_{sr} and α_{ss}); different albedos of adjacent ground (R_g) at measurement site and study area; and cloud cover (C) differences between the valley location of the measurement site and the mountain location of the study stream. If the observed data were adjusted for topographic, and ground albedo differences, it is believed that the value of R_g could be reduced to a more realistic value for Spawn Creek and that the results from techniques 1 and 3 would be closer over the entire 24 hour period.

Technique 2 represents a different distribution of the same total amount of radiation that is predicted in technique 3. An important factor determining the different distributions is that sunrise and sunset times used in technique 2 were estimated for Spawn Creek and not

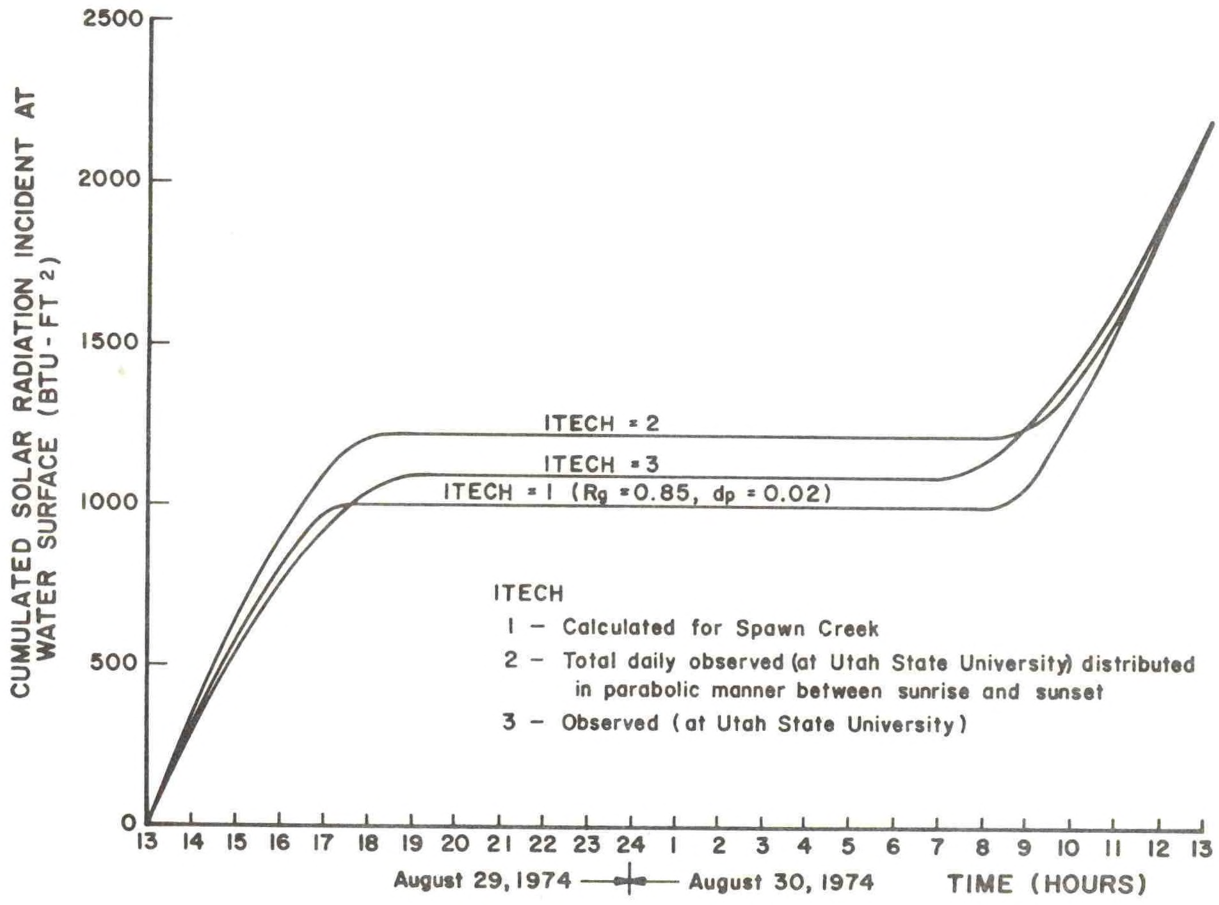


Figure 3.7. Comparison of solar radiation calculated by the three techniques.

the USU measurement site. The earlier sunset and later sunrise used in technique 2,compared with those observed in technique 3, reflects the greater degree of topographic obstruction at Spawn Creek. If sunset and sunrise times in technique 2 were set equal to those observed in technique 3 a better correspondence would be expected between these two approaches.

Vegetative radiation

Long-wave radiation emitted by the forest canopy was not accounted for in the current version of DSTEMP. Pluhowski (1970) proposed applying Stefan-Boltzmann's law to the problem of estimating incident and reflected vegetative radiation at the stream surface. Written directly in the form of Equation 3. 31, Pluhowski's approach was:

$$\phi_v = \epsilon \sigma (T_a + 459.67)^4 \quad \ldots \ldots \ldots \quad (3.61)$$

$$\phi_{vr} = R_\ell \phi_v \quad \ldots \ldots \ldots \ldots \quad (3.62)$$

in which

ϵ emissivity factor for forest canopy (ϵ = 1.0 for solid canopy)

σ Stefan-Boltzmann constant ($1.74*10^{-9}$ BTU hrs^{-1} ft^{-2} deg. R^4)

T_a absolute temperature of the air above the ground as an approximation to the effective leaf temperature (deg. R)

R_ℓ reflectivity of water surface to long-wave radiation ($R_\ell = 0.03$ according to Harbeck, 1958)

This component would probably be important in subreaches flowing through densely forested areas.

Atmospheric radiation

Anderson (1954) proposed the following empirical relationship for incident long-wave atmospheric radiation flux:

$$\phi_a = \beta \epsilon \sigma (T_a + 459.67)^4 \quad . \; . \; . \; . \; . \; . \; . \; . \quad (3.63)$$

in which

β atmospheric radiation factor (dimensionless)

ϵ emissivity of the atmosphere ($\epsilon = 1.0$)

Based on a statistical analysis of Anderson's results and on later work by Burt (1958), Raphael (1962) developed Figure 3.8 in which β was represented as a function of vapor pressure and cloud cover:

$$\beta = AA(C) + BB(C)\, e_a \quad . \; . \; . \; . \; . \; . \; . \; . \quad (3.64)$$

in which

C cloud cover in an integer number of tenths of cover

AA(C), BB(C) empirical coefficients in Equation 3.64 with different values for C = 0, 10. The values used in

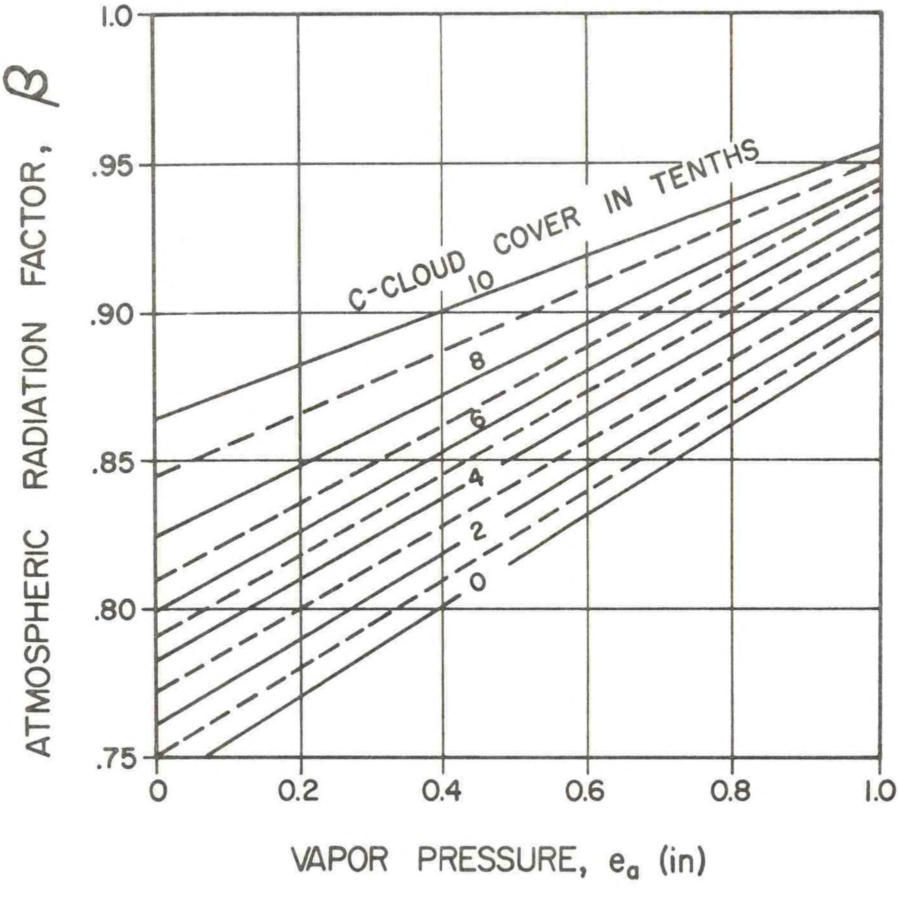


Figure 3.8. Atmospheric radiation factor, β (after Raphael, 1962).

AA(C) and BB(C) were taken from Novotny and Krenkel (1971) and are contained in the input description for read statements 32 and 33 in the DSTEMP input description (Appendix A)

e_a vapor pressure of air (ins. Hg)

Vapor pressure of air was calculated using a modified version of the Magnus-Tetens formula (Kleinschmidt, 1935):

$$e_a = \exp\left[\frac{8.642\ T_d - 683.0}{0.5556\ T_d + 219.5}\right] \quad . \quad . \quad . \quad . \quad . \quad (3.65)$$

in which

T_d dew point temperature (deg. F)

Long-wave atmospheric radiation flux reflected at the stream surface was estimated by:

$$\phi_{ar} = R_\ell \phi_a \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3.66)$$

<u>Back radiation</u>

Countering the incoming fluxes of heat from the sun, atmosphere, and forest is the long-wave radiation emitted by the stream itself. Long-wave back radiation from the stream was computed by a piece-wise-linear approximation to Stefan-Boltzmann's law with an emissivity factor for water of $\epsilon = 0.97$ (Anderson, 1954):

$$\phi_b = B1(T) + B2(T)T \quad . \; . \; . \; . \; . \; . \; . \; . \qquad (3.67)$$

in which

T stream temperature (deg. F)

B1(T), B2(T) coefficients in the piecewise-linear approximation to Stefan-Boltzmann's law depending on stream temperature range:

T	B1	B2
32 - 68	68.27	0.8815
68 - 104	54.25	1.084

Latent heat of vaporization associated with evaporation

Many empirical formulas are available for estimating evaporation from water bodies (Wunderlich, 1972). Each of these formulas involves coefficients that should be estimated from field experiments. A generalized version of the empirical evaporation equation was adapted for use in DSTEMP. Latent heat of vaporization removed from the stream by the evaporating water mass was estimated by:

$$\phi_e = \rho L_v Nu (e_s - e_a) \quad . \; . \; . \; . \; . \; . \; . \; . \qquad (3.68)$$

in which

ρ density of water (62.3 lbs. ft^{-3})

L_v latent heat of vaporization of water (1053 BTU lbs^{-1})

N mass transfer coefficient (evaluated by field experiment or during model calibration procedure) (ins. Hg^{-1})

- u wind speed (mph)
- e_s saturation vapor pressure of air (ins. Hg)
- e_a vapor pressure of air (ins. Hg)

Saturation vapor pressure of air was calculated by a piecewise-linear approximation (Wunderlich, 1972) to the Magnus-Tetens formula (Equation 3.65) in which T was substituted for T_d:

$$e_s = ES1(T) + ES2(T)T \quad \ldots\ldots\ldots \quad (3.69)$$

in which

ES1(T), ES2(T) coefficients in the piecewise-linear approximation to Magnus-Tetens formula depending on stream temperature range. Values used for ES1(T) and ES2(T) are listed in the input description for read statements 35 and 36 in the DSTEMP input description (Appendix A).

Conduction

Bowen (1926) related heat losses to the air by conduction across a water surface, to latent heat of vaporization associated with evaporation from the water surface:

$$R = \frac{\phi_c}{\phi_e} = 6.49\left[\frac{T - T_a}{e_s - e_a}\right]\frac{P}{P_o} \quad \ldots\ldots \quad (3.70)$$

in which

R Bowen's ratio (a dimensionless constant, see Bowen, 1926)

P atmospheric pressure at study area (ins. Hg)

P_o atmospheric pressure at sea level

Heat losses by conduction were estimated by substituting Equation 3.68 and P_o = 29.92 ins. Hg into Equation 3.70 and then solving for ϕ_c:

$$\phi_c = 0.217\,(T - T_a)\,P\rho\,L_v\,Nu \qquad . \; . \; . \; . \; . \qquad (3.71)$$

<u>Latent heat of fusion associated with snowfall</u>

The current version of DSTEMP does not include an estimation of the latent heat of fusion and other heat required to convert snow falling into the stream to water. Adapting an approach used by Jeppson (1975) the heat lost by the stream in melting snow is given by:

$$\phi_{sn} = q_{sn}\,\rho\,[L_f + C_{sn}\,(T - T_r)] \qquad . \; . \; . \; . \; . \qquad (3.72)$$

in which

q_{sn} snow (ft. s^{-1})

L_f latent heat of fusion (143.5 BTU lbs^{-1})

C_{sn} specific heat of ice (0.50 BTU lbs^{-1} deg. F^{-1})

Surface layer renewal

Heat supply or removal by surface renewal was also omitted from the current version of DSTEMP. It could be represented using an approach proposed by Novotny and Krenkel (1971):

$$\phi_w = k_w (T_s - T) \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (3.73)$$

$$k_w \simeq 3.96 \times 10^4 k \left(\frac{U}{H}\right)^{0.33} \quad . \; . \; . \; . \; . \; . \quad (3.74)$$

in which

- T_s surface water temperature (deg. F)
- k coefficient of thermal conductivity (BTU ft^{-1} s^{-1} deg. F^{-1})
- U velocity of stream (ft. s^{-1})
- H depth of flow (ft.)

To calculate ϕ_w an estimate of T_s is required. Novotny and Krenkel (1971) proposed a technique for calculating T_s from T, the bulk water temperature, by applying a heat balance at the air-water interface. If T_s is estimated it should also be used in place of T in the estimation of ϕ_b (Equation 3.67), ϕ_e (Equation 3.68), and ϕ_c (Equation 3.70).

Solar radiation absorbed by streambed

After reflection at the stream surface the remainder of the incident solar radiation flux enters the stream. Approximately 60 percent of the solar radiation (Novotny and Krenkel, 1971) entering the stream is immediately absorbed in the water surface (Figure 3.9). Within the stream solar radiation is absorbed in an exponential manner which can be described fairly well by Beer's law. Thus the solar radiation flux absorbed by the streambed was estimated by:

$$\phi_{bs} = (1 - R_b)(1 - s)(\phi_s - \phi_{sr}) \exp(-\eta H) \quad . \quad . \quad . \quad (3.75)$$

in which

R_b reflectivity of streambed (found experimentally or in calibration procedure) (dimensionless)

s proportion of solar radiation entering stream that is absorbed in the water surface (usually 0.6)

η bulk extinction coefficient (mean value for solar radiation 0.008 ft^{-1}, Roesner, 1969) (ft^{-1})

Back radiation from streambed

This component was not modeled in the current version of DSTEMP. If an emissivity of the streambed could be established then it is proposed that the Stefan-Boltzmann's law could be applied based on the temperature of the streambed-stream interface.

Conductive flux across streambed

In Comer et al. (1975) a regression relationship was developed to predict conductive flux across the streambed of Spawn Creek based on

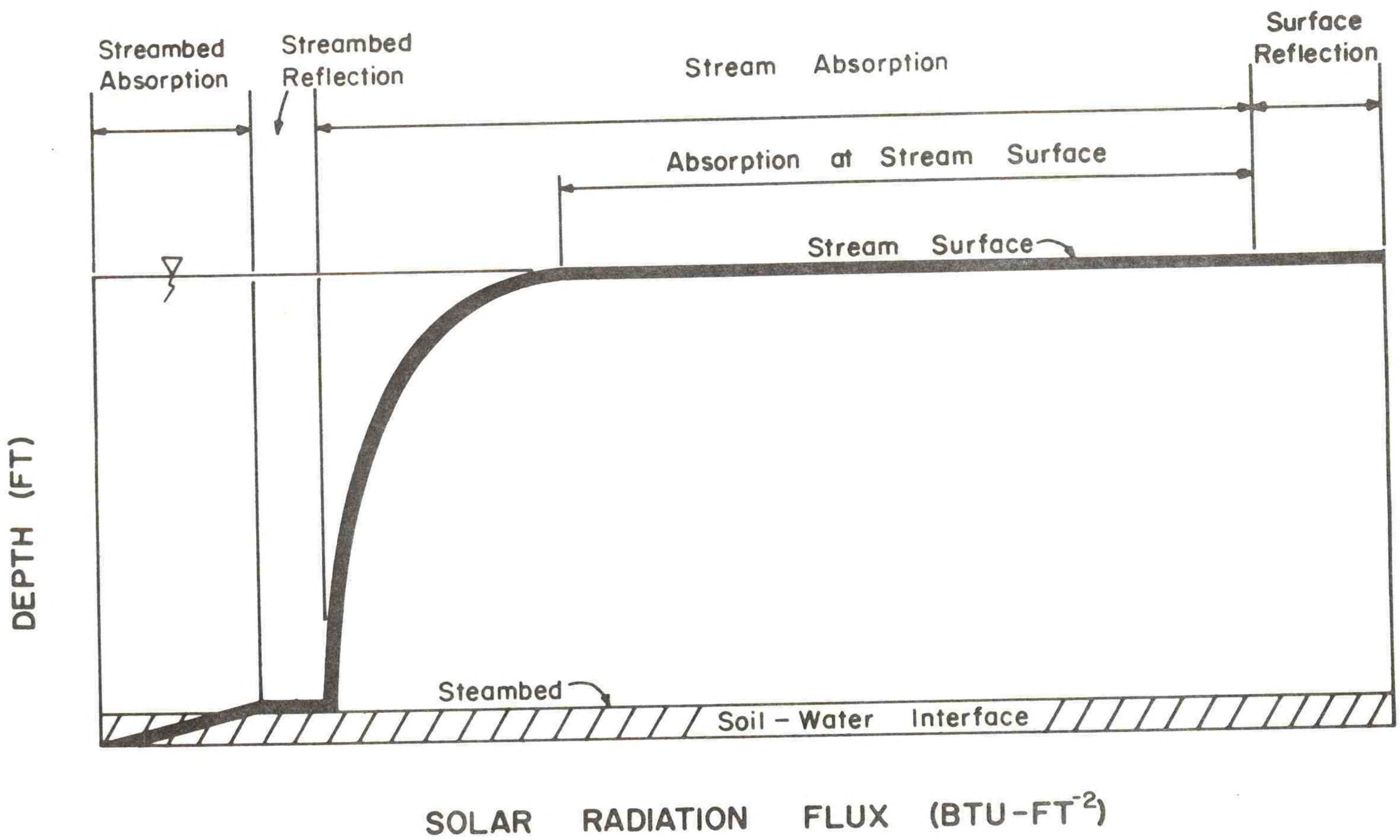


Figure 3.9. Dissipation of incident solar radiation flux.

experimental data:

$$\phi_{bc} = \alpha_1 + \alpha_2 \phi_{bs} + \alpha_3 T_g + \alpha_4 T \quad . \quad . \quad . \quad . \quad . \qquad (3.76)$$

in which

$\alpha_1, \alpha_2, \alpha_3, \alpha_4$ regression coefficients

T_g groundwater temperature (deg. F)

CHAPTER 4

APPLICATION OF DSTEMP TO BRAZOS-LITTLE RIVERS, TEXAS

Introduction

A search was made for a river system on which to demonstrate the Dynamic Stream Temperature Model (DSTEMP) and its linkage to the Implicit Dynamic Routing Program (DNRT). The following criteria were selected for the river system:

1) A river-tributary system is preferred to a single river

2) Streamflow and stream temperature data should be available at the upstream boundaries of the main river and tributary and at the downstream boundary of the main river

3) Streamflow at the upstream boundaries of the river system should contribute the major portion of the streamflow at the downstream boundary and therefore lateral inflow is small

4) No reservoirs between upstream and downstream boundaries

5) No major sources of thermal pollution or streamflow for which records do not exist

The third criterion was established because streamflow-stream temperature modeling in a river system with large lateral inflow becomes mainly a problem of estimating lateral inflow rates and lateral inflow temperatures. In the absence of these lateral inflow data they should be estimated using a two-dimensional hydrology-water temperature model applied to the catchment areas of the river system. At present, such a model does not exist for water temperature. In order that the predictions from DSTEMP should not be dominated by lateral inflow temperature estimates a river system with small lateral inflow was sought such that hydrograph-thermograph routing and meteorologic considerations were the most important aspects of the stream temperature simulation.

After an extensive search with the assistance of the Chief, Branch of Quality of Water, USGS, and several USGS District Chiefs, the Brazos-Little Rivers in Texas were found to closely satisfy the criteria listed above. In the remainder of this chapter the data collection, streamflow modeling, DSTEMP problem set-up, and results of the Brazos-Little application are described.

Brazos-Little River System

The section of the Brazos-Little River System modeled in this study was bounded by USGS streamflow gages at Highbank, Cameron, and College Station (Figure 4.1). Stream temperature records were available at the Highbank and Cameron gages but not at College Station. Therefore, stream temperature records from the Bryan gage, 9 miles downstream, were used for comparison with stream temperatures predicted by the DSTEMP model at college stations. On the basis of channel characteristics the 65.5 mile section of the Brazos River was divided into 13 subreaches, and the 33.6 mile section of the Little River was divided into 8 subreaches. At the confluence of the rivers an arbitrarily small subreach was

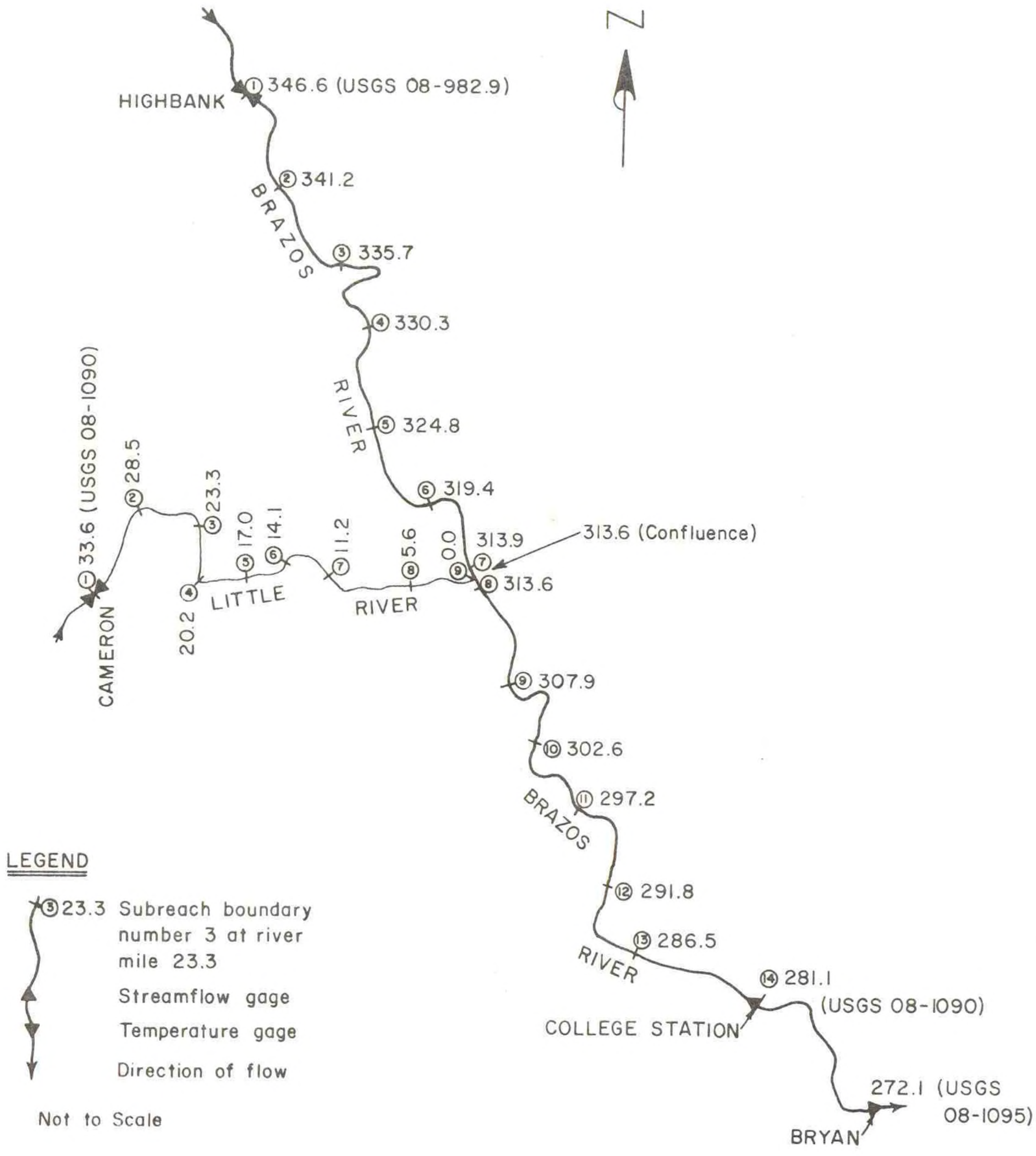


Figure 4. 1. Schematic of Brazos-Little River System.

defined on the Brazos River for addition of the Little River treated as lateral inflow over the small subreach.

Data Sources

Several storms during the 1973 water year were selected for possible simulation. Streamflow and stream temperature data were obtained from the USGS Surface Water Records and Water Quality Records. Topographic quadrangle maps, and rating curves and cross-sections for the gaging stations were furnished by the USGS, Austin, Texas.

Meteorologic data were taken from Local Climatic Data published by NOAA. Additional unpublished meteorologic data for College Station were supplied on microfilm from the National Climatic Center, Asheville, North Carolina. Solar radiation data observed at College Station were made available by the Texas State Climatologist.

Streamflow Modeling

Data preparation for application of DNRT to the Brazos-Little Rivers was undertaken jointly by the contractors (Utah Water Research Laboratory) and the client (Hydrologic Research Laboratory, National Weather Service, NOAA). Final calibration of DNRT for unsteady flow conditions was accomplished by D. L. Fread of NOAA. Output from the calibrated DNRT model was written onto computer disc storage files at Utah State University, and then read as input by the DSTEMP model.

DSTEMP Problem Set-Up

A partial listing of DSTEMP model input is contained in Figure 4.2. The listing was obtained using the print option, IPRT = 1, which excludes hydraulic and stream geometry data generated by DNRT. All components of surface heat transfer available in the current version of DSTEMP were used, but streambed heat transfer components were considered negligible. Solar radiation was calculated using the third technique (ITECH = 3). A 12 hour computational time increment was used.

Surface and subsurface components of lateral inflow were lumped together and no point sources of thermal effluents were represented. Initial temperatures along the river system were estimated by linear interpolation between the upstream and downstream boundaries while maintaining a heat balance at the confluence of the two rivers. Comparison of observed and predicted stream temperatures was possible at only one location, the downstream boundary.

Standard values of the various meteorologic coefficients listed in Appendix A were used in this application. Three meteorologic data groups were defined:

1) Brazos River, subreaches 1-7: using precipitation and dry bulb air temperatures observed at Highbank and other meteorologic data from Waco.

2) Little River, subreaches 1-8: using precipitation and dry bulb air temperatures observed at Cameron and other meteorologic data from Waco.

```
LISTING OF DATA

KRR                9        3          0          0          0          1
NTNS              47        2
BRAZOS RIVER (HIGHBANK-BRYAN) AND LITTLE RIVER (CAMERON-CONFLUENCE) TEXAS   -
24:00 HRS DEC 5 - 24:00 HRS DEC 28, 1972
       MILES      FT2      FT       FT         FT  FT2S-1  FTS-1  CFS         CFS
  DF     DF     DF    BTU     DF       DF     DF
IOHT     1         1          0          1          1          1          1          0
                   0          0          0
PHCF     1   62.3170     0.9998 1053.0000   143.5000     0.0300     0.0150     0.6000
              0.0600
TIME             340    24.0000    30.7500     0.4500     0.0000     0.0000
CCF1           0.600    429.000      0.060.50000E-04.17400E-08     1.0000
CCF2          0.0000     0.0000     0.0000     0.0000
IOGT               0          1          0          0
TLBGK1   1   41.0000    40.8700    40.7500    40.6200    40.5000    40.3700    40.2500
             40.1200    40.0000    39.8700    39.7500    39.6200    39.5000    39.3700
             39.2500    39.1200    39.0000    38.8700    38.7500    38.6200    38.5000
             38.3700    38.2500    38.1200    38.0000    37.8700    48.0000    58.1200
             58.0000    57.8700    57.7500    57.6200    57.5000    57.3700    57.2500
             57.1200    57.0000    56.8700    56.7500    56.6200    56.5000    56.3700
             56.2500    56.1200    56.0000    55.8700    55.7500
TLBGK2   1   41.0000    40.8700    40.7500    40.6200    40.5000    40.3700    40.2500
             40.1200    40.0000    39.8700    39.7500    39.6200    39.5000    39.3700
             39.2500    39.1200    39.0000    38.8700    38.7500    38.6200    38.5000
             38.3700    38.2500    38.1200    38.0000    37.8700    48.0000    58.1200
             58.0000    57.8700    57.7500    57.6200    57.5000    57.3700    57.2500
             57.1200    57.0000    56.8700    56.7500    56.6200    56.5000    56.3700
             56.2500    56.1200    56.0000    55.8700    55.7500
TSICK1L1 1   54.0000    54.3300    54.6800    55.0100    55.3500    55.6900    56.0300
             52.0100    52.3400    52.6700    53.0000    53.3400    53.6700    54.0000
TSICK2L1 1   45.0000    45.3200    45.6400    45.8300    46.0300    46.2100    46.3900
             46.7300    47.0800
TSLSK1   1   54.0000    50.0000    46.0000    46.0000    46.0000    46.0000    46.0000
             48.0000    50.0000    48.0000    46.0000    45.0000    43.0000    43.0000
             43.0000    44.0000    45.0000    45.5000    46.0000    45.0000    43.0000
             43.0000    43.0000    42.0000    41.0000    42.0000    43.0000    45.5000
             48.0000    50.0000    52.0000    51.0000    50.0000    49.0000    48.0000
             48.0000    46.0000    46.0000    48.0000    48.0000    48.0000    49.0000
             50.0000    49.0000    48.0000    48.0000    48.0000
TSLSK2   1   45.0000    45.5000    46.0000    46.0000    46.0000    45.5000    45.0000
             45.5000    46.0000    45.5000    45.0000    45.0000    45.0000    45.0000
             45.0000    45.5000    46.0000    45.5000    45.0000    45.0000    45.0000
             44.0000    43.0000    43.0000    43.0000    43.0000    43.0000    44.5000
             46.0000    46.0000    46.0000    46.0000    46.0000    47.0000    48.0000
             48.0000    48.0000    47.0000    46.0000    46.0000    46.0000    47.0000
             48.0000    49.0000    50.0000    50.0000    50.0000
NOT                1
TSC  114     54.0000    50.0000    46.0000    45.5000    45.0000    45.5000    46.0000
             46.0000    46.0000    44.5000    43.0000    43.0000    43.0000    43.0000
             43.0000    43.0000    43.0000    43.0000    43.0000    43.0000    43.0000
             43.0000    43.0000    42.0000    41.0000    42.0000    43.0000    46.5000
             50.0000    50.5000    51.0000    50.5000    50.0000    52.0000    54.0000
             52.5000    51.0000    52.5000    54.0000    54.0000    54.0000    53.5000
             53.0000    53.0000    53.0000    53.0000    53.0000
AA       1    0.7400     0.7500     0.7600     0.7710     0.7830     0.7930     0.8000
              0.8100     0.8250     0.8450     0.8660
BB       1    0.1500     0.1500     0.1500     0.1430     0.1380     0.1370     0.1350
              0.1300     0.1200     0.1050     0.0900

TE            50.0000    68.0000    86.0000
ES1           -0.1380    -0.5460    -1.4400    -3.1330
ES2            0.0098     0.0180     0.0312     0.0509
SHADK1   1     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000
               0.0000     0.0000     0.0000     0.0000     0.0000     0.0000
SHADK2   1     0.1500     0.1500     0.1500     0.1500     0.1500     0.1500     0.1500
               0.1500
NG                  3          2
IO                  0          1          1          0          1          1
NRG K1   1          1          1          1          1          1          1          3
                    3          3          3          3          3          3
NRG K1   1          2          2          2          2          2          2          2
                    2
QR   G1E 1     0.0000     0.0000     0.1100     0.0100     0.0000     0.5100     0.1300
               0.0000     1.6100     0.0200     0.0000     0.0000     0.0000     0.0000
               0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000
               0.0000     0.0000
TR   G1E 1    26.0000    29.0000    40.0000    40.0000    30.0000    29.0000    36.0000
              34.0000    36.0000    31.0000    27.0000    30.0000    41.0000    51.0000
              51.0000    42.0000    37.0000    44.0000    40.0000    39.0000    40.0000
              37.0000    45.0000
TA   G1E 1    44.0000    33.0000    41.0000    43.0000    35.0000    30.0000    41.0000
              39.0000    40.0000    38.0000    34.0000    34.0000    42.0000    59.0000
              57.0000    54.0000    46.0000    58.0000    52.0000    46.0000    49.0000
              45.0000    51.0000
TD   G1E 1    16.0000    22.0000    39.0000    38.0000    27.0000    26.0000    34.0000
              31.0000    35.0000    26.0000    17.0000    22.0000    37.0000    48.0000
              47.0000    35.0000    29.0000    32.0000    33.0000    33.0000    29.0000
              27.0000    39.0000
ATPRG1E  1    29.7900    29.6900    29.4900    29.5200    29.7300    29.6700    29.5800
              29.7200    29.6000    29.9300    29.1900    29.0700    29.7700    29.5600
              29.2300    29.3400    29.3700    29.3100    29.6500    29.6100    29.7900
              29.6700    29.4200
WDVEG1E  1    19.7000     7.3000     6.2000     9.8000    17.0000    10.6000     5.8000
               8.6000    12.8000    16.0000     7.9000     9.1000    11.4000     7.8000
              11.1000    17.3000     8.6000    11.7000    10.8000     4.8000    10.9000
              10.9000    13.7000
ICS  G1E 1          3         10         10         10         10         10         10
                    6         10          9          0          9         10          7
                    8          4          0          0          0          8          0
                    4         10
ICL  G1E 1          5         10         10         10         10         10          8
                    6         10          6          0          5         10          8
                    7          4          0          0          2          6          2
                    2          9
DYSL 1E  1   278.0000   226.0000   108.0000   108.0000   117.0000   117.0000    95.0000
              95.0000    58.0000    58.0000    84.0000    84.0000   307.0000   307.0000
             299.0000   299.0000    88.0000    88.0000   299.0000   299.0000   571.0000
             571.0000   434.0000   434.0000   106.0000   106.0000   179.0000   179.0000
             296.0000   296.0000   264.0000   264.0000   540.0000   540.0000   520.0000
             570.0000   533.0000   533.0000   522.0000   522.0000   529.0000   529.0000
             531.0000   531.0000   263.0000   263.0000
QR   G2E 1     0.0000     0.0000     0.0500     0.0300     0.0000     0.0300     0.3200
               0.0000     0.0000     0.3700     0.0000     0.0000     0.0000     0.0000
               0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000
               0.0000     0.0000
TR   G2E 1    26.0000    29.0000    40.0000    40.0000    30.0000    29.0000    36.0000
              34.0000    36.0000    31.0000    27.0000    30.0000    41.0000    51.0000
              51.0000    42.0000    37.0000    44.0000    40.0000    39.0000    40.0000
              37.0000    45.0000
TA   G2E 1    44.0000    33.0000    42.0000    45.0000    36.0000    31.0000    41.0000
```

Figure 4.2. Partial listing of DSTEMP model input for the Brazos-Little River System (December 5-28, 1972).

```
                 39.0000   41.0000   38.0000   37.0000   38.0000   48.0000   63.0000
                 63.0000   55.0000   48.0000   58.0000   54.0000   50.0000   51.0000
                 48.0000   54.0000
TD   G2E   1     16.0000   22.0000   39.0000   38.0000   27.0000   26.0000   34.0000
                 31.0000   35.0000   26.0000   17.0000   22.0000   37.0000   48.0000
                 47.0000   35.0000   29.0000   32.0000   33.0000   33.0000   29.0000
                 27.0000   39.0000
ATPRG2E    1     29.7900   29.6900   29.4900   29.5200   29.7300   29.6700   29.5800
                 29.7200   29.6000   29.9300   29.1900   29.0700   29.7700   29.5600
                 29.2300   29.3400   29.3700   29.3100   29.6500   29.6100   29.7900
                 29.6700   29.4200
WDVEG2E    1     19.7000    7.3000    6.2000    9.8000   17.0000   10.6000    5.8000
                  8.6000   12.8000   16.0000    7.9000    9.1000   11.4000    7.8000
                 11.1000   17.3000    8.6000   11.7000   10.8000    4.8000   10.9000
                 10.9000   13.7000
ICS  G2E   1           3        10        10        10        10        10        10
                       6        10         9         0         9        10         7
                       8         4         0         0         0         8         0
                       4        10
ICL  G2E   1           5        10        10        10        10        10         8
                       6        10         6         0         5        10         6
                       7         4         0         0         2         6         2
                       2         9
DYSL 2E    1    228.0000  228.0000  108.0000  108.0000  117.0000  117.0000   95.0000
                 95.0000   58.0000   58.0000   84.0000   84.0000  307.0000  307.0000
                299.0000  299.0000   88.0000   88.0000  299.0000  299.0000  571.0000
                571.0000  434.0000  434.0000  106.0000  106.0000  179.0000  179.0000
                296.0000  296.0000  264.0000  264.0000  540.0000  540.0000  520.0000
                520.0000  533.0000  533.0000  522.0000  522.0000  529.0000  529.0000
                531.0000  531.0000  263.0000  263.0000
QR   G3E   1      0.0000    0.0400    0.0600    0.0200    0.1800    0.0600    0.1600
                  0.0000    0.6400    0.0000    0.0000    0.0000    0.0100    0.0000
                  0.0000    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
                  0.0000    0.0000
TR   G3E   1     32.0000   31.0000   42.0000   45.0000   31.0000   31.0000   38.0000
                 32.0000   38.0000   32.0000   31.0000   32.0000   44.0000   55.0000
                 58.0000   45.0000   38.0000   51.0000   42.0000   43.0000   39.0000
                 43.0000   39.0000
TA   G3E   1     34.0000   36.0000   44.0000   47.0000   37.0000   32.0000   41.0000
                 36.0000   41.0000   37.0000   35.0000   36.0000   45.0000   60.0000
                 62.0000   49.0000   45.0000   57.0000   48.0000   48.0000   48.0000
                 46.0000   48.0000
TD   G3E   1     21.0000   24.0000   41.0000   44.0000   29.0000   30.0000   34.0000
                 27.0000   35.0000   25.0000   17.0000   17.0000   39.0000   53.0000
                 55.0000   40.0000   30.0000   36.0000   35.0000   36.0000   30.0000
                 26.0000   44.0000
ATPRG3E    1     29.9100   29.8700   29.6700   29.6800   29.8800   29.8200   29.7800
                 29.9100   29.7700   30.1600   30.4000   30.2600   30.0000   29.7900
                 29.4300   29.5100   29.5800   29.5700   29.8500   29.8400   29.9800
                 29.8900   29.6300
WDVEG3E    1     18.6000    8.5000    3.7000    7.6000   15.8000    9.3000    9.9000
                 10.6000   13.5000   16.2000    6.8000    6.2000   10.4000    3.5000
                  9.2000   18.4000    6.3000    9.0000    9.7000    3.2000   10.5000
                  5.4000   13.6000
ICS  G3E   1           9        10        10        10        10        10         9
                       7        10        10         0         8        10        10
                       9         9         0         0         0         3         1
                       5        10
ICL  G3E   1           8        10        10        10        10        10         8
                       6        10         7         0         6        10         9
                       8         7         0         0         0         4         3
```

```
                       3         8
DYSL 3E    1    228.0000  228.0000  108.0000  108.0000  117.0000  117.0000   95.0000
                 95.0000   58.0000   58.0000   84.0000   84.0000  307.0000  307.0000
                299.0000  299.0000   88.0000   88.0000  299.0000  299.0000  571.0000
                571.0000  434.0000  434.0000  106.0000  106.0000  179.0000  179.0000
                296.0000  296.0000  264.0000  264.0000  540.0000  540.0000  520.0000
                520.0000  533.0000  533.0000  522.0000  522.0000  529.0000  529.0000
                531.0000  531.0000  263.0000  263.0000
```

Figure 4.2. Continued.

3) Brazos River, subreaches 9-13: using meteorologic data observed at College Station

Observed solar radiation data at College Station were used in all the meteorologic data groups. These data were adjusted for an instrument bias by adding 20% to the reported value. All meteorologic data were input for a meteorologic time interval of 24 hours except solar radiation data which were input for the 12 hour computational time intervals.

Results

Figures 4.3a and c show the upstream streamflow boundary conditions for the dynamic routing model, DNRT, for the period of December 5-28, 1972. A comparison of the observed and predicted hydrographs at the downstream boundary is represented by Figure 4.3e. This figure indicates that very good agreement was achieved between model responses and observed flows.

The strategy for calibration of DSTEMP was as follows:

1) Adjust coefficients affecting surface heat transfer components

2) Adjust estimate of lateral inflow thermograph

During the early stage of model calibration the first technique (ITECH=1) for calculating solar radiation was used. However, a comparison of solar radiation predicted by this technique with values observed at College Station indicated that low values were generally over-estimated and that high values were generally under-estimated. It was not feasible to draw any conclusions about the technique for estimating solar radiation

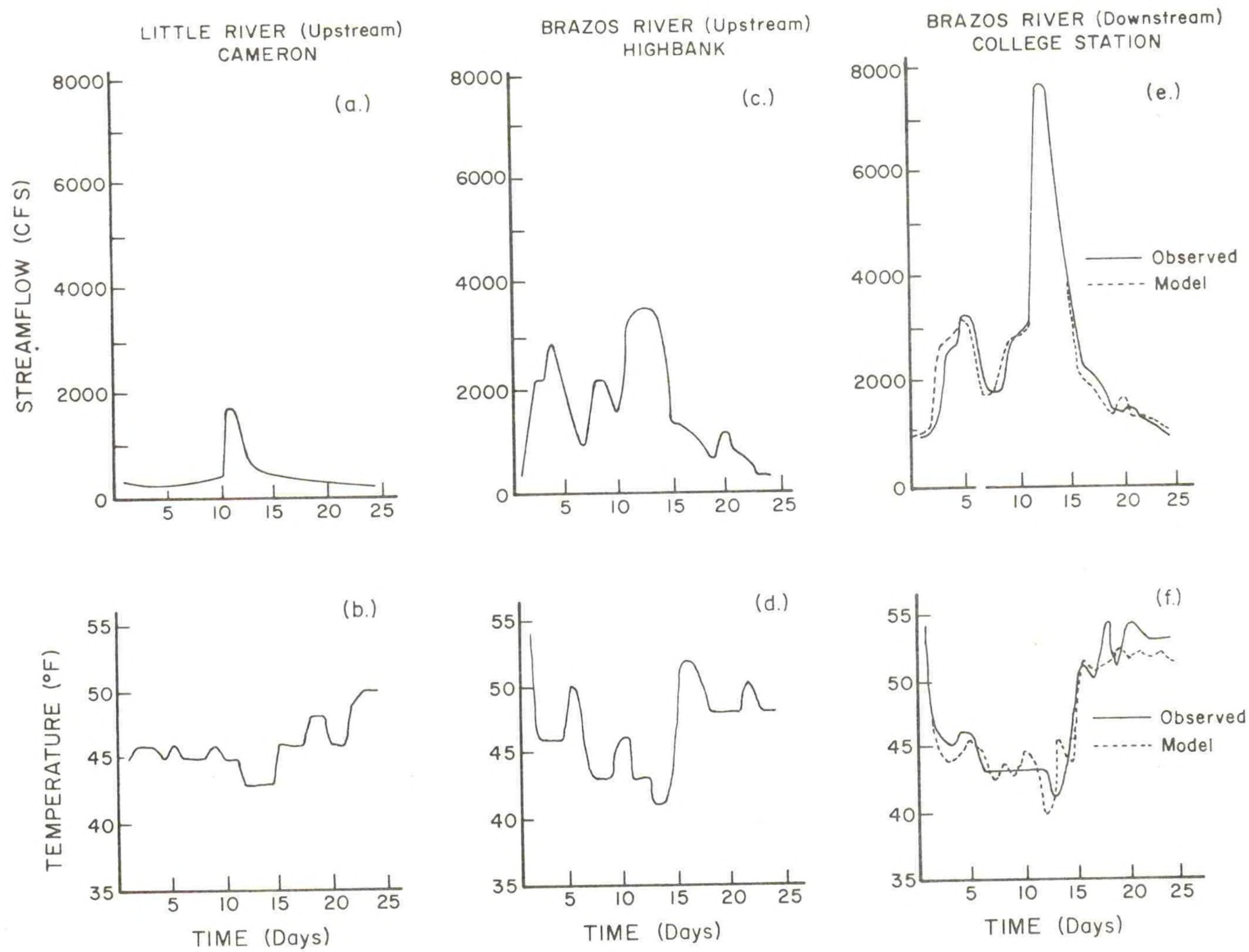


Figure 4.3. Hydrographs and thermographs at upstream and downstream boundaries of Brazos-Little River System including model predictions (December 5-28, 1972).

based on these results since the instrument with which solar radiation data were observed was known to be out of adjustment (Griffiths, 1975, personal communication). However, because the predicted stream temperature reflected the apparent discrepancies in the solar radiation predictions it was decided to use the observed solar radiation data adjusted for instrument bias (i.e. ITECH=3).

The USGS at Austin, Texas, estimated shading on the Brazos River to be 5% and on the Little River to be 25%. These values were reduced to 0% and 15% respectively for winter conditions.

Heat transfer by evaporation and conduction across the stream surface are directly proportional to the mass transfer coefficient, N (see Equations 3.68 and 3.71). A value of N = 0.00005 ins. Hg^{-1} was found to yield reasonable values of evaporation and conduction.

During the storm period the lateral inflow thermograph was considered to be highly dependent on air temperature. Therefore a lateral inflow thermograph (Figure 4.4) was assumed based on the variation in air temperature.

The following factors should be considered when evaluating the adequacy of the simulation results:

1) Thermographs used by the USGS are rated by the manufacturer as accurate to within $2^{o}F$ (Rawson, 1970)

2) Observed stream temperatures used in this study were based on instantaneous values selected randomly within 24 hour intervals on the continuous thermograph trace. In contrast, model predictions were for time points spaced twelve hours apart. Therefore, a comparison between a predicted and an observed mean temperature may be a comparison between temperatures with up to 24 hours difference in occurrence.

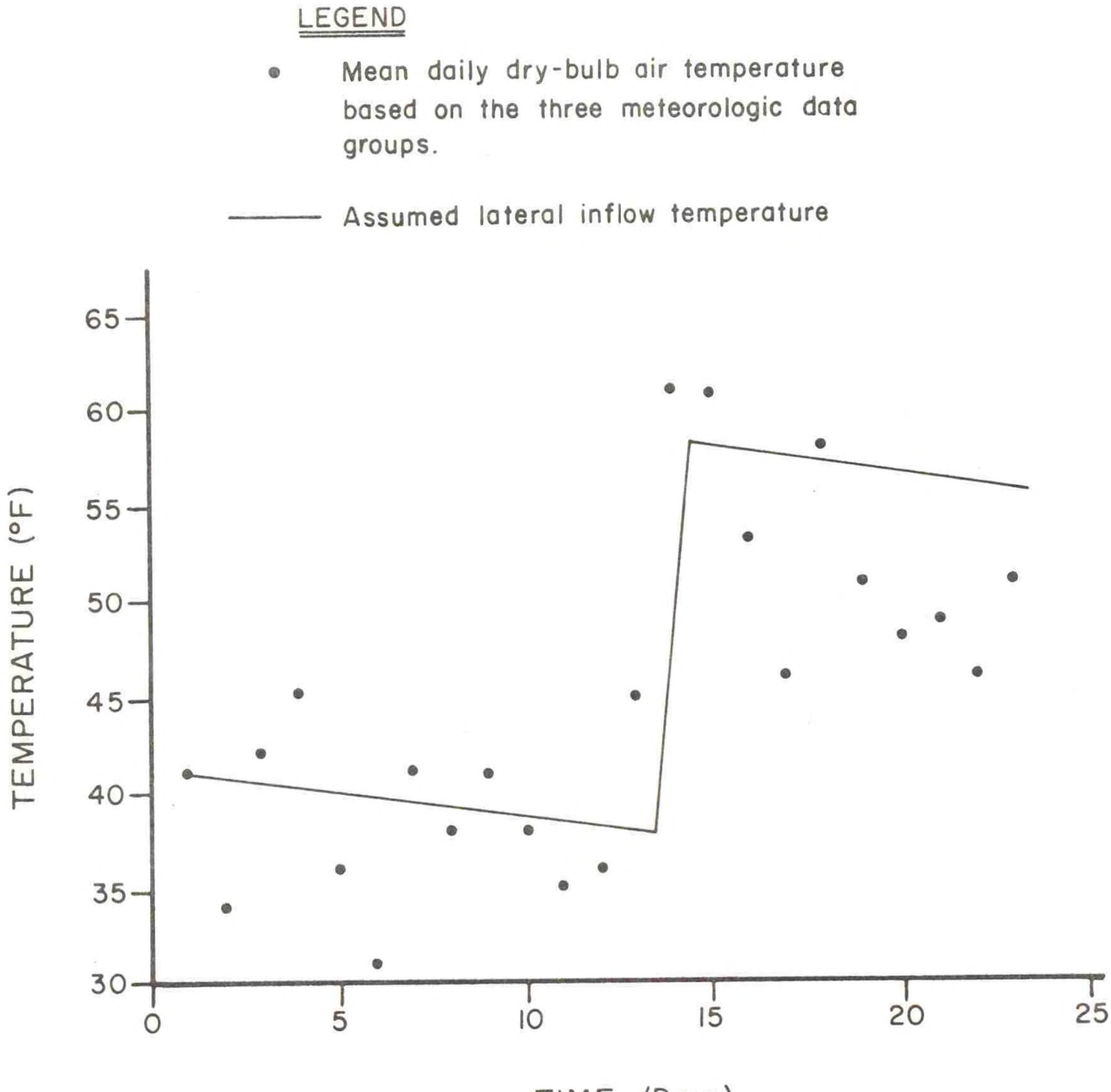


Figure 4.4. Assumed lateral inflow thermograph.

3) DSTEMP predicts stream temperatures that are average for the stream cross-section, whereas observed stream temperatures are measured at single locations in the cross-section.

4) The observed thermograph in this study was located 9 miles downstream of the point at which stream temperatures were predicted.

Upstream boundary conditions for stream temperature are shown in Figures 4.3b and d. Observed and predicted thermographs at the downstream boundary are represented by Figure 4.3f. A trough in the predicted thermograph coincides with the peak of the hydrograph (Figure 4.3e) at day 12 but misses the trough in the observed thermograph by one day. Predicted temperatures after day 16 are generally low compared with observed temperatures. Overall agreement is quite good with a correlation coefficient, R^2, equal to 84%.

CHAPTER 5

CONCLUSIONS AND FURTHER WORK

A Dynamic Stream Temperature Model (DSTEMP) has been developed and tested. The current version of DSTEMP is suitable for application in temperature simulations on small streams or large river systems. This versatility is enhanced by the capability of substituting different methods of calculating heat transfer components, or suppressing components that are unimportant on certain streams. Thus process studies such as those performed on Spawn Creek (Comer, et al., 1975) can be handled by DSTEMP. Also, the simulation of stream temperature regimes in large river systems is facilitated by the meteorologic data group concept described in Chapter 3 and Appendix A. Dynamic aspects of the flow and temperature representation by DNRT-DSTEMP are essential to obtain predictions of critical, but transient, stream temperature conditions that may endanger aquatic environment.

Although the current versions of DNRT-DSTEMP offer a very flexible tool for dynamic simulation of streamflow - stream temperature there remain some areas of further work. Suggestions for further work on DNRT and DSTEMP are listed below:

DNRT

1) Distinguish between surface and subsurface lateral inflow contributions. Could be achieved through linkage to a two-dimensional hydrology model.

2) Add capability for handling point loads.

DSTEMP

1) Generate thermographs for lateral inflows by linkage with a two-dimensional hydrology -- water temperature model. At present the estimation of these thermographs is mainly the result of intuitive guesses and trial-and-error matching of observed and predicted thermographs after the nonadvective heat transfer processes are calibrated.

2) Add frictional heat flux and those components of heat exchange ommitted from the current version.

3) Add to the solar radiation subroutine, for ITECH = 1, an algorithm for calculating the variation of snow albedo with the age of snowpack adjacent to the stream.

4) Input cloud type and vary coefficients in Equation 3.54 as described by Anderson (1954).

5) Allow for computational time intervals different to the data time interval by interpolating between input data (does not apply to meteorologic data).

6) Calculate statistics to summarize model performances based on observed stream temperatures.

7) Plot predicted and observed stream temperatures to assist in model calibration or evaluation of model predictions.

8) Include an ice formation and melt algorithm to extend the temperature range over which the model is applicable.

9) Add a reservoir algorithm.

10) Complete the option to use S. I. units.

11) Apply estimation theory to the real time stream temperature forecasting problem. This will facilitate "updating" as data become available. It could also be used to provide "best" estimates of lateral inflow temperatures.

It is considered that the addition of the above features to the DNRT-DSTEMP models will further enhance their practical value to river forecasters.

REFERENCES

Albertson, O. L., B. A. Tichenor, J. Seaders, and F. J. Burgess. 1974. Stream temperature prediction by digital computer techniques. Department of Civil Engineering, Oregon State University, Corvallis, Oregon. 27 p.

Amein, M., and C. S. Fang. 1970. Implicit flood routing in natural channels. Journal of the Hydraulics Division, ASCE, 96(HY 12): 2481-2500. December.

Anderson, E. R. 1954. Energy-budget studies, water loss investigations: Lake Hefner studies. SCS Professional Paper 269.

Bolsenga, S. T. 1964. Daily suns of global radiation for cloudless skies. Technical Report No. 160. U.S. Army Material Command, Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire. November.

Bowen, I. S. 1926. The ratio of heat losses by conduction and by evaporation from any water surface. Physical Review, 27:779-787. July.

Bowles, D. S., J. P. Riley, and G. B. Shih. 1975. An application of the Utah State University Watershed Simulation Model to the Entiat Experimental Watershed, Washington State. Final report to Pacific Northwest Forest and Range Experiment Station, United States Forest Service.

Brown, G. W. 1969. Predicting temperature in small streams. Water Resources Research 5:68-75.

Brown, G. W. 1970. Predicting the effect of clearcutting on stream temperature. J. Soil and Water Conserv. 25:11-13.

Brown, G. W. 1972. An improved temperature prediction model for small streams. Oregon State University, Water Resources Research Institute, WRRI-16.

Burt, W. V. 1958. Heat budget terms for Middle Snake River Reservoirs. Technical Report No. 6, Reference 58-7. School of Science, Oregon State College, Corvallis, Oregon. December.

Buttner. 1953. Linke's Meteorologisches Taschenbuch, Volume 2. Geest and Portig K. G., Leipzig.

Comer, L. E., D. S. Bowles, and W. J. Grenney. 1975. Field investigations and mathematical model for heat transfer processes in the bed of a small stream. Utah Water Research Laboratory, College of Engineering, Utah State University, Logan, Utah 84322. 103 p.

Dailey, J. E., and D. R. F. Harleman. 1972. Numerical model for the prediction of transient water quality in estuary networks. Ralph M. Parsons Laboratory for Water Resources and Hydrodynamics, Report No. 158, Department of Civil Engineering, M.I.T. October.

Dake, J. M. K., and D. R. F. Harleman. 1969. Thermal stratification in lakes: analytical and laboratory studies. Water Resources Research 5(2):484-495. April.

Dingman, S. L., and A. Assur. 1967. The effect of thermal pollution on river--ice conditions--Part 1. United States Army Cold Regions Research and Engineering Laboratory, Hanover, N.H. December.

Edinger, J. E., D. W. Duttweiler, and J. C. Geyer. 1968. The response of water temperatures to meteorological conditions. Water Resources Research, 4(5):1137-1143. October.

Edinger, J. E., and J. C. Geyer. 1965. Heat exchange in the environment. EEI Publication No. 65-902, Edison Electric Institute, New York, New York. 259 p.

Fischer, H. B. 1973. Longitudinal dispersion and turbulent mixing in open-channel flow. In: Annual review of fluid mechanics. Annual Reviews Inc., Palo Alto, California. p. 59-78.

Fread, D. L. 1973. Technique for implicit dynamic routing in rivers with tributaries. Water Resources Research 9(4):918-926. August.

Fread, D. L. 1974. Implicit dynamic routing of floods and surges in the Lower Mississippi. Presented at the American Geophysical Union Spring National Meeting in Washington, D.C. April 8-12. p. 26.

Harbeck, G. E. 1958. Water loss investigations: Lake Mead Studies. USGS Professional Paper 298.

Harleman, D. R. F., D. N. Borcard, and T. O. Majarian. 1973. A predictive model for transient temperature distributions in unsteady flows. Ralph M. Parsons Laboratory for Water Resources and Hydrodynamics, Report No. 175, Department of Civil Engineering, M.I.T. November.

Harper, Martin E. 1972. Development and application of a multiparametric mathematical model of water quality. Doctor of Philosophy Dissertation, University of Washington.

Jeppson, R. W. 1975. Prediction of stream temperature and rate of ice formation. Unpublished manuscript.

Jobson, H. E., and N. Yotsukura. 1973. Mechanics of heat transfer in nonstratified open-channel flows. Chapter 8 in Environmental impact on rivers (River Mechanics Vol. III). Edited by H. W. Shen. Water Resource Publications, Fort Collins, Colorado. 680 p.

Kimball, H. H. 1927, 1928, 1930. Measurements of solar radiation intensity and determination of its depletion by the atmosphere. Monthly Weather Review, Volumes 55, 56, and 58.

Kleinschmidt, E. 1935. Handbuch der Meteorologischen Instrumente. Springer, Berlin. p. 201.

List, R. T. 1963. Smithsonian Meteorologic Tables (6th Edition) Smithsonian Institution, Washington, D.C.

McKee, J. E., and H. W. Wolf. 1963. Water quality criteria. Second Edition, Sacramento, Calif. 548 p.

Morse, W. L. 1970. Stream temperature prediction model. Water Resources Research, 6(1):290-302. February.

Morse, W. L. 1972a. Stream temperature prediction under reduced flow. Proc. ASCE, Journal of Hydraulics Division, 98 (HY6): 1031-1047. June.

Morse, W. L. 1972b. Stochastic stream temperature model. _In_ Proc. International Symposium on Uncertainties in Hydrologic and Water Resource Systems, Tucson, Arizona. pp. 324-339. Dec. 11-14.

Novotny, V., and P. A. Krenkel. 1971. Heat transfer in flowing streams. Report No. 7, Department of Environmental and Water Resources Engineering, Vanderbilt University School of Engineering, Nashville, Tennessee. September.

Pailey, P. P., E. O. Macagno, and J. F. Kennedy. 1974. Winter-regime thermal response of heated streams. Journal of the Hydraulics Division, Proc. ASCE 100(HY4):531-550. April.

Parker, F. L., and P. A. Krenkel. 1969. Engineering aspects of thermal pollution. Vanderbilt University Press. 340 p.

Pivovarov, A. A. 1973. Thermal conditions in freezing lakes and rivers. The Israeli Program for Scientific Translation. Jerusalem. (Russian edition, 1972). 136 p.

Pluhowski, E. J. 1970. Urbanization and its effect on the temperature of the streams on Long Island, New York. USGS Professional Paper 627-D. 110 p.

Raphael, J. M. 1962. Prediction of temperature in rivers and reservoirs. Journal of the Power Division, ASCE, 88(PO2):157-181. July.

Rawson, J. 1970. Reconnaissance of water temperature of selected streams in southeastern Texas. Report 105, Texas Water Development Board. p. 2.

Roesner, L. A. 1969. Mathematical models for the net heat rate of heat transfer through the air-water interface of a flowing stream. Ph. D. dissertation, University of Washington.

Texas Water Development Board. 1971. Simulation of water quality in streams and canals. Texas Water Development Board, report 128.

Timofeyev, M. P., and S. P. Malevskiy-Malevich. 1967. Patterns of thermal regime of the surface layer of water. In Soviet Hydrology: Selected Papers 1967. No. 1, 102.

Sutton, G. O. 1953. Micrometeorology. McGraw Hill, New York, New York. 333 p.

Viskanta, R., and J. S. Toor. 1972. Radiant energy transfer in waters. Water Resources Research 8(3):595-608. June.

Vugts, H. F. 1974. Calculation of temperature variations of small mountain streams. Journal of Hydrology, 23:267-278.

Wunderlich, W. O. 1968. The water temperature regime of fully-mixed streams. Report No. 15 (preliminary), Tennessee Valley Authority, Water Resources Research Laboratory, Norris, Tennessee. 64 p.

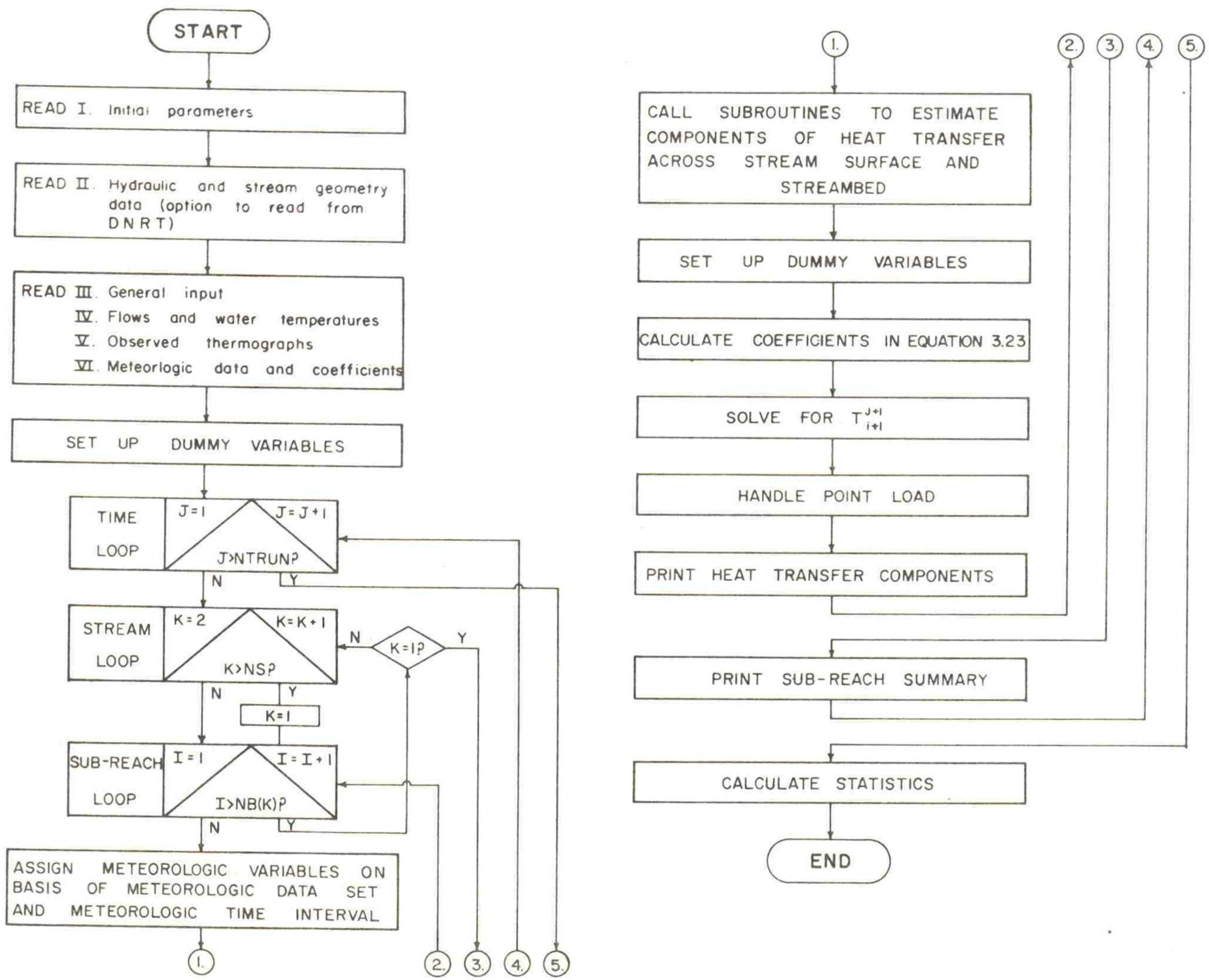
Wunderlich, W. O. 1972. Heat and mass transfer between a water surface and the atmosphere. Report No. 14, Tennessee Valley Authority, Water Resources Research Laboratory, Norris, Tennessee. 173 p. April.

APPENDIX A

Users Manual for Dynamic Stream Temperature Model (DSTEMP)

Page

1. Overall Flowchart of Dynamic Stream Temperature Model(DSTEMP).



2. Input Data and Decision Parameters for Dynamic Stream Temperature Model (DSTEMP)

Notes

1. Input data and decision parameters for DSTEMP are divided into six groups:

   I Initial parameter
   II Hydraulic and stream geometry data
   III General input
   IV Flows and water temperatures
   V Observed thermographs
   VI Meteorologic data and coefficients

2. Computer mnemonics are defined at their first appearance in a read statement. Three important subscripts used are:

   I Computational point or sub-reach index
   J Time point or time interval index
   K Stream index

3. Each 80 column input record contains a 10 character card identification followed by seven 10 character data fields. Each read statement described below commences with a four character code defining the card type. Columns 5 to 10 may be used for identifiers such as the indicies I, J, and K, and card sequence numbers.

4. The beginning and end of DO-loops are indicated by notes in parenthesis immediately before and after the first and last read statements respectively, in DO-loops.

5. Units for the variables to be read are included in the following descriptions of input data. The units are those used by the National Weather Service and United States Geological Survey in published data which are likely to be used in applications of DSTEMP. In an attempt to allow for a future option in which S. I. units will be used, coefficients, physical constants and headings in which units are printed are all read as input. When the S. I. option is introduced S. I. equivalents will be substituted for the British units used at present.

6. When all seven data fields are used on the last card read in a read statement, a blank card must be placed after that card. This measure is necessary because of a limitation in the structure of the FORTRAN read formats.

7. "b" indicates a blank column in the card identification field.

I. Initial Parameters

1. "KRRb," KRR, ITECH, NTRUN, IOSS, IDTCST, IPRT - Format (A10, 6I10)

"KRRb"	Card type identification
KRR	Number of computer input unit from which output from Dynamic Routing Program (DNRT) is read. Transfer of hydraulic and stream geometry data may be accomplished via disc, magnetic tape, punched cards, etc. Alternatively these data may be directly input to DSTEMP.
ITECH	Technique option for calculating solar radiation. ITECH = 1 Solar radiation calculated ITECH = 2 Total daily observed solar radiation distributed between sunrise and sunset in parabolic manner. ITECH = 3 Solar radiation observed in each time interval DT(J) used directly.
NTRUN	Number of time intervals to be run. NTRUN $\leq$ NT (Use during calibration to execute only first NTRUN time intervals - hence reduce computer time during initial stages of calibration). If NTRUN = 0, then NTRUN will be set equal to NT by the program.
IOSS	Input option for reading steady state hydraulic and stream geometry data (Applies to read statements 8 to 13) IOSS = 0 Unsteady flows IOSS = 1 Steady state flows (Useful if steady state hydraulic and stream geometry data are input directly to DSTEMP without the use of DNRT)

IDTCST — Input option for constant time step (Applies to read statement 3 - if transfering data from DNRT then set IDTCST = 0)

- IDTCST = 0 — time step varies - read a value for each time interval DT(J)
- IDTCST = 1 — constant time step - read only the constant value of the time step

IPRT — Print option for selective output of input data and decision parameters

- IPRT = 0 — All input data and decision parameters are printed (Use to provide complete record at first calibration run)
- IPRT = 1 — All input data and decision parameters except hydraulic and stream geometry data (read statements 3-13) are printed (Use when removing errors from punched card input)
- IPRT = 2 — Only coefficients, parameters, and data that are varied during calibration are printed (Use during calibration)

II. Hydraulic and stream geometry data (transferred from DNRT or directly input to DSTEMP)

2. "NTNS," NT, NS - Format (A10, 2I10)

"NTNS" — Card type identification

NT — Number of time points (equals number of time intervals plus one)

NS — Number of streams

- NS = 1 — Main stream only
- NS = 2 — Main stream and 1 tributary, etc.

3. "DTbb", (DT(J), J = 1, NTI) - Format (A10, 7 F10.0/(10X, 7 F10.0))

"DTbb"	Card type identification
J	Time point or time interval index
DT(J)	Length of Jth time interval in <u>hours</u> (DT(J) ≤ 24 hours)
NTI	Number of time intervals to be read
	NTI = NT-1 if IDTCST = 0
	NTI = 1 if IDTCST = 1

4. "NBbb", (NB(K), K = 1, NS) - Format (A10, 7 I10/(10X, 7 I10))

"NBbb"	Card type identification
K	Stream index
	K = 1 main stream
	K = 2, NS tributaries
NB(K)	Number of computational points on nodes in Kth stream (NB(K) ≥ 2)

(Omit read statement 5 if NS = 1)

5. "NJUN", (NJUN(K), K = 2, NS) - Format (A10, 7 I10/(10X, 7 I 10))

"NJUN"	Card type identification
NJUN(K)	Number of main stream reach over which Kth tributary enters main stream

(Read statements 6 to 12 are read for one stream (K subscript) at a time)

6. "Xbbb", (X(I, K), I = 1, NX) - Format (A10, 7F10.0/(10X, 7F10.0))

"Xbbb"	Card type identification
I	Computational point or sub-reach index
X(I, K)	River distance in miles at the Ith computationsl point
NX	NB(K)

7. "DDXb", (DDX(I, K), I = 1, NX1) - Format (A10, 7F10.0/(10X, 7F10.0))

"DDXb"	Card type identification
DDX(I, K)	Length in feet of Ith sub-reach between Ith and (I+1)th computational points
NX1	Number of sub-reaches = NB(K)-1

(Read statements 8 to 12 are read for one time point (J subscript) at a time. A total of NTI time points are read: NTI = NT if IOSS = 0, NTI = 1 if IOSS = 1)

8. "CSAb", (CSA(I, J, K), I = 1, NX) - Format (A10, 7F10.0/(10X, 7F10.0))

"CSAb"	Card type identification
CSA(I, J, K)	Cross-sectional area of flow in $feet^2$ at Ith computational point.

9. "BDbb", (BD(I, J, K), I = 1, NX) - Format (A10, 7F10.0/(10X, 7F10.0))

"BDbb"	Card type identification
BD(I, J, K)	Top width of flow in feet at Ith computational point

10. "PMbb", (PM(I, J, K), I = 1, NX) - Format (A10, 7F10.0/(10X, 7F10.0))

"PMbb"	Card type identification
PM(I, J, K)	Wetted perimeter in feet at Ith computational point

11. "QSbb", (QS(I, J, K), I = 1, NX) - Format (A10, 7F10.0/(10X, 7F10.0))

"QSbb"	Card type identification
QS(I, J, K)	Streamflow rate in cfs at Ith computational point

12. "ELVT", (ELVTN(I, J, K), I = 1, NX) - Format (A10, 7F10.0/(10X, 7F10.0))

"ELVT"	Card type identification
ELVTN(I, J, K)	Elevation of water surface at Ith computational point in feet above mean sea level.

13. "QLbb", (QL(I, J, K), I = 1, NX1) - Format (A10, 7F10.0/(10X, 7F10.0))

"QLbb"	Card type identification
QL(I, J, K)	Surface lateral inflow in $cfs \cdot ft^{-1}$ over Ith sub-reach (Include tributary inflow to main stream)

(End of J- and K- loops)

III. General input

14. (TITLE(L), L = 1, 30) - Format (20A4/10A4)

TITLE(L)	Title for DSTEMP output tables. Should describe stream location, period of data, and purpose of model run.

15. (UNIT(L), L = 1, 30) - Format (20A4/10A4)

UNIT(L) Part of the heading in an output table. UNIT contains the units of the following variables:

	Columns	British Units	SI Units
X(I, K)	5 to 12	"MILES"	"KM"
CSA(I, J, K)	13 to 21	"FT2"	"M2"
BD(I, J, K)	22 to 28	"FT"	"M"
PM(I, J, K)	29 to 35	"FT"	"M"
DDX(I, J, K)	36 to 44	"FT"	"M"
QL(I, J, K)	48 to 52	"FT2S-1"	"M2S-1"
QG(I, J, K)	53 to 59	"FTS-1"	"MS-1"
QP(I, J, K)	60 to 66	"CFS"	"M3S-1"
QS(I, J, K)	67 to 75	"CFS"	"M3S-1"
TL(I, J, K)	76 to 84	"DF"	"DC"
TG(I, J, K)	85 to 90	"DF"	"DC"
TP(I, J, K)	91 to 96	"DF"	"DC"
Heat Exchange	97 to 102	"BTU"	"KJ"
Stream Temperature	103 to 108	"DF"	"DC"
	109 to 114	"DF"	"DC"
	115 to 120	"DF"	"DC"

16. "IOHT", (IOHTC(IC), IC = 1, 11) - Format (A10, 7I10/(10X, 4I10))

"IOHT" Card type identification

IC Component of heat transfer index

IOHTC(IC) Option to include or exclude different components of heat transfer across the air-water and water-streambed interfaces.

IC	Component
1.	Incident and reflected solar radiation at stream surface
2.	Incident and reflected long wave radiation from adjacent vegetation at stream surface[1]
3.	Incident and reflected atmospheric radiation at stream surface
4.	Back radiation from stream
5.	Latent heat of vaporization associated with evaporation from stream surface
6.	Conduction across stream surface
7.	Latent heat of fusion associated with snow falling on stream[1]
8.	Surface renewal losses[1]
9.	Absorption of solar radiation by streambed and streambed conduction
10.	Back radiation from streambed[1]

IOHTC(IC) = 0   Exclude ICth component
IOHTC(IC) = 1   Include ICth component

[1]This component is not modeled in the current version of DSTEMP - set IOHTC(IC) = 0

17. "PROP", RHO, CP, FLHV , FLHF , ATREF, ATEN, SURABS, SOLREF - Format (A10, 7F10.0/(10X, F10.0))

"PROP"	Card type identification (Properties of water)
RHO	Density of water (62.317 $lbs.\ ft.^{-3}$)

CP — Specific heat of water at constant pressure (0.9988 $\underline{Btu.\ lbs.^{-1}\ deg.F^{-1}}$)

FLHV — Latent heat of vaporization of water (1053 $\underline{Btu.\ lbs.^{-1}}$)

FLHF — Latent heat of fusion of water (143.5 $\underline{Btu.\ lbs.^{-1}}$)

ATREF — Proportion of incident atmospheric radiation reflected at water surface (usually 0.03)

ATEN — Bulk extinction coefficient (Equation 3.75) for attenuation of solar radiation transmitted through stream depth (usually 0.015 $\underline{ft.^{-1}}$)

SURABS — Proportion of solar radiation entering water surface that is immediately absorbed (usually 0.6)

SOLREF — Proportion of incident solar radiation reflected at water surface (can leave blank if ITECH =1).

18. "TIME", IDAY2, FHR2, FLAT, DTSL, FHSR, FHSS - Format (A10, I10, 5F10.0)

"TIME" — Card type identification

IDAY2 — Day number counting from January 1st of DT(1), the first time point

FHR2 — Time in <u>hours</u> measured from midnight of DT(1), the first time point. Daylight saving time should be corrected to standard time if ITECH = 1

FLAT — Latitude in <u>degrees</u> of streams to be modeled (can leave blank if ITECH ≠ 1)

DTSL — Time difference between local and standard meridian in <u>hours</u> (can leave blank if ITECH ≠ 1) Computed by:

$$DTSL = \frac{e}{15}(LSM - LLM)$$

in which

LSM — longitude of standard meridian in degrees from Greenwich (75^{o}W for Eastern Standard Time)

LLM — longitude of local meridian in degrees from Greenwich

$e = -1$ for west longitude

$e = +1$ for east longitude

FHSR — Standard time of sunrise in hours measured from midnight (can leave blank if ITECH $\neq$ 2)

FHSS — Standard time of sunset in hours measured from midnight (can leave blank if ITECH $\neq$ 2)

19. "COF1", THETA, SOLCST, DSTDEP, FMTC, SIGMA, BOTREF - Format (A10, 3F10.0, 2E10.5, F10.0)

"COF1" — Card type identification

THETA — Weighting factor for implicit four-point finite difference technique (THETA = 0.55 minimizes the loss of accuracy associated with greater values while avoiding the possibility of a weak or pseudo-instability in many cases of slowly varying transients in large rivers (Fread, 1974); can range 0.5-1.0)

SOLCST — Solar constant (429 $Btu.\ ft.^{-2}\ hrs.^{-1}$)

DSTDEP — Total dust depletion coefficient of the direct solar beam by scattering and absorption (See Table 3.2)

FMTC — Mass transfer coefficient in $ins.\ Hg.^{-1}$

SIGMA — Stefan - Boltzmann constant (1.74 E-9 $Btu.\ hrs.^{-1}\ ft.^{-2}\ {}^{o}R^{4}$)

BOTREF — Reflectivity of streambed

20. "COF2", (COEF(L), L = 1, 4) - Format (A10, 4F10.0)

"COF2" — Card type identification

COEF(L) — Regression coefficients for predicting streambed conduction (Equation 3.76) (leave blank if IOHTC(9) = 0)

IV. Flows and water temperatures

21. "IOQT", IOQGTG, IOTL, NTL, NP - Format (A10, 4F10.0)

"IOQT" Card type identification

IOQGTG Input option for reading QG (I, K) and TG (I, K) (Applies to read statements 22 and 23)

- IOQGTG = 0 do not read QG(I, K) and TG(I, K)
- IOQGTG = 1 read QG(I, K) (in cfs. $ft.^{-2}$) and TG(I, K)
- IOQGTG = 2 read QG(I, K) (in cfs. $ft.^{-1}$) and TG(I, K)

IOTL Input option for reading TL (1, J, K) (Applies to read statement 24)

- IOTL = 0 do not read TL (1, J, K)
- IOTL = 1 read TL (1, J, K) and set (TL(I, J, K), I = 2, NX1) = TL(1, J, K) i.e., the same TL vs. time data ("background thermograph") is to be used for each sub-reach of the Kth stream

NTL Number of sub-reaches in which "background thermograph" read in read statement 24 is to be overwritten. This option might be used in sub-reaches where un-modeled tributaries enter and therefore the lateral inflow thermograph would be different to the "background thermograph" read in read statement 24. (Applies to read statement 25)

NP Number of point loads to be read in.

(Read statements 22 and 23 are read if IOQGTG =1 and are read for one stream (K subscript) at a time)

22. "QGbb", (QG(I, K), I = 1, NX1) - Format (A10, 7F10.0/(10X, 7F10.0))

"QGbb" Card type identification

QG(I, K) Steady state value of groundwater exchange between Ith reach and groundwater body. Infiltration to the groundwater body must be given a negative sign and seepage from the groundwater body must be given a positive sign. If units of QG(I, K) are $cfs.\ ft.^{-2}$ then set IOQGTG = 1 and if $cfs.\ ft.^{-1}$ then set IOQGTG = 2. (in read statement 21).

23. "TGbb", (TG(I,K), I = 1 NX1) - Format (A10, 7F10.0/(10X, 7F10.0))

"TGbb" Card type identification

TG(I, K) Steady state temperature in deg. F of groundwater below Ith sub-reach and at a depth such that the variation in temperature is negligible over the period for which the model is run. Seeping groundwater is assumed to leave the stream at the temperature of the stream.

(End of K-loop)

(Read statement 24 is read if IOTL = 1 and is read for one stream (K subscript) at a time)

24. "TLBG", (TL(1, J, K), J = 1, NT) - Format (A10, 7F10.0/(10X, 7F10.0))

"TLBG" Card type identification

TL(1, J, K) "Background thermograph" in deg. F for Kth stream. Thermograph is read into first sub-reach position (I=1) in TL array and then the remaining sub-reaches (I=2, NX1) are assigned the same thermograph values.

(End of K-loop)

(Read statement 25 is read NTL times and is omitted if NTL = 0)

25. "TLKI", K, I, (TL (I, J, K), J = 1, NT) - Format (A4, 2I2, 2X, 7F10.0/(10X, 7F10.0))

"TLKI" Card type identification

TL(I, J, K) Thermograph in deg. F for Ith sub-reach on the Kth stream. This thermograph replaces the "background thermograph" in the Ith sub-reach on the Kth stream. These thermographs may, for example, be developed from temperatures of unmodeled tributary streams entering the main stream. For sub-reaches in which modeled tributaries enter the main stream, the computed tributary temperatures at the point of confluence will be assigned to TL(I, J, K) by the program. Therefore there is no need to input a thermograph for sub-reaches in which tributaries enter the main stream.

(Read statement 26 is read for one stream (K subscript) at a time)

26. "TSIC", (TS(I, 1, K, L), I = 1, NX) - Format (A10, 7F10.0/(10X, 7F10.0))

"TSIC" Card type identification

TS(I, 1, K, L) Initial condition (J = 1) of stream temperature in deg. F for Ith computational point. If NP ≥ 0 then TS(I, 1, K, L) is read consecutively for L = 1 and L = 2. The purpose of the subscript L in the TS array is to store two values of stream temperature at computational points where point loads enter the stream. Because of the assumption of instantaneous and complete mixing at each stream section predicted values of stream temperature will jump at the location of a point load. L = 1 indexes stream temperature immediately downstream (after point load) of the computational point and L = 2 indexes the stream temperature immediately upstream (before point load) of the computational point. At computational points where point loads do not enter the stream, the stream temperatures indexed under L = 1 and L = 2 are identical. If NP = 0 then only L = 1 values are read.

(End of K-loop)

(Read statement 27 is read for one stream (K subscript) at a time)

27. "TSUS", (TS(1, J, K, 1), J = 1, NT) - Format (A10, 7F10.0/ (10X, 7F10.0))

"TSUS"	Card type identification
TS(1, J, K, 1)	Upstream (I = 1) boundary condition for stream temperature in deg. F

(End of K-loop)

(Read statements 28 and 29 are read NP times and are omitted if NP = 0)

28. "QPbb", K, I, (QP(I, J, K), J = 1, NT) - Format (A4, 2I2, 2X, 7F10.0/(10X, 7F10.0))

"QPbb"	Card type identification
QP(I, J, K)	Flowrate in cfs of point load entering stream at Ith computational point on Kth stream. At present point loads are not accounted for in the Dynamic Routing Program (DNRT). Therefore to maintain a mass balance, point loads in DSTEMP should have a flowrate that is not significant when compared with the streamflow rate. Point loads that are significant thermally and in terms of flow should be treated as lateral inflow over a short sub-reach and input through DNRT.

29. "TPbb", K, I, (TP(I, J, K), J = 1, NT) - Format (A4, 2I2, 2X, 7F10.0/(10X, 7F10.0))

"TPbb"	Card type identification
TP(I, J, K)	Thermograph in deg. F for point load entering stream at Ith computational point on Kth stream

V. Observed thermographs

30. "NOTb", NOT - Format (A10, I10)

"NOTb"	Card type identification

NOT	Number of computational points for which observed thermographs are to be input

(Read statement 31 is read NOT times and is omitted if NOT = 0)

31. "TSOb", K, I, (TSO(INOT, J), J = 1, NT) - Format (A4, 2I2, 2X, 7F10.0/(10X, 7F10.0))

"TSOb"	Card type identification
INOT	Index for observed thermographs (INOT = 1, NOT). The index INOT is stored in array INOTN(I, K).
TSO(INOT, J)	INOTth observed thermograph in <u>deg. F</u>

VI. <u>Meteorologic data and coefficients</u>

32. "AAbb", (AA (IC), IC = 1, 11) - Format (A10, 7F10.0/(10X, 4F10.0))

"AAbb"	Card type identification
AA(IC)	Coefficients in the empirical expression (Equation 3.64) for the atmospheric radiation factor β. Standard values are: (0.740, 0.750, 0.760, 0.771, 0.783, 0.793, 0.800, 0.810, 0.825, 0.845, 0.866)

33. "BBbb", (BB(IC), IC = 1, 11) - Format (A10, 7F10.0/(10X, 4F10.0))

"BBbb"	Card type identification
BB(IC)	Coefficients in the empirical expression (Equation 3.64) for the atmospheric radiation factor β. Standard values are: (0.150, 0.150, 0.150, 0.143, 0.138, 0.137, 0.135, 0.130, 0.120, 0.105, 0.090)

34. "TEbb", (TE(IE), IE = 1, 3) - Format (A10, 3F10.0)

"TEbb"	Card type identification
TE(IE)	Temperatures in deg. F that divides the linear approximations to the empirical expression (Equation 3.69) for saturation vapor pressure. Standard values: (50, 68, 86)

35. "ES1b", (ES1(IE), IE = 1, 4) - Format (A10, 4F10.0)

"ES1b"	Card type identification
ES1(IE)	Coefficients in the emprical expression (Equation 3.69) for saturation vapor pressure. Standard values: (-0.138, -0.548, -1.440, -3.133) in. Hg.

36. "ES2b", (ES2(IE), IE = 1, 4) - Format (A10, 4F10.0)

"ES2b"	Card type identification
ES2(IE)	Coefficients in the empirical expression (Equation 3.69) for saturation vapor pressure. Standard values: (0.0098, 0.0180, 0.0312, 0.0509) (in. Hg.) $(deg. F)^{-1}$

(Read statements 37 to 40 are read for one stream (K subscript) at a time)
(Omit read statements 37 to 39 if ITECH ≠ 1)

37. "ALSR", (ALSR (I, K), I = 1, NX1) - Format (A10, 7F10.0/(10X, 7F10.0))

"ALSR"	Card type identification
ALSR(I, K)	Solar altitude in degrees for Ith sub-reach at sunrise. For flat, unobstructed horizon ALSR(I, K) = 0 deg.

38. "ALSS", (ALSS(I, K), I = 1, NX1) - Format (A10, 7F10.0/(10X, 7F10.0))

"ALSS"	Card type identification
ALSS(I, K)	Solar altitude in degrees for Ith sub-reach at sunset. For flat, unobstructed horizon ALSS(I, K) = 0 deg.

39. "GRDR", (GRDRF(I, K), I = 1, NX1) - Format (A10, 7F10.0/(10X, 7F10.0))

"GRDR"	Card type identification
GRDRF(I, K)	Albedo of ground surface adjacent to stream (see Table 3.3)

40. "SHAD", (SHADE(I, K), I = 1, NX1) - Format (A10, 7F10.0/(10X, 7F10.0))

"SHAD"	Card type identification
SHADE(I, K)	Fraction of sky shaded from the stream surface by vegetation or other obstructions excluding cloud cover in Ith sub-reach. Shading is expressed as a decimal fraction; for example, 25% shading should be input as 0.25. Figure A1 may be useful when estimating the amount of shading.

(End of K-loop)

41. "NGbb", NG, IMDT - Format (A10, 2I10)

"NGbb"	Card type identification
NG	Number of sets of observed meteorologic data to be read. A meteorologic data set is a complete set of data for all the meteorologic variables required in DSTEMP. Several meteorologic groups may be used for modeling a stream system. Each set of meteorologic data is applied to a different group of sub-reaches for which the observed data is considered representative. Several types of data are required for each meteorologic data set. For applications in which National Weather Service meteorologic data are used some data types, such as air temperature, are available at many more locations than other variables. In these

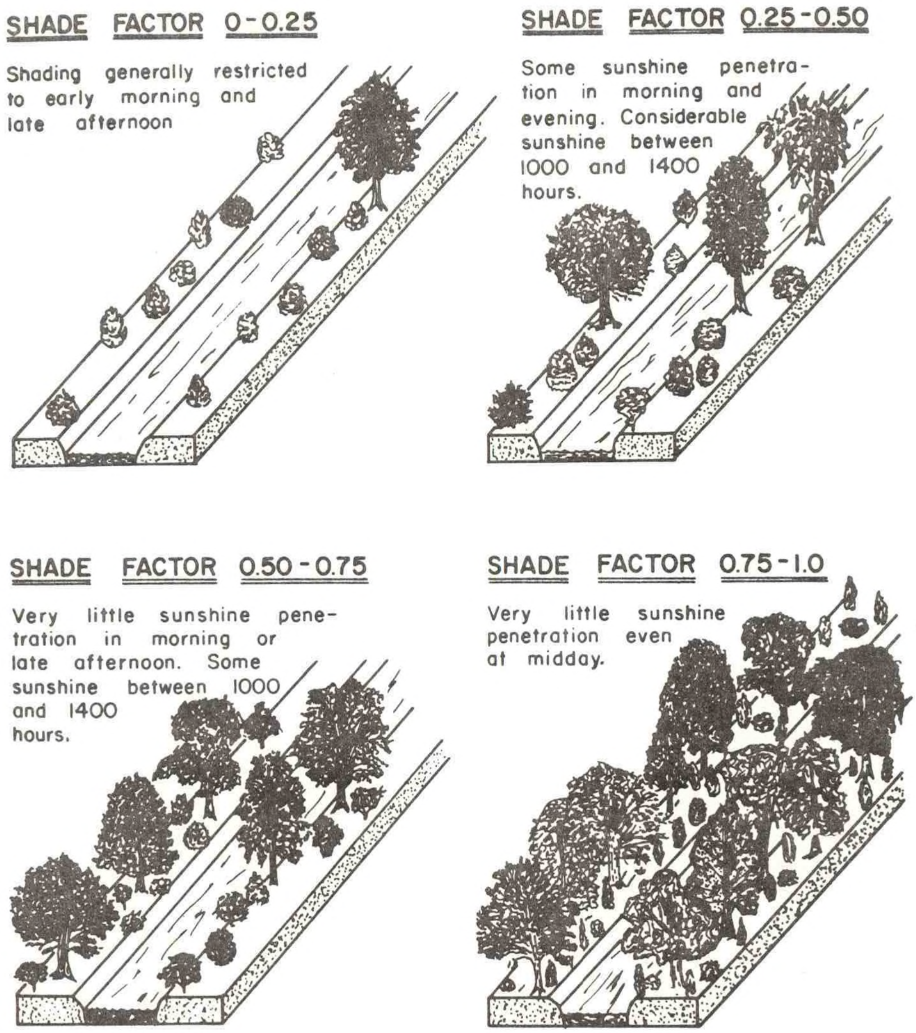


Figure A.1. Aid to estimating shade factor (after Pluhowski, 1970).

cases the same values of the less available variables, such as wind velocity and atmospheric pressure, may be reused in several meteorologic data sets in which air temperature is the only variable that changes from data set to data set. The decision on the number of meteorologic data sets to be used will depend on the relative location of meteorologic stations and the study reaches, and also on meteorologic variability.

IMDT — Ratio of number of computational time intervals (NT-1) to the number of meteorologic time intervals. For example: if the computational time interval is 3 hours and meteorologic data is available at daily intervals then IMDT = 24/3 = 8 (See Figure 3.1). In this example meteorologic data for the first meteorologic time interval will be reused for each of the first 8 computational time intervals. Meteorologic data from the second meteorolgic time interval will be be reused for each of the computational time intervals 9 to 16 and so on. IMDT should be set to 1 the computational time interval is variable. (Applies to read statements 44 to 53).

42. "IObb" IOQE, IOQR, IOTR, IORH, IOATPR, IOICL - Format (A10, 6I10)

"IObb" — Card type identification

IOQE — Input option for reading QE(IG, JM). (Applies to read statement 44)

IOQE = 0 do not read QE(IG, JM)
IOQE = 1 read QE(IG, JM)

IOQR — Input option for reading QR(IG, JM). (Applies to read statement 45)

IOQR = 0 do not read QR(IG, JM)
IOQR = 1 read QR(IG, JM)

IOTR — Input option for reading TR(IG, JM). (Applies to read statement 46)

IOTR = 0 do not read TR(IG, JM). In this case TR(IG, JM) is set equal to TA(IG, JM) by the program

IOTR = 1 read TR(IG, JM)

IORH Input option for reading TD(IG, JM). (Applies to read statement 48)

IORH = 0 Dew point temperatures read into TD(IG, JM)
IORH = 1 Relative humidities read into TD(IG, JM) and converted to dew point temperatures by the program.

IOATPR Input option for reading ATPR(IG, JM). (Applies to read statement 49)

IOATPR = 0 do not read ATPR(IG, JM). In this case ATPR(IG, JM) is estimated on the basis of elevation above mean sea level.
IOATPR = 1 read ATPR(IG, JM)

IOICL Input option for reading ICL(IG, JM). (Applies to read statement 52)

IOICL = 0 do not read ICL(IG, JM). In this case ICL(IG, JM) is set equal to ICS(IG, JM) by the program
IOICL = 1 read ICL(IG, JM)

(Read statement 43 is read for one stream (K subscript) at a time)

43. "NRGb", (NRG(I, K), I = 1, NX1) - Format (A10, 7I10/(10X, 7I10))

"NRGb" Card type identification

NRG(I, K) Number of the meteorologic data set to be used in the Ith sub-reach. The selection of the data set for the Ith reach should be based on the representativeness of the selected data set to the meteorologic conditions in the Ith sub-reach

(End K-loop)

(Read statements 44 to 53 and read for one meteorologic data set (IG subscript) at a time - total of NG sets)

(Omit read statement 44 if IOQE = 0)

44. "QEbb", (QE(IG, JM), JM = 1, NTM) - Format (A10, 7F10.0/(10X, 7F10.0))

"QEbb"	Card type identification
IG	Meteorologic data set index
JM	Meteorologic time interval index
NTM	Number of time intervals for which meteorologic data is to be read, where NTM = (NT-1)/IMDT
QE(IG, JM)	Evaporation in inches per computational time interval for the IGth meteorologic data set.

(Omit read statement 45 if IOQR = 0)

45. "QRbb", (QR(IG, JM), JM = 1, NTM) - Format (A10, 7F10.0/(10X, 7F10.0))

"QRbb"	Card type identification
QR(IG, JM)	Precipitation in inches per computational time interval for the IGth meteorologic data set

(Omit read statement 46 if IOTR = 0)

46. "TRbb", (TR(IG, JM), JM = 1, NTM) - Format (A10, 7F10.0/(10X, 7F10.0))

"TRbb"	Card type identification
TR(IG, JM)	Wet - bulb temperature (used as rainfall temperature) in deg. F averaged over the computational time interval for the IGth meteorologic data set.

47. "TAbb", (TA(IG, JM), JM = 1, NTM) - Format (A10, 7F10.0/(10X, 7F10.0))

"TAbb" Card type identification

TA(IG, JM) Dry - bulb temperature in deg. F averaged over the computational time interval for the IGth meteorologic data set.

48. "TDRH", (TD(IG, JM), JM = 1, NTM) - Format (A10, 7F10.0/ (10X, 7F10.0))

"TDRH" Card type identification

TD(IG, JM) If IORH = 0 then TD(IG, JM) is dew point temperature in deg. F averaged over the computational time interval for the IGth meteorologic data set.

If IORH = 1 then TD(IG, JM) is relative humidity as a percentage averaged over the computational time interval for the IGth meteorologic data set.

(Omit read statement 49 if IOATPR = 0)

49. "ATPR", (ATPR(IG, JM), JM = 1, NTM) - Format (A10, 7F10.0/(10X, 7F10.0))

"ATPR" Card type identification

ATPR(IG, JM) Atmospheric pressure in inches Hg. averaged over the computational time interval for the IGth meteorologic data set.

50. "WDVE", (WDVEL(IG, JM), JM = 1, NTM) - Format (A10, 7F10.0/(10X, 7F10.0))

"WDVE" Card type identification

WDVEL(IG, JM) Wind wpeed in miles per hour averaged over the computational time interval for the IGth meteorologic data set.

51. "ICSb", (ICS(IG, JM), JM = 1, NTM) - Format (A10, 7I10/(10X, 7I10))

"ICSb" Card type identification

ICS(IG, JM) Cloud cover in an integer number of tenths of cover averaged over the computational time interval for the IGth meteorologic data set. If the meteorologic time interval is 24 hours then ICS(IG, JM) is the average cloud cover between sunrise and sunset.

(Omit read statement 52 if IOICL = 0)

52. "ICLb", (ICL(IG, JM), JM = 1, NTM) - Format (A10, 7I10/(10X, 7I10))

"ICLb" Card type identification

ICL(IG, JM) Cloud cover in an integer number of tenths of cover averaged over the computational time interval for the IGth meteorologic data set. If the meteorologic time interval is 24 hours then ICL(IG, JM) is the average cloud cover over the 24 hour period.

(Omit read statement 53 if ITECH = 1)

53. "DYSL", (DYSL(IG, JM), JM = 1, NTM) - Format (A10, 7F10.0/(10X, 7F10.0))

"DYSL" Card type identification

DYSL(IC, JM) If ITECH = 2 then DYSL(IG, JM) is total incident solar radiation observed between sunset and sunrise in Btu. $ft.^{-2}$ day^{-1}. If the meteorologic time interval is not equal to 24 hours then repeat the value of total incident solar radiation for all meteorologic time intervals contained in the 24 hour period.

If ITECH = 3 then DYSL(IG, JM) is total incident solar radiation observed over the computational time interval in Btu. $ft.^{-2}DT(J)^{-1}$.

(End of IG-loop)

3. Program listing.

```
FILE  5=INPUT

FILE  6=OUTPUT

FILE  8(KIND=PACK, TITLE="NOAAOUT", MAXRECSIZE=80, BLOCKSIZE=720,
     .UNITS=CHARACTERS, AREASIZE=20, AREAS=1000, SAVEFACTOR=999)



C   ************************************************
C**** DYNAMIC STREAM TEMPERATURE MODEL (DSTEMP) *
C   ************************************************

C     DAVID S BOWLES, UTAH WATER RESEARCH LABORATORY, LOGAN, UTAH 84322

      DOUBLE PRECISION ACOD

      COMMON/GEOM/NB(2),NJUN(2),X(14,2),DDX(14,2),CSA(14,300,2),
     .              BD(14,300,2),PM(14,300,2),FLAT,ELVIN(14,300,2),ELV,
     .              ALSR(14,2),ALSS(14,2),ALSRR,ALSSS,GRDRF(14,2),
     .              SHADE(14,2),DPAV
      COMMON/TIME/DT(300),TIME(300),IDAY(300),DTSL,DTHR,FHR1,FHR2,
     .              IDAY1,IDAY2,FHSR,FHSS
      COMMON/FLOW/QS(14,300,2),QL(14,300,2),QG(14,2),QP(14,300,2),
     .              QR(3,300),QE(3,300),QRR,QEE,QLP(2),QLM(2),QGP,QGM,
     .              QG1(14,2)
      COMMON/METL/WRG(14,2),CC1(13),CC2(13),CC3(2),CC4(2),WDVEL(3,300),
     .              ICS(3,300),ICSS,ICL(3,300),ICLL,WDVELL,ATREF,SIGMA,
     .              RHO,FLHV,FNTC,SOLCST,DSTDEP,ATPR(3,300),ATPRR,
     .              DYSL(3,300),DAYSOL,ATEN,BOTREF,SURABS,SOLREF,
     .              AA(11),BB(11),TE(3),ES1(4),ES2(4),CTOT(14,300,2)
      COMMON/TEMP/TS(14,300,2,2),TSO(2,300),INOTN(14,2),TG1(14,2),
     .              TL(14,300,2),TG(14,2),TR(3,300),TRR,TP(14,300,2),
     .              TA(3,300),TD(3,300),TSAV,TDD,TAA
C     COMMON/STAT/
      COMMON/GENL/UNIT(30),TITLE(30),I,J,K,IG,PI,PI2,DTOR,KW,
     .              ET,IOHTC(10),ITECH,COEF(6),D31

 500  FORMAT(A10,7F10.0/(10X,7F10.0))
 501  FORMAT(1H ,A10,7F10.4/(1H ,10X,7F10.4))
 502  FORMAT(A10,7I10/(10X,7I10))
 503  FORMAT(1H ,A10,7I10/(1H ,10X,7I10))
 504  FORMAT(A4,2I2,2X,7F10.0/(10X,7F10.0))
 505  FORMAT(1H ,A4,2I2,2X,7F10.4/(1H ,10X,7F10.4))
 506  FORMAT(A10,I10,6F10.0/(10X,7F10.0))
 507  FORMAT(1H ,A10,I10,6F10.4/(1H ,10X,7F10.4))
 508  FORMAT(A10,3F10.0,2E10.5,2F10.0)
 509  FORMAT(1H ,A10,3F10.3,2E10.5,2F10.4)
 512  FORMAT(1H1,15HLISTING OF DATA//)
 515  FORMAT(20A4/10A4)
 520  FORMAT(1H ,120(1H=)/1H ,4HCOMP,30X,9HHYDRAULIC,32X,43HMET    INFLOW
     . TEMPS    HEATEX     STREAM TEMPS/1H ,
     .120HPT       RIVER  X-SECTN     TOP WETTED   SUB-RCH LATINF+ GRDWTR  P
     .OINT   STREAM GP LATIN GWINF PT LD  /FT2  CALCULATED OBSER/1H ,
     .120HNO  DISTANCE       AREA  WIDTH  PERIM   LENGTH TRIBINF INFLOW
     .LOAD    -FLOW NO  TEMP  TEMP  TEMP   /DT D/STM U/STM  -VED/1H0,
     .30A4/1H ,120(1H=)/)
 521  FORMAT(1H ,4HMAIN)
 522  FORMAT(1H ,I3,2F9.2,2F7.2,24X,F7.2,F9.2,15X,F6.2,6X,2F6.2)
 523  FORMAT(1H ,I3,2F9.2,2F7.2,F9.2,F8.4,1X,F6.5,F7.2,F9.2,I3,3F6.2,
     .F6.0,2F6.2)
 524  FORMAT(1H ,4HTRIB,I1)
 525  FORMAT(1H1,30A4//64H STREAM TEMPERATURES, ADVECTIVE HEAT SOURCES,
     .AND HYDRAULIC DATA/1H ,63(1H*)//19H INITIAL CONDITIONS,4X,
     .11H TIME PT NO,I3,8H       DAY,I4,5H HOUR,F6.2/)
 526  FORMAT(1H1,30A4//54H COMPONENTS OF HEAT EXCHANGE AT STREAM SURFACE
     . AND BED/1H ,53(1H*)//17H TIME INTERVAL NO,I3,11H    SIZE DT=,F4.0,
     .6H HRS,8H    (DAY,I4,5H HOUR,F6.2,9H   TO  DAY,I4,5H HOUR,F6.2,
     .1H)/)
 527  FORMAT(1H ,35HALL UNITS ARE BTUFT-2 PER DT IN HRS//1H ,120(1H*)/
     .1H ,31X,22HSURFACE      COMPONENTS,37X,14HBED COMPONENTS,6X,
     .6HTOTALS/1H ,
     .120HREACH    SOLAR RADIATION      VEGTN RADTN   ATMOS RADTN    BACK
     .   EVAP   COND  SNOW  SURF BEDAB  BACK   BED   SURF     BED/1H ,
     .120HNO       INCIDT REFLEC ABSORP INCIDT REFLEC INCIDT REFLEC  RADTN
     .  LHVAP          LHFUS RENEW SOLRD BEDRD  COND EXCHGE EXCHGE/1H ,
     .120(1H*)/)
 528  FORMAT(1H ,I3,3X,10F7.0,5F6.0,2F7.0)
 529  FORMAT(1H0,120(1H=))
 530  FORMAT(1H1,30A4//64H STREAM TEMPERATURES, ADVECTIVE HEAT SOURCES,
     .AND HYDRAULIC DATA/1H ,63(1H*)//11H TIME PT NO,I3,8H      DAY,I4,
     .5H HOUR,F6.2/)
 531  FORMAT(1H+,114X,F6.2)
 532  FORMAT(1H ,20A4)

C  ** INITIALISE
      KR=5
      KW=6
      PI=3.141592654
      PI2=2*PI
      DTOR=57.29577951
      WRITE(KW,512)
      READ(KR,502)ACOD,KRR,ITECH,NTRUN,IOSS,IOTCST,IPRT
      WRITE(KW,503)ACOD,KRR,ITECH,NTRUN,IOSS,IOTCST,IPRT

C   ************************************************
C *** READ OUTPUT FROM NOAA FLOOD ROUTING PROGRAM *
C   ************************************************
      READ(KRR,502)ACOD,NT,NS
      WRITE(KW,503)ACOD,NT,NS
      NT1=NT-1
      IF(NTRUN-NT)2,10,5
 2    IF(NTRUN)5,5,10
 5    NTRUN=NT
 10   IF(IDTCST)23,23,15
 15   READ(KRR,500)ACOD,DT(1)
      IF(IPRT.EQ.0)WRITE(KW,501)ACOD,DT(1)
      DO 20 J=2,NT1
      DT(J)=DT(1)
 20   CONTINUE
      GOTO 25
 23   READ(KRR,500)ACOD,(DT(J),J=1,NT1)
      IF(IPRT.EQ.0)WRITE(KW,501)ACOD,(DT(J),J=1,NT1)
 25   READ(KRR,502)ACOD,(NB(K),K=1,NS)
      IF(IPRT.EQ.0)WRITE(KW,503)ACOD,(NB(K),K=1,NS)
      IF(NS-1)28,28,26
 26   READ(KRR,502)ACOD,(NJUN(K),K=2,NS)
      IF(IPRT.EQ.0)WRITE(KW,503)ACOD,(NJUN(K),K=2,NS)
C     READ STREAM-BY-STREAM
 28   DO 40 K=1,NS
      NX=NB(K)
      NX1=NX-1
      READ(KRR,500)ACOD,(X(I,K),I=1,NX)
      IF(IPRT.EQ.0)WRITE(KW,501)ACOD,(X(I,K),I=1,NX)
```

3. Program listing (continued).

```
      READ(KRR,500)ACOD,(DDX(I,K),I=1,NX1)
      IF(IPRT.EQ.0)WRITE(KW,501)ACOD,(DDX(I,K),I=1,NX1)
      NTI=NT
      IF(IOSS)30,30,29
29    NTI=1
30    DO 35 J=1,NTI
      READ(KRR,500)ACOD,(CSA(I,J,K),I=1,NX)
      IF(IPRT.EQ.0)WRITE(KW,501)ACOD,(CSA(I,1,K),I=1,NX)
      READ(KRR,500)ACOD,(BD(I,J,K),I=1,NX)
      IF(IPRT.EQ.0)WRITE(KW,501)ACOD,(BD(I,J,K),I=1,NX)
      READ(KRR,500)ACOD,(PM(I,J,K),I=1,NX)
      IF(IPRT.EQ.0)WRITE(KW,501)ACOD,(PM(I,J,K),I=1,NX)
      READ(KRR,500)ACOD,(QS(I,J,K),I=1,NX)
      IF(IPRT.EQ.0)WRITE(KW,501)ACOD,(QS(I,J,K),I=1,NX)
      READ(KRR,500)ACOD,(ELVTN(I,J,K),I=1,NX)
      IF(IPRT.EQ.0)WRITE(KW,501)ACOD,(ELVTN(I,J,K),I=1,NX)
      READ(KRR,500)ACOD,(QL(I,J,K),I=1,NX1)
      IF(IPRT.EQ.0)WRITE(KW,501)ACOD,(QL(I,J,K),I=1,NX1)
35    CONTINUE
      IF(IOSS)40,40,36
36    DO 38 J=2,NT
      DO 37 I=1,NX
      CSA(I,J,K)=CSA(I,1,K)
      BD(I,J,K)=BD(I,1,K)
      PM(I,J,K)=PM(I,1,K)
      QS(I,J,K)=QS(I,1,K)
      ELVTN(I,J,K)=ELVTN(I,1,K)
      QL(I,J,K)=QL(I,1,K)
37    CONTINUE
38    CONTINUE
40    CONTINUE
C *** TEMPORARY CALCULATION OF LATERAL INFLOW IN JUNCTION REACHES
C     ON MAIN STREAM - REMOVE WHEN CORRECT QL READ FROM DNRT
      DO 42 K=2,NS
      I=NJUN(K)
      I1=I-1
      NX=NB(K)
      DO 41 J=1,NT
      QL(I,J,1)=QL(I1,J,1)+QS(NX,J,K)/DDX(I,1)
41    CONTINUE
42    CONTINUE
C     ******************************************************************
C *** READ INPUT DATA TO DYNAMIC STREAM TEMPERATURE MODEL (DSTEMP) *
C     ******************************************************************
C  *1 GENERAL
C   * HEADINGS
      READ(KR,515)(TITLE(L),L=1,30)
      WRITE(KW,532)(TITLE(L),L=1,30)
      READ(KR,515)(UNIT(L),L=1,30)
      IF(IPRT.LT.2)WRITE(KW,532)(UNIT(L),L=1,30)
C   * HEAT TRANSFER COMPONENT CALCULATION OPTIONS
      READ(KR,502)ACOD,(IOHTC(IC),IC=1,10)
      IF(IPRT.LT.2)WRITE(KW,503)ACOD,(IOHTC(IC),IC=1,10)
C   * PROPERTIES OF WATER
      READ(KR,500)ACOD,RHO,CP,FLHV,FLHF,ATREF,ATEN,SURABS,SOLREF
      IF(IPRT.LT.2)WRITE(KW,501)ACOD,RHO,CP,FLHV,FLHF,ATREF,ATEN,SURABS,
     *                        SOLREF
C   * TIME FACTORS
      READ(KR,506)ACOD,IDAY2,FHR2,FLAT,DTSL,FHSR,FHSS
      IF(IPRT.LT.2)WRITE(KW,507)ACOD,IDAY2,FHR2,FLAT,DTSL,FHSR,FHSS
      FLAT=FLAT/DTOR
C   * WEIGHTING FACTOR FOR IMPLICIT FOUR-POINT FINITE DIFFERENCE METHOD
C     AND OTHER COEFFICIENTS
      READ(KR,508)ACOD,THETA,SOLCST,DSTDEP,FMTC,SIGMA,BOTREF
      WRITE(KW,509)ACOD,THETA,SOLCST,DSTDEP,FMTC,SIGMA,BOTREF
      READ(KR,500)ACOD,(COEF(L),L=1,4)
      WRITE(KW,501)ACOD,(COEF(L),L=1,4)
C  *2 FLOWS AND WATER TEMPERATURES
      READ(KR,502)ACOD,IOQGTG,IOTL,NTL,NP
      WRITE(KW,503)ACOD,IOQGTG,IOTL,NTL,NP
      IF(IOQGTG)46,46,43
43    DO 45 K=1,NS
      NX1=NB(K)-1
C     SUBTRACT QG FROM QL FOR MASS BALANCE?
      READ(KR,500)ACOD,(QG(I,K),I=1,NX1)
      WRITE(KW,501)ACOD,(QG(I,K),I=1,NX1)
      READ(KR,500)ACOD,(TG(I,K),I=1,NX1)
      WRITE(KW,501)ACOD,(TG(I,K),I=1,NX1)
45    CONTINUE
46    IF(IOTL)54,54,47
47    DO 50 K=1,NS
      NX1=NB(K)-1
      READ(KR,500)ACOD,(TL(1,J,K),J=1,NT)
      WRITE(KW,501)ACOD,(TL(1,J,K),J=1,NT)
      DO 49 I=2,NX1
      DO 48 J=1,NT
      TL(I,J,K)=TL(1,J,K)
48    CONTINUE
49    CONTINUE
50    CONTINUE
54    IF(NTL)65,65,55
55    DO 60 INTL=1,NTL
      READ(KR,504)ACOD,K,I,(TL(I,J,K),J=1,NT)
      WRITE(KW,505)ACOD,K,I,(TL(I,J,K),J=1,NT)
60    CONTINUE
C   * INITIAL CONDITION FOR STREAM TEMPERATURE
65    DO 75 K=1,NS
      DO 70 L=1,2
      NX=NB(K)
      READ(KR,500)ACOD,(TS(I,1,K,L),I=1,NX)
      WRITE(KW,501)ACOD,(TS(I,1,K,L),I=1,NX)
      IF(NP)75,75,70
70    CONTINUE
75    CONTINUE
C     ON MAIN STREAM REACH WHERE TRIBUTARY ENTERS, SET TL AT J=1 FROM
C     TS INITIAL CONDITION OF TRIBUTARY AT CONFLUENCE
      IF(NS-1)79,79,76
76    DO 78 K=2,NS
      I=NJUN(K)
      II=NB(K)
      TL(I,1,1)=TS(II,1,K,1)
78    CONTINUE
C     SET TS(I,1,K,2)=TS(I,1,K,1) FOR INITIAL CONDITIONS
79    DO 83 K=1,NS
      NX=NB(K)
      DO 82 I=2,NX
      TS(I,1,K,2)=TS(I,1,K,1)
82    CONTINUE
83    CONTINUE
C   * UPSTREAM BOUNDARY CONDITIONS FOR STREAM TEMPERATURE
      DO 85 K=1,NS
      READ(KR,500)ACOD,(TS(1,J,K,1),J=1,NT)
      IF(IPRT.LT.2)WRITE(KW,501)ACOD,(TS(1,J,K,1),J=1,NT)
85    CONTINUE
C   * POINT LOADS
      IF(NP)91,91,87
```

3. Program listing (continued).

```
 87     DO 90 IP=1,NP
        READ(KR,504)ACOD,K,I,(QP(I,J,K),J=1,NT)
        IF(IPRT.LT.2)WRITE(KW,505)ACOD,K,I,(QP(I,J,K),J=1,NT)
        READ(KR,504)ACOD,K,I,(TP(I,J,K),J=1,NT)
        IF(IPRT.LT.2)WRITE(KW,505)ACOD,K,I,(TP(I,J,K),J=1,NT)
 90     CONTINUE
C  *3   OBSERVED THERMOGRAPHS
 91     READ(KR,502)ACOD,NOT
        IF(IPRT.LT.2)WRITE(KW,503)ACOD,NOT
        IF(NOT)102,102,92
 92     DO 100 INOT=1,NOT
        READ(KR,504)ACOD,K,I,(TSO(INOT,J),J=1,NT)
        IF(IPRT.LT.2)WRITE(KW,505)ACOD,K,I,(TSO(INOT,J),J=1,NT)
        INOTN(I,K)=INOT
100     CONTINUE
C  *4   METEOROLOGIC
C   *   MET COEFFICIENTS
102     READ(KR,500)ACOD,(AA(IC),IC=1,11)
        IF(IPRT.LT.2)WRITE(KW,501)ACOD,(AA(IC),IC=1,11)
        READ(KR,500)ACOD,(BB(IC),IC=1,11)
        IF(IPRT.LT.2)WRITE(KW,501)ACOD,(BB(IC),IC=1,11)
        READ(KR,500)ACOD,(TE(IE),IE=1,3)
        IF(IPRT.LT.2)WRITE(KW,501)ACOD,(TE(IE),IE=1,3)
        READ(KR,500)ACOD,(ES1(IE),IE=1,4)
        IF(IPRT.LT.2)WRITE(KW,501)ACOD,(ES1(IE),IE=1,4)
        READ(KR,500)ACOD,(ES2(IE),IE=1,4)
        IF(IPRT.LT.2)WRITE(KW,501)ACOD,(ES2(IE),IE=1,4)
C       READ STREAM-BY-STREAM
        DO 110 K=1,NS
        NX=NB(K)
        NX1=NX-1
        IF(ITECH-2)104,108,108
104     READ(KR,500)ACOD,(ALSR(I,K),I=1,NX1)
        IF(IPRT.LT.2)WRITE(KW,501)ACOD,(ALSR(I,K),I=1,NX1)
        READ(KR,500)ACOD,(ALSS(I,K),I=1,NX1)
        IF(IPRT.LT.2)WRITE(KW,501)ACOD,(ALSS(I,K),I=1,NX1)
        DO 105 I=1,NX
        ALSR(I,K)=ALSR(I,K)/DTOR
        ALSS(I,K)=ALSS(I,K)/DTOR
105     CONTINUE
        READ(KR,500)ACOD,(GRDRF(I,K),I=1,NX1)
        IF(IPRT.LT.2)WRITE(KW,501)ACOD,(GRDRF(I,K),I=1,NX1)
108     READ(KR,500)ACOD,(SHADE(I,K),I=1,NX1)
        IF(IPRT.LT.2)WRITE(KW,501)ACOD,(SHADE(I,K),I=1,NX1)
110     CONTINUE
C   *   READ MET GROUP ASSIGNMENTS FOR SUB-REACHES AND MET INPUT OPTIONS
        READ(KR,502)ACOD,NG,IMDT
        IF(IPRT.LT.2)WRITE(KW,503)ACOD,NG,IMDT
        READ(KR,502)ACOD,IOQE,IOQR,IOTR,IORH,IOATPR,IOICL
        IF(IPRT.LT.2)WRITE(KW,503)ACOD,IOQE,IOQR,IOTR,IORH,IOATPR,IOICL
        IF(NG-1)117,117,112
112     DO 115 K=1,NS
        NX1=NB(K)-1
        READ(KR,502)ACOD,(NRG(I,K),I=1,NX1)
        IF(IPRT.LT.2)WRITE(KW,503)ACOD,(NRG(I,K),I=1,NX1)
115     CONTINUE
        GOTO 120
117     DO 119 K=1,NS
        NX1=NB(K)-1
        DO 118 I=1,NX1
        NRG(I,K)=1
118     CONTINUE
119     CONTINUE
C       READ MET DATA GROUP-BY-GROUP
120     NTM=NT1/IMDT
        DO 140 IG=1,NG
        IF(IOQE)123,123,122
122     READ(KR,500)ACOD,(QE(IG,JM),JM=1,NTM)
        IF(IPRT.LT.2)WRITE(KW,501)ACOD,(QE(IG,JM),JM=1,NTM)
123     IF(IOQR)130,130,126
126     READ(KR,500)ACOD,(QR(IG,JM),JM=1,NTM)
        IF(IPRT.LT.2)WRITE(KW,501)ACOD,(QR(IG,JM),JM=1,NTM)
130     IF(IOTR)132,132,131
131     READ(KR,500)ACOD,(TR(IG,JM),JM=1,NTM)
        IF(IPRT.LT.2)WRITE(KW,501)ACOD,(TR(IG,JM),JM=1,NTM)
132     READ(KR,500)ACOD,(TA(IG,JM),JM=1,NTM)
        IF(IPRT.LT.2)WRITE(KW,501)ACOD,(TA(IG,JM),JM=1,NTM)
        READ(KR,500)ACOD,(TD(IG,JM),JM=1,NTM)
        IF(IPRT.LT.2)WRITE(KW,501)ACOD,(TD(IG,JM),JM=1,NTM)
C       CALCULATE DEW POINT TEMPERATURE IF RELATIVE HUMIDITY READ IN TD
        IF(IORH)135,135,133
133     DO 134 JM=1,NTM
        TAA=TA(IG,JM)
        DUM=(ALOG10(TD(IG,JM))-2.)/7.5+(TAA-32.)/(TAA+395.14)
        TD(IG,JM)=427.14*(DUM/(1.-DUM))+32.
134     CONTINUE
        IF(IOATPR)136,136,135
135     READ(KR,500)ACOD,(ATPR(IG,JM),JM=1,NTM)
        IF(IPRT.LT.2)WRITE(KW,501)ACOD,(ATPR(IG,JM),JM=1,NTM)
136     READ(KR,500)ACOD,(WDVEL(IG,JM),JM=1,NTM)
        IF(IPRT.LT.2)WRITE(KW,501)ACOD,(WDVEL(IG,JM),JM=1,NTM)
        READ(KR,502)ACOD,(ICS(IG,JM),JM=1,NTM)
        IF(IPRT.LT.2)WRITE(KW,503)ACOD,(ICS(IG,JM),JM=1,NTM)
        IF(IOICL)138,138,137
137     READ(KR,502)ACOD,(ICL(IG,JM),JM=1,NTM)
        IF(IPRT.LT.2)WRITE(KW,503)ACOD,(ICL(IG,JM),JM=1,NTM)
138     IF(ITECH-2)140,139,1393
139     NTM1=NTM
        GOTO 1396
1393    NTM1=NT1
1396    READ(KR,500)ACOD,(DYSL(IG,JM),JM=1,NTM1)
        IF(IPRT.LT.2)WRITE(KW,501)ACOD,(DYSL(IG,JM),JM=1,NTM1)
140     CONTINUE

C  **   SET UP DUMMY VARIABLES
        D1=1.-THETA
        D2=THETA/2.
        D3=D1/2.
        D4=1./(RHO*CP)
        TIME(1)=FHR2
        IDAY(1)=IDAY2

C       *************
C ***   TIME LOOP *
C       *************

        JM=1
        J=1
        GOTO 301
141     J1=J+1
        D5=1./(7200.*DT(J))
        D5A=2.*D5
        FHR1=FHR2
        IF(FHR1-24.)143,142,143
142     FHR1=0.
        IDAY1=IDAY2+1
        GOTO 144
143     IDAY1=IDAY2
144     DTHR=DT(J)
```

3. Program listing (continued).

```
      FHR2=FHR1+DTHR
      IF(FHR2-24.)147,147,145
  145 FHR2=FHR2-24.
      IDAY2=IDAY1+1
      GOTO 148
  147 IDAY2=IDAY1
  148 IF(IDAY2-365)152,152,150
  150 IDAY2=IDAY2-365
  152 TIME(J1)=FHR2
      IDAY(J1)=IDAY2
      WRITE(KW,526)(TITLE(L),L=1,30),J,DT(J),IDAY(J),TIME(J),IDAY(J1),
     .              TIME(J1)
      WRITE(KW,527)
C    ***********************************************************
C *** STREAM LOOP (TRIBUTARIES FIRST, MAIN STREAM LAST) *
C    ***********************************************************
      IF(NS-1)165,165,158
  158 K=2
      K1=K-1
      GOTO 170
C   * SAVE TRIBUTARY STREAM TEMPERATURE FOR INFLOW TO MAIN STREAM
  160 I=NJUN(K)
      TL(I,J1,1)=T
      K=K+1
      K1=K-1
      IF(K-NS)170,170,165
  165 K=1
      K1=0
      WRITE(KW,521)
      GOTO 172
  170 WRITE(KW,524)K1
  172 NX1=NB(K)-1
C    ******************
C *** SUB-REACH LOOP *
C    ******************
      DO 295 I=1,NX1
      I1=I+1
C  ** CALCULATE NON-ADVECTIVE HEAT FLUXES AS LINEAR FUNCTIONS OF STREAM
C     TEMPERATURE
C   * DETERMINE MET GROUP FOR SUB-REACH
      IG=NRG(I,K)
C   * DETERMINE MET DATA TIME STEP
  176 JMDT=IMDT*JM
      IF(J-JMDT)180,180,178
  178 JM=JM+1
C   * SET UP DUMMY VARIABLES
C     CONVERT QE & QR IN INCHES/DT(J)-HOURS TO FEET/SEC
  180 QEE=QE(IG,JM)/(43200.*DT(J))
      QRR=QR(IG,JM)/(43200.*DT(J))
      TAA=TA(IG,JM)
      IF(IOTR)185,185,190
  185 TRR=TR(IG,JM)
      GOTO 191
  190 TRR=TAA
  191 TDD=TD(IG,JM)
      ELV=D2*(ELVTN(I,J1,K)+ELVTN(I1,J1,K))+D3*(ELVTN(I,J,K)
     .    +ELVTN(I1,J,K))
C     ESTIMATE ATMOSPHERIC PRESSURE BASED ON ELEVATION IF ATPR NOT READ
      IF(IDATPR)192,192,193
  192 ATPRR=29.92-.00084*ELV
      GOTO 194
  193 ATPRR=ATPR(IG,JM)
  194 WDVELL=WDVEL(IG,JM)
      ICSS=ICS(IG,JM)
      ICLL=ICL(IG,JM)
      IF(IOICL)195,196,196
  195 ICLL=ICS(IG,JM)
  196 DAYSOL=DYSL(IG,J)
      TIJ=TS(I,J,K,1)
      TIJ1=TS(I,J1,K,1)
      TI1J=TS(I1,J,K,2)
      TSAV=(TI1J+TIJ1+TIJ)/3.
      D17=BD(I,J1,K)
      D18=BD(I1,J1,K)
      D19=BD(I,J,K)
      D20=BD(I1,J,K)
      D27=CSA(I,J1,K)
      D28=CSA(I1,J1,K)
      D29=CSA(I,J,K)
      D30=CSA(I1,J,K)
      D31=TG(I,K)
      DPAV=D2*(D27/D17+D28/D18)+D3*(D29/D19+D30/D20)
      DX=DDX(I,K)
      D6=THETA/DX
      D7=D1/DX
      ALSRR=ALSR(I,K)
      ALSSS=ALSS(I,K)
C   * OBTAIN NET NON-ADVECTIVE HEAT TRANSFER ACTING OVER SURFACE AREA
C     IN LINEAR FORM
      C1=0.
      C2=0.
      IF(IOHTC(1))198,198,197
  197 CALL SOLRAD(CC1(1),CC1(2),CC2(1),CC2(2))
  198 IF(IOHTC(2))200,200,199
  199 CALL VEGRAD(CC1(4),CC1(5),CC2(4),CC2(5))
  200 IF(IOHTC(3))202,202,201
  201 CALL ATRAD(CC1(6),CC1(7),CC2(6),CC2(7))
  202 IF(IOHTC(4))204,204,203
  203 CALL BAKRAD(CC1(8),CC2(8))
  204 IF(IOHTC(5))206,206,205
  205 CALL EVLHV(CC1(9),CC2(9))
  206 IF(IOHTC(6))208,208,207
  207 CALL COND(CC1(10),CC2(10))
  208 IF(IOHTC(7))210,210,209
  209 CALL SNLHF(CC1(11),CC2(11))
  210 IF(IOHTC(8))212,212,211
  211 CALL SURLRL(CC1(12),CC2(12))
  212 IF(IOHTC(9))214,214,213
  213 CALL BEDSRD(CC1(13),CC2(13))
  214 DO 215 IC=1,13
      C1=C1+CC1(IC)
      C2=C2+CC2(IC)
  215 CONTINUE
      C1=C1*D5A
      C2=C2*D5A
C   * OBTAIN NET HEAT TRANSFER ACTING OVER STREAM BED AND BANKS IN
C     LINEAR FORM
      C3=0.
      C4=0.
      IF(IOHTC(10))218,218,217
  217 CALL BEDBRD(CC3(1),CC4(1))
  218 IF(IOHTC(9))220,220,219
  219 CALL BEDCON(CC3(2),CC4(2))
  220 DO 221 IC=1,2
      C3=C3+CC3(IC)
      C4=C4+CC4(IC)
```

3. Program listing (continued).

```
 221  CONTINUE
      C3=C3*D5A
      C4=C4*D5A
C  ** SET UP DUMMY VARIABLES
      D8=D4*C1
      D9=D4*C2
      D10=D4*C3
      D11=D4*C4
      D21=PM(I,J1,K)
      D22=PM(I1,J1,K)
      D23=PM(I,J,K)
      D24=PM(I1,J,K)
C   * SEPARATE +VE & -VE VALUES OF QG & QL
      QGP=0.
      QGM=0.
      QGG=QG(I,K)
      QG1(I,K)=QGG
      IF(IDQGTG-1)235,223,222
 222  QGG=QGG/(D2*(D21+D22)+D3*(D23+D24))
      QG1(I,K)=QGG
C     IF BED CONDUCTION MODELED THEN STREAM TEMPERATURE IS USED FOR
C     TEMPERATURE OF GROUNDWATER ENTERING STREAM BECAUSE HEATING OF
C     GROUNDWATER IS INCLUDED IN BED CONDUCTION - OTHERWISE USE
C     TG AS INPUT FOR TEMPERATURE AT WHICH GROUNDWATER ENTERS STREAM
 223  IF(IOHTC(9))224,224,228
 224  IF(QGG)228,235,230
 228  QGM=QGG
      GOTO 235
 230  QGP=QGG
 235  DO 260 JJ=J,J1
      II=JJ-J+1
      QLP(II)=0.
      QLM(II)=0.
      QLL=QL(I,JJ,K)
      IF(QLL)245,260,250
 245  QLM(II)=QLL
      GOTO 260
 250  QLP(II)=QLL
 260  CONTINUE
      D12=D10+QGP*D31
      D13=D11+QGM
      D14=D9-QEE
      D15=QLM(2)
      D16=QLM(1)
      D25=QS(I1,J1,K)
      D26=D8+QRR*TRR
C  ** CALCULATE COEFFICIENTS
      A=D5*D27-D6*QS(I,J1,K)-D2*(D14*D17+D13*D21+D15)
      B=D5*D28+D6*D25-D2*(D14*D18+D13*D22+D15)
      C=D5*D29+D7*QS(I,J,K)+D3*(D14*D19+D13*D23+D16)
      D=D5*D30-D7*QS(I1,J,K)+D3*(D14*D20+D13*D24+D16)
      E=D2*(D26*(D17+D18)+D12*(D21+D22)+2.*QLP(2)*TL(I,J1,K))
     . +D3*(D26*(D19+D20)+D12*(D23+D24)+2.*QLP(1)*TL(I,J,K))
C  ** SOLVE FOR STREAM TEMPERATURE AT I+1,J+1
      TI1J1=(C*TIJ+D*TI1J+E-A*TIJ1)/B
      TSAV=D2*(TIJ1+TI1J1)+D3*(TIJ+TI1J)
C     STORE GROUNDWATER TEMPERATURE IN TG1 FOR PRINTING
      IF(QGM)261,262,261
 261  TG1(I,K)=TSAV
      GOTO 266
 262  IF(QGP)264,264,263
 263  TG1(I,K)=D31
      GOTO 266
 264  TG1(I,K)=0.
C  ** POINT LOAD
 266  QPL=QP(I1,J1,K)
      IF(QPL)270,270,268
 268  T=(D25*TI1J1+QPL*TP(I1,J1,1))/(D25+QPL)
      GOTO 275
 270  T=TI1J1
 275  TS(I1,J1,K,1)=T
      TS(I1,J1,K,2)=TI1J1
C    ************************************
C *** PRINT HEAT TRANSFER COMPONENTS *
C    ************************************
      DO 285 IC=1,13
      CC1(IC)=CC1(IC)+CC2(IC)*TSAV
 285  CONTINUE
      DO 290 IC=1,2
      CC3(IC)=CC3(IC)+CC4(IC)*TSAV
 290  CONTINUE
      C1=(C1+C2*TSAV)/D5A-CC1(13)
      C3=(C3+C4*TSAV)/D5A+CC1(13)
      CTOT(I,J1,K)=C1+C3
      CC1(3)=CC1(1)+CC1(2)+CC1(13)
      WRITE(KW,528)I,(CC1(IC),IC=1,13),(CC3(IC),IC=1,2),C1,C3
      CC1(3)=0.

 295  CONTINUE
C     END OF SUB-REACH LOOP

      IF(K-1)297,297,160
C     END OF STREAM LOOP

 297  WRITE(KW,529)

C    ***************************
C *** PRINT SUB-REACH SUMMARY *
C    ***************************
      J=J+1
C  ** TITLES
 301  IF(J-1)302,302,303
 302  WRITE(KW,525)(TITLE(L),L=1,30),J,IDAY(J),TIME(J)
      GOTO 304
 303  WRITE(KW,530)(TITLE(L),L=1,30),J,IDAY(J),TIME(J)
 304  WRITE(KW,520)(UNIT(L),L=1,30)
      DO 385 K=1,NS
      K1=K-1
      KP=K+1
      IF(K1)325,325,305
C  ** TRIBUTARIES
 305  WRITE(KW,524)K1
      NX1=NB(K)-1
      DO 315 I=1,NX1
      LL=1
      IF(QP(I,J,K))309,308,307
 307  LL=2
 308  WRITE(KW,523)I,X(I,K),CSA(I,J,K),BD(I,J,K),PM(I,J,K),DDX(I,K),
     .               QL(I,J,K),QG1(I,K),QP(I,J,K),QS(I,J,K),NRG(I,K),
     .               TL(I,J,K),TG1(I,K),TP(I,J,K),CTOT(I,J,K),
     .               (TS(I,J,K,L),L=1,LL)

      INOT=INOTN(I,K)
      IF(INOT)315,315,310
 310  WRITE(KW,531)TSO(INOT,J)
 315  CONTINUE
      I=NB(K)
      LL=1
```

3. Program listing (continued).

```
      IF(QP(I,J,K))320,320,319
319   LL=2
320   WRITE(KW,522)I,X(I,K),CSA(I,J,K),BD(I,J,K),PM(I,J,K),QP(I,J,K),
     .             QS(I,J,K),TP(I,J,K),(TS(I,J,K,L),L=1,LL)
      INOT=INOTN(I,K)
      IF(INOT)325,325,322
322   WRITE(KW,531)TSO(INOT,J)
C  ** MAIN STREAM
325   WRITE(KW,521)
      IF(NS-K)330,330,335
330   NX1=NB(1)-1
      GOTO 340
335   NX1=NJUN(KP)
340   IF(K1)345,345,350
345   NXO=1
      GOTO 360
350   NXO=NJUN(K)+1
360   DO 380 I=NXO,NX1
      LL=1
      IF(QP(I,J,1))363,363,362
362   LL=2
363   WRITE(KW,523)I,X(I,1),CSA(I,J,1),BD(I,J,1),PM(I,J,1),DDX(I,1),
     .             QL(I,J,1),QG1(I,1),QP(I,3,1),QS(I,J,1),NRG(I,1),
     .             TL(I,J,1),TG1(I,1),TP(I,J,1),CTOT(I,J,1),
     .             (TS(I,J,1,L),L=1,LL)
      INOT=INOTN(I,1)
      IF(INOT)380,380,365
365   WRITE(KW,531)TSO(INOT,J)
380   CONTINUE
385   CONTINUE
      I=NX1+1
      LL=1
      IF(QP(I,J,1))395,395,390
390   LL=2
395   WRITE(KW,522)I,X(I,1),CSA(I,J,1),BD(I,J,1),PM(I,J,1),QP(I,J,1),
     .             QS(I,J,1),TP(I,J,1),(TS(I,J,1,L),L=1,LL)
      INOT=INOTN(I,1)
      IF(INOT)399,399,397
397   WRITE(KW,531)TSO(INOT,J)
399   WRITE(KW,529)

      IF(J-NTRUN)141,450,450
C     END OF TIME LOOP

C     ************************
C *** CALCULATE STATISTICS *
C     ************************

450   STOP
      END
```

```
      SUBROUTINE SOLRAD(C11,C12,C21,C22)
C     ***************************************************************
C**** TO ESTIMATE INCIDENT AND REFLECTED SOLAR RADIATION OVER TIME *
C     INTERVAL DT(J)                                               *
C     ***************************************************************
      COMMON/GEOM/NB(2),NJUN(2),X(14,2),DDX(14,2),CSA(14,300,2),
     .            BD(14,300,2),PM(14,300,2),FLAT,ELVTN(14,300,2),ELV,
     .            ALSR(14,2),ALSS(14,2),ALSRR,ALSSS,GRDRF(14,2),
     .            SHADE(14,2),DPAV
      COMMON/TIME/DT(300),TIME(300),IDAY(300),DTSL,DTHR,FHR1,FHR2,
     .            IDAY1,IDAY2,FHSR,FHSS
      COMMON/FLOW/QS(14,300,2),QL(14,300,2),QG(14,2),QP(14,300,2),
     .            QR(3,300),QE(3,300),QRR,QEE,QLP(2),QLM(2),QGP,QGM,
     .            QG1(14,2)
      COMMON/METL/NRG(14,2),CC1(13),CC2(13),CC3(2),CC4(2),WDVEL(3,300),
     .            ICS(3,300),ICSS,ICL(3,300),ICLL,WDVELL,ATREF,SIGMA,
     .            RHO,FLHV,FNTC,SOLCST,DSTDEP,ATPR(3,300),ATPRP,
     .            DYSL(3,300),DAYSOL,ATEN,BOTREF,SURABS,SOLREF,
     .            AA(11),BB(11),TE(3),ES1(4),ES2(4),CTOT(14,300,2)
      COMMON/TEMP/TS(14,300,2,2),TSO(2,300),INOTN(14,2),TG1(14,2),
     .            TL(14,300,2),TG(14,2),TR(3,300),TPR,TP(14,300,2),
     .            TA(3,300),TD(3,300),TSAV,TDD,TAA
C     COMMON/STAT/
      COMMON/GENL/UNIT(30),TITLE(30),I,J,K,IG,PI,PI2,DTOR,KW,
     .            ET,IOHTC(10),ITECH,COEF(6),D31

C   * INITIALISE
      C11=0.
      C12=0.
      C21=0.
      C22=0.
      IF(ITECH-2)5,125,175
C     *******************************************
C *** TECHNIQUE 1 - SOLAR RADIATION CALCULATED *
C     *******************************************

C  ** CALCULATE RELATIVE DISTANCE EARTH - SUN, ANGULAR FRACTION OF
C     YEAR, AND EQUATION OF TIME
5     R=1.+.017*COS(.0172142063*(186-IDAY2))
      ANFYR=1.72028E-2*(IDAY2-1)
      ANFYR2=2.*ANFYR
      ET=-.12357*SIN(ANFYR)+.004289*COS(ANFYR)-.153809*SIN(ANFYR2)
     .   -.060783*COS(ANFYR2)
      ET=DTSL-ET
      DELTA=ARSIN(.3978685709*SIN(4.885783951+ANFYR+3.342E-2*SIN(ANFYR)
     .      -1.33797608E-3*COS(ANFYR)+3.47983746E-4*SIN(ANFYR2)-
     .      2.82743339E-5*COS(ANFYR2)))
C  ** CALCULATE HOUR ANGLE AND STANDARD TIME OF SUN RISE
      ANHSR=(SIN(ALSRR)-SIN(FLAT)*SIN(DELTA))/(COS(FLAT)*COS(DELTA))
      IF(ANHSR)15,20,20
15    ANHSR=PI+ARCOS(ABS(ANHSR))
      GOTO 25
20    ANHSR=PI2-ARCOS(ABS(ANHSR))
25    FHSR=3.819718634*ANHSR+ET-12.
      IF(FHR2-FHSR)200,200,28
C  ** CALCULATE HOUR ANGLE AND STANDARD TIME OF SUN SET
28    ANHSS=(SIN(ALSSS)-SIN(FLAT)*SIN(DELTA))/(COS(FLAT)*COS(DELTA))
      IF(ANHSS)30,35,35
30    ANHSS=PI-ARCOS(ABS(ANHSS))
      GOTO 40
35    ANHSS=ARCOS(ABS(ANHSS))
40    FHSS=3.819718634*ANHSS+ET+12.
      IF(FHR1-FHSS)43,200,200
```

3. Program listing (continued).

```
C   ** ELIMINATE PARTS OF DT OUTSIDE SUNRISE - SUNSET PERIOD
 43    IF(FHR1-FHSR)45,50,50
 45    FH1=FHSR
       GOTO 65
 50    FH1=FHR1
 65    IF(FHR2-FHSS)70,75,75
 70    FH2=FHR2
       GOTO 80
 75    FH2=FHSS
C   ** CALCULATE PRECIPITABLE WATER CONTENT OF THE ATMOSPHERE
 80    PWC=EXP(.03411*TDD-2.076235566)
       DUM=-(.465+.34036*PWC)
C   ** INTEGRATE SOLAR RADIATION OVER FH1-FH2
       AS=SIN(FLAT)*SIN(DELTA)
       AC=COS(FLAT)*COS(DELTA)
       OAMCST=(1.-6.879166667E-6*ELV)**5.256
       DUM1=1.-DSTDEP
       DUM2=.5*GRDRF(I,K)
       DUM3=1.+DSTDEP
       DUM4=(1.-.0065*ICSS**2)*(1.-SHADE(I,K))
       FH=FH2-FH1
       N=IFIX(FH)
       IF(N-FH)82,85,85
 82    N=N+1
 85    IF(N-4)86,87,87
 86    N=4
 87    DEL=FH/N
       DFH1=FH1
       DFH2=FH1+DEL/2.
       DFH3=FH1+DEL
       DO 120 L=1,N
       CALL HRANGL(DFH1,DANH1)
       CALL HRANGL(DFH2,DANH2)
       CALL HRANGL(DFH3,DANH3)
       DC11=SOLCST*(AS*(DFH3-DFH1)+3.819718634*AC*(SIN(DANH3)
     .       -SIN(DANH1)))/R**2
       SINAL=AS+AC*COS(DANH2)
       IF(SINAL-.00001)95,95,90
 90    ALDEG=DTOR*ARSIN(SINAL)
       RF=1.18/ALDEG**(.77)
       GOTO 100
 95    SINAL=0.
       ALDEG=0.
       RF=1.
C   ** CALCULATE OPTICAL AIR MASS
 100   OAM=OAMCST/(SIN(ALPHA)+.15*(ALDEG+3.885)**(-1.253))
C   ** CALCULATE MEAN ATMOSPHERIC TRANSMISSION COEFFICIENTS
       ATC1=EXP(DUM*(.129+.171*EXP(-.88*OAM))*OAM)
       ATC2=EXP(DUM*(.179+.421*EXP(-.721*OAM))*OAM)
       DC11=DC11*(ATC2+.5*(DUM1-ATC1))/(1.-DUM2*(DUM3-ATC1))*DUM4
       C11=C11+DC11
       C12=C12-DC11*RF
       DFH1=DFH1+DEL
       DFH2=DFH2+DEL
       DFH3=DFH3+DEL
 120   CONTINUE
       GOTO 200

C     ****************************************************************
C *** TECHNIQUE 2 - OBSERVED TOTAL DAILY SOLAR RADIATION DISTRIBUTED *
C       BETWEEN SUNRISE AND SUNSET                                    *
C     ****************************************************************

C   ** ELIMINATE PARTS OF DT OUTSIDE SUNRISE - SUNSET PERIOD
 125   IF(FHR2-FHSR)200,200,130
 130   IF(FHR1-FHSS)135,200,200
 135   IF(FHR1-FHSR)140,145,145
 140   FH1=FHSR
       GOTO 150
 145   FH1=FHR1
 150   IF(FHR2-FHSS)155,160,160
 155   FH2=FHR2
       GOTO 165
 160   FH2=FHSS
C   ** INTEGRATE SOLAR RADIATION OVER FH1-FH2
 165   W=12.*DAYSOL/(FHSS-FHSR)**3
       XX1=FH1-FHSR
       XX2=FH2-FHSR
       XX12=XX1*XX1
       XX22=XX2*XX2
       C11=(W*(FHSS-FHSR)*(XX22-XX12)/4.-W*(XX22*XX2-XX12*XX1)/6.)
     .       *(1.-SHADE(I,K))
       C12=-C11*SOLREF
       GOTO 200

C     *******************************************************
C *** TECHNIQUE 3 - USE OBSERVED SOLAR RADIATION DATA *
C     *******************************************************

 175   C11=DAYSOL*(1.-SHADE(I,K))
       C12=-C11*SOLREF

 200   RETURN
       END


       SUBROUTINE HRANGL(F,A)
C     *******************************************************
C**** TO CONVERT STANDARD TIME IN HOURS TO HOUR ANGLE *
C     *******************************************************
       COMMON/GENL/UNIT(30),TITLE(30),I,J,K,IG,PI,PI2,DTOR,KW,
     .              ET,IJHTC(10),ITECH,COEF(6),C31

       IF(F-12.)5,5,10
 5     A=(F+12.-ET)*.2617993878
       GOTO 15
 10    A=(F-12.-ET)*.2617993878
 15    IF(A)20,35,25
 20    A=A+PI2
       GOTO 35
 25    IF(A-PI2)35,35,30
 30    A=A-PI2
 35    RETURN
       END
```

3. Program listing (continued).

```
      SUBROUTINE VEGRAD(C14,C15,C24,C25)
      RETURN
      END


      SUBROUTINE ATRAD(C16,C17,C26,C27)
C     ***************************************************************
C**** TO ESTIMATE INCIDENT AND REFLECTED ATMOSPHERIC RADIATION OVER *
C     TIME INTERVAL DT(J)                                           *
C     ***************************************************************
      COMMON/GEOM/NB(2),NJUN(2),X(14,2),DDX(14,2),CSA(14,300,2),
     .              BD(14,300,2),PM(14,300,2),FLAT,ELVTN(14,300,2),ELV,
     .              ALSR(14,2),ALSS(14,2),ALSRR,ALSSS,GRDRF(14,2),
     .              SHADE(14,2),DPAV
      COMMON/TIME/DT(300),TIME(300),IDAY(300),DTSL,DTHR,FHR1,FHR2,
     .              IDAY1,IDAY2,FHSR,FHSS
      COMMON/FLOW/QS(14,300,2),QL(14,300,2),QG(14,2),QP(14,300,2),
     .              QR(3,300),QE(3,300),QRR,QEE,QLP(2),QLM(2),QGP,QGM,
     .              QG1(14,2)
      COMMON/METL/NRG(14,2),CC1(13),CC2(13),CC3(2),CC4(2),WDVEL(3,300),
     .              ICS(3,300),ICSS,ICL(3,300),ICLL,WDVELL,ATREF,SIGMA,
     .              RHO,FLHV,FMTC,SOLCST,DSTDEP,ATPR(3,300),ATPRR,
     .              DYSL(3,300),DAYSOL,ATEN,BOTREF,SURABS,SOLREF,
     .              AA(11),BB(11),TE(3),ES1(4),ES2(4),CTOT(14,300,2)
      COMMON/TEMP/TS(14,300,2,2),TSO(2,300),INOTN(14,2),TG1(14,2),
     .              TL(14,300,2),TG(14,2),TR(3,300),TRR,TP(14,300,2),
     .              TA(3,300),TD(3,300),TSAV,TDD,TAA
C     COMMON/STAT/
      COMMON/GENL/UNIT(30),TITLE(30),I,J,K,IG,PI,PI2,DTOR,KW,
     .              ET,IOHTC(10),ITECH,COEF(6),D31

      C26=0.
      C27=0.
      ICL1=ICLL+1
      EA=EXP((8.642*TDD-683.)/(.5556*TDD+219.5))
      BETA=AA(ICL1)+BB(ICL1)*EA
      C16=BETA*SIGMA*(TAA+459.67)**4*DTHR
      C17=-ATREF*C16
      RETURN
      END


      SUBROUTINE BAKRAD(C18,C28)
C     ***************************************************************
C**** TO ESTIMATE BACK RADIATION FROM WATER SURFACE OVER TIME *
C     INTERVAL DT(J)                                               *
C     ***************************************************************
      COMMON/GEOM/NB(2),NJUN(2),X(14,2),DDX(14,2),CSA(14,300,2),
     .              BD(14,300,2),PM(14,300,2),FLAT,ELVTN(14,300,2),ELV,
     .              ALSR(14,2),ALSS(14,2),ALSRR,ALSSS,GRDRF(14,2),
     .              SHADE(14,2),DPAV
      COMMON/TIME/DT(300),TIME(300),IDAY(300),DTSL,DTHR,FHR1,FHR2,
     .              IDAY1,IDAY2,FHSR,FHSS
      COMMON/FLOW/QS(14,300,2),QL(14,300,2),QG(14,2),QP(14,300,2),
     .              QR(3,300),QE(3,300),QRR,QEE,QLP(2),QLM(2),QGP,QGM,
     .              QG1(14,2)
      COMMON/METL/NRG(14,2),CC1(13),CC2(13),CC3(2),CC4(2),WDVEL(3,300),
     .              ICS(3,300),ICSS,ICL(3,300),ICLL,WDVELL,ATREF,SIGMA,
     .              RHO,FLHV,FMTC,SOLCST,DSTDEP,ATPR(3,300),ATPRR,
     .              DYSL(3,300),DAYSOL,ATEN,BOTREF,SURABS,SOLREF,
     .              AA(11),BB(11),TE(3),ES1(4),ES2(4),CTOT(14,300,2)
      COMMON/TEMP/TS(14,300,2,2),TSO(2,300),INOTN(14,2),TG1(14,2),
     .              TL(14,300,2),TG(14,2),TR(3,300),TRR,TP(14,300,2),
     .              TA(3,300),TD(3,300),TSAV,TDD,TAA
C     COMMON/STAT/
      COMMON/GENL/UNIT(30),TITLE(30),I,J,K,IG,PI,PI2,DTOR,KW,
     .              ET,IOHTC(10),ITECH,COEF(6),D31

      IF(TSAV-68.)10,10,20
   10 C18=-68.27*DTHR
      C28=-.8815*DTHR
      RETURN
   20 C18=-54.25*DTHR
      C28=-1.084*DTHR
      RETURN
      END


      SUBROUTINE SNLHF(C111,C211)
      RETURN
      END
```

3. Program listing (continued).

```
      SUBROUTINE SURLRL(C112,C212)
      RETURN
      END


      SUBROUTINE EVLHV(C19,C29)
C     ******************************************************************
C**** TO ESTIMATE LATENT HEAT OF VAPORISATION SUPPLIED BY STREAM TO *
C     EVAPORATING WATER OVER TIME INTERVAL DT(J)                       *
C     ******************************************************************
      COMMON/GEOM/NB(2),NJUN(2),X(14,2),DDX(14,2),CSA(14,300,2),
     .            BD(14,300,2),PM(14,300,2),FLAT,ELVTN(14,300,2),ELV,
     .            ALSR(14,2),ALSS(14,2),ALSRR,ALSSS,GRDRF(14,2),
     .            SHADE(14,2),DPAV
      COMMON/TIME/DT(300),TIME(300),IDAY(300),DTSL,DTHR,FHR1,FHR2,
     .            IDAY1,IDAY2,FHSR,FHSS
      COMMON/FLOW/QS(14,300,2),QL(14,300,2),QG(14,2),QP(14,300,2),
     .            QR(3,300),QE(3,300),QRR,QEE,QLP(2),QLM(2),QGP,QGM,
     .            QG1(14,2)
      COMMON/METL/NRG(14,2),CC1(13),CC2(13),CC3(2),CC4(2),WDVEL(3,300),
     .            ICS(3,300),ICSS,ICL(3,300),ICLL,WDVELL,ATREF,SIGMA,
     .            RHO,FLHV,FMTC,SOLCST,DSTDEP,ATPR(3,300),ATPRR,
     .            DYSL(3,300),DAYSOL,ATEN,BOTREF,SURABS,SOLREF,
     .            AA(11),BB(11),TE(3),ES1(4),ES2(4),CTOT(14,300,2)
      COMMON/TEMP/TS(14,300,2,2),TSC(2,300),INOTN(14,2),TG1(14,2),
     .            TL(14,300,2),TG(14,2),TR(3,300),TRR,TP(14,300,2),
     .            TA(3,300),TD(3,300),TSAV,TDD,TAA
C     COMMON/STAT/
      COMMON/GENL/UNIT(30),TITLE(30),I,J,K,IG,PI,PI2,DTOR,KW,
     .            ET,IOHTC(10),ITECH,COEF(6),D31

      EA=EXP((8.642*TDD-683.)/(.5556*TDD+219.5))
      DUM=RHO*FLHV*FMTC*WDVELL*DTHR
      DO 10 IE=1,3
      IF(TSAV-TE(IE))15,15,10
   10 CONTINUE
      IE=4
   15 C19=-DUM*(ES1(IE)-EA)
      C29=-DUM*ES2(IE)
      RETURN
      END


      SUBROUTINE COND(C110,C210)
C     ******************************************************************
C**** TO ESTIMATE HEAT TRANSFER BY CONDUCTION AT AIR-WATER INTERFACE *
C     OVER TIME INTERVAL DT(J)                                          *
C     ******************************************************************
      COMMON/GEOM/NB(2),NJUN(2),X(14,2),DDX(14,2),CSA(14,300,2),
     .            BD(14,300,2),PM(14,300,2),FLAT,ELVTN(14,300,2),ELV,
     .            ALSR(14,2),ALSS(14,2),ALSRR,ALSSS,GRDRF(14,2),
     .            SHADE(14,2),DPAV
      COMMON/TIME/DT(300),TIME(300),IDAY(300),DTSL,DTHR,FHR1,FHR2,
     .            IDAY1,IDAY2,FHSR,FHSS
      COMMON/FLOW/QS(14,300,2),QL(14,300,2),QG(14,2),QP(14,300,2),
     .            QR(3,300),QE(3,300),QRR,QEE,QLP(2),QLM(2),QGP,QGM,
     .            QG1(14,2)
      COMMON/METL/NRG(14,2),CC1(13),CC2(13),CC3(2),CC4(2),WDVEL(3,300),
     .            ICS(3,300),ICSS,ICL(3,300),ICLL,WDVELL,ATREF,SIGMA,
     .            RHO,FLHV,FMTC,SOLCST,DSTDEP,ATPR(3,300),ATPRR,
     .            DYSL(3,300),DAYSOL,ATEN,BOTREF,SURABS,SOLREF,
     .            AA(11),BB(11),TE(3),ES1(4),ES2(4),CTOT(14,300,2)
      COMMON/TEMP/TS(14,300,2,2),TSO(2,300),INOTN(14,2),TG1(14,2),
     .            TL(14,300,2),TG(14,2),TR(3,300),TRR,TP(14,300,2),
     .            TA(3,300),TD(3,300),TSAV,TDD,TAA
C     COMMON/STAT/
      COMMON/GENL/UNIT(30),TITLE(30),I,J,K,IG,PI,PI2,DTOR,KW,
     .            ET,IOHTC(10),ITECH,COEF(6),D31

      C210=-3.362714687E-4*ATPRR*RHO*FLHV*FMTC*WDVELL*DTHR
      C110=-C210*TAA
      RETURN
      END
```

3. Program listing (continued).

```
      SUBROUTINE BEDSRD(C113,C213)
C     ****************************************************************
C**** TO ESTIMATE SOLAR RADIATION ABSORPED BY STREAM BED OVER TIME    *
C     INTERVAL DT(J)                                                  *
C     ****************************************************************
      COMMON/GEOM/NB(2),NJUN(2),X(14,2),DDX(14,2),CSA(14,300,2),
     .               BD(14,300,2),PM(14,300,2),FLAT,ELVTN(14,300,2),ELV,
     .               ALSR(14,2),ALSS(14,2),ALSRR,ALSSS,GRDRF(14,2),
     .               SHADE(14,2),DPAV
      COMMON/TIME/DT(300),TIME(300),IDAY(300),DTSL,DTHR,FHR1,FHR2,
     .               IDAY1,IDAY2,FHSR,FHSS
      COMMON/FLOW/QS(14,300,2),QL(14,300,2),QG(14,2),QP(14,300,2),
     .               QR(3,300),QE(3,300),QRR,QEE,QLP(2),QLM(2),QGP,QGM,
     .               QG1(14,2)
      COMMON/METL/NRG(14,2),CC1(13),CC2(13),CC3(2),CC4(2),WDVEL(3,300),
     .               ICS(3,300),ICSS,ICL(3,300),ICLL,WDVELL,ATREF,SIGMA,
     .               RHO,FLHV,FMTC,SOLCST,DSTDEP,ATPR(3,300),ATPRR,
     .               DYSL(3,300),DAYSOL,ATEN,BOTREF,SURABS,SOLREF,
     .               AA(11),BB(11),TE(3),ES1(4),ES2(4),CTOT(14,300,2)
      COMMON/TEMP/TS(14,300,2,2),TSO(2,300),INOTN(14,2),TG1(14,2),
     .               TL(14,300,2),TG(14,2),TR(3,300),TRR,TP(14,300,2),
     .               TA(3,300),TD(3,300),TSAV,TDD,TAA
C     COMMON/STAT/
      COMMON/GENL/UNIT(30),TITLE(30),I,J,K,IG,PI,PI2,DTOR,KW,
     .               ET,IOHTC(10),ITECH,COEF(6),D31

      C113=-(1.-BOTREF)*(1.-SURABS)*(CC1(1)+CC1(2))*EXP(-ATEN*DPAV)
      C213=0.
      RETURN
      END


      SUBROUTINE BEDBRD(C31,C41)
      RETURN
      END
```

```
      SUBROUTINE BEDCON(C32,C42)
C     ****************************************************************
C**** TO ESTIMATE HEAT TRANSFER BY CONDUCTION AT STREAM BED-WATER     *
C     INTERFACE OVER TIME INTERVAL DT(J)                              *
C     ****************************************************************
      COMMON/GEOM/NB(2),NJUN(2),X(14,2),DDX(14,2),CSA(14,300,2),
     .               BD(14,300,2),PM(14,300,2),FLAT,ELVTN(14,300,2),ELV,
     .               ALSR(14,2),ALSS(14,2),ALSRR,ALSSS,GRDRF(14,2),
     .               SHADE(14,2),DPAV
      COMMON/TIME/DT(300),TIME(300),IDAY(300),DTSL,DTHR,FHR1,FHR2,
     .               IDAY1,IDAY2,FHSR,FHSS
      COMMON/FLOW/QS(14,300,2),QL(14,300,2),QG(14,2),QP(14,300,2),
     .               QR(3,300),QE(3,300),QRR,QEE,QLP(2),QLM(2),QGP,QGM,
     .               QG1(14,2)
      COMMON/METL/NRG(14,2),CC1(13),CC2(13),CC3(2),CC4(2),WDVEL(3,300),
     .               ICS(3,300),ICSS,ICL(3,300),ICLL,WDVELL,ATREF,SIGMA,
     .               RHO,FLHV,FMTC,SOLCST,DSTDEP,ATPR(3,300),ATPRR,
     .               DYSL(3,300),DAYSOL,ATEN,BOTREF,SURABS,SOLREF,
     .               AA(11),BB(11),TE(3),ES1(4),ES2(4),CTOT(14,300,2)
      COMMON/TEMP/TS(14,300,2,2),TSO(2,300),INOTN(14,2),TG1(14,2),
     .               TL(14,300,2),TG(14,2),TR(3,300),TRR,TP(14,300,2),
     .               TA(3,300),TD(3,300),TSAV,TDD,TAA
C     COMMON/STAT/
      COMMON/GENL/UNIT(30),TITLE(30),I,J,K,IG,PI,PI2,DTOR,KW,
     .               ET,IOHTC(10),ITECH,COEF(6),D31

      C32=(COEF(1)-CC1(13)*COEF(2)/DTHR+COEF(3)*D31)*DTHR
      C42=COEF(4)*DTHR
      RETURN
      END
```

4. Examples of input and output (a) main stream only (Spawn Creek, see Comer et al., 1975).

```
LISTING OF DATA

KRF              5          3          2          1          1          0
NTAS            25          1
DT       1  1.0000
NB               6
X           0.0000     0.4000     0.7800     0.8000     1.2300     1.6500
DOX      2415.0000  2015.0000   100.0000  2240.0000  2240.0000
CSA         3.1700     4.5800     2.3900     3.2100     3.2900     6.2100
BD          7.0000     6.5000     4.2000     4.2000     5.5000     9.4000
PM          8.0000     7.0000     5.2000     5.2000     6.7000    10.0000
QS          4.0100     4.3700     4.7200     6.3400     8.5000    10.6600
ELVT     6460.0000  6275.0000  6127.0000  6120.0000  6035.0000  5950.0000
GL          0.0000     0.0000     0.0162     0.0008     0.0008
DSTEMP PUN 1  SPAWN CREEK     AUGUST 29-30, 1974  DIURNAL **CALIBRATION**
  HOURLY INTERVALS
       MILES       FT2       FT        FT          FT  FT2S-1  FTS-1     CFS        CFS
  CF     DF     DF   BTU     DF      DF      DF
IOFT     1           1          0          1          1          1          1          0
                     0          0          0
PREP     1     62.3170     0.9988  1053.0000   143.5000     0.0300     0.0152     0.6000
                0.0800
TIME               241    13.0000    40.0000     0.4667     8.2500    18.5000
COEF 1           0.550    429.000      0.020.10000E-02.17400E-08     0.3000
COEF 2      -3573.8000     0.3880    78.6600    -4.9520
IOCT                 2          0          3          0
QG              0.0002     0.0002     0.0002     0.0002     0.0002
TG             48.7000    48.7000    48.7000    48.7000    48.7000
TL    1 3      50.0000    50.5000    50.5000    50.0000    49.0000    48.5000    47.0000
               46.0000    45.5000    45.5000    45.0000    44.5000    44.5000    44.0000
               44.0000    44.0000    44.0000    44.0000    43.5000    44.0000    45.0000
               46.5000    48.0000    49.0000    50.0000
TL    1 4      56.7000    57.2000    57.6000    56.6000    55.4000    53.7000    52.4000
               49.3000    47.5000    45.6000    44.6000    43.7000    42.8000    42.5000
               41.7000    41.4000    41.2000    40.6000    40.3000    40.4000    42.1000
               44.8000    47.5000    52.0000    55.7000
TL    1 5      56.7000    57.2000    57.6000    56.6000    55.4000    53.7000    52.4000
               49.3000    47.5000    45.6000    44.6000    43.7000    42.8000    42.5000
               41.7000    41.4000    41.2000    40.6000    40.3000    40.4000    42.1000
               44.8000    47.5000    52.0000    55.7000
TSICL1         46.0000    48.0000    50.0000    50.0000    52.0000    54.0000
TSLS     1     46.0000    46.0000    46.5000    46.5000    46.5000    46.0000    46.0000
               45.5000    45.5000    45.5000    45.0000    45.0000    45.0000    45.0000
               44.5000    44.5000    44.5000    44.5000    44.5000    44.5000    44.5000
               43.5000    44.5000    45.5000    46.0000
NOT                  2
TSC1  1 4      50.0000    50.5000    50.5000    50.0000    49.0000    48.5000    47.0000
               46.0000    45.5000    45.5000    45.0000    44.5000    44.5000    44.0000
               44.0000    44.0000    44.0000    44.0000    43.5000    44.0000    45.0000
               46.5000    48.0000    49.0000    50.0000
TSC2  1 6      54.0000    54.5000    55.0000    54.0000    53.0000    51.5000    50.5000
               48.0000    47.0000    46.0000    45.5000    45.0000    44.5000    44.5000
               44.0000    44.0000    44.0000    43.5000    43.5000    43.5000    45.0000
               47.5000    49.5000    52.0000    53.0000
AA       1      0.7400     0.7500     0.7600     0.7710     0.7830     0.7930     0.8000
                0.8100     0.8250     0.8450     0.8660
BB       1      0.1500     0.1500     0.1500     0.1430     0.1380     0.1370     0.1350
                0.1300     0.1200     0.1050     0.0900
TE             50.0000    68.0000    86.0000
ES1            -0.1380    -0.5480    -1.4400    -3.1330
```

```
ES2             0.0098     0.0180     0.0312     0.0509
SHAD            0.5000     0.4000     0.0500     0.0000     0.0000
NG                   2          1
IO                   0          0          0          1          0          1
NRE                  1          1          1          2          2
TA       1     81.0000    80.0000    82.0000    81.0000    81.0000    76.0000    64.0000
               57.0000    52.0000    48.0000    44.0000    43.0000    40.0000    38.0000
               37.0000    36.0000    34.0000    34.0000    34.0000    54.0000    70.0000
               77.0000    76.0000    80.0000
TDRH     1     12.0000    12.0000    13.0000    14.0000    14.0000    14.0000    25.0000
               40.0000    50.0000    62.0000    68.0000    72.0000    78.0000    84.0000
               85.0000    87.0000    89.0000    90.0000    90.0000    55.0000    37.0000
               24.0000    19.0000    18.0000
WDVE     1      5.5000     5.0000     5.0000     5.0000     4.0000     3.0000     2.7500
                2.5000     1.7500     1.0000     1.5000     2.0000     2.0000     2.0000
                1.5000     1.0000     1.2500     1.5000     1.2500     1.0000     0.5000
                0.0000     3.2500     6.5000
ICS      1           2          2          2          2          2          2          2
                     2          2          2          2          2          1          1
                     1          1          0          0          0          0          0
                     0          0          0
ICL      1           2          2          2          2          2          2          2
                     2          2          2          2          2          1          1
                     1          1          0          0          0          0          0
                     0          0          0
DYSL     1    279.9000   254.5000   219.4000   164.1000   122.4000    46.1000     3.6900
                0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000
                0.0000     0.0000     0.0000     0.0000     0.0000    80.0000   174.8000
              225.0000   258.9000   278.1000
TA     2 1     75.0000    75.0000    71.0000    66.0000    62.0000    60.0000    57.0000
               55.0000    54.0000    53.0000    52.0000    52.0000    57.0000    52.0000
               56.0000    60.0000    63.0000    68.0000    73.0000    77.0000    77.0000
               75.0000    76.0000    76.0000
TDRH   2 1     12.0000    12.0000    13.0000    14.0000    14.0000    14.0000    25.0000
               40.0000    50.0000    62.0000    68.0000    72.0000    78.0000    84.0000
               85.0000    87.0000    89.0000    90.0000    90.0000    55.0000    37.0000
               24.0000    19.0000    18.0000
WDVE   2 1      5.5000     5.0000     5.0000     5.0000     4.0000     3.0000     2.7500
                2.5000     1.7500     1.0000     1.5000     2.0000     2.0000     2.0000
                1.5000     1.0000     1.2500     1.5000     1.2500     1.0000     0.5000
                0.0000     3.2500     6.5000
ICS    2 1           2          2          2          2          2          2          2
                     2          2          2          2          2          1          1
                     1          1          0          0          0          0          0
                     0          0          0
ICL    2 1           2          2          2          2          2          2          2
                     2          2          2          2          2          1          1
                     1          1          0          0          0          0          0
                     0          0          0
DYSL   2 1    279.9000   254.5000   219.4000   164.1000   122.4000    46.1000     3.6900
                0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000
                0.0000     0.0000     0.0000     0.0000     0.0000    80.0000   174.8000
              225.0000   258.9000   278.1000
```

DSTEMP RUN 1 SPAWN CREEK AUGUST 29-30, 1974 DIURNAL **CALIBRATION** HOURLY INTERVALS

STREAM TEMPERATURES, ADVECTIVE HEAT SOURCES, AND HYDRAULIC DATA

INITIAL CONDITIONS TIME PT NO 1 DAY 241 HOUR 13.00

COMP PT NO	RIVER DISTANCE (MILES)	X-SECTN AREA (FT2)	TOP WIDTH (FT)	WETTED PERIM (FT)	HYDRAULIC SUB-RCH LENGTH (FT)	LATINF+ TRIBINF (FT2S-1)	GRDWTR INFLOW (FTS-1)	POINT LOAD (CFS)	STREAM -FLOW (CFS)	MET GP NO	INFLOW TEMPS LATIN TEMP (DF)	GWINF TEMP (DF)	PT LD TEMP (DF)	HEATEX /FT2 /DT (BTU)	STREAM TEMPS CALCULATED D/STM (DF)	U/STM (DF)	OBSER-VED (DF)
MAIN																	
1	0.00	3.17	7.00	8.00	2415.00	0.0000	.00000	0.00	4.01	1	0.00	0.00	0.00	0.	46.00		
2	0.40	4.58	6.50	7.00	2015.00	0.0000	.00000	0.00	4.37	1	0.00	0.00	0.00	0.	48.00		
3	0.78	2.39	4.20	5.20	100.00	0.0162	.00000	0.00	4.72	1	50.00	0.00	0.00	0.	50.00		
4	0.80	3.21	4.20	5.20	2240.00	0.0008	.00000	0.00	6.34	2	56.70	0.00	0.00	0.	50.00		50.00
5	1.23	3.29	5.50	6.70	2240.00	0.0008	.00000	0.00	8.50	2	56.70	0.00	0.00	0.	52.00		
6	1.65	6.21	9.40	10.00				0.00	10.66				0.00		54.00		54.00

DSTEMP RUN 1 SPAWN CREEK AUGUST 29-30, 1974 DIURNAL **CALIBRATION** HOURLY INTERVALS

COMPONENTS OF HEAT EXCHANGE AT STREAM SURFACE AND BED

TIME INTERVAL NO 1 SIZE DT= 1. HRS (DAY 241 HOUR 13.00 TO DAY 241 HOUR 14.00)

ALL UNITS ARE BTUFT-2 PER DT IN HRS

REACH NO	SOLAR RADIATION INCIDT	REFLEC	ABSORP	SURFACE COMPONENTS VEGTN RADTN INCIDT	VEGTN RADTN REFLEC	ATMOS RADTN INCIDT	ATMOS RADTN REFLEC	BACK RADTN	EVAP LHVAP	COND	SNOW LHFLS	SURF RENEW	BED COMPONENTS BEDAB SOLRD	BACK BECRD	BED COND	TOTALS SURF EXCHGE	BED EXCHGE
MAIN																	
1	140.	-11.	129.	0.	0.	116.	-3.	-110.	-71.	100.	0.	0.	0.	0.	0.	160.	0.
2	168.	-13.	155.	0.	0.	116.	-3.	-112.	-78.	95.	0.	0.	0.	0.	0.	172.	0.
3	266.	-21.	245.	0.	0.	116.	-3.	-112.	-81.	93.	0.	0.	0.	0.	0.	257.	0.
4	280.	-22.	258.	0.	0.	110.	-3.	-114.	-96.	71.	0.	0.	0.	0.	0.	224.	0.
5	280.	-22.	258.	0.	0.	110.	-3.	-115.	-112.	65.	0.	0.	0.	0.	0.	202.	0.

DSTEMP RUN 1 SPAWN CREEK AUGUST 29-30, 1974 DIURNAL **CALIBRATION** HOURLY INTERVALS

STREAM TEMPERATURES, ADVECTIVE HEAT SOURCES, AND HYDRAULIC DATA

TIME PT NO 2 DAY 241 HOUR 14.00

COMP PT NO	RIVER DISTANCE (MILES)	X-SECTN AREA (FT2)	TOP WIDTH (FT)	WETTED PERIM (FT)	HYDRAULIC SUB-RCH LENGTH (FT)	LATINF+ TRIBINF (FT2S-1)	GRDWTR INFLOW (FTS-1)	POINT LOAD (CFS)	STREAM -FLOW (CFS)	MET GP NO	INFLOW TEMPS LATIN TEMP (DF)	GWINF TEMP (DF)	PT LD TEMP (DF)	HEATEX /FT2 /DT (BTU)	STREAM TEMPS CALCULATED D/STM (DF)	U/STM (DF)	OBSER-VED (DF)
MAIN																	
1	0.00	3.17	7.00	8.00	2415.00	0.0000	.00002	0.00	4.01	1	0.00	48.70	0.00	160.	46.00		
2	0.40	4.58	6.50	7.00	2015.00	0.0000	.00003	0.00	4.37	1	0.00	48.70	0.00	172.	49.23		
3	0.78	2.39	4.20	5.20	100.00	0.0162	.00003	0.00	4.72	1	50.50	48.70	0.00	257.	49.66		
4	0.80	3.21	4.20	5.20	2240.00	0.0008	.00003	0.00	6.34	2	57.20	48.70	0.00	224.	50.23		50.50
5	1.23	3.29	5.50	6.70	2240.00	0.0008	.00002	0.00	8.50	2	57.20	48.70	0.00	202.	53.13		
6	1.65	6.21	9.40	10.00				0.00	10.66				0.00		54.70		54.50

DSTEMP RUN 1 SPAWN CREEK AUGUST 29-30, 1974 DIURNAL **CALIBRATION** HOURLY INTERVALS

COMPONENTS OF HEAT EXCHANGE AT STREAM SURFACE AND BED

TIME INTERVAL NO 2 SIZE DT= 1. HRS (DAY 241 HOUR 14.00 TO DAY 241 HOUR 15.00)

ALL UNITS ARE BTUFT-2 PER DT IN HRS

REACH NO	SOLAR RADIATION INCIDT	SOLAR RADIATION REFLEC	SOLAR RADIATION ABSORP	SURFACE COMPONENTS VEGTN RADTN INCIDT	VEGTN RADTN REFLEC	ATMOS RADTN INCIDT	ATMOS RADTN REFLEC	BACK RADTN	EVAP LHVAP	COND	SNOW LHFUS	SURF RENEW	BED COMPONENTS BEDAB SOLRD	BACK BECRD	BED COND	TOTALS SURF EXCHGE	BED EXCHGE
MAIN																	
1	127.	-1C.	117.	0.	0.	115.	-3.	-110.	-67.	88.	0.	0.	0.	0.	C.	139.	0.
2	153.	-12.	140.	0.	0.	115.	-3.	-112.	-74.	83.	0.	0.	0.	0.	0.	149.	0.
3	242.	-19.	222.	0.	0.	115.	-3.	-113.	-77.	81.	C.	0.	C.	0.	C.	226.	C.
4	255.	-2C.	234.	0.	0.	110.	-3.	-114.	-91.	64.	C.	0.	0.	0.	C.	200.	0.
5	255.	-20.	234.	0.	0.	110.	-3.	-116.	-104.	58.	0.	0.	0.	0.	C.	179.	C.

DSTEMP RUN 1 SPAWN CREEK AUGUST 29-30, 1974 DIURNAL **CALIBRATION** HOURLY INTERVALS

STREAM TEMPERATURES, ADVECTIVE HEAT SOURCES, AND HYDRAULIC DATA

TIME PT NO 3 DAY 241 HOUR 15.00

COMP PT NO	RIVER DISTANCE MILES	X-SECTN AREA FT2	TOP WIDTH FT	WETTED PERIM FT	HYDRAULIC SUB-RCH LENGTH FT	LATINF+ TRIBINF FT2S-1	GRDWTR INFLOW FTS-1	POINT LOAD CFS	STREAM-FLOW CFS	MET GP NO	INFLOW TEMPS LATIN TEMP DF	GWINF TEMP DF	PT LD TEMP DF	HEATEX /FT2 /DT BTU	STREAM TEMPS CALCULATED D/STM DF	CALCULATED U/STM DF	OBSERVED DF
MAIN																	
1	0.00	3.17	7.00	8.CC	2415.00	0.0000	.00002	0.00	4.01	1	0.00	48.70	C.00	139.	46.50		
2	0.40	4.58	5.50	7.0C	2015.00	0.0000	.00003	0.00	4.37	1	C.00	48.70	C.00	149.	48.84		
3	0.78	2.39	4.20	5.20	100.00	0.0162	.00003	0.00	4.72	1	50.50	48.70	0.00	226.	50.56		
4	0.80	3.21	4.20	5.20	2240.00	0.0008	.00003	0.00	6.34	2	57.60	48.70	0.00	200.	50.58		50.50
5	1.23	3.29	5.50	6.70	2240.00	0.0008	.00002	0.00	8.50	2	57.60	48.70	C.00	179.	52.82		
6	1.65	6.21	9.40	10.00				0.00	10.66				C.00		54.89		55.00

Note: These output tables continue through time point No. 25, day 242, hour 13:00.

4. Example of input and output (b) main stream and one tributary.

```
LISTING OF DATA

KRF                 5         1         0         0         0         0
NTAB                3         2
DT          [illegible]   24.0000
NB        [illegible]         3
NJUN                3
X    K1       50.0000   49.8100   49.4300   49.4300   49.0500
DDX  K1     1000.0000 2000.0000   10.0000 2000.0000
CSA  K1J1    100.0000  100.0000  100.0000  120.0000  120.0000
BD   K1J1     25.0000   25.0000   25.0000   26.0000   26.0000
PM   K1J1     33.0000   33.0000   33.0000   35.2300   35.2300
QS   K1J1    500.0000  500.0000  500.0000  600.0000  600.0000
ELVTK1J1    6000.0000 5999.0000 5997.0000 5997.0000 5995.0000
QL   K1J1      0.0000    0.0000   10.0000    0.0000
CSA  K1J2    100.0000  100.0000  100.0000  120.0000  120.0000
BD   K1J2     25.0000   25.0000   25.0000   25.0000   26.0000
PM   K1J2     33.0000   33.0000   33.0000   35.2300   35.2300
QS   K1J2    500.0000  500.0000  500.0000  600.0000  600.0000
ELVTK1J2    6000.0000 5999.0000 5997.0000 5997.0000 5995.0000
QL   K1J2      0.0000    0.0000   10.0000    0.0000
CSA  K1J3    100.0000  100.0000  100.0000  120.0000  120.0000
BD   K1J3     25.0000   25.0000   25.0000   26.0000   26.0000
PM   K1J3     33.0000   33.0000   33.0000   35.2300   35.2300
QS   K1J3    500.0000  500.0000  500.0000  600.0000  600.0000
ELVTK1J3    6000.0000 5999.0000 5997.0000 5997.0000 5995.0000
QL   K1J3      0.0000    0.0000   10.0000    0.0000
X    K2        0.7576    0.2941    0.0000
DDX  K2     2500.0000 1500.0000
CSA  K2J1     19.2000   19.6000   20.0000
BD   K2J1      9.6000    9.8000   10.0000
PM   K2J1     13.6000   13.8000   14.0000
QS   K2J1     96.0000   98.0000  100.0000
ELVTK2J1    6005.0000 6000.0000 5997.0000
QL   K2J1      0.0008    0.0013
CSA  K2J2     19.2000   19.6000   20.0000
BD   K2J2      9.6000    9.8000   10.0000
PM   K2J2     13.6000   13.8000   14.0000
QS   K2J2     96.0000   98.0000  100.0000
ELVTK2J2    6005.0000 6000.0000 5997.0000
QL   K2J2      0.0008    0.0013
CSA  K2J3     19.2000   19.6000   20.0000
BD   K2J3      9.6000    9.8000   10.0000
PM   K2J3     13.6000   13.8000   14.0000
QS   K2J3     96.0000   98.0000  100.0000
ELVTK2J3    6005.0000 6000.0000 5997.0000
QL   K2J3      0.0008    0.0013
MAIN & TRIBUTARY DUMMY DEBUGGING DATA

        MILES        FT2       FT        FT             FT   FT2S-1   FTS-1      CFS        CFS
  CF     BF     DF   BTU       DF        DF       DF
IOFT     1           1         0                  1          1          1          1          0
                     0         0                  0
PRCP     1    62.3170         0.9988 1053.0000  143.5000     0.0300     0.0000     0.0000
               0.0000
TIME                222   21.0000   40.0000    0.4667     0.0000     0.0000
COEF     1      0.550   429.000       0.100.27900E-03.17100E-08    0.0000
COEF     2     0.0000    0.0000    0.0000    0.0000
IOGT                0         1         0         1
TL   K1        0.0000    0.0000    0.0000
```

```
TL   K2            70.0000   70.0000   70.0000
TSICK1L1           77.0000   77.0000   77.0000   77.0000   77.0000
TSICK1L2           77.0000   77.0000   77.0000   77.0000   77.0000
TSICK2L1           77.0000   77.0000   77.0000
TSICK2L2           77.0000   77.0000   77.0000
TSLSK1L1           77.0000   75.0000   79.0000
TSLSK2L1           77.0000   75.0000   79.0000
QP    1 5         100.0000  100.0000  100.0000
TP    1 5         100.0000  100.0000  100.0000
NOT                      0
AA          1       0.7400    0.7500    0.7600    0.7710    0.7830    0.7930    0.8000
                    0.8100    0.8250    0.8450    0.8660
BB          1       0.1500    0.1500    0.1500    0.1430    0.1380    0.1370    0.1350
                    0.1300    0.1200    0.1050    0.0900
TE                 50.0000   68.0000   86.0000
ES1                -0.1380   -0.5480   -1.4400   -3.1330
ES2                 0.0098    0.0180    0.0312    0.0509
ALSRK1              0.0000   20.0000   20.0000   20.0000
ALSSK1              5.0000    5.0000    5.0000    5.0000
GRCRK1              0.2000    0.2000    0.2000    0.2000
BLECK1              0.2000    0.2000    0.2000    0.2000
ALSRK2             20.0000   10.0000
ALSSK2             10.0000   10.0000
GRCRK2              0.2000    0.2000
BLCCK2              0.0500    0.0500
NG                       2         1
IO                       0         0         0         0         1         1
NRC  K1                  1         2         2         2
NRC  K2                  1         2
TA   G1            50.0000   80.0000
TD   G1            50.0000   70.0000
ATFRG1             29.5000   29.5000
WDVEG1             10.0000    5.0000
ICS  G1                  5         3
ICL  G1                  4         2
TA   G2            55.0000   75.0000
TD   G2            45.0000   65.0000
ATFRG2             29.5000   29.5000
WDVEG2             10.0000    5.0000
ICS  G2                  6         4
ICL  G2                  5         3
```

MAIN & TRIBUTARY DUMMY DEBUGGING DATA

STREAM TEMPERATURES, ADVECTIVE HEAT SOURCES, AND HYDRAULIC DATA

INITIAL CONDITIONS TIME PT NO 1 DAY 222 HOUR 21.00

COMP PT NO	RIVER DISTANCE MILES	X-SECTN AREA FT2	TOP WIDTH FT	WETTED PERIM FT	SUBREACH LENGTH FT	LATINF+ TRIBINF FT2S-1	GRDWTR INFLOW FT3-1	POINT LOAD CFS	STREAM -FLOW CFS	WET CP NO	LATIN TEMP DF	GWINF TEMP DF	PT LD TEMP DF	HEATEX /FT2 /DT BTU	CALCULATED D/STM DF	CALCULATED U/STM DF	OBSER -VED DF
MAIN																	
1	50.00	100.00	25.00	33.00	1000.00	0.0000	.00000	0.00	500.00	1	0.00	0.00	0.00	C.	77.00		
2	49.81	100.00	25.00	33.00	2000.00	0.0000	.00000	0.00	500.00	2	0.00	0.00	0.00	C.	77.00		
3	49.43	100.00	25.00	33.00	10.00	10.0000	.00000	0.00	500.00	2	77.00	0.00	0.00	C.	77.00		
TRIB1																	
1	0.76	19.20	9.60	13.60	2500.00	0.0004	.00000	0.00	96.00	1	70.00	0.00	0.00	C.	77.00		
2	0.28	19.60	9.80	13.80	1500.00	0.0013	.00000	0.00	98.00	2	70.00	0.00	0.00	C.	77.00		
3	0.00	20.00	10.00	14.00				0.00	100.00				0.00		77.00		
MAIN																	
4	49.43	120.00	25.00	35.23	2000.00	0.0000	.00000	0.00	600.00	2	0.00	0.00	0.00	C.	77.00		
5	49.05	120.00	26.00	35.23				100.00	600.00				100.00		77.00	77.00	

MAIN & TRIBUTARY DUMMY DEBUGGING DATA

COMPONENTS OF HEAT EXCHANGE AT STREAM SURFACE AND BED

TIME INTERVAL NO 1 SIZE DT= 3. HRS (DAY 222 HOUR 21.00 TO DAY 222 HOUR 24.00)

ALL UNITS ARE BTUFT-2 PER DT IN HRS

REACH NO	SOLAR RADIATION INCIDT	SOLAR RADIATION REFLEC	SOLAR RADIATION ABSORP	VEGTN RADTN INCIDT	VEGTN RADTN REFLEC	ATMOS RADTN INCIDT	ATMOS RADTN REFLEC	BACK RADTN	EVAP LHVAP	COND	SNOW LHFUS	SURF RENEW	BED COMPONENTS BEDAB SOLRD	BED COMPONENTS BACK BEDRD	BED COMPONENTS BED COND	TOTALS SURF EXCHGE	TOTALS BED EXCHGE
TRIB1																	
1	0.	0.	0.	0.	0.	312.	-9.	-409.	-309.	-86.	C.	0.	0.	0.	0.	-502.	C.
2	0.	C.	0.	0.	0.	300.	-9.	-409.	-340.	-112.	C.	0.	0.	0.	0.	-570.	0.
MAIN																	
1	0.	0.	0.	0.	0.	312.	-9.	-410.	-311.	-87.	C.	0.	C.	0.	0.	-505.	0.
2	0.	C.	0.	0.	0.	300.	-9.	-410.	-345.	-114.	C.	0.	0.	0.	0.	-577.	0.
3	0.	0.	0.	0.	0.	300.	-9.	-409.	-344.	-114.	C.	0.	0.	0.	0.	-576.	0.
4	0.	0.	0.	0.	0.	300.	-9.	-409.	-344.	-113.	0.	0.	0.	0.	C.	-575.	0.

MAIN & TRIBUTARY [illegible] DATA

STREAM TEMPERATURES, [illegible] HEAT [illegible] AND HYDRAULIC DATA

TIME PT NO [illegible] DAY [illegible]

COMP PT NO	RIVER DISTANCE MILES	X-SECTN AREA FT2	TOP WIDTH FT	WETTED PERIM FT	SUBREACH LENGTH FT	LATINF+ TRIBINF FT2S-1	GRDWTR INFLOW FT3-1	POINT LOAD CFS	STREAM -FLOW CFS	WET CP NO	LATIN TEMP DF	GWINF TEMP DF	PT LD TEMP DF	HEATEX /FT2 /DT BTU	CALCULATED D/STM DF	CALCULATED U/STM DF	OBSER -VED DF
MAIN																	
1	50.00	100.00	25.00	33.00	1000.00	0.0000	.00000	0.00	500.00	1	0.00	0.00	0.00	-505.	75.00		
2	49.81	100.00	25.00	33.00	2000.00	0.0000	.00000	0.00	500.00	2	0.00	0.00	0.00	-577.	75.00		
3	49.43	100.00	25.00	33.00	10.00	10.0000	.00000	0.00	500.00	2	74.32	0.00	0.00	-576.	74.98		
TRIB1																	
1	0.76	19.20	9.60	13.60	2500.00	0.0004	.00000	0.00	96.00	1	70.00	0.00	0.00	-502.	75.00		
2	0.28	19.60	9.80	13.80	1500.00	0.0013	.00000	0.00	98.00	2	70.00	0.00	0.00	-570.	74.63		
3	0.00	20.00	10.00	14.00				0.00	100.00				0.00		74.32		
MAIN																	
4	49.43	120.00	26.00	35.23	2000.00	0.0000	.00000	0.00	600.00	2	0.00	0.00	0.00	-575.	74.87		
5	49.05	120.00	26.00	35.23				100.00	600.00				100.00		78.47	74.88	

MAIN & TRIBUTARY DUMMY DEBUGGING DATA

COMPONENTS OF HEAT EXCHANGE AT STREAM SURFACE AND BED

TIME INTERVAL NO 2 SIZE DT= 24. HRS (DAY 222 HOUR 24.00 TO DAY 223 HOUR 24.00)

ALL UNITS ARE BTUFT-2 PER DT IN HRS

REACH NO	SOLAR RADIATION INCIDT	SOLAR RADIATION REFLEC	SOLAR RADIATION ABSORP	SURFACE COMPONENTS VEGTN RADTN INCIDT	VEGTN RADTN REFLEC	ATMOS RADTN INCIDT	ATMOS RADTN REFLEC	BACK RADTN	EVAP LHVAP	COND	SNOW LHFUS	SURF RENEW	BED COMPONENTS BEDAB SOLRD	BACK BECRD	BED COND	TOTALS SURF EXCHGE	BED EXCHGE
TRIB1																	
1	1412.	-90.	1322.	0.	0.	3032.	-91.	-3309.	-497.	63.	0.	0.	0.	0.	0.	518.	0.
2	1384.	-92.	1293.	0.	0.	2884.	-87.	-3305.	-746.	-43.	0.	0.	0.	0.	0.	-3.	0.
MAIN																	
1	1247.	-88.	1159.	0.	0.	3032.	-91.	-3310.	-504.	61.	0.	0.	0.	0.	0.	347.	0.
2	1140.	-74.	1066.	0.	0.	2884.	-87.	-3310.	-760.	-48.	0.	0.	0.	0.	0.	-254.	0.
3	1140.	-74.	1066.	0.	0.	2884.	-87.	-3309.	-757.	-47.	0.	0.	0.	0.	0.	-250.	0.
4	1140.	-74.	1066.	0.	0.	2884.	-87.	-3308.	-755.	-46.	0.	0.	0.	0.	0.	-246.	0.

MAIN & TRIBUTARY DUMMY DEBUGGING DATA

STREAM TEMPERATURES, ADVECTIVE HEAT SOURCES, AND HYDRAULIC DATA

TIME PT NO 3 DAY 223 HOUR 24.00

COMP PT NO	RIVER DISTANCE MILES	X-SECTN AREA FT2	HYDRAULIC TOP WIDTH FT	WETTED PERIM FT	SUB-RCH LENGTH FT	LATINF+ TRIBINF FT2S-1	GRDWTR INFLOW FTS-1	POINT LOAD CFS	STREAM -FLOW CFS	MET GP NO	INFLOW TEMPS LATIN TEMP DF	GWINF TEMP DF	PT LD TEMP DF	HEATEX /FT2 /DT BTU	STREAM TEMPS CALCULATED D/STM DF	U/STM DF	OBSER -VED DF
MAIN																	
1	50.00	100.00	25.00	33.00	1000.00	0.0000	.00000	0.00	500.00	1	0.00	0.00	0.00	347.	79.00		
2	49.81	100.00	25.00	33.00	2000.00	0.0000	.00000	0.00	500.00	2	0.00	0.00	0.00	-254.	78.99		
3	49.43	100.00	25.00	33.00	10.00	10.0000	.00000	0.00	500.00	2	79.01	0.00	0.00	-250.	78.96		
TRIB1																	
1	0.76	19.20	9.60	13.60	2500.00	0.0008	.00000	0.00	96.00	1	70.00	0.00	0.00	518.	79.00		
2	0.28	19.60	9.80	13.80	1500.00	0.0013	.00000	0.00	98.00	2	70.00	0.00	0.00	-3.	79.04		
3	0.00	20.00	10.00	14.00				0.00	100.00				0.00		79.01		
MAIN																	
4	49.43	120.00	26.00	35.23	2000.00	0.0000	.00000	0.00	600.00	2	0.00	0.00	0.00	-246.	78.97		
5	49.05	120.00	26.00	35.23				100.00	600.00				100.00		81.93	78.92	